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Testing of High Current By-pass Diodes for the LHC Magnet Quench Protection

V. Berland, D. Hagedorn, F. Rodriguez-Mateos

Within the framework of the Large Hadron Collider (LHC) R&D programme, CERN is performing experiments to establish the current carrying capability of irradiated diodes at liquid Helium temperatures for the superconducting magnet protection. Even if the diodes are degraded by radiation dose and neutron fluence, they must be able to support the by-pass current during a magnet quench and the de-excitation of the superconducting magnet ring. During this discharge, the current in the diode reaches a maximum value up to 13 kA and decreases with an exponential time constant of 100 s. Two sets of 75 mm wafer diameter epitaxial diodes, one irradiated and one non-irradiated, were submitted to this experiment. The irradiated diodes have been exposed to radiation in the accelerator environment up to 20 kGy and then annealed at room temperature. After the radiation exposure the diodes had shown a degradation of forward voltage of 50% which reduced to about 14% after the thermal annealing. During the long duration high current tests, one of the diodes was destroyed and the other two irradiated diodes showed a different

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Abstract **: Within the framework of the Large Hadron Collider (LHC) R&D programme, CERN is performing experiments to establish the current carrying capability of irradiated diodes at liquid Helium temperatures for the superconducting magnet protection. Even if the diodes are degraded by radiation dose and neutron fluence, they must be able to support the by-pass current during a magnet quench and the de-excitation of the superconducting magnet ring. During this discharge, the current in the diode reaches a maximum value up to 13 kA and decreases with an exponential time constant of 100 sec. Two sets of 75 mm wafer diameter epitaxial diodes, one irradiated and one non-irradiated, were submitted to this experiment. The irradiated diodes have been exposed to radiation in the accelerator environment up to 20 kGy and then annealed at room temperature. After the radiation exposure the diodes had shown a degradation of forward voltage of 50 % which reduced to about 14 % after the thermal annealing. During the long duration high current tests, one of the diodes was destroyed and the other two irradiated diodes showed a different behaviour compared with non-irradiated diodes.**

I. Introduction

The quench protection of the main ring dipole and quadruple magnet for the proposed Large Hadron Collider at CERN is based on self-protected magnet and high current by-pass diodes. There is no practical way to extract a major fraction of the stored energy from the quenching magnet, which is in a series chain of magnets. Self protection of the magnet is achieved by stainless steel heater strips mounted on the outer layers of each magnet. As soon as a quench is detected, capacitors are discharged through the heaters and the increasing resistance of the quenching magnet causes the magnet current to commutate over to the by-pass diodes. These are mounted inside the He II vessel in order to reduce the heat load on the cryogenic system caused by safety leads. The copper blocks, mounted on each side of the diode and acting as heat sinks and current connections, have to absorb an energy of about 1.5 MJ, when the whole magnet ring is de-energised with a time constant of about 100 s.

The results presented in this paper are related to the behaviour of diodes submitted to a high pulse current corresponding to the current discharge of the machine during magnet quench [1,2]. The tests were made with non-irradiated diodes and with irradiated diodes at liquid Helium temperature.

A. Devices under test

The endurance tests are performed on 75 mm diameter diode samples manufactured by Siemens (EUPEC : E) and GEC-Plessey (M) with 22 µm epitaxial layer. Diodes N° E8, E16, E22 and M1, M2, M3 are not irradiated and diodes N° E6, E13, E17 were irradiated in the SPS accelerator up to a total dose of 20 kGy . Afterward, they were annealed at room temperature.
Three diodes are stacked together and separated by Cu-heat sinks. Platinum sensors are mounted in each heat sink to measure the temperature inside the copper. On each diode there are two electrodes corresponding to the Cathode and to the Anode. The diodes are clamped under a force of 42 kN to assure the electrical and thermal contact. Electrodes at both edges of the heat sink allow us to measure the contact resistance between each heat sink and the corresponding diode electrode (cathode or anode). All diodes are characterised by their forward and reverse voltage before and after irradiation and before and after the endurance tests [3].

B. Test procedure

A 20 kA, 10 V computer controlled power supply provides the required current pulse. The initial current I_0 and the time constant τ could be changed. In our case τ is equal to 100 s, and I_0 varies between 5 kA and 14 kA. Due to the high current and the long time constant, the internal diode temperature increases rapidly during the first 30 seconds following the peak current I_0. This temperature increase creates a decrease of the forward voltage due to the moving of the forward current/voltage characteristics towards lower voltages. Shortly after, the temperature stabilises (stationary state) and the forward voltage stays constant.

The non-irradiated diodes (E8, E16, E22 and M1, M2, M3) are submitted to 100 s time constant exponential currents with I_0 = 5 kA, 10 kA and five times with I_0 = 14 kA. On the irradiated diodes (E6, E13, E17), currents of I_0 = 5 kA, 10 kA, 12 kA, 13 kA, and five times 14 kA were applied. Afterwards reverse and forward voltages were measured to verify if the endurance tests had affected the characteristics of the diodes.

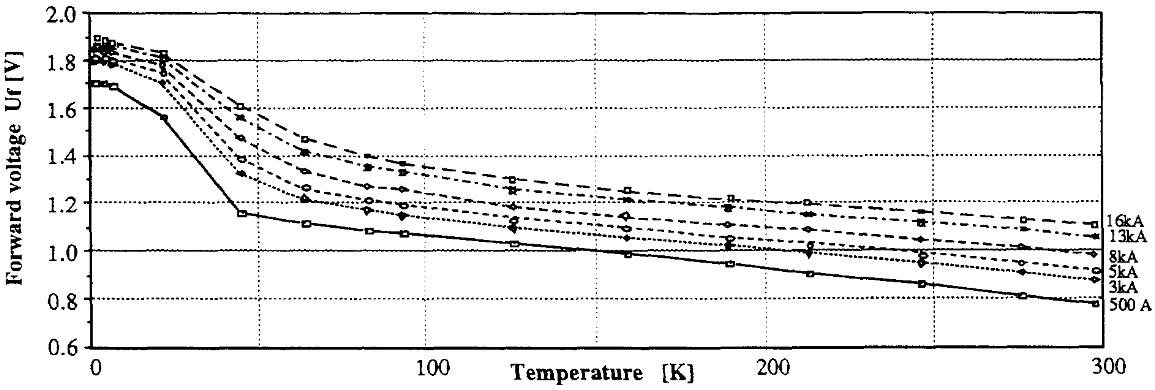

Fig. 1. Typical $U_f(T)$ for different forward currents for 75 mm Ø and 22μm epitaxial layer thickness diodes.

II. Diode wafer temperature

A. Forward characteristics at different temperatures

As the endurance test passes high current in the diodes, it is important to be able to determine the wafer temperature during this test. By measuring the forward characteristics $I_f(U_f)$ at different temperatures (from 1.8 K to 300 K), it has been established that the forward voltage $U_f(I)$ (I is a fixed current) varies nearly linear with temperature T in the range of 70 K to 300 K : $U_f(T,I) = a(I)T + b(I)$. The diode itself is used as a thermometer. Figure 1 gives an example of curves $U_f(T)$ for different currents and T varying between 2 K and 300 K.

B. Internal temperature during endurance test

The I_f vs. U_f characteristics of each diode are measured at 77 K and about 300 K. Then, by a linear interpolation 70 - 300 K, we can determine the family of $U_f(T,I)$ curves relative to the tested diodes and similar to those plotted in figure 1.

During the endurance test the diode voltage and the applied exponential current are measured. The wafer temperature is derived in the range of 70 K and 300 K with an estimated relative error of ± 5 K.

III. Results

A. Non-irradiated diodes

The figure 2 is a plot of the applied current I_f and the forward voltage U_f obtained during the last endurance high current test for the non-irradiated Eupec and GEC-Plessey diodes (with I_0 = 14 kA and τ = 100 s).

1) Eupec diodes :

The behaviour of the three Eupec diodes is similar. At the turn-on current, the diode presents a voltage peak of about 1.6 V. The diode voltage then decreases slowly due to the temperature increase, and reaches a saturated value of about 1 V. We have derived the diode internal temperature using the function $U_f(T,I)$. The obtained temperature curve is plotted on the figure 3. A maximum of temperature of about 230 K is reached after 30 s. This is due to the high level of the applied current at the beginning of the test. Then, as the current decreases, the temperature inside the diode decreases and stays fairly constant at around 180 K. The results obtained for the previous runs with I_0 = 14 kA were identical. We can conclude that the endurance tests for I_0 = 14 kA did not affect the three diodes and are reproducible.

2) GEC-Plessey diodes :

The three GEC-Plessey diodes show similar results. After the turn-on current, the forward voltage is about 1.1 V. In the same time, the diode temperature increases up to 350 K, which is much more than for Eupec diodes. This is attributed to the internal resistance which is much more important in GEC-Plessey diodes than in Eupec ones. After this maximum internal temperature, voltage and temperature decrease to 0.9 V and 280 K respectively. The saturated forward voltage is intrinsic to the diode and depends on the temperature. That explains why the forward voltage saturates at a lower value than for forward voltage in the case of the Eupec diode.

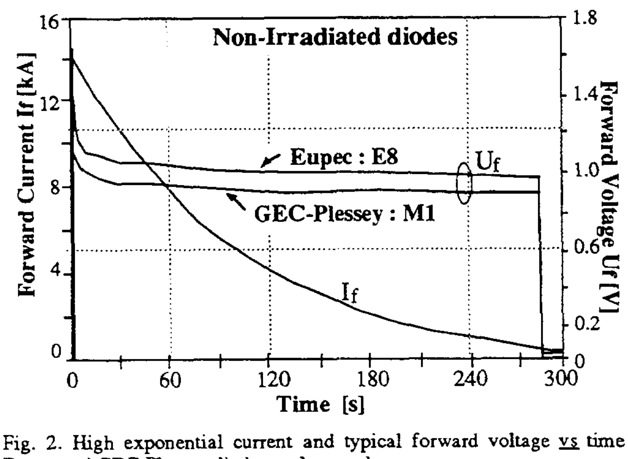

Fig. 2. High exponential current and typical forward voltage vs time : Eupec and GEC-Plessey diode results are shown.

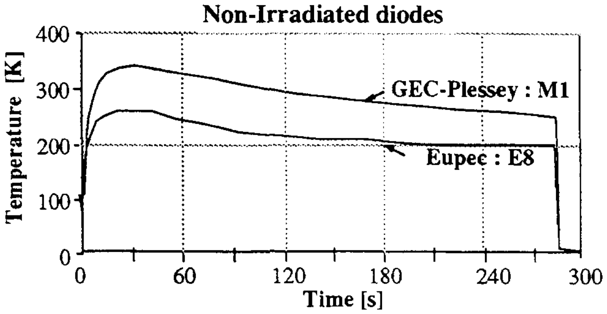

Fig. 3. Internal diode temperature vs time.

B. Irradiated diodes

Before the endurance tests, the diodes were degraded by the radiation dose. They were thermally annealed : afterwards the residual degradation in the forward voltage is about 14 % (Fig. 4). The E13 and E17 diodes behave somewhat differently from the non-irradiated diodes. The diode E6 shows a significantly different behaviour.

A detailed analysis of the results of the diodes E13 and E17 shows that the behaviour becomes significant during the third run (I_0 = 12 kA). A turn-on voltage of about 1.8 V is observed and immediately afterwards a decrease down to 1.3 V (t = 5 s). Then, the voltage slightly increases again. This second maximum value appears at a time of around 30 s, corresponding to the time the maximum value was reached for the non-irradiated diodes. Afterwards, the forward voltage decreases as in the non-irradiated diode case to about 1 V. This behaviour is observed for all of the next runs. Concerning the temperature inside the diodes, and considering the five last runs (I_0 = 14 kA), the first maximum temperature is about 200 K. After 30 s, the temperature slowly increases up to 330 K. The forward voltage and the internal temperature are drawn on the figure 5 for the E13 diode.

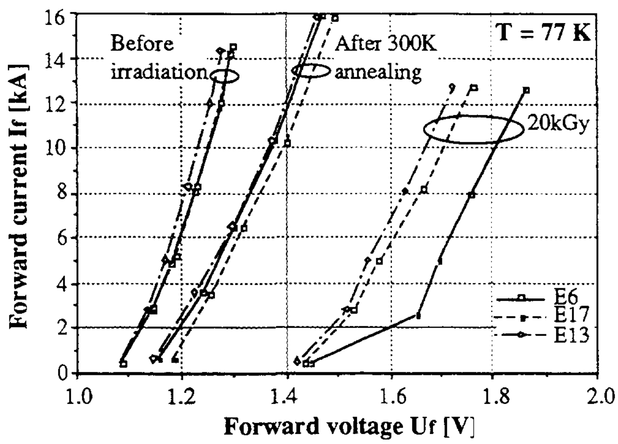

Fig. 4. Forward voltage degradation after 20 kGy total dose and after the annealing.

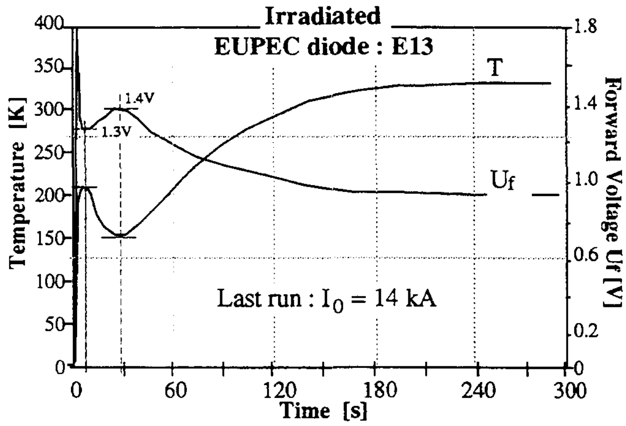

Fig. 5. Internal diode temperature and forward voltage during the last endurance test performed on an irradiated Eupec diode.

The E6 diode fails during the sixth run. The previous runs already show some failure signs. The temperature calculation method is no longer valid since the calibration has changed. The forward voltage results are shown in the figure 6. For the third run (I_0 = 12 kA), there is already a strange behaviour that becomes worst for the following runs. Run 8 and 9 (I_0 = 14 kA) show very dispersed values and finally, the diode forward voltage drops down to 0.4 V.

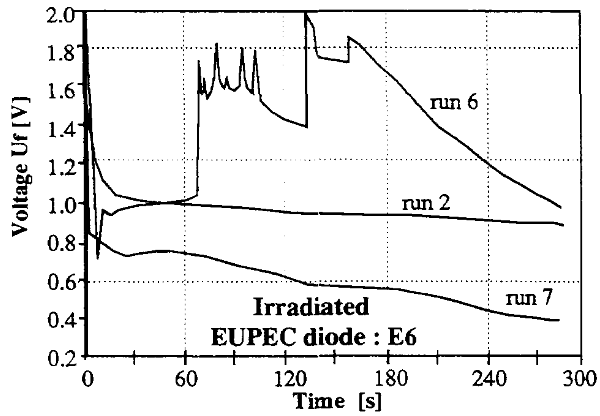

Fig. 6. Forward voltage of the E6 diode during run 2, run 6 and run 7 : failure appears at run 6.

IV. Electrical Measurements after Endurance Tests

A. Forward and reverse Current/Voltage characteristics

1) EUPEC non-irradiated diodes

The electrical characteristics of Eupec diode (forward and reverse current/voltage $I_f(U_f)$ and $I_r(U_r)$ [3]) measured at 77 K for non-irradiated diodes after the endurance tests are the same as the measurements performed before the endurance tests. We can conclude that the high current endurance tests have not affected the electrical performances of the devices.

2) GEC-Plessey non-irradiated diodes

After the endurance test, we have noticed on GEC-Plessey non-irradiated diodes (M1, M2 and M3) that the forward current/voltage characteristics were not changed but that reverse current/voltage characteristics showed a short circuit behaviour. No more reverse voltage was obtained and the equivalent resistance in reverse bias was about 4 to 15 Ω. The origin of this failure in reverse voltage will be investigated.

3) Eupec irradiated diodes

Concerning the irradiated diodes, the E13 and E17 diodes present the same characteristics as before the endurance test in forward and in reverse voltages. The case of the destroyed E6 diode is different since it shows zero reverse voltage and a high forward voltage. After the diode was opened, it was observed that the diode was burned out ; the silicon wafer was melted and one of the molybdenum disks displaced. An imperfect packaging before testing can not be excluded. Equally, it can not be excluded that the degradation in U_f (increase) due to irradiation is the origin of the destruction during the endurance test. As we have no endurance test results before irradiation on this sample, it is difficult to have a precise idea of the source of this failure.

B. Electrical contact resistance

During the endurance test, the electrical contacts between the heatsinks and the diodes increase due to the electrical copper resistivity and the contact pressure both varying with temperature. The contacts are characterised by their equivalent resistance. As observed in figure 7, this resistance increases during the endurance test. The copper resistance increase is not significant since it varies from 9×10^{-9} Ω (at 4.2 K) to about 2×10^{-8} Ω (at 200 K). The contact itself increases during endurance test (non-homogeneous pressure on the whole surface, radial temperature gradient). The heatsink temperature obtained from the Platinum thermometer is shown in figure 8 for non-irradiated and irradiated diodes. It increases and reaches a maximum value of 180 K for non-irradiated diodes and of 220 K for irradiated diodes.

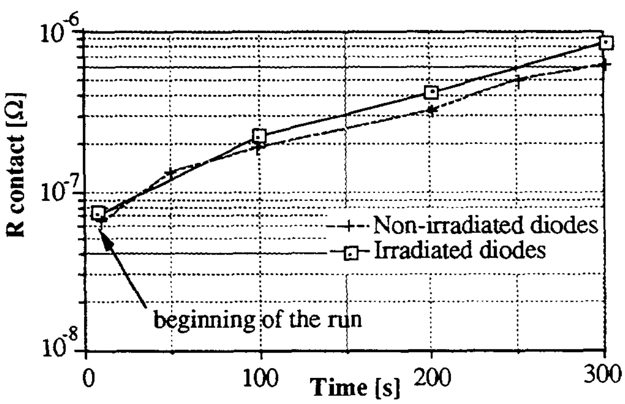

Fig. 7. Contact resistance evolution during 14 kA endurance high current test .

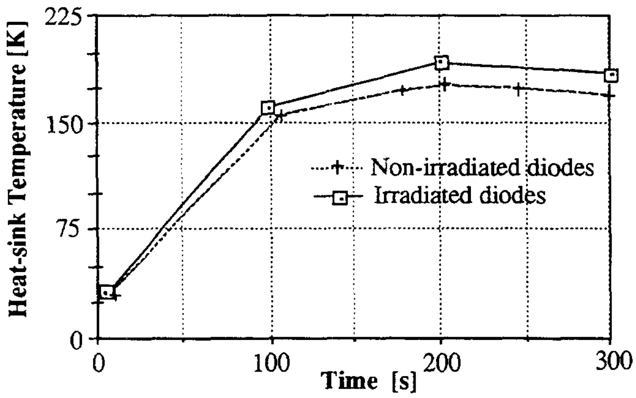

Fig. 8. Heatsink temperature during endurance high current test : I_0 = 14 kA.

V. Conclusion

The exponential current decaying with a time constant of 100 causes a temperature increase in the silicon wafer.

At the maximum current of 14 kA, the internal temperature in the wafer reaches a maximum of around **250 K** for the non-irradiated diodes and **330 K** for the irradiated ones. By measuring the $I_f(U_f)$-characteristics at 77 K and 300 K, it is possible to use the diode itself as temperature sensor and to monitor the wafer temperature during high current cycling tests (endurance tests).

The radiation degradation affects the endurance test diode behaviour. One of the irradiated diodes (E6) did not survive the successive tests after 13 kA. The reason for its destruction is still unknown. An imperfect package or degradation of U_f due to the irradiation could be the origin of the destruction and the displacement of the disc.

For a final conclusion as to whether a degradation in U_f of about 14% or more due to irradiation could lead to a destruction of the diode, further endurance tests on diodes irradiated up to 35 kGy must be carried out.

Acknowledgment

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