EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 688

RADIATION RESISTANCE AND LIFE TIME ESTIMATES AT CRYOGENIC TEMPERATURES OF SERIES PRODUCED BY-PASS DIODES FOR THE LHC MAGNET PROTECTION

R. Denz, A.Gharib, D. Hagedorn

Abstract

For the protection of the LHC superconducting magnets about 2100 specially developed by-pass diodes have been manufactured in industry and more than one thousand of these diodes have been mounted into stacks and tested in liquid helium.
By-pass diode samples, taken from the series production, have been submitted to irradiation tests at cryogenic temperatures together with some prototype diodes up to an accumulated dose of about 2 kGy and neutron fluences up to about $3.0\ 10^{13}$ n cm^{-2} with and without intermediate warm up to 300 K.
The device characteristics of the diodes under forward bias and reverse bias have been measured at 77 K and ambient versus dose and the results are presented.
Using a thermo-electrical model and new estimates for the expected dose in the LHC, the expected lifetime of the by-pass diodes has been estimated for various positions in the LHC arcs.
It turns out that for all of the by-pass diodes across the arc elements the radiation resistance is largely sufficient. In the dispersion suppresser regions of the LHC, on a few diodes annual annealing during the shut down of the LHC must be applied or those diodes may need to be replaced after some time.

Accelerator Technology Department

Presented at the 2003 Cryogenic Engineering Conference and International Cryogenic Materials Conference
CEC/ICMC 2003
22-26 September 2003, Anchorage, Alaska

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 29 January 2004

RADIATION RESISTANCE AND LIFE TIME ESTIMATES AT CRYOGENIC TEMPERATURES OF SERIES PRODUCED BY-PASS DIODES FOR THE LHC MAGNET PROTECTION

R. Denz, A.Gharib, D. Hagedorn

CERN, CH-1211 Geneva 23, Switzerland

ABSTRACT

For the protection of the LHC superconducting magnets about 2100 specially developed by-pass diodes have been manufactured in industry and more than one thousand of these diodes have been mounted into stacks and tested in liquid helium.

By-pass diode samples, taken from the series production, have been submitted to irradiation tests at cryogenic temperatures together with some prototype diodes up to an accumulated dose of about 2 kGy and neutron fluences up to about 3.0 10^{13} n cm^{-2} with and without intermediate warm up to 300 K.

The device characteristics of the diodes under forward bias and reverse bias have been measured at 77 K and ambient versus dose and the results are presented.

Using a thermo-electrical model and new estimates for the expected dose in the LHC, the expected lifetime of the by-pass diodes has been estimated for various positions in the LHC arcs.

It turns out that for all of the by-pass diodes across the arc elements the radiation resistance is largely sufficient. In the dispersion suppresser regions of the LHC, on a few diodes annual annealing during the shut down of the LHC must be applied or those diodes may need to be replaced after some time.

INTRODUCTION

In the LHC specially developed high current diodes of the diffusion type will be used as by-pass elements in case of a magnet quench. These diodes are installed inside the magnet cryostat relatively close to the beam and are exposed to radiation resulting from beam-gas interactions and proton losses.

The development of these series diodes of the diffusion type is a result from testing numerous prototype and pre-series diodes during which a compromise had to be found between the required radiation resistance, the highest possible reverse blocking voltage, and a reasonable yield for the mass production in industry. The manufacturing challenge was to achieve the necessary process control to meet the narrow n-base which is required for a radiation resistant device [1].

Recent estimations indicate that maximum irradiation level occurs in the dispersion suppresser region of the LHC [1-2]. For the diodes installed on quadrupoles, the maximum dose of about 2700 Gy during 20 years is expected whereas the maximum neutron fluence of about 2.0 10^{13} n cm^{-2} will occur on the dipole diodes in this region.

Each diode package must be able to conduct an ultimate current pulse of 13 kA peak with a nominal decay time constant of about 105 s for the dipole diode and of about 50 s for the quadrupole diode respectively. The heat sinks for the dipole diode package have to absorb an energy of about 1.4 MJ, the heat sinks for one quadrupole diode an energy of about 0.7 MJ. The diodes must operate within a temperature range of 1.8 K - 450 K, withstand the associated thermal stresses, and continue to operate reliably after several cold-warm cycles (endurance tests) before final installation.

In earlier tests it has been observed that diodes irradiated at liquid helium temperature and at liquid nitrogen temperature show the same trend as regards irradiation hardness [3]. Furthermore, annealing tests have demonstrated that the effect of annealing on the forward bias characteristics by warm up from 4.2 K to 77 K is negligibly small [4]. It has also been shown that the knowledge of the forward bias characteristics at 77 K and 300 K and the application of a simple interpolation algorithm based on the pn-junction theory are sufficient to use the diode proper as thermometer in the temperature range from 77 K up to about 450 K [3].

For the simulation of the temperature transients inside the irradiated diode and adjacent heat sinks the electro-thermal model described elsewhere was used [3].

IRRADIATION PROCEDURE

Eight 75 mm diameter diffusion power diodes, specially manufactured by DYNEX SEMICONDUCTOR Ltd (GB) were submitted to irradiation tests at liquid nitrogen temperature in the north area target zone (TCC2) of the CERN SPS accelerator. Six of the 8 diodes were taken from the series production and two of them were prototype diodes irradiated for comparison. The diode samples were exposed in 4 steps to a maximum dose of about 2 kGy corresponding to a fast neutron fluence (equivalent to 1 MeV) of about 2.8 10^{13} cm^{-2} as shown in TABLE 1. After each irradiation step, the device characteristics under forward bias and reverse bias were measured at 77 K.

Four out of eight diodes samples (set 1) were kept at 77 K until the end of the campaign,

TABLE 1. Absorbed doses and neutron fluences in the two dewars irradiated in TCC2 at CERN.Doses and fluences have been monitored with an accuracy of about ± 30 % and ± 50 % respectively.

Irradiation step	Protons on T4 [1.0 10^{17}]	Dewar 1 Dose [Gy)]	Dewar 1 Fluence [n cm^{-2}]	Dewar 2 Dose [Gy]	Dewar 2 Fluence [n cm^{-2}]
1	3.69	560	7.0 10^{12}	600	7.0 10^{12}
2	3.60	450	6.0 10^{12}	380	6.0 10^{12}
3	3.36	480	6.4 10^{12}	410	6.4 10^{12}
4	3.44	500	8.5 10^{12}	420	8.5 10^{12}
Total :	**14.1**	**1990**	**2.8 10^{13}**	**1810**	**2.8 10^{13}**

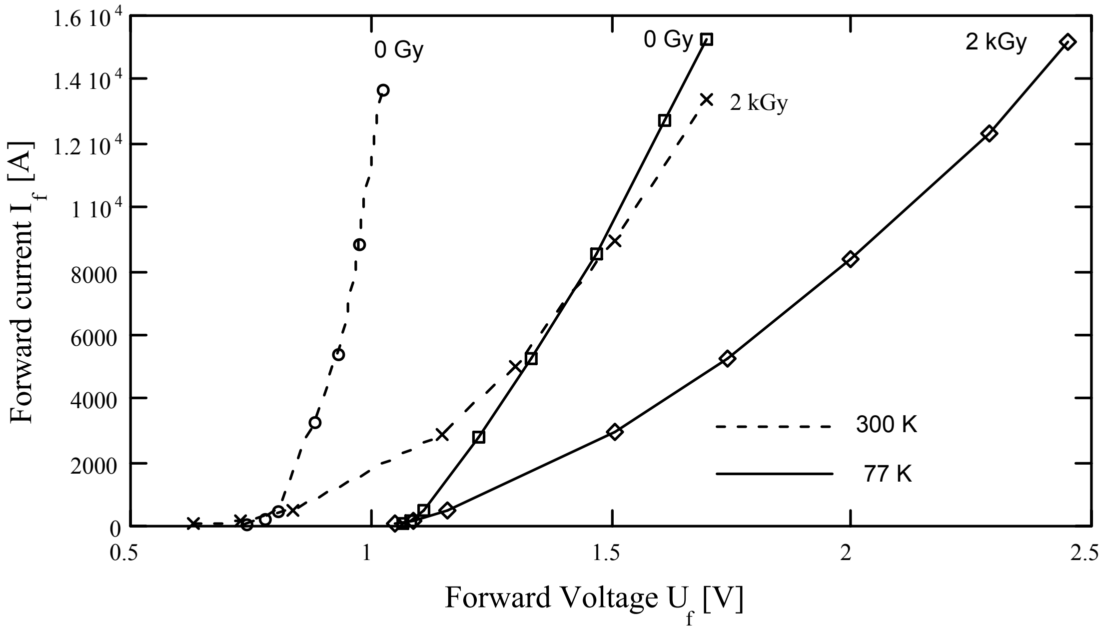

FIGURE 1. Typical forward bias current-voltage characteristics measured at 77 K and 300 K (dotted line) before and after irradiation up to 2 kGy of a series diode sample without intermediate warm up.

after which the electrical characteristics were also measured at 300 K.

The other four diode samples (set 2) were warmed up to about 300 K (annealed) after each irradiation step and the electrical characteristics were measured in order to study the effect of partial annealing of the irradiation induced effects.

FORWARD AND REVERSE BIAS CHARACTERISTICS VERSUS RADIATION DOSE

Forward bias characteristics versus dose

Figure 1 shows a typical example of the forward bias current-voltage characteristics measured at 77 K and about 300 K (dotted line) before and after irradiation up to 2 kGy.

When introducing these forward bias characteristics into the thermo-electrical model, the maximum wafer temperature before and after each irradiation step can be calculated for any current level.

In Figure 2 is shown the altered forward voltage at forward bias current I_f = 12 kA as a function of the received dose for a diode without intermediate warm up (annealing) and in Figure 3 for a diode with intermediate annealing. The decrease in forward voltage after each annealing step at 300 K is clearly visible and may help to prolong the lifetime of the diode. Especially at 77 K, the prototype diode shows a lower increase of the forward voltage versus dose compared to the series diodes.

Reverse bias characteristics versus dose

The measured reverse bias characteristics of a series diode at 77 K and about 300 K before and after irradiation up to 2 kGy without intermediate warm up to 300 K are shown in Figure 4. The leakage current in reverse bias before the sudden increase is very low at 77 K and at 300 K before irradiation. After irradiation up to 2 kGy the leakage current at

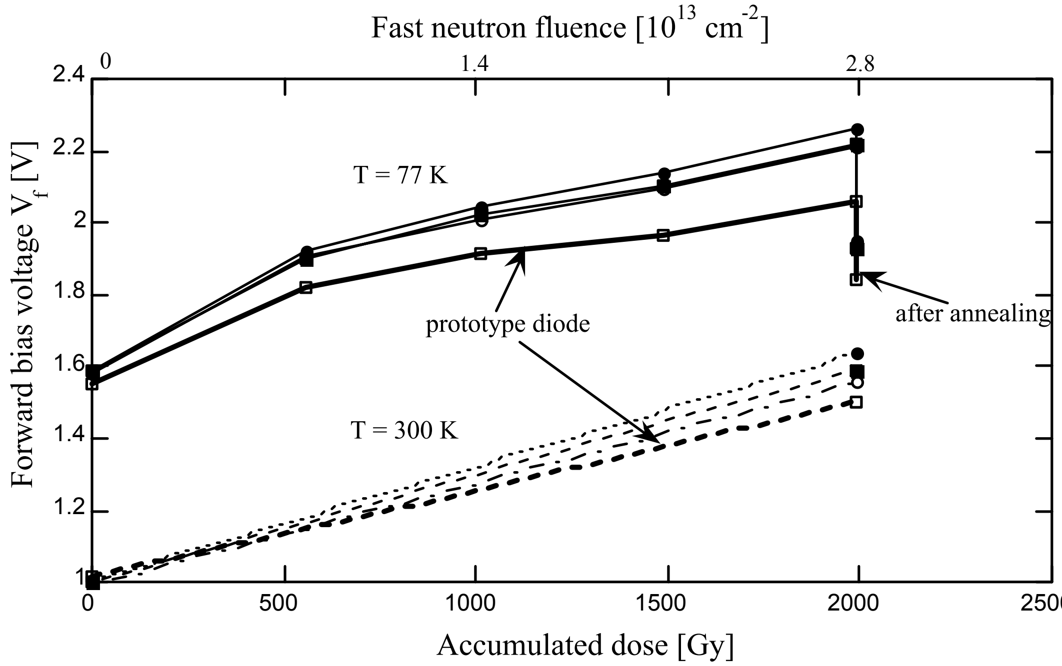

FIGURE 2. Forward bias voltage V_f at forward current I_f = 12 kA versus accumulated dose at 77 K and 300 K for one prototype- and 3 series diodes without intermediate warm up.

300 K has increased significantly. The reverse bias voltage at reverse bias reference current I_r = 1 mA is even lower than at 77 K. Figure 5 shows the measured reverse bias voltage V_r versus dose at 77 K and 300 K for one diode with and one diode without intermediate warm up. The reverse bias voltage increases with dose by about 5% -10% at 77 K whereas at 300 K a significant decrease with dose of about 20 % has been observed. In fact, V_r at

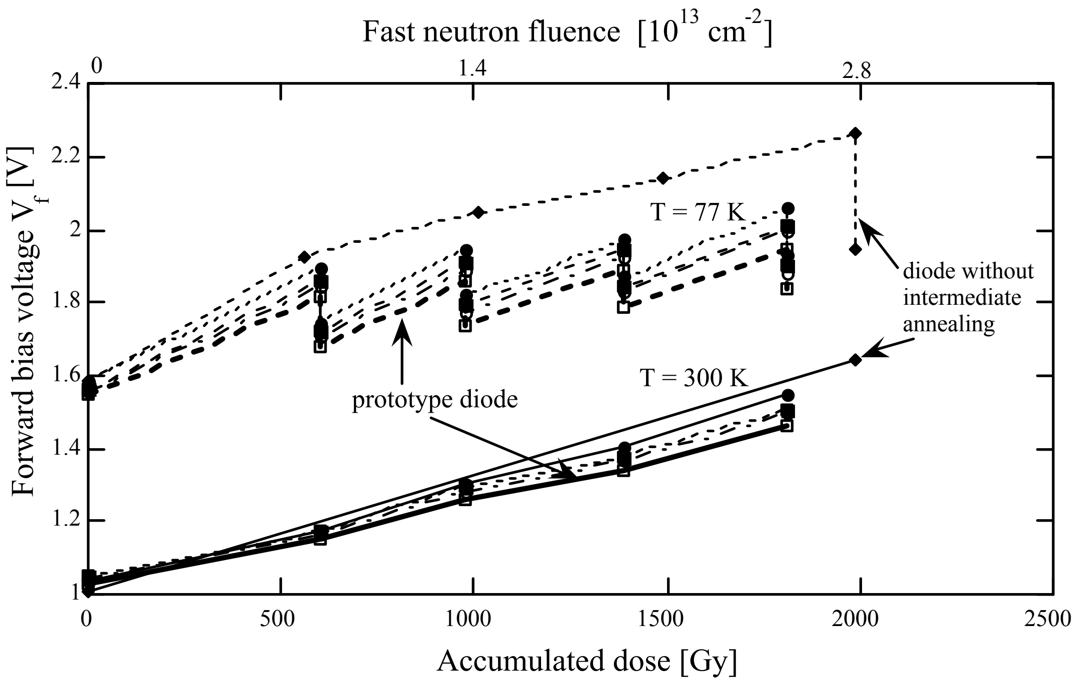

FIGURE 3. Forward bias voltage V_f at forward current I_f = 12 kA versus accumulated dose at 77 K and 300 K for one prototype- and 3 series diodes with intermediate warm up. For comparison is also shown one diode without intermediate annealing.

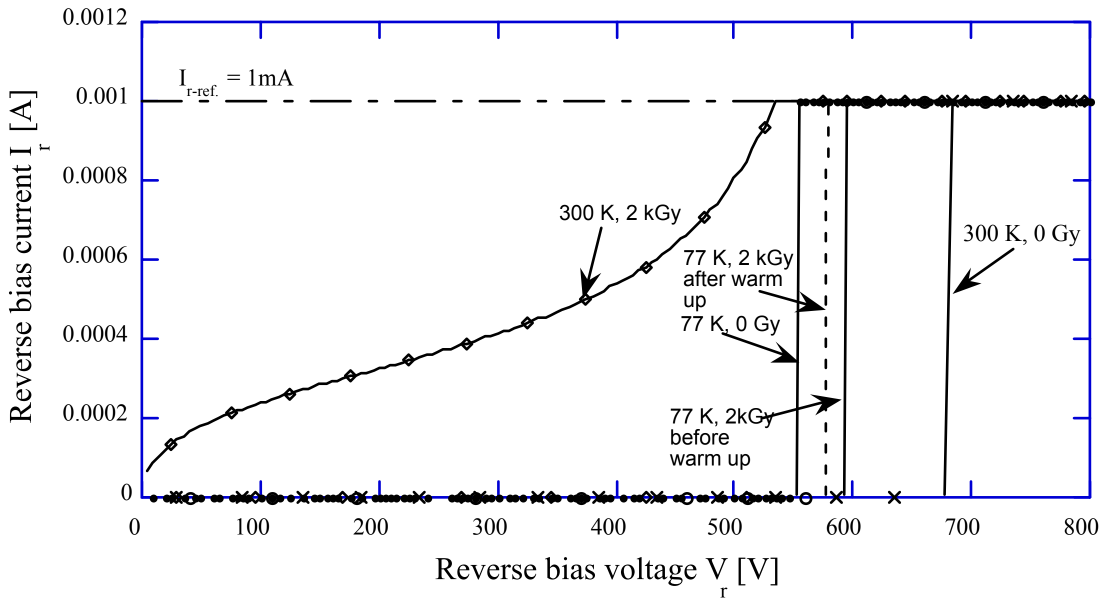

FIGURE 4. Measured reverse bias characteristics of a series diode at 77 K and 300 K before and after irradiation

300 K is now even lower than at 77 K, just the opposite as before irradiation. The different behaviour of the reverse bias voltage versus irradiation dose at 300 K and at 77 K can be explained by the following:

At room temperature the irradiation with fast neutrons leads to the production of defects in the semiconductor material. At neutron fluences in the order of 10^{12} ncm^{-2} the main effect is the creation of recombination centres leading to a reduction of the minority carrier lifetime. The minority carrier lifetime will also be reduced by surface recombination centres, which are caused by ionising radiation (in case of TCC2 mainly gammas)[5]**.** According to the Shockley-Hall-Read theory, a reduced minority carrier lifetime leads in consequence to an increased leakage current under reverse bias. The increased leakage current finally leads to the observation of a reduced reverse breakdown voltage.

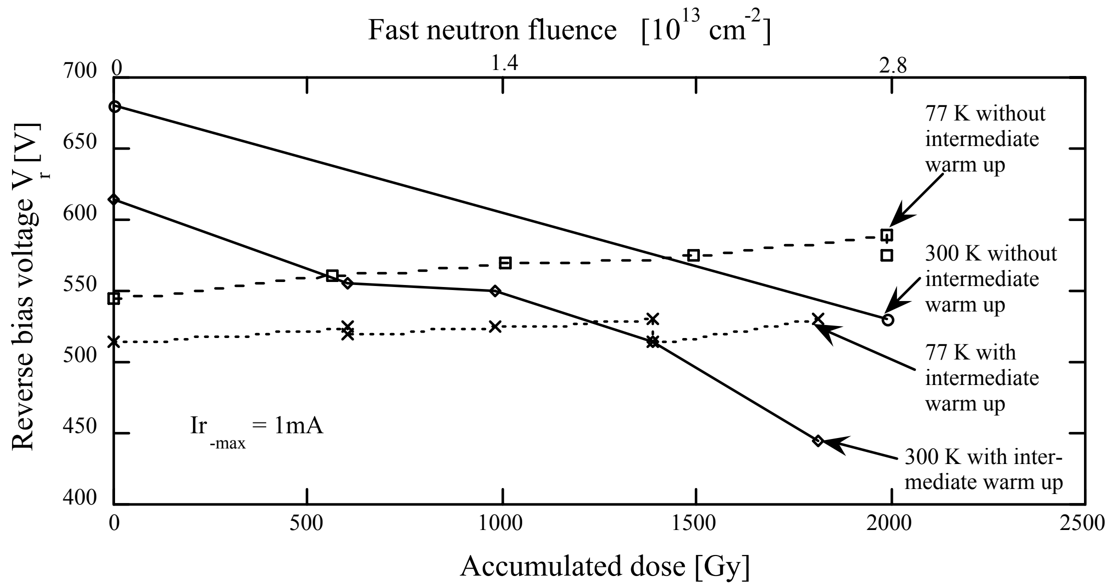

FIGURE 5. Typical reverse bias voltage V_r (I_r = 1mA) at 77 K and 300 K versus accumulated dose of one diode with intermediate warm up to 300 K and one diode without intermediate warm up to 300 K.

TABLE 2. Estimated average doses to diodes and to silicon wafers in the LHC normal arcs and in the dispersion suppresser regions. Maximum doses are given in bold. (MB = bending dipole, Q = quadrupole)

Dose to diodes in dispersion suppresser regions								
Average dose over full diode region [Gy/year]				Dose to Silicon wafer only [Gy/year]				**Accumulated dose to Si-wafer only at DS 5 in 20 years**
	DS 1	DS 5			DS 1	DS 5		
Magnet	Point loss	Interact.	Beam-gas	Magnet	Point loss	Interact.	Beam-gas	[Gy]
Q11	16.1	127.8	12.9	Q11 Si 1	100.3	134.3	13.2	**2700**
-	-	-	-	Q11 Si 2	57.7	63.3	11.8	1300
MB11A	2.9	44.3	16.8	MB11A	8.3	10.7	1.5	214
MB9A	67.6	75.4	5.3	MB9A	15.8	16.7	1.2	334
MB9B	400.8	497.5	15.7	MB9B	38.3	47.2	1.9	944
MB8A	25.0	20.0	3.6	MB8A	10.8	9.9	1.3	198
MB8B	9.2	7.5	5.3	MB8B	5.9	4.6	2.6	92

Dose to diodes in the normal arcs		
	Dose to Silicon wafer only [Gy/year]	**Accumulated dose in 20 years**
Magnet	Beam gas	[Gy]
Dipole Type A	1.9	38
Quadrupole: Si - wafer of diode 1	12.8	**256**
Quadrupole: Si - wafer of diode 2	8.8	176
Dipole Type B	3.7	74

At low temperatures the behaviour of the pn-junction under reverse bias is mainly affected by the carrier freeze-out effect and the reduced phonon scattering rate. The latter reduces the level for impact ionisation and thus leads to the observation of a reduced reverse breakdown voltage compared to the values at T = 300 K [6]. At liquid nitrogen temperature the leakage current is significantly reduced and the device becomes less sensitive to radiation damage. The introduced defects act mainly as traps for injected carriers and therefore increase the threshold for the reverse breakdown slightly.

NEWLY ESTIMATED IRRADIATION DOSES IN THE LHC

Recently, new estimations for the expected annual dose and high energy particle fluence due to point losses and beam-gas interactions have been carried out at CERN for the superconducting magnets in the dispersion suppresser regions and for the standard arc magnets [1-2]. Hot-spot regions with doses per year > 100 Gy were identified and details of the dose to the by-pass diodes presented taking into account the lower dose during running-in. TABLE 2 gives an overview of the expected doses in Gy per year to the diodes of the different magnet elements in the normal arcs and in the dispersion suppresser regions. Presented are only those locations, where the dose is higher than about 50 Gy in 20 years. As can be seen, the average dose for the full diode region (diode capsule) is about one order of magnitude higher than for the thin Silicon wafer only (MB9B). The dose to the diodes in the dispersion suppresser regions is mainly due to point loss interactions whereas for the normal arc regions the dose is mainly due to beam-gas. The dose to the Silicon wafers in the normal arcs will not exceed about 250 Gy in 20 years, whereas the dose to some Silicon wafers of the quadrupole diode stacks (Q11) in the dispersion suppresser region DS 5 amounts to about 2.7 kGy in 20 years.

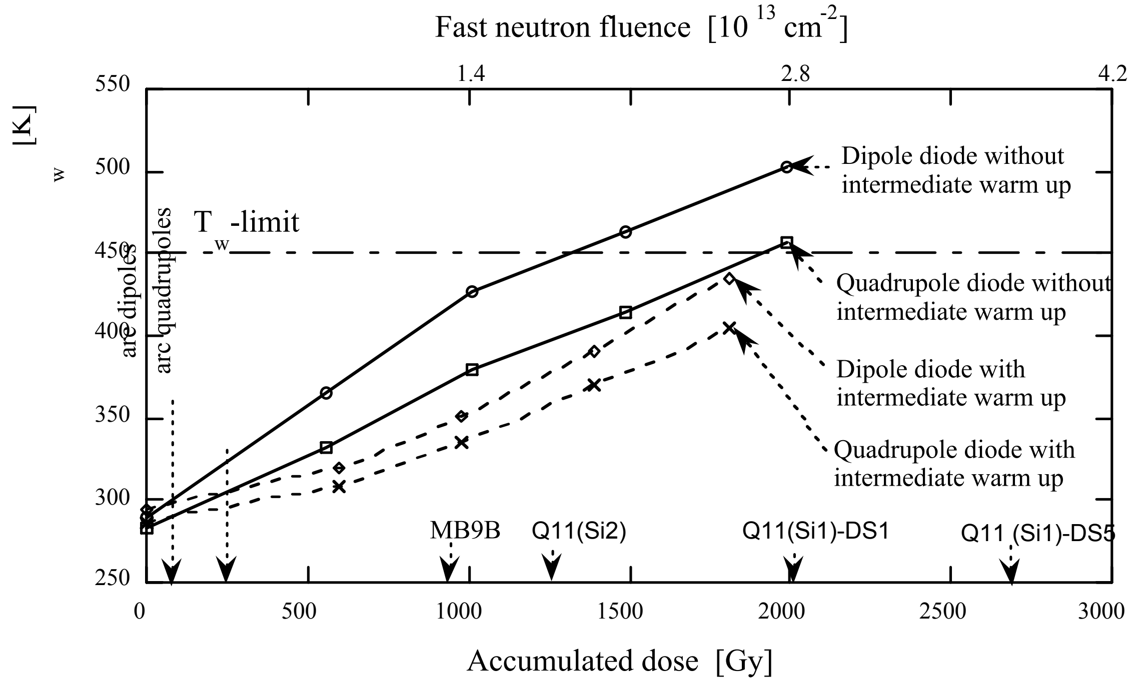

FIGURE 6. Estimated wafer temperature T_w versus accumulated dose and fluence for a dipole stack diode and for a quadrupole stack diode with and without intermediate annealing at 300 K and expected maximum doses for regular arc magnets and some magnets in the hot-spot dispersion suppresser regions.

EXPECTED LIFETIME OF SERIES DIODES

For the estimation of the expected lifetime of the series produced diodes, the measured I_f-U_f characteristics versus dose (up to 2 kGy) of the diode with the highest increase in forward bias voltage has been used. For the electro-thermal modelling, it is assumed that this diode is mounted into a stack for the dipole and for the quadrupole by-pass.

According to the diode operating conditions in case of a superconducting magnet quench, the current increases within about 0.5 s to 13 kA and decays exponentially with a time constant of 105 s for the dipole diode stack and with a time constant of 50 s for the quadrupole diode stack. In Figure 6 is presented the maximum wafer temperature versus accumulated irradiation dose and fluence for the two different diode stack types with and without intermediate warm up to 300 K(annealing). The relatively fast increase of the wafer temperature below about 1 kGy reflects the increase of the forward voltage within this range of irradiation dose as shown in Figure 2. As the liquid helium vaporises within the first few seconds, purely adiabatic conditions were assumed during the electro-thermal modelling.

The upper limit of the wafer temperature of about 450 K, given by the diode manufacturer for these diode types, will be exceeded for the dipole stack diode without intermediate annealing above about 1.3 kGy and with intermediate annealing above about 1.8 kGy. The upper dose limit for the quadrupole stack diodes amounts to about 1.9 kGy without intermediate annealing and to about 2.2 kGy (extrapolated) with intermediate annealing.

For the regular arc magnets the radiation resistance is largely sufficient, whereas for the diodes in the dispersion suppresser region DS5 (Q11), annual annealing or even a replacement of the diodes after about 10 to 15 years must be envisaged. Furthermore, at the rim of the diode towards the beam, the dose can be five times higher resulting in a reduced life time. Current crowding and thus higher wafer temperatures within the reduced wafer area with larger distance from the beam off, less radiation damage must be expected.

As shown above, the ratio dose/fluence is not the same for the different regions in the LHC and also the ratio dose/fluence during the irradiation of the series diodes in the north area target zone of the CERN SPS accelerator is different, so that the following measures are recommended to monitor the degradation of diodes during the operation of the LHC :

- Installation of radiation monitoring devices close to the diode location in all areas where high doses must be expected.
- Well defined position (distance to diode) of dosimeters will allow an estimation of the accumulated dose.
- If the accumulated dose exceeds a certain level, about 1.5 kGy, then, as qualitative indicator of degradation, the turn on voltage V_{to} of the diode at 1.8 K, should be measured [4].
- If the turn-on voltage exceeds by about 1 V the reference value before irradiation, then either the diode should be replaced directly or the forward bias voltage characteristics $I_f(U_f)$ in situ at about 77 K and at about 300 K shall be measured to estimate the remaining lifetime of the diode.

CONCLUSIONS

The test results show that for these diffusion-type diodes a reasonable compromise has been achieved between the required radiation resistance, the highest possible reverse blocking voltage, and a reasonable yield for the mass production in industry.

The increase of forward bias voltage as a function of dose for the series produced diodes is only insignificantly higher than for the prototype diodes. The reverse bias voltage at 77 K increases slightly with dose but decreases remarkably at 300 K.

The newly estimated doses for the arc magnets is low, so that for all of the by-pass diodes across the arc elements the radiation resistance is largely sufficient. However, for a few locations in the dispersion suppresser regions of the LHC, the dose may exceed the upper limit of about 2 kGy for diodes installed across the quadrupole magnets. Therefore in these hot spots a frequent monitoring of the dose and measurement of the turn-on voltage at 1.8 K is necessary. Annealing, during magnet quenching and annual warm-up to 300 K for measurements, will prolong the lifetime of the diodes. Where this cannot be applied, a replacement of the diodes after about 10-15 years may be necessary or, in the very few locations, the installation of more radiation resistant epitaxial diodes should be foreseen [7].

REFERENCES

1. Gharib, A., Hagedorn, D. et al. "Cryogenic testing of high-current by-pass diodes for the protection of the superconducting magnets in the LHC," *This conference*, M3-D-03.
2. Fynbo, A.C. and Stevenson, G. "Annual doses in the standard LHC ARC sections, " Engineering Specification LHC-S-ES-0001, 6.12.2001.
3. Fynbo, A.C. and Stevenson G., "Radiation environment in the dispersion suppressor regions of IR1 and IR5 of the LHC," LHC-Project Note 296, 27.2.2002.
4. Denz, R., Gerstenberg, H. and Hagedorn, D., "Annealing of superconducting magnet protection diodes," in *Proceedings of ICEC17*, IOP, Bristol, p.463.
5. Berland,V., Hagedorn, D. et al., "Annealing of superconducting magnet protection diodes," *Proceedings of EPAC 96*, Sitges, Spain, IOP, p. 2234.
6. Messenger, G. and Ash, M. "The effects of radiation on electronic systems", *Van Nostrand Reinhold, NewYork*, 1992, chapter 9, pp.112-123.
7. Coull, L., Denz, R. and Hagedorn, D., "High current diffusion type diodes at cryogenic temperatures for the LHC superconducting magnet protection," *LHC project report 131,* CERN, August 1997.