CHARACTERISATION OF THE RADIATION HARDNESS OF CRYOGENIC BYPASS DIODES FOR THE HL-LHC INNER TRIPLET CIRCUIT*

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Abstract

The powering layout of the new HL-LHC Nb_3Sn triplet circuits is the use of cryogenic bypass diodes, where the diodes are located inside an extension to the magnet cryostat, operated in superfluid helium and exposed to radiation. Therefore, the radiation hardness of different type of bypass diodes has been tested at low temperatures in CERN's CHARM irradiation facility during the operational year 2018. The forward characteristics, the turn on voltage and the reverse blocking voltage of each diode were measured weekly at 4.2 K and 77 K, respectively, as a function of the accumulated radiation dose. The diodes were submitted to a dose close to 12 kGy and a 1 MeV equivalent neutron fluence of 2.2×10^{14} n/cm^2. After the end of the irradiation campaign the annealing behaviour of the diodes was tested by increasing the temperature slowly to 300 K. This paper describes the experimental setup, the measurement procedure and discusses the results of the measurements.

INTRODUCTION

For the High-Luminosity LHC (HL-LHC), novel Nb_3Sn based inner triplet quadrupole magnets are going to be installed as the final focus quadrupoles for the interaction points 1 and 5 of the LHC [1–4]. The complexity of these inner triplet circuits calls for the installation of cold diodes in parallel of the quadrupole magnets Q1, Q2a, Q2b and Q3 (see Fig. 1). The diodes will be located in a dedicated cryostat close to the separation dipole D1, immersed in superfluid helium and exposed to significant radiation levels from the debris of the interaction point. At the foreseen position, a dose of 30 kGy and a 1 MeV equivalent neutron fluence of 2×10^{14} n/cm^2 was estimated using the FLUKA Monte Carlo code [7, 8] for the lifetime of the HL-LHC [9].

To verify that cold diodes can be used in the above described radiation environment, an irradiation campaign was performed in the CERN High energy AcceleratoR Mixed field facility (CHARM) [10–12]. A sketch of the experimental setup is shown in Fig.2. The cryostat is cryocooler based and houses two stacks of four diodes each. One of the stacks is thermally anchored to the first stage of the cryocooler, which is operated between 50 and 77 K. The other stack is thermally anchored to the second stage of the cryocooler and kept at 4.2 K. The setup allows to measure the turn-on (U_{to}) and reverse bias voltage (U_{rev}) in-situ for all diodes. In addition, the forward characteristics ($U_f(I)$) of the diodes on the first cryocooler stage were measured with short current pulses of up to 18 kA at 77 K. A more detailed description of the experimental setup and the in-situ measurements can be found in [13].

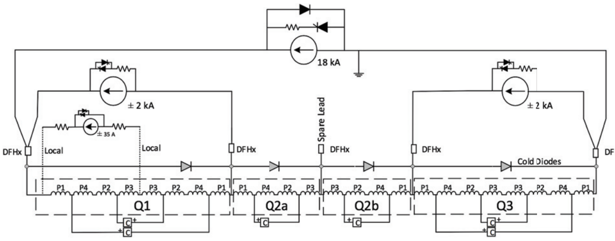

Figure 1: Circuit layout of the HL-LHC inner triplet, showing the quadrupoles Q1, Q2a, Q2b, Q3, the main, and trim power converters with their crowbars, the Coupling Loss Induced Quench protection systems (C) and the cold diodes [5, 6].

In the experiment, so-called *LHC reference*, *thin base* and *very thin base* power diffusion diodes were used, each having a specific p^+nn^+ doping profile and n-base width. The n-base width is hereby defined as the distance of the intersections of the p^+ and n^+ doping profiles with the n-doping level of the Silicon wafer before the diffusion process. Table 1 provides an overview of the parameters of the different diodes used in the experiment. Note, that the n-base width does not have an impact on U_{to} or $U_f(I)$ of the virgin diodes. However, U_{rev} decreases with decreasing n-base width.

Table 2 summarizes the dose and 1 MeV equiv. neutron fluence accumulated for each diode at the end of the 6 month long irradiation campaign.

RESULTS OF THE IRRADIATION CAMPAIGN

Forward Voltage at 77 K

Figure 3 shows the measured relative increase of the forward voltage U_f in diode D4 as function of the accumulated 1 MeV equiv. neutron fluence for currents from 1 kA to

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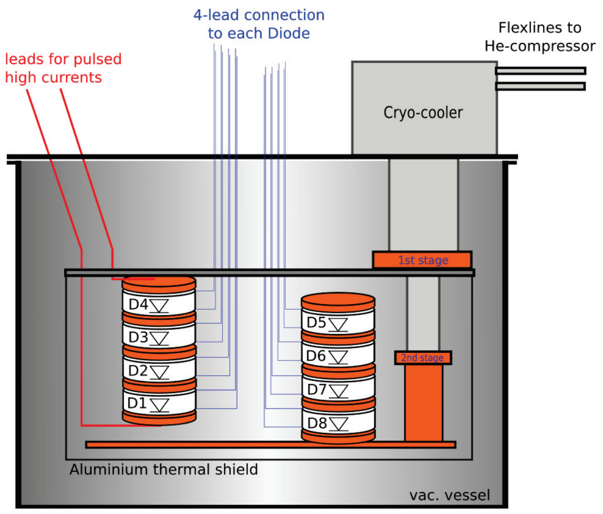

Figure 2: Sketch of the experimental setup for testing the radiation hardness of cold diodes for the HL-LHC triplet. The cryostat is based on a cryocooler and houses two stacks of 4 diodes each.

Table 1: Diode prototypes and corresponding labels used in this article. Furthermore the temperatures at which the characterization was performed is indicated.

Diode label	**Temp.**	**n-base width**	**U$_{rev}$**
LHC Reference		10±5 μm	520±10 V
D1	77 K		
D8	4.2 K		
Thin base		0±5 μm	400±10 V
D2	77 K		
D7	4.2 K		
Very thin base		-10±5 μm	250±20 V
D3, D4	77 K		
D5, D6	4.2 K		

Table 2: Accumulated dose and 1 MeV equiv. neutron fluence at the end of the irradiation campaign in each diode. The values were derived from FLUKA simulations per proton on target times 2.81×10^{17} protons on target. The uncertainty was estimated to 20 %.

Diode	**D1**	**D2**	**D3**	**D4**
Fluence (10^{14} cm^{-2})	2.09	2.15	2.27	2.28
Dose (kGy)	10.40	11.17	11.06	10.24
Diode	**D5**	**D6**	**D7**	**D8**
Fluence (10^{14} cm^{-2})	1.74	1.75	1.70	1.66
Dose (kGy)	11.00	11.02	12.20	9.75

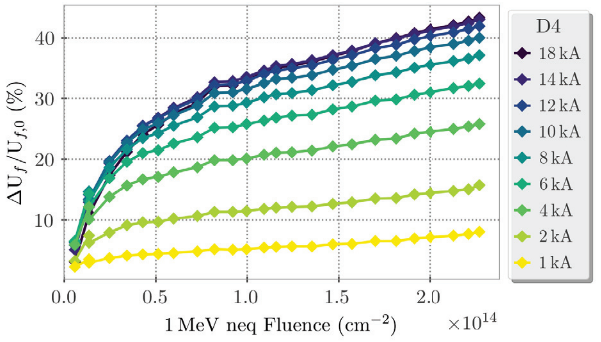

Figure 3: Measured relative increase of the forward voltage U_f in diode D4 as function of the accumulated 1 MeV equiv. neutron fluence for currents from 1 kA to 18 kA.

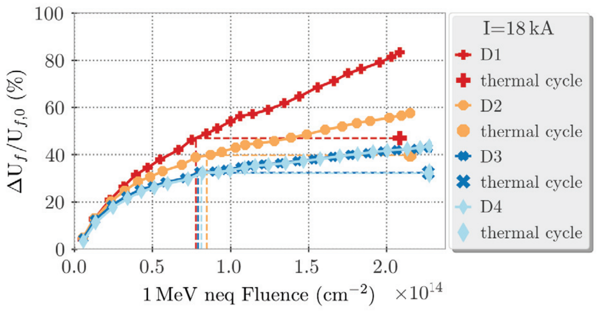

Figure 4: Relative change of the forward voltage U_f versus the accumulated 1 MeV equiv. neutron fluence at 18 kA for the diodes D1, D2, D3 and D4. The last measurement points of each diode indicate the value of U_f after a thermal cycle to room temperature. The dotted lines indicate the equivalent accumulated fluence levels for these U_f values.

18 kA. The absolute value of U_f for the virgin diode varies from 1.14 V at 1 kA to 1.72 V at 18 kA. A steep increase of the forward voltage can be observed for currents above 2 kA reaching nearly 43 % at the end of the campaign for 18 kA. Below 2 kA the total increase stays within 15 %. The slope of the increase flattens significantly above a fluence of $\sim 0.8 \times 10^{14}$ n/cm^2, which indicates two different regimes of radiation damage. The other diodes showed qualitatively the same behaviour. However, depending on the diode type, the absolute increase was significantly higher.

Figure 4 shows the relative change of U_f versus the accumulated 1 MeV equiv. neutron fluence at 18 kA for the diodes D1, D2, D3 and D4. The diodes with the smallest *n*-base widths (D3, D4) show with 40 % the lowest increase of U_f and are in very good agreement with one another. For the LHC reference diode (D1) U_f nearly doubles and the *thin base* width diode (D2) lays in between the two other types.

Turn-on Voltage at 4.2 K

The turn-on voltage U_{to} was defined for this experiment as the voltage across the diode, when the current through the diode reaches 200 mA. This current threshold ensures that the diode has been fully opened. The measurement of U_{to} was performed during a linear voltage ramp with a ramp rate

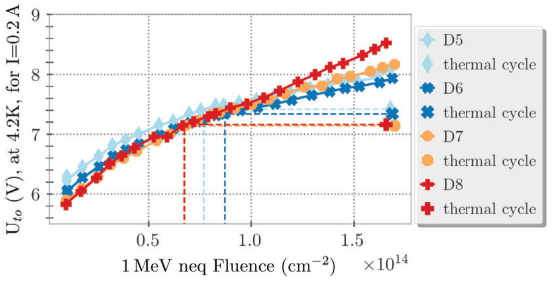

Figure 5: Turn-on voltage U_{to} of D5, D6, D7 and D8 as a function of the accumulated 1 MeV equiv. neutron fluence measured at a current of $I = 0.2$ A at 4.2 K. The last measurement points of each diode indicate the value of U_{to} after a thermal cycle to room temperature. The dotted lines indicate the equivalent accumulated fluence levels for these U_{to} values.

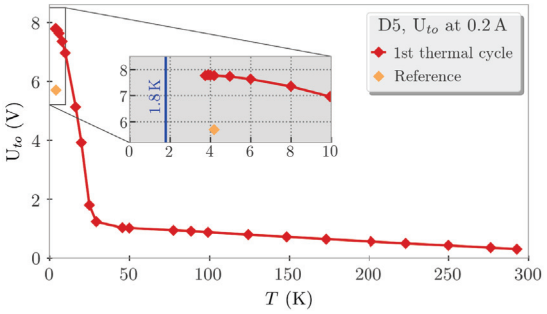

Figure 6: U_{to} of diode D5 from 3.9 K to room temperature and zoom between 0 and 10 K.

of 50 V/s. Figure 5 shows U_{to} for D5, D6, D7 and D8 as a function of the accumulated 1 MeV equiv. neutron fluence. Due to the radiation damage U_{to} increased between 1.8 V or 30 % and 2.7 V or 46 %. As observed for the change of U_f, the *LHC reference* diode type experiences the strongest and the *very thin base* type the least degradation.

Figure 6 shows U_{to} of diode D5 from 3.9 K to room temperature. The measurements were performed during a slow warm up following the end of the irradiation campaign. It can be clearly seen, that U_{to} slowly increases for decreasing temperatures and that it steeply rises below 30 K and then flattens out between 5 and 3.9 K. Therefore, no significant increase of U_{to} is expected between 3.9 K and the future operating temperature of the cold diodes of 1.8 K.

Reverse bias voltage

For this experiment the reverse bias voltage U_{rev} was defined as the voltage required to drive a current of 1 mA through the diode in reverse operation. During the measurements a logarithmic current sweep was performed from 1 μA to 1 mA. Figure 7 shows U_{rev} for all diodes as a function of the accumulated 1 MeV equiv. neutron fluence. An increase of up to 20 % was observed. It is important to mention that

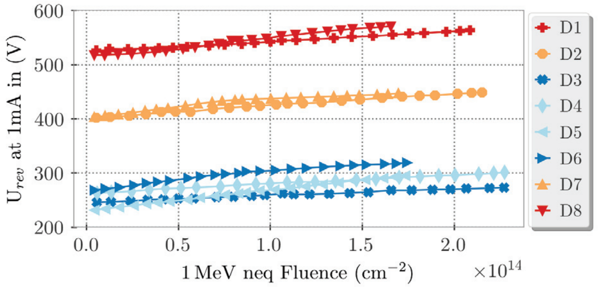

Figure 7: Reverse bias voltage required to drive a current of 1 mA through the diode in reverse operation as a function of the accumulated 1 MeV equiv. neutron fluence.

diodes of the same type have a very similar U_{rev} independent of their operating temperature (4.2 K or 77 K).

THERMAL ANNEALING STUDY

After the end of the irradiation campaign a thermal cycle to room temperature was performed with the whole experimental setup. After the re-cooldown U_{to}, U_{rev} and U_f were measured again. Partial annealing was observed in U_{to} (see Fig. 5) and U_f (see Fig. 4) for all diodes. The observed absolute annealing in the diodes is the greater the higher the absolute degradation was at the end of the irradiation campaign. However, it can be clearly seen that the annealing decreases the relative change of U_f to the levels observed at a third of the final accumulated fluence for all diodes. For U_{rev} no significant change due to annealing was observed.

CONCLUSION

Three types of power diodes with different doping profiles, were irradiated in CERN's CHARM facility at 4.2 K and $50 - 77$ K. In the diodes a 1 MeV equiv. neutron fluence of up to 2.2×10^{14} n/cm^2 was accumulated. Regular in-situ measurements of the turn-on voltage (U_{to}), reverse bias voltage (U_{rev}) and the forward characteristics ($U_f(I)$) with short current pulses up to 18 kA were performed during the whole irradiation campaign and after a thermal cycle at the end. A significant degradation of the turn-on voltages U_{to} and forward voltages U_f has been observed in all diode types due to the irradiation. However, the diodes with the very thin n-base width experienced considerably less degradation of U_{to} and U_f than the LHC reference diodes. The reverse bias voltage improved in all cases slightly during the irradiation campaign. A thermal cycle to room temperature for annealing showed that U_f could be reduced to levels which were similar to a third of the accumulated fluence in all diode types.

The irradiation campaign has successfully verified, that all of the tested diode types fulfill the requirements for the use in the HL-LHC triplet circuits up to the accumulated fluence levels. However, it was decided to use the most radiation tolerant very thin n-base width type diode, as the final radiation levels at the future diode positions in the LHC tunnel pose rather large uncertainties.

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