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EXPERIMENTAL SETUP TO CHARACTERIZE THE RADIATION HARDNESS OF CRYOGENIC BYPASS DIODES FOR THE HL-LHC INNER TRIPLET CIRCUITS*†

A. Will‡[1,2], A. Bernhard[2], G. D'Angelo[1], R. Denz[1], M. Favre[1], D. Hagedorn[1], G. Kirby[1], T. Koettig[1], A. Monteuuis[1], A.-S. Mueller[2], F. Rodriguez-Mateos[1], A. Siemko[1], K. Stachon[1], M. Valette[1], L. Vammen Kistrup[3], A. Verweij[1], D. Wollmann[1]

[1] CERN, 1211 Geneva 23, Switzerland

[2] Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

[3] KEA Copenhagen School of Design and Technology, Copenhagen, Denmark

Abstract

For the high luminosity upgrade of the Large Hadron Collider (LHC), it is planned to replace the existing triplet quadrupole magnets with Nb_3Sn quadrupole magnets, which provide a comparable integrated field gradient with a significantly increased aperture. These magnets will be powered through a novel superconducting link based on MgB_2 cables. One option for the powering layout of this triplet circuit is the use of cryogenic bypass diodes, where the diodes are located inside an extension to the magnet cryostat and operated in superfluid helium. Hence, they are exposed to radiation. For this reason the radiation hardness of existing LHC type bypass diodes and more radiation tolerant prototype diodes needs to be tested up to the radiation doses expected at their planned position during their lifetime. A first irradiation test is planned in CERN's CHARM facility starting in spring 2018. Therefore, a cryo-cooler based cryostat to irradiate and test LHC type diodes in-situ has been designed and constructed. This paper will describe the properties of the sample diodes, the experimental roadmap and the setup installed in CHARM. Finally, the first measurement results will be discussed.

INTRODUCTION

HL-LHC Inner Quadrupole Triplet

The replacement of the inner triplet quadrupole magnets in interaction point IP1 and IP5 of the LHC by Nb_3Sn magnets in the High Luminosity Large Hadron Collider project requires a redesign of the powering scheme. In order to feed currents up to 18 kA to the triplet, MgB_2 cable based superconducting links will be installed, connecting the magnets in the LHC tunnel with the power converters in the new radiation free underground cavern [1, 2]. The powering scheme includes bypass diodes for magnet protection in case of a quench [3]. One option would use cryogenic bypass diodes, as shown in Fig. 1, located in the magnet cryostat, close to the beam axis and immersed in liquid helium. As opposed to diodes located in the new cavern, this option would avoid large over-currents through the superconducting link in case of failures.

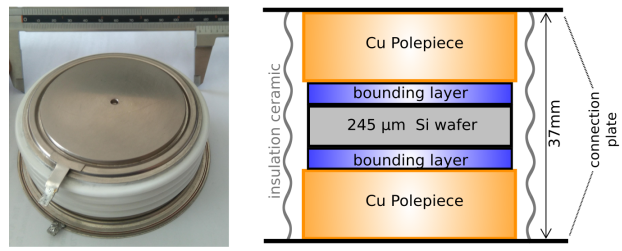

Figure 1: Picture and schematics (not to scale) of cryogenic bypass diode as used in LHC and potentially to be used in HL-LHC.

On the other hand they will be exposed to high radiation doses, leading to a potential degradation of the diode characteristics, which has to be quantified. The integrated radiation dose at the location of the cold diodes is estimated to reach up to 30 kGy and 10^{15} n/cm^2 over the HL-LHC lifetime [4].

Previous Qualification Campaigns

As known from previous qualification campaigns, exposure of diodes to radiation leads to a rise of the forward bias voltage, potentially up to an open circuit in the worst case. During qualification campaigns for the LHC, diffusion type diodes supplied by Dynex[1] with a base width of around 10 µm had been tested up to 2 kGy respectively $3 \cdot 10^{13}$ n/cm^2 [5, 6]. The same type of diode had later been qualified to doses up to 1.2 kGy and $2.2 \cdot 10^{14}$ n/cm^2 to be used at FAIR [7], however not radiation exposed at 4 K, for lower maximum currents and with intermediate warm-ups.

New Prototype Diodes

LHC type diodes and two new prototype diodes, also produced by Dynex, are currently being tested and qualified for the potential use in the HL-LHC inner triplet. The two new prototypes have base widths of 0 ± 5 µm and -10 ± 5 µm. The radiation hardness is expected to increase with decreasing base width, while on the other hand the reverse blocking voltage is decreasing.

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‡ andreas.will@cern.ch

[1] Dynex Semiconductor Ltd (Lincoln, GB)

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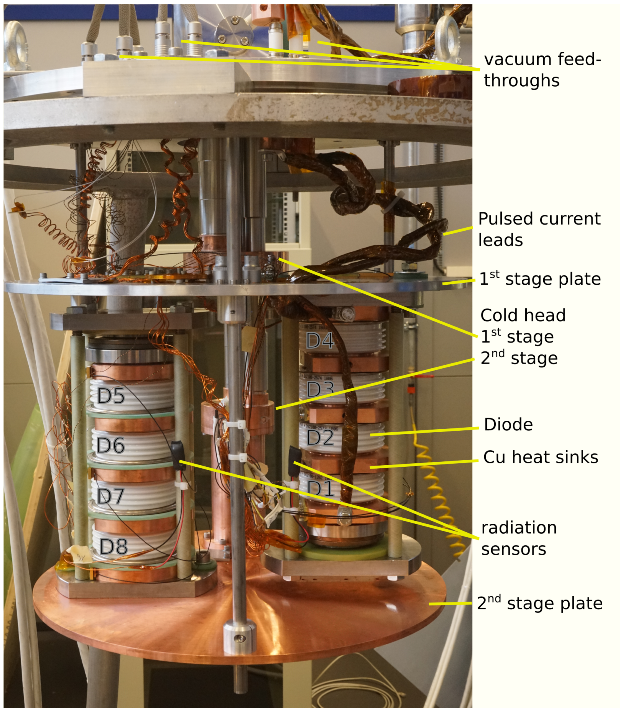

Figure 2: Picture of the cryostat setup demonstrating the assembly and placement of the diodes.

CHARM Irradiation Facility

The radiation tests will be performed at the CERN high-energy accelerator test facility (CHARM), where 24 GeV/c protons, extracted from CERN's Proton Synchrotron (PS), are impacting a metal target to create a mixed radiation environment [8]. A new irradiation position close to the facility's target and below the beam axis has been evaluated for this purpose. The estimated dose on the diodes at this position is 0.5 kGy and 10^{13} n/cm^2 per week [9]. Within this year's irradiation period, it is aimed to achieve a total dose of 16 kGy and $>3.2 \cdot 10^{14}$ n/cm^2.

CRYOSTAT DESIGN

The diodes should be tested in-situ during the irradiation period without intermediate warm up. The temperatures of main interest to perform the measurements are 4.2 K and 77 K. This allows a comparison to previous measurements, performed in liquid helium and liquid nitrogen. However, the characteristics at other temperatures is of interest as well. Furthermore, as access to the facility is very limited, the system has to be remotely controlled, with an effective distance of $\approx$ 40 m from the control room to the cryostat inside the irradiation area, following a concrete cable chicane.

Therefore, a two stage pulse tube cryocooler-based cryostat has been designed, which can be operated with the first stage at 77 K, and the second stage at 4.2 K simultaneously. Furthermore, both stages allow a wider temperature range to be set using heaters on both stages.

Figure 2 shows the opened setup without the vacuum vessel and thermal shield. The two stacks of four diodes each are attached to the two stages. The stacks are equipped with two diodes with -10 µm base width on the position closest to beam (D3+D4 and D5+D6), one diode with 0 µm base width below (D7, D2) and one LHC type reference diode at the bottom (D1, D8), with the largest distance to the beam.

Each diode is equipped with two voltage and two current leads, allowing individual four-point measurements. The diodes on the stack attached to the 77 K stage are connected in series; two current leads allow to apply current pulses of few ms duration with amplitudes up to 18 kA. The diodes on the stack attached at the 4 K stage are insulated from each other.

There are copper spacers between the diodes, acting as heat sinks during the measurements. The temperatures are continuously monitored at each of the cryo-cooler's stage plates as well as on three heat sinks within each stack. The temperature of each diode is, therefore, known with a precision of ±0.2 K.

Commissioning of the Cryostat

During the commissioning of the cryostat system, an equilibrium temperature of the first stage of 33 K was reached. The diode stack attached to this stage converges to a temperature range of 43.6 K for D4 to 44.3 K for D1, due to the additional heat load from the high current leads, which are directly connected to the stack. The second stage converged to a temperature of 2.9 K, the diode stack attached to this stage achieved a temperature range of 3.5 K for D8 and 3.8 K for D5. Both temperatures give a sufficient margin in cooling power and allow the diode temperatures to be set accurately, using the stage heaters with feedback from the temperature sensors on the stacks.

In-Situ Measurements during Irradiation

Four quantities will be measured to evaluate the degradation of the diode characteristics as a function of absorbed dose, three of them can be recorded on both stacks at all available temperatures:

- The turn-on voltage V_{to}, by applying a triangular voltage pulse with a defined voltage ramp rate and simultaneously measuring the current through and voltage drop over the diode. The voltage ramp rate is matched to the ramp rates observed in the LHC main dipole magnets during a quench, which is in the order of 50 V/s. Voltage ramp rates up to 10 kV/s are possible.
- The reverse bias voltage V_{rev} up to a reverse bias current of 1 mA.
- The capacitance using an LCR meter and an excitation voltage amplitude below V_{to}.

On the 77 K stack, it is possible to additionally test the full forward characteristics of the diodes $V_f(I)$ as a function of the applied current up to 18 kA. This is done step-wise

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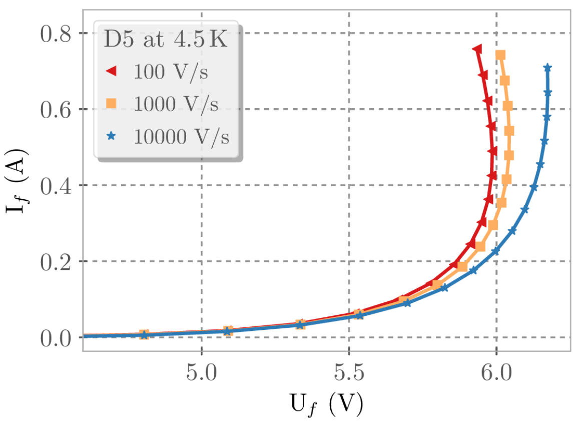

Figure 3: Turn-on voltage measured on D5 (N-base width -10 µm) for different voltage ramp rates at 4.5 K.

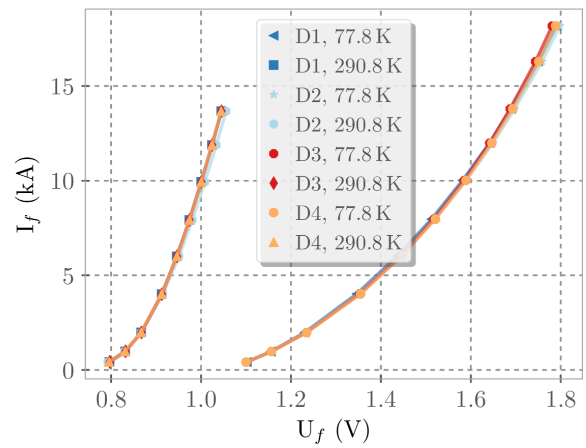

Figure 4: Characteristics of the diodes D1-4 on the 77 K stack for different measured temperatures.

by applying half-sinusoidal current pulses of varying amplitudes with a pulse width of few milliseconds and measuring the voltage drop across each diode in the stack.

FIRST MEASUREMENTS

After the successful commissioning of the cryostat in the facility, before the irradiation had started, a first full characterization of the diodes in the setup has been performed.

Turn-On Voltage

At 77 K, the temperature rise during a measurement due to ohmic losses is expected to be negligible. However the heat capacity of one diode at 4.2 K, consisting mainly of copper, is in the order of 0.5 J/K. The deposited energy due to the measurement can lead to a measurable temperature rise of the diode and the adjacent heat sinks, even for small and short DC currents. The results of the turn-on voltage measurements at 4.5 K for various voltage ramp rates ranging from 100 V/s to 10 kV/s are shown exemplarily for Diode D5 in Fig. 3. The heating for the slower voltage ramp rates leads to a lower measured forward voltage. To determine the turn-on voltage it is therefore essential to choose the fastest available ramp rate to minimize this effect.

Forward Bias Characteristics

Due to the inductance of the long power cables from the pulse generator to the cryostat, the current pulse is significantly broadened, leading to a pulse-width of up to 3 ms. The forward characteristics at 77 K and 298 K were measured and are shown in Figure 4. All the diodes behave similarly.

Temperature Rise Due to Radiationn

During the irradiation of the diodes, i.e. when beam is impacting the CHARM target, a temperature rise of the second stage stack up to a peak temperature of 5.9 K was observed. Thermal simulations of the setup in COMSOL[2] showed this to be in agreement with the heat load expected by the radiation. As the stack's connection plate to the interface is made from stainless steel, a rather bad thermal conductor at these low temperatures, the heat load to the stack of few tens of milliwatt due to radiation is sufficient to lift the stack's temperature to a higher equilibrium level. However, the diode annealing temperature is far above the observed value, therefore this will not affect experimental goals. The measurements will be performed during the weekly shutdown, where heating due to irradiation is not an issue, allowing the characterization of the diodes at the desired temperature of 4.2 K.

CONCLUSION

The commissioning of a cryostat system to be used for in-situ qualification of cryogenic by-pass diodes under the influence of radiation has been performed successfully. In total, eight diodes of three different types were installed to be qualified during the 2018 irradiation period. The characteristics for currents up to 18 kA at room temperature and 77 K, as well as the characteristics up to 1 A at 4.5 K could be measured before the start of the irradiation. The setup is currently waiting to be installed permanently into CHARM, in the coming weeks.

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[2] COMSOL Multiphysics® 5.3

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