CRYOGENIC BEAM LOSS MONITORS FOR THE SUPERCONDUCTING MAGNETS OF THE LHC*

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Abstract

The Beam Loss Monitor detectors close to the interaction points of the Large Hadron Collider are currently located outside the cryostat, far from the superconducting coils of the magnets. In addition to their sensitivity to lost beam particles, they also detect particles coming from the experimental collisions, which do not contribute significantly to the heat deposition in the superconducting coils. In the future, with beams of higher energy and brightness resulting in higher luminosity, distinguishing between these interaction products and dangerous quench-provoking beam losses from the primary proton beams will be challenging. The system can be optimised by locating beam loss monitors as close as possible to the superconducting coils, inside the cold mass in a superfluid helium environment, at 1.9 K. The dose then measured by such Cryogenic Beam Loss Monitors would more precisely correspond to the real dose deposited in the coil. The candidates under investigation for such detectors are based on $p^+{-}n{-}n^+$ silicon and single crystal Chemical Vapour Deposition diamond, of which several have now been mounted on the outside of cold mass of the superconducting coil in the cryostat of the Large Hadron Collider magnets. This contribution will present the mechanical and electrical designs of these systems, as well as the results of their qualification testing including results of a cryogenic irradiation test.

INTRODUCTION

Motivation

The magnets close to the LHC interaction points (IPs) are exposed to high irradiation from the collision debris. It has been shown in Fluka simulation [1] that with the present configuration of the installed Beam Loss Monitoring (BLM) in this region, the ability to measure the energy deposition in the coil is limited because of this debris, masking the real beam loss signal (see fig. 1).

The particle showers from beam loss measured by the present BLM configuration are partly shielded by the cryostat and the iron yoke of the magnets. The system can hence be optimised by locating beam loss monitors as close as possible to the elements that need protecting. This is what is foreseen for the High Luminosity LHC (HL-LHC) upgrade,

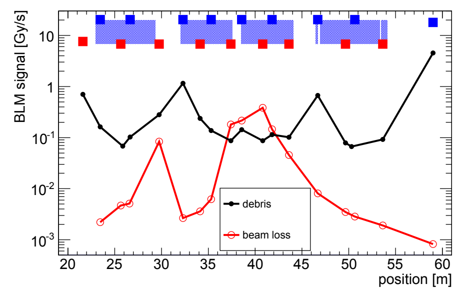

Figure 1: Doses in the coil and signal in the existing BLMs; black: BLM signal from collision debris (one point for each BLM); red: BLM signal from quench-provoking losses inside second central superconducting quadrupole magnet in the focusing triplet (Q2B).

where the BLM will be located near the superconducting coils inside the cold mass of the magnets in superfluid helium at a temperature of 1.9 K [2] (see fig. 2, courtesy of P. Ferracin)).

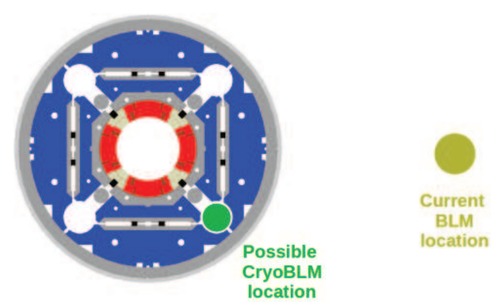

Figure 2: Cross section of a large aperture superconducting insertion magnet (MQXF) foreseen for HL-LHC with the current BLM placement and the future possible Cryogenic BLM location shown.

The advantage being that the dose measured by the Cryogenic BLM would more precisely correspond to the dose deposited in the superconducting coil [3].

Cryogenic BLM Requirements

From the mechanical point of view the main challenges of the Cryogenic BLM system is the low temperature of 1.9 K and 20 years, maintenance free operation [3]. Furthermore the Cryogenic BLM needs to work in a magnetic field of 2 T and at a pressure of 1.1 bar, and capable of withstanding a fast pressure rise up to 20 bar in case of a magnet quench.

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The electronic requirements, for a detector, are that is linear between 0.1 and 10 mGy/s and has a response time faster than 1 ms. Simulations of detector response were performed to estimate the allowable distance between the detector and amplifier and the best associated resistor and capacitor parameters. All the selected detector technologies are based on ionisation with subsequent charge carrier transport within the detector bulk material. The candidates under investigation are p^+-n-n^+ silicon [4] and single crystal Chemical Vapour Deposition (scCVD) diamond [5] detectors.

CRYOGENIC RADIATION TEST

The Cryogenic BLM specifications represents a completely new and demanding set of criteria that has never been investigated in such a form before. A certain knowledge about radiation hardness of particle detector is available for the temperature of outer space (2.7 K), from the requirements of space based experiments, but little is known for detectors below this temperature. The main unknown is the combination of the cold environment with a total ionizing radiation dose of 2 MGy. This is why the first radiation-hardness test of the diamond and the silicon detectors in liquid helium environment were recently performed at CERN [6].

Setup

The main aim of the cryogenic irradiation test was to investigate the radiation hardness of ionizing radiation detectors in liquid helium at 1.9 K. After careful preparations, the irradiation experiment was performed in the Proton synchrotron (PS) IRRAD beam line T7 in the East Experimental Area at CERN. This beam line is frequently used for sample irradiation and detector performance tests [7].

The detectors under investigation were:

- Single crystal CVD diamond with a thickness of 500 μm, an active area of 22 mm^2 and gold as metallisation material.
- p^+-n-n^+ silicon wafers with a thickness of 300 μm, an active area of 23 mm^2 and aluminium as metallisation material.

The T7 beam line provides protons with a particle momentum of 24 GeV/c. The beam intensity is 1.3 10^{11}protons/cm^2 per spill with an rms beam size at the samples location of about 1 cm^2. The spill duration is between 400 ms and 450 ms.

For the final implementation in the LHC, direct current (DC) measurements are required. It was therefore decided to characterise radiation hardness of the detectors by looking at DC measurements. These measurements were performed using a Keithley 6517, which enabled a high voltage bias to be applied while measuring the current at the same time. A LabVieW was written for data acquisition.

Results

At the end of the irradiation a total integrated fluence of 1.22 10^{16} protons/cm^2 was reached, corresponding to an integrated dose of about 3.26 MGy for the silicon and 3.42 MGy for the diamond detectors. The bias voltage could be switched from -400 V to +400 V for all detectors.

The silicon has a larger signal than the diamond at the beginning of irradiation, but the situation changes rapidly (see fig. 3). The reduction in signal corresponding to 20 years of LHC operation (2 MGy) is of a factor of 52 ±11 for the silicon device at 300 V and of a factor of 14 ±3 for the diamond detector at 400 V.

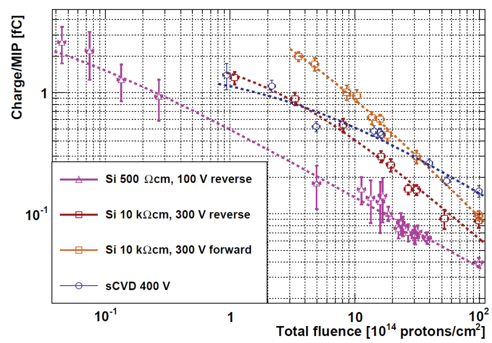

Figure 3: Degradation curves of scCVD diamond detector at 400 V compared with 10 kΩcm silicon detector at 300 V and 500 Ωcm silicon at 100 V reverse as reference curve [3].

In liquid helium, the major downside of silicon detectors compared to diamond, its high leakage current, disappears. The leakage current for the silicon remains below 100 pA at 400 V, even under forward bias for an irradiated diode. However, the diamond is seen to perform better for very high fluence and suffers less variation in its output.

INSTALLATION OF CRYOGENIC BLMS ON THE OUTSIDE OF THE COLD MASS OF THE LHC MAGNETS

As a safety critical system, the long term stability of the BLM detectors is a high priority criterion. It has therefore been decided to install several Cryogenic BLMs on the outside of cold mass of existing LHC magnets.

During Long Shut-down 1 (LS1) four cryogenic radiation detectors were mounted on the outside of the cold mass containing the superconducting coils in the cryostat of two LHC dipole magnets. These four detectors consisted of one 500 μm scCVD diamond detector (see fig. 4, place nr 1), one 100 μm silicon detector (see fig. 4, place nr 2) and two 300 μm silicon detectors (see fig. 4, places nr 3 and 4).

Two types of detector holders were also used, one Al_2O_3 based ceramic holder for one of the scCVD diamond detectors (see fig. 5) and seven FR-4 glass-reinforced epoxy laminate based holders for the other locations (see fig. 6). Taking into consideration that the final Cryogenic BLMs have to be available, reliable and operate for 20 years radiation hard connectors, feedthroughs and semi-rigid coaxial cables were used.

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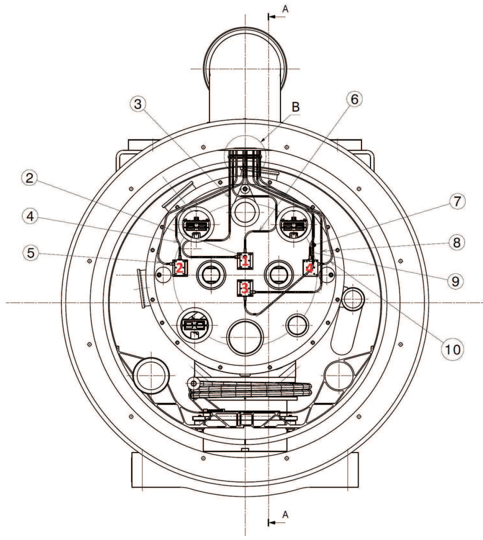

Figure 4: Cross section of an LHC dipole magnet showing the outer cryostat, the inner cold mass housing the superconducting coils and the position of cryogenic radiation detectors on the end of the cold mass.

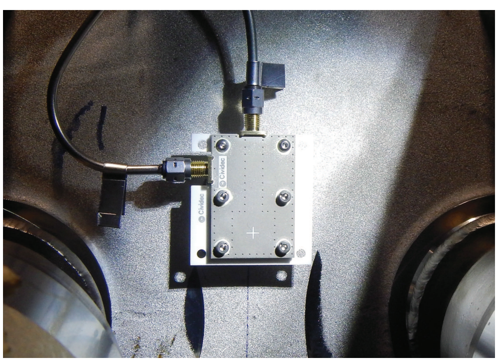

Figure 5: scCVD diamond detector mounted using a ceramic based holder.

Tests

A multistep testing procedure was performed on all detectors. Before installation the detector holders were immersed into liquid helium to test their low temperature resistance. During the installation the detectors were checked using ionizing radiation (see fig. 7), and, for the silicon detectors, using visible light.

After the interconnection between the two magnets where the detectors were located was closed and the cryostat were under vacuum a Current-Voltage (IV) curve measurement of the detectors was performed. The results (see fig. 8 and 9) show that the leakage current is at a reasonably low level, which should allow the measurement of beam losses with a high signal to noise ratio.

These first cryogenic radiation detectors installed in operational, superconducting LHC magnets will not only allow the behaviour of the detectors to be tested in realistic conditions, but also determine the validity of the integration in a setup at 1.9 K, in a magnetic field and under vacuum.

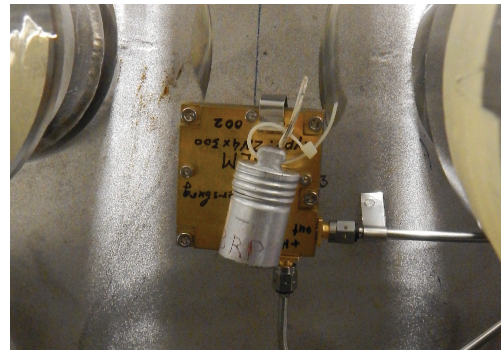

Figure 6: p^+-n-n^+ silicon detector mounted using an FR-4 glass-reinforced epoxy laminate based holder during testing with a gamma-radiation source (capsule).

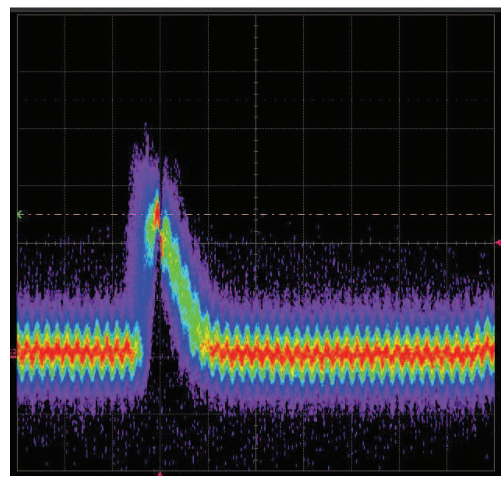

Figure 7: Beta-radiation induced signal from a scCVD diamond cryogenic radiation detector in the LHC magnet (80 mV on vertical and 40 ns on horizontal scale).

First results with beam are expected in early 2015, when the LHC starts its second operational run.

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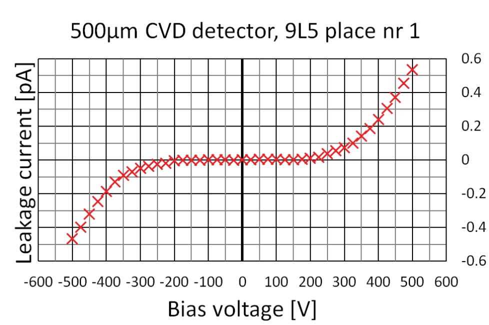

Figure 8: Leakage current of scCVD radiation detector as measured in a LHC superconducting dipole magnet at a temperature of 295 K.

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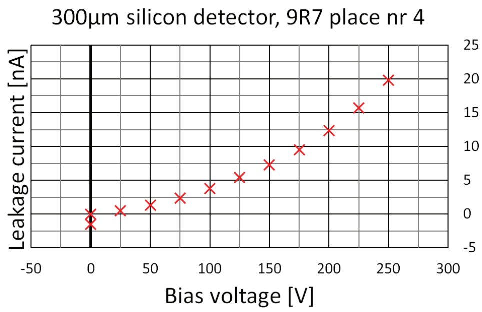

Figure 9: Leakage current of $p^{+}-n-n^{+}$ silicon radiation detector as measured in an LHC dipole magnet at a temperature of 295 K.

and, T. Koettig), C. Arregui Rementeria, A. Mereghetti, E. Griesmayer (CIVIDEC Instrumentation GmbH), C. Weiss, L. Gatignon, M. Glaser, F. Ravotti, RD39 collaboration (especially: J. Haerkoenen, E. Verbitskaya and P. Luukka), E. Guillermain, H. Pernegger, H. Jansen, V. Parma, T. Renaglia and a number of Beam Instrumentation group members at CERN.

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