OPERATION OF SILICON, DIAMOND AND LIQUID HELIUM DETECTORS IN THE RANGE OF ROOM TEMPERATURE TO 1.9 K AND AFTER AN IRRADIATION DOSE OF SEVERAL MEGA GRAY *

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Abstract

At the triplet magnets, close to the interaction regions of the Large Hadron Collider (LHC), the current Beam Loss Monitoring (BLM) system is sensitive to the debris from the collision points. For future beams, with higher energy and intensity the expected increase in luminosity implicate an increase of the debris from interaction products covering the quench-provoking beam losses from the primary proton beams. The investigated option is to locate the detectors as close as possible to the superconducting coil, where the signal ratio of both is optimal. Therefore the detectors have to be located inside the cold mass of the superconducting magnets in superfluid helium at 1.9 Kelvin.

Past measurements have shown that a liquid helium ionisation chamber, diamond and silicon detectors are promising candidates for cryogenic beam loss monitors. The carrier parameter, drift velocity, and the leakage current changes will be shown as a function of temperature. New high irradiation test beam measurements at room temperature and 1.9 Kelvin will reveal the radiation tolerance of the different detectors.

INTRODUCTION

The magnets close to the Interaction Points (IP) are exposed to radiation from the collision debris. With the present configuration of the installed BLM in this region, the ability to measure the energy deposition in the coil is limited because of the debris, masking the beam loss signal (see figure 1).

To overcome this limitation a solution, based on placing radiation detectors inside the cold mass close to the coils, is investigated (see figure 2).

Low intensity beam tests in cold have been successfully performed at CERN in the Proton Synchrotron (PS) beam line T9 in 2011 and 2012 [1]. The silicon diode's FWHM of the signal from a Minimum Ionising Particle (MIP) is of 2.5 ± 0.7 ns and that for the diamond detector the FWHM is of 3.6 ± 0.8 ns at liquid helium temperatures. With these detectors a fast detection system can hence be designed.

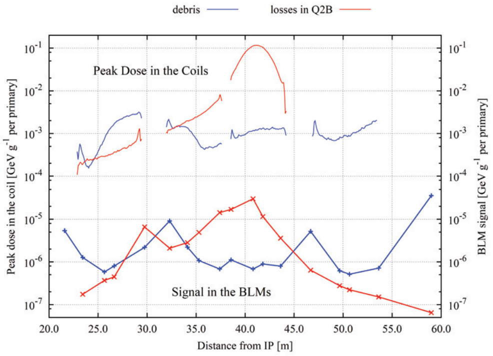

Figure 1: Simulated dose in the coil and signal in the BLM shown for two different situations: one for the debris from the interaction region (blue) and one for a simulated dangerous loss (red). The signal due to the debris can mask the signal from a dangerous loss [2].

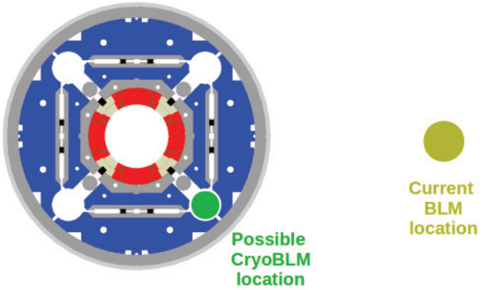

Figure 2: MQXF magnet cross section (courtesy of P. Ferracin) with the current BLM placement and the future possible Cryogenic BLM location.

The main experimental challenge for this project was to investigate the radiation hardness of the silicon and diamond detectors at liquid helium temperatures. The radiation dose at the cryogenic BLM placements was estimated to be of 2 MGy in 20 years.

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EXPERIMENTAL SETUP

The irradiation experiment with the detectors immersed in liquid helium could be performed in the end of 2012 in the PS beam line T7, which is frequently used for sample irradiation [4]. Figure 3 shows all detectors and their modules (see also [5]). At the outer extremities of the detectors were aluminium foils to confirm the total dose at the end of the irradiation. Figure 4 shows the cryostat during installation inside the irradiation zone.

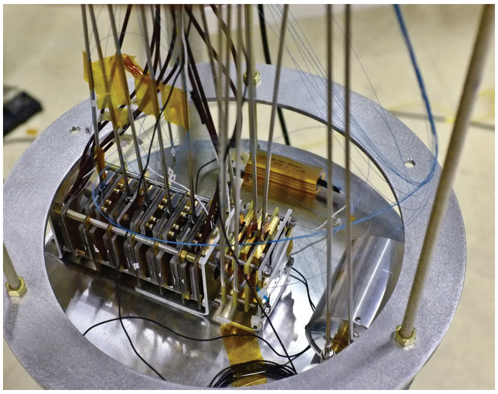

Figure 3: Detectors mounted on the ground plate of the cryostat insert.

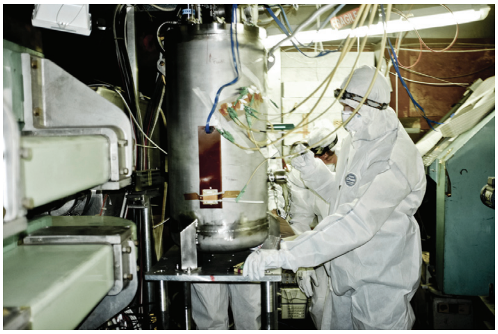

Figure 4: The cryostat during instalation in the irradiation zone.

Beam Characteristics

The PS beam of the T7 beam line consists of protons with a particle momentum of 24 GeV/c. The beam intensity was of 1.3 10^{11}protons/cm^2 per spill with an Root Mean Square (RMS) size at the samples of about 1 cm^2. The spill duration was 450 ms, with one to three spills within 45 s.

Table 1: The Relevant Silicon and Diamond Samples for the Presented Measurements in this Work

Detector	Resistivity [Ωcm]	Thickness [μm]	Active area [mm^2]
Si-10kOhm-1	10k	300	5x5
Si-500Ohm	500	300	5x5
sCVD-1		500	4.7x4.7

Detector Samples

The Silicon (Si) and single crystal Chemical Vapour Deposition (CVD) diamond detectors (sCVD) under investigation are summarised in the table.

The liquid helium ionisation chamber prototypes consist of parallel metallic plates connected with stabilisation rods. Between the plates is the liquid helium as detection medium.

Measurement Procedure

The current produced in the detectors by the beam particles was measured. In the offline analysis the current is integrated over the spill duration, the offset is subtracted and the obtained charge is normalised with the spill intensity in order to obtain the collected charge per MIP. The number of protons is known from a Secondary Emission Chamber (SEC) [3]. In parallel all relevant cryogenic information, such as temperature, pressure and liquid helium level was recorded.

SILICON AND DIAMOND DETECTOR

At the end of the irradiation a total integrated fluence of $1.22 \cdot 10^{16}$ protons/cm^2 could be reached, corresponding to an integrated dose of about 3.26 MGy for the silicon detectors and 3.42 MGy for the diamond detectors.

Leakage Current

Figure 5 shows that not only the reverse silicon leakage current goes down to 50 pA at 100 V, but also the forward current is only of 60 pA at -400 V for an irradiated silicon detector in cold. Directly after irradiation, the silicon diode showed a leakage current of 1.2 mA at 100 V and 288 K.

The diamond detector leakage currents stayed below 100 pA for all voltages and also for temperatures up to room temperature, even after high irradiation, which is one of the main advantages of diamond material compared to silicon diodes.

Degradation Curves

Figure 6 and 7 show the signal decrease with increased proton fluence for the single crystal CVD diamond

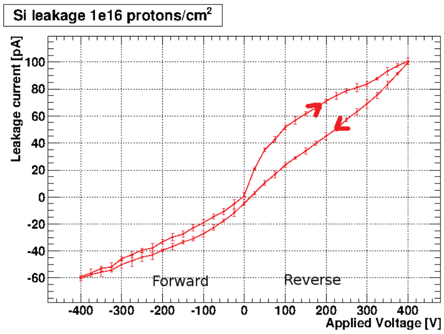

Figure 5: Silicon leakage current at liquid helium temperatures.

detector and the silicon diode respectively. The curve for the 500 Ωcm silicon sensor with 100 V reverse bias has been plotted in all graphics as reference curve.

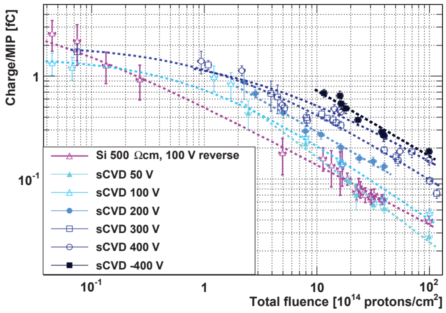

Figure 6: Degradation curves of the single crystal CVD diamond detector at different voltages with the silicon 500 Ωcm 100 V reverse as reference curve.

The decrease of the collected charge per MIP Q_{MIP} with increased fluence ϕ can be modelled [6] and the measured data can be fit through:

$$Q_{MIP}(\phi) = Q_{MIP}(0) \sum_{i=e^-,h} \frac{\mu_i E \tau_i(\phi)}{d} \cdot \left[1 - \left(\frac{\mu_i E \tau_i(\phi)}{d}\right)\left(1 - e^{-\frac{d}{\mu_i E \tau_i(\phi)}}\right)\right] \quad (1)$$

where $Q_{MIP}(\phi)$ is the collected charge per MIP at a fluence ϕ, $Q_{MIP}(0)$ is the initial collected charge of the non-irradiated detector, the sum is performed over the electrons and holes, μ_i is the charge carrier mobility, E is the applied electric field, d is the detector thickness and τ_i is the charge carrier life time, which can be written as:

$$\tau_i(\phi) = \frac{\tau_i(0)}{1 + \tau_i(0) \cdot \phi \frac{d \frac{1}{\tau_i(\phi)}}{d\phi}} \quad (2)$$

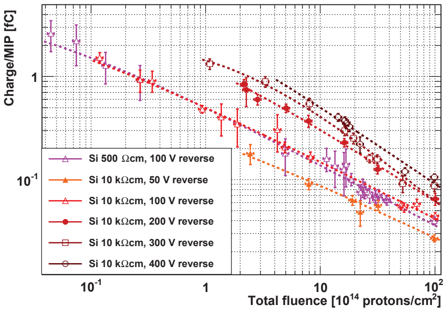

Figure 7: Silicon 10 kΩcm degradation curves under reverse bias with the silicon 500 Ωcm 100 V reverse as reference curve. The 100 V reverse curves of the two detectors with different resistivity match each other.

Figure 8 depicts the degradation curves of the 10 kΩcm silicon detector and the ones of the single crystal diamond detector. The silicon diode had a larger signal than diamond detectors at a low irradiation level, but the situation changed with increased fluence. For the silicon detectors at liquid helium temperatures, measurements could be performed under forward bias application, which is known as Current Injected Detector (CID) [7]. The forward bias modus of the silicon detector lead to high signals at the beginning of the irradiation, but the signal decrease at higher fluence was faster compared to the reverse bias operation.

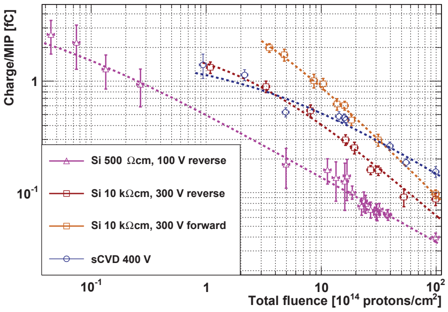

Figure 8: Degradation curves of single crystal diamond detector at 400 V compared with 10 kΩcm silicon detector at 300 V and the silicon 500 Ωcm 100 V reverse as reference curve.

LIQUID HELIUM CHAMBER

The charge carriers in liquid helium build up special structures, which contain up to several hundred of helium atoms and slow down the drift of the charge carriers. No fast detection system can be designed based on the charge carrier collection, but the liquid helium chamber is insensitive to radiation damage.

During the beam tests, the collected charge at 1.8 K with an applied electric field of 200 V/mm was of 0.12 ± 0.01 fC/cm/MIP. Further the current design of the liquid helium chamber enables protection from steady state losses (happening in the order of seconds) and any losses that are slower than 180 μs.

CONCLUSIONS

The expected reduction in signal over 20 years (2 MGy) of LHC operation is a factor of 25 ± 5 for the silicon device and a factor of 14 ± 3 for the diamond detector. With silicon and diamond sensors a fast detection system can be designed allowing bunch by bunch resolution. The LHe chamber on the other hand is an elegant solution due to its insensitivity to radiation damage. The results hence show the advantage of combining the two approaches, by using solid-state detectors for a fast protection system, while the LHe chamber can be used in parallel for calibration and for the protection from steady state losses.

OUTLOOK

An improvement of the radiation hardness can be obtain through the use of thinner detectors, for which the Charge Collection Distance (CCD) stays constant until a higher fluence. Further measurements, models and simulations will enable further conclusions. First CryoBLM prototypes (silicon and diamond detectors) have been installed on the cold mass of an LHC magnet (see figure 9). This and additional installations will enable to gain further experience with the detectors long term performance and will bring an unprecedented insight to LHC beam losses.

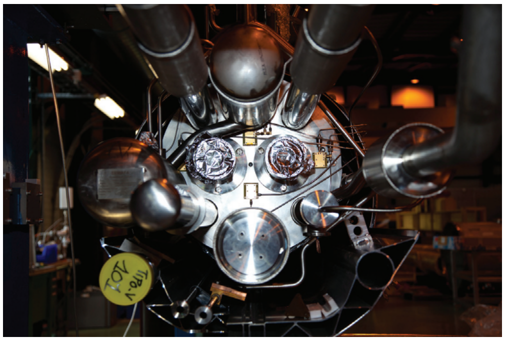

Figure 9: Silicon and diamond detectors installed on the cold mass of the superconducting quadrupole magnet to install in the LHC ring.

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