RADIATION TOLERANCE OF CRYOGENIC BEAM LOSS MONITOR DETECTORS

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Abstract

At the triplet magnets, close to the interaction regions of the LHC, the current Beam Loss Monitoring system is sensitive to the particle showers resulting from the collision of the two beams. For the future, with beams of higher energy and intensity resulting in higher luminosity, distinguishing between these interaction products and possible quench-provoking beam losses from the primary proton beams will be challenging. Investigations are therefore underway to optimise the system by locating the beam loss detectors as close as possible to the superconducting coils of the triplet magnets. This means putting detectors inside the cold mass in superfluid helium at 1.9 K. Previous tests have shown that solid state diamond and silicon detectors as well as liquid helium ionisation chambers are promising candidates. This paper will address the final open question of their radiation resistance for 20 years of nominal LHC operation, by reporting on the results from high irradiation beam tests carried out at CERN in a liquid helium environment.

INTRODUCTION

The magnets close to the Interaction Points are exposed to high radiation fields due to collision debris. With the present configuration of the installed Beam Loss Monitors (BLM) in this region, the ability to measure energy deposition in the coil is limited because of the debris, masking the beam loss signal [1]. Due to the proximity of the interaction point, a differentiation between signals from dangerous accidental losses and from the continuous collision debris is difficult. This is a critical issue for LHC machine protection. A solution to this problem, based on placing radiation detectors (CryoBLMs) inside the cold mass close to the coils, is investigated. The advantage would be that the dose measured by the detector would more precisely correspond to the dose deposited in the superconducting coil.

The detectors currently under investigation are:

- single crystal chemical vapor deposition (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 280 μm, an active area of 23 mm^2 and aluminium as metallisation material and
- a liquid helium chamber prototype, using liquid helium as detection medium.

Low intensity beam tests in cold have been successfully performed at CERN in the Proton Synchrotron (PS) beam line T9 in 2011 and 2012 [2]. With silicon and diamond sensors a fast detection system can be designed allowing both bunch by bunch resolution in the LHC and DC measurements for steady state losses. A fast system might be of interest for the LHC upgrade not only for the triplet magnets, but also for other critical locations.

The main experimental challenge for this project was to investigate the radiation hardness of the semiconducting sensors at liquid helium temperatures of 1.9 K (superfluid helium). The radiation dose at the CryoBLM placements is estimated to be of 1 MGy in 10 years.

The detector performance in liquid helium under high irradiation is unknown. One expectation for silicon is that the leakage current decreases at 1.9 K even under high irradiation, which should ameliorate the detector performance. Another expectation is that no detraping of charges, even from shallow defects, occurs at liquid helium temperatures. This can have a positive effect on the detector signal, as the occupied radiation defects are neutralised and can not trap further charges, but it can also have a negative effect, because stably trapped charges lead to possible detector bulk polarisation and inhomogeneous electric fields. In addition a possible accumulation of charges between the detector material and the metallic contacts could highly degradate the detector performance. Therefore even a complete disapparition of the detector signal could be imaginable. Only irradiation tests can bring the final answer about the actual detector radiation hardness in cold.

IRRADIATION EXPERIMENT

After careful preparations, the irradiation experiment could be performed in the end of 2012 in the PS beam line T7, which is frequently used for sample irradiation and detector performance tests [3]. Those tests allowed to measure the detector signal degradation, which will further be shown.

In figure 1, one can see all detectors and their modules (see also [4]). They are arranged on the ground plate and ready to be placed inside the cryostat. At the outer extremities of the detectors are aluminum foils to confirm the total dose at the end of the irradiation.

In figure 2, one can see the cryostat and the liquid helium transfer line installed inside the irradiation zone.

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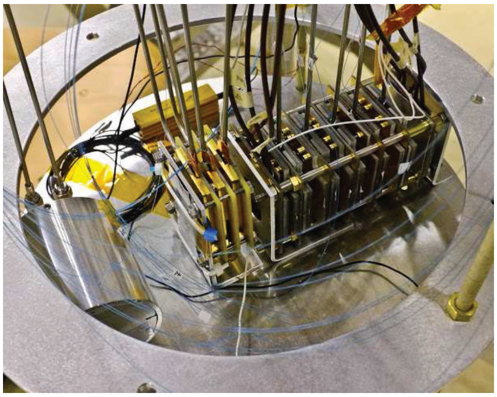

Figure 1: Detector modules mounted on plate and ready for cooling down and irradiating.

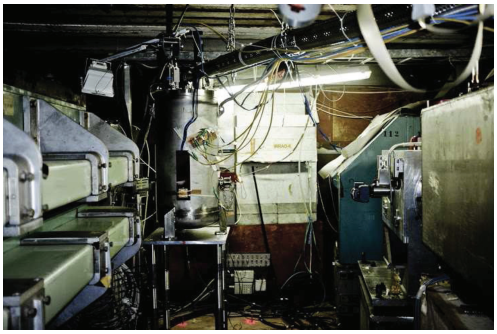

Figure 2: Cryostat and liquid helium transfer line installed in the active zone.

Beam Characteristics

The PS beam of the T7 beam line consists of protons with a particle momentum of 24 GeV/c. The beam intensity is of $1.3 \cdot 10^{11}$ protons/cm^2 per spill with an RMS size at focus of about 1 cm^2. The conversion of the energy deposition of 24 GeV/c protons into a dose (MGy) allows to compare the irradiation tests with the future situation in the LHC. The spill duration is of 400 to 450 ms.

Measurement Procedure

For the final application as BLM in the LHC, direct current (DC) measurements are prefered. It was therefore decided to characterise the detectors radiation hardness with respect to DC measurements. Those DC measurements were done using a Keithley 6517. The instrument enables to apply the voltage and measure the current at the same time. For data acquisition a LabVieW program has been written.

In the offline analysis the detector current is integrated, the offset is subtracted and the obtained charge is normalised with the spill intensity, which is known from a Secondary Emission Chamber (SEC) [5].

In parallel all relevant cryogenic information, such as temperature, pressure and liquid helium level was recorded.

RESULTS

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 silicon. The voltage could be switched from -400 V to +400 V for all detectors. This means for silicon that a forward bias has been applied, which is known as Current Injected Detector (CID) [6].

Damage Curves

The figures 3 and 4 show the reduction in charge collection for the 10 kΩcm silicon device and the single crystal diamond for voltages from 50 V to 400 V. The observation is that silicon has a larger signal than diamond at the beginning of the irradiation, but the situation changes rapidly. The reduction in signal over 20 years (2 MGy) of LHC operation 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. During the final warmup to room temperature the silicon signal recovers by a factor of 8, compared to the one in liquid helium. A maximum warmup to 80 K is expected in the LHC magnets. Only above 135 K a signal recovery is noticeable.

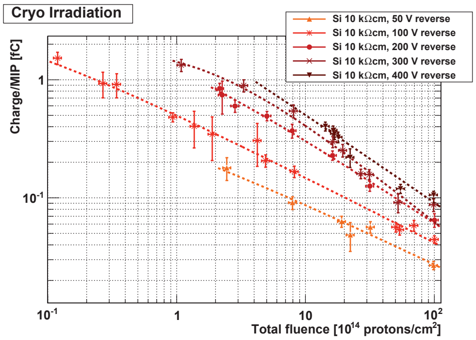

Figure 3: Signal reduction for the silicon detector with increased fluence for different voltages.

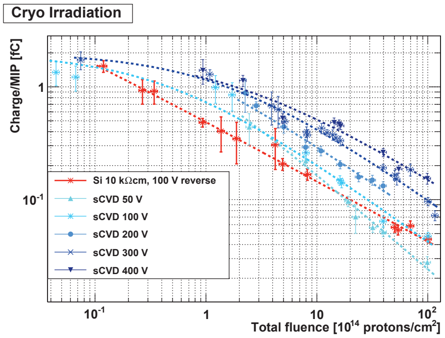

Figure 4: Signal reduction for the diamond detector with increased fluence for different voltages.

Further analysis of the data and the fitting parameters in comparison with a tested liquid helium chamber and the

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BLM application criteria will allow to say which detector has the best potential as CryoBLM.

Voltage Scan

The voltage scans for the two presented detectors at different fluencies are depicted in the figures 5 and 6. In the voltage scans for silicon, positive voltage stands for forward bias.

There is no full charge collection for single crystal diamond above a voltage of 100 V, as it would be expected for non-irradiated single crystal diamond at room temperature. The situation for silicon detectors is similar, where an initial full depletion voltage does not lead to full charge collection anymore.

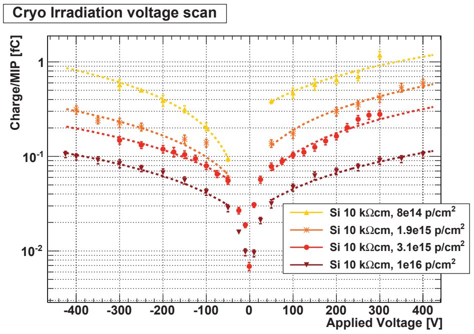

Figure 5: Voltage scan with the silicon detector at different fluences.

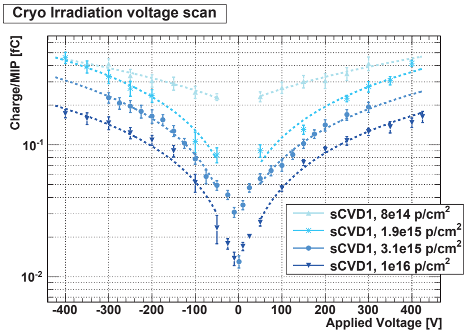

Figure 6: Voltage scan with the diamond detector at different fluences.

Leakage Current

For silicon the observation from figure 7 is that not only the reverse silicon leakage current goes down to 40 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 produced a leakage current of 1.2 mA at 100 V and 288 K.

The diamond leakage currents stay 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 compared to silicon.

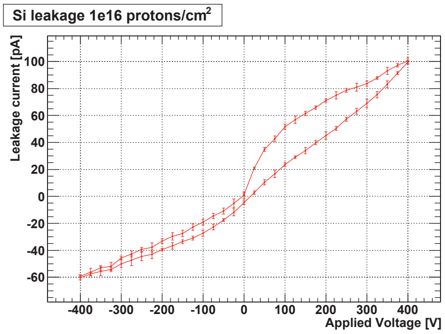

Figure 7: Silicon leakage current in liquid helium.

CONCLUSIONS AND OUTLOOK

In liquid helium, the major downside of silicon compared to diamond disappears: the leakage current for silicon is below 100 pA at 400 V, even under forward bias for an irradiated diode. The performed experiments allowed to observe the radiation effect on the detectors sensitivity for silicon and single crystal diamond. For the BLM application as a safety critical system, the long term stability of the detectors is a high priority criteria. The data therefore requires more time for treatment to allow further application relevant conclusions and physical results. Silicon and diamond detectors have been installed on the cold mass of an LHC magnet. This location will enable to gain further experience with the detectors long term performance and will bring an unprecedented insight to LHC beam losses.

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