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In situ radiation test of silicon and diamond detectors operating in superfluid helium and developed for beam loss monitoring

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ABSTRACT

As a result of the foreseen increase in the luminosity of the Large Hadron Collider, the discrimination between the collision products and possible magnet quench-provoking beam losses of the primary proton beams is becoming more critical for safe accelerator operation. We report the results of ongoing research efforts targeting the upgrading of the monitoring system by exploiting Beam Loss Monitor detectors based on semiconductors located as close as possible to the superconducting coils of the triplet magnets. In practice, this means that the detectors will have to be immersed in superfluid helium inside the cold mass and operate at 1.9 K. Additionally, the monitoring system is expected to survive 20 years of LHC operation, resulting in an estimated radiation fluence of 1×10^{16} proton/cm^2, which corresponds to a dose of about 2 MGy. In this study, we monitored the signal degradation during the *in situ* irradiation when silicon and single-crystal diamond detectors were situated in the liquid/superfluid helium and the dependences of the collected charge on fluence and bias voltage were obtained. It is shown that diamond and silicon detectors can operate at 1.9 K after 1×10^{16} p/cm^2 irradiation required for application as BLMs, while the rate of the signal degradation was larger in silicon detectors than in the diamond ones. For Si detectors this rate was controlled mainly by the operational mode, being larger at forward bias voltage.

1. Introduction

The superconducting magnets of the Large Hadron Collider (LHC) located close (within a few tens of meters) to the Interaction Points (IP) of the proton beams are exposed to high-radiation fields due to the collision debris. The Beam Loss Monitoring (BLM) system is an integral component of the LHC, which measures the particle showers from beam losses. BLM signals which exceed the protection thresholds trigger the beam abort system. By these means the quench of the superconducting magnet coils can be prevented and various LHC components are protected from damage. The sensitivity of the monitors depends on their location and orientation with respect to the beam. It has been shown using Fluka simulation [1] that with the present configuration of the BLMs installed outside the cryostats of the final focusing triplet magnets, the ability to measure energy deposition into the magnet coils is limited because of the collision debris, which mask the beam loss signals. This is illustrated in Fig. 1, where the signals in the BLM sensors are shown for cases of beam debris and the occurrence of a quench-provoking beam loss. At the top of the figure the location of magnets Q1–Q3 and BLMs is visualized, with the BLMs placed inside or outside the ring, giving signals with a small difference. As a result of the proximity of the interaction point, differentiation between the signals from the quench-provoking beam losses and from the continuous collision debris is difficult.

There is an ongoing activity that started in 2011 to upgrade the BLM systems of the LHC by installing the sensors inside the cold mass, as close as possible to the superconducting coils. The direct advantage of cryogenic BLMs (CryoBLMs) would be that the measured dose corresponds more precisely to the dose deposited into the coil. The main requirements for CryoBLMs are listed below:

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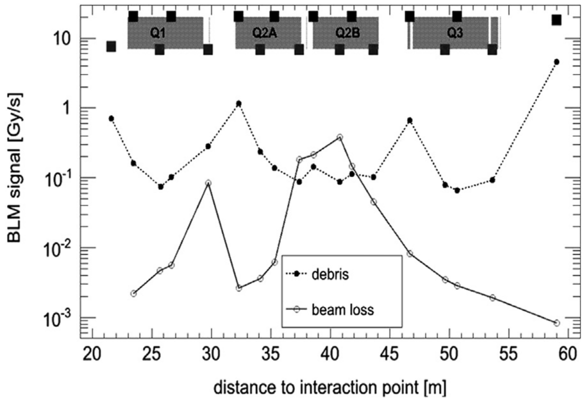

Fig. 1. BLM signal from debris and from quench-provoking beam losses (one point for each BLM) in the inner triplet region of the LHC. At the top the locations of the magnets (Q1–Q3) and BLMs (small boxes) are visualized.

1. A low operational temperature of 1.9 K (superfluid helium).
2. An integrated dose of about 2 MGy (in 20 years, without accidents).
3. The detector response should be linear between 0.1 and 10 mGy/s, which is the range of signals expected close to the quench, and faster than 1 ms.
4. The CryoBLM sensors should work in a magnetic field of 2 T and at a pressure of 1.1 bar, withstanding a fast rise in pressure up to about 20 bar.
5. Once the detectors have been installed into the LHC, no access will be possible; therefore the detectors need to be reliable and stable for 20 years.
6. A predictable rate of the sensitivity degradation with a minimal deviation over a large number of sensors, which should be guaranteed by the sensor processing and calculated from the parameters of the sensor material and construction (dimensions and technology).

Two types of BLM radiation detectors based on either silicon or diamond material are currently under investigation. Radiation detectors made of silicon are cost-effective due to application of industrial planar technology. Their radiation hardness properties at room temperature (*RT*) and insignificant cooling are rather well known because of the numerous investigations of the CERN-RD50 collaboration ([2,3]) and they are widely used for tracking of charged particles in high-energy physics experiments.

The advantage of diamond detectors with regard to radiation hardness arises from the wide bandgap of diamond and the higher displacement energy, plus higher carrier mobility [4]. Therefore the dark current is almost negligible, even at *RT*, and no active cooling is needed. This makes it possible to build fast and low-noise charged particle diamond detectors [5–7] which are a very favorable option for a smaller scale or unique applications of single devices such as radiation monitoring at certain points of the LHC experiments, or in which it is impossible to construct an active cooling system. Recently, diamond detectors were tested in the collimation area of the CERN LHC to study their feasibility as Fast Beam Loss Monitors in a high-radiation environment [8,9]. However, the large electron–hole pair creation energy in diamond material leads to a reduced signal compared with silicon of equal thickness and energy of minimum ionizing particles (MIP).

The first beam test of nonirradiated semiconductor prototypes of BLM sensors was performed at LHe temperature at CERN in the Proton Synchrotron (PS) beam line T9 [10,11]. All the detectors that were tested proved to be operational in direct current (DC) and single-particle counting (AC) modes when placed at ~2 K. In addition to overall functionality at very low temperatures, the next important issue to be addressed is the radiation hardness of silicon and diamond detectors under the operational conditions of BLMs. Earlier the characteristics of irradiated Si detectors at temperatures in the range from 77 K to *RT* were investigated to explain the so-called “Lazarus effect” [12]. It was shown that the recovery of the signal occurred at $T \sim 180$ K in detectors irradiated at *RT*, which was not affected by the temperature of irradiation (*RT* and 85 K were tested) or by reverse annealing [13]. It was demonstrated that the origin of the temporary recovery of the detector sensitivity is the change in the occupancy of radiation-induced trapping centers by electrons and holes, which is not stable over time and therefore is not an issue for the improvement of the detector radiation hardness.

From the physics of radiation defect formation it is expected that radiation damage on semiconductor materials can be substantially different at the LHe temperature compared to *RT* and even at the temperature of liquid nitrogen. For example, at such low temperatures the reduced migration of primary defects, interstitials and especially vacancies [14,15] may change the radiation defect energy level spectrum and affect the properties of carrier capture and emission. Reverse annealing, which is one of the main causes of radiation degradation of Si detectors around *RT*, would be significantly reduced or even ceased completely.

The first *in situ* irradiation test at 1.9 K of Si and diamond detectors developed for CryoBLMs was performed at CERN during November and December 2012, and its description and experimental data were presented in fragments in Refs. [11,16–18]. The detectors were installed inside a liquid helium cryostat while being irradiated *in situ* by 24 GeV/c protons provided by the CERN PS accelerator. This test beam experiment is particularly unique because of the very low temperature of 1.9 K and high integrated radiation dose of up to 2 MGy. The main task of this study is gaining insight into the radiation hardness of Si and diamond detectors at such a low temperature and verifying that the detectors can operate under the conditions listed above in points 1 and 2 required for semiconductor CryoBLMs. The overall description of the experiment, its results and qualitative analysis are reported taking into account the physics of semiconductor detector operation under irradiation.

2. Experimental setup and procedures

Irradiation campaigns at *RT* (or around) are usually carried out in steps, namely, the samples are first irradiated to the desired fluence *F* and then brought, under temperature- and time controlled conditions, into a laboratory for characterization. After the measurements, the samples might be returned into the irradiation for the next step, and the thermal history of the samples is recorded. In the case of the experiment at liquid helium temperature this is, however, not possible (unless the beam can be stopped) since warming-up the samples even to 80 K can result in significant defect annealing and, thus, misleading conclusions about the physical properties of the irradiated material and the sensors. Therefore cryogenic irradiation test must be performed as *in situ* test with the measurements carried out permanently using a special cryostat and proper cabling.

2.1. Irradiation

The cryogenic *in situ* irradiation test was performed at PS East Hall (T7 experimental area) at CERN during November and December 2012. The energy of the proton beam was 23 GeV and the full width at half-maximum of the beam diameter was tuned to be about 1 cm at the detector location. The beam intensity was 1.3×10^{11} proton/cm^2 per 400 ms spill, corresponding to about 1×10^{10} proton/s on the detectors and the planned maximum fluence of 1×10^{16} proton/cm^2 was reached. The fluence and the