EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN - TS Department

EDMS Nr: 473714 TS-Note-2004-006
Group reference: TS-LEA 4 May 2004

THE RADIATION MONITORING SYSTEM FOR THE LHC EXPERIMENTS AND EXPERIMENTAL AREAS

L. Fernandez-Hernando[1], M. Glaser[2], Ch. Ilgner[3], A. Macpherson[4], A. Oh[5], T. Pritchard[6],
F. Ravotti[3], R. Stone[7], E. Tsesmelis[3], S. Worm[7]

Abstract

With the high energies stored in the beams of the LHC, special attention needs to be paid to accident scenarios involving beam losses which may have an impact on the installed experiments. Among others, an unsynchronized beam abort and a D1 magnet failure are considered serious cases. According to simulations, the CMS inner tracker in such accident scenarios can be damaged by instantaneous rates which are many orders of magnitude above normal conditions. Investigations of synthetic diamond as a beam condition monitor sensor, capable of generating a fast beam dump signal, will be presented. Furthermore, a system to monitor the radiation fields in the experimental areas is being developed. It must function in the radiation fields inside and around the experiments, over a large dynamic range. Several new active and passive sensors, such as RadFET, OSL (Optically Stimulated Luminescence) sensors, p-i-n diodes, Polymer-Alanine Dosimeters and TLDs (Thermoluminescent Dosimeters) are under investigation. Recent results obtained in test beams and in the laboratory, including a GEANT4 Monte Carlo simulation of the sensor housing, are presented.

---

[1] CERN, dept. TS/LEA and Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
[2] CERN, dept. PH/TA1
[3] CERN, dept. TS/LEA
[4] CERN and Paul-Scherrer-Institut, Villigen, Switzerland
[5] CERN, dept. PH/CMD
[6] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[7] Rutgers, the State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854-8019, USA

Presented at the TS Workshop
Archamps, France, May 4 – May 6, 2004

1 INTRODUCTION

As present and future particle accelerators like the CERN Large Hadron Collider move to higher and higher beam energies and intensities, the requirement on the performance of associated beam monitors is increased. For the CERN LHC with its 7TeV proton beams at a nominal peak luminosity of 10^{34}cm^{-2}s^{-1}, beam losses can be potentially damaging to both the accelerator and the experiments. Whilst a Beam Loss Monitor system [1] is being developed for the accelerator, a complementary system in the experimental areas is required. For this reason a Beam Condition Monitor (BCM) is being developed. It will be based on fast and radiation hard beam sensors.

Chemical vapor deposited (CVD) diamond was chosen as material for the BCM sensor for its properties. Various samples of CVD diamond have been characterized extensively with beta particles from a ^{90}Sr source and with protons from a high intensity beam to assess the suitability of such sensors for application to the BCM system. Preliminary results from these investigations are presented.

For the experimental areas a monitoring system, capable of dealing with the varying radiation environment throughout the caverns, needs to be set up. A variety of active and passive sensors has been investigated in view of their response to different types of radiation [13]. For MOSFET dosimeters (RadFETs), the fast-neutron response became of practical interest for their utilization in the radiation environment of the CERN LHC experiments. For this reason a dedicated test beam was carried out [2]. The influence of the RadFETs housing (simulated using polyethylene slabs of different thicknesses) was studied with the GEANT4 simulation package.

2 BEAM CONDITION MONITORING

The purpose of the BCM is to provide real-time radiation monitoring within CMS [3] and ATLAS [4] to detect and initiate protection procedures for detector subsystems at the onset of beam instabilities and accidents. The goal is to provide monitoring information in the time scale of the LHC beam structure of 25 ns.

BCM sensors will be located close to the beam pipe, at a distance of about 1.5 m from the interaction points. Fast electronics placed outside the main volume of the spectrometers will process the signal from the sensors.

There are several beam accident scenarios which could be potentially dangerous for the experiments [5], [6]. The time-scale of a beam accident is dependent on the failure and can vary from 250 ns to several milliseconds. The flux during the beam accidents is expected to increase by a factor of up to 10^9 compared to normal running conditions. The flux during normal operation near the interaction point is 50 to 60 (minimum ionizing particles)/(cm^{2}µs) [7].

2.1 Diamond characterization

Polycrystalline CVD diamond was chosen for investigation as the BCM sensor because of its high radiation hardness [8], fast response time, and minimal services requirements.

The charge collection properties of several samples were characterized with beta particles from a ^{90}Sr source approximating minimum ionizing particles (MIPs). The metal contacts were characterized by measuring the I-V curves.

A MIP in diamond will generate on average 36 electron-hole pairs per µm [9]. The generated electron-hole pairs will drift toward the electrodes driven by the applied electric field. The collection distance δ is a measure of the efficiency of collecting the generated charge in the bulk:

$$\delta = \frac{Q_C}{Q_G} \cdot d \qquad (1)$$

where QC is the collected charge, QG the primary ionization charge produced by the particle and d the detector thickness. In the case of small efficiencies, the collection distance corresponds to the sum of the average drift distance of electrons and holes. Fig. 1 shows the dependence of δ on the electric field.

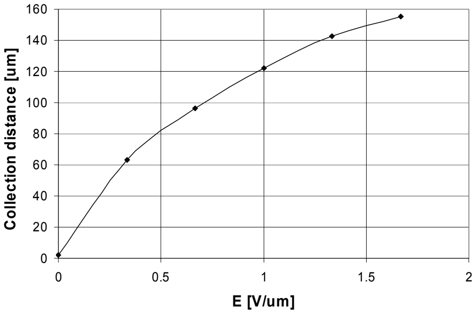

Fig. 1:. δ versus electrical field for a 300 µm thick diamond (fully pumped, i.e. all charge traps are completely filled up) with the electrons from the ^{90}Sr source. Each point represents the signal from the diamond to a minimum-ionizing particle after a stabilization period of 4 hours to avoid any polarization effect.

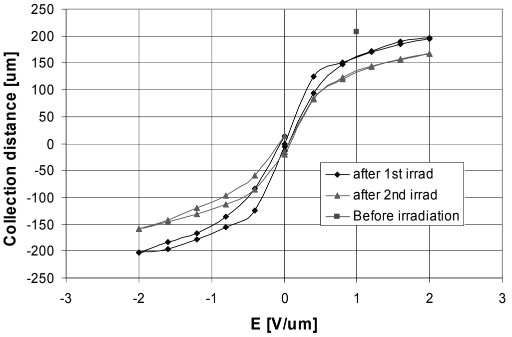

Fig. 2:. δ versus electrical field curves after a first irradiation of 10^{15}protons/cm^2 and after second irradiation of $2.8\cdot10^{15}$protons/cm^2, to the same 500 µm thick polycrystalline CVD diamond. The value of δ before irradiation at 1V/µm is also given.

2.2 Radiation tolerance

The radiation tolerance was tested with protons up to a fluence of $2.8\cdot10^{15}$protons/cm^2 which is equivalent to the fluence expected after 10 years of normal operating conditions in the LHC near the CMS interaction point. We have observed a degradation of δ by 28 % after the second irradiation. The plot of δ versus the electrical field in Fig. 2 shows an example of this study for a 500 µm thick diamond. The value of δ before irradiation for an electrical field of 1 V/µm is also given.

The measurement cycle started at 0 V and scanned the full range between +1000 V and -1000 V in steps of 200 V. The hysteresis observed is due to polarization and depolarization effects. Each point on the graph represents the signal from the diamond after 20 minutes of applying the bias. The polarization effect has not stabilized by this time.

2.3 Test beam measurements

For the purpose of testing the response to a flux equivalent to the “worst case” beam accident scenario, samples were placed in a dedicated high intensity 24GeV/c proton beam from the Proton Synchrotron (PS) IRRAD1 facility at CERN [10].

This worst case scenario is assumed to be that of an unsynchronized beam abort accident [11], [12]. From simulation it has been estimated that ~10^{12} protons are lost in the CMS region, and that for the BCM, the fluence is ~10^9protons/cm^2, delivered in ~250 ns.

In order to approximate an unsynchronized beam abort, the beam spill was composed of one up to a maximum of eight bunches, each containing ~10^{11} protons at an energy of 23.1 GeV (minimum-ionizing particles). The 1σ width of the bunch was 10.5 ns, and the inter-bunch spacing was 262 ns.

The sensor was connected via a 16 m long 50Ω coaxial cable, terminated by a matched attenuator. A *LeCroy* LC564 A 1 GHz bandwidth digital oscilloscope was used to record the signals.

Fig. 4 shows the response for a single bunch from diamonds CDS116 (500 µm thick sample-irradiated) and CDS126 (300 µm thick sample-irradiated), at a beam, where aluminum activation measured a particle fluence of about $3\cdot10^8$protons/cm^2.

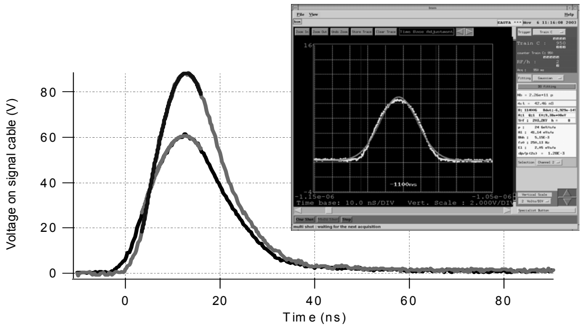

Fig. 3: Signal response from two different diamonds for a single bunch. The signal structure can be compared with the bunch structure from the PS machine (see insert).

With sample CDS126 we measured a σ = 10.5 ns, while for the CDS116 σ = 9.0 ns was obtained. The values are comparable to the PS bunch structure, whose σ was 10.5 ns.

Integrating these pulses and taking into account the δ for each diamond at the corresponding bias and the area of the metallization, we obtain the number of protons per cm^2 that traversed the sensors. The value found for CDS126 is $8.7 \cdot 10^7$protons/cm^2, and for CDS116 it is $9.8 \cdot 10^7$protons/cm^2, showing a reasonable agreement between the two samples.

3 RADIATION MONITORS

In order to comply with the radiation-monitoring requirements throughout the LHC experimental caverns and detectors, a variety of different sensors, both passive and active, have to be provided to the experiments. The following sections present several new techniques [13].

3.1 Optically Stimulated Luminescence

Optically Stimulated Luminescence (OSLs) is an effect that can be used for dosimetric purposes: ionizing radiation generates electron-hole pairs that get trapped by dopants with energy levels located in the wide band gap of the OSL material. In order to retrieve the dose information, the material is stimulated with infrared light (wavelength: 800-1500 nm) which leads to an emission of light in the visible range (500-700 nm), proportional to the received ionizing radiation dose (see Fig. 4) [14].

OSL materials in the form of thin films were also used during the CVD diamond irradiation for the BCM sensor. Figure 5 shows the test beam profile as

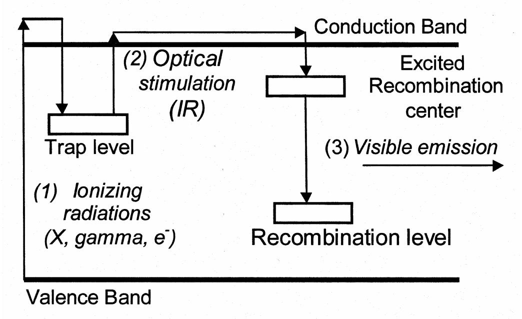

Fig. 4: OSL band scheme, electron-hole pair generation under radiation and readout. (Courtesy of L. Dusseau , Montpellier University)

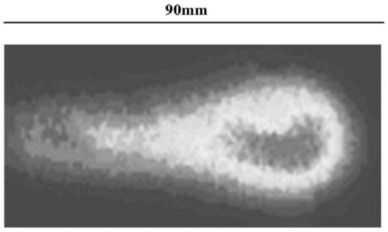

Fig. 5: OSL film, exposed to the proton beam of the CVD diamond test.

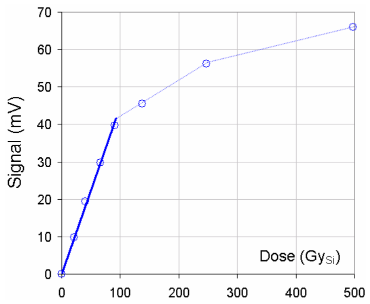

Fig. 6: OSL response over the dynamic range.

recorded by the dosimetric response of the OSL film. Figure 6 gives instead an example of the dosimetric response of the OSL material used at CERN over the dynamic range, which starts at about 100 μGy.

OSL material itself doesn't suffer from radiation damage. Once read out, its sensitivity is as it was in the un-irradiated state.

Currently two approaches for automatic and remote readout of the OSL materials are under investigation: GaAsP photodiodes with the sensitive OSL directly deposed on the photodiode's active surface and optical fiber readout. These solutions will simplify the light collection for remote readout as well as the radiation hardness required for a remote radiation sensor.

3.2 RadFETs

RadFET dosimeters are p-channel MOS transistors that are used to measure the ionizing dose via a charge build-up in the SiO_2 layer of the device. The growth of the transistor threshold voltage V_{th} is proportional to the deposited dose when a constant current passes through the device [15]. RadFETs are integrating dosimeters. They are usually used where regular measurements of doses over long periods of time are required [16].

The study of the influence of the plastic material used as packaging of some RadFET dosimeters became a key issue for the utilization of such devices in a neutron based environment like the one expected around the LHC experiments. The effects of different PE covers, simulating the RadFET packaging, was thus investigated experimentally and using the GEANT4 Monte-Carlo simulation tool. The GEANT4 simulations show that the dominating effect in a fast neutron field is the production of recoil protons.

The experiment demonstrates, in good agreement with the GEANT4 predictions, that the mounting of the RadFET housing as well as the surrounding material has a significant influence on the response to neutrons. Placing low Z materials close to the device can strongly increase its sensitivity. This effect can be useful for the application, but induces large errors in the dose measurement if neglected [2].

Thus, for the use of RadFETs in radiation fields containing neutrons, gammas and other particles, as in the CERN LHC experiments, special care has to be taken.

3.3 PIN diodes

Another dosimetric concept is based on silicon p-i-n diodes. Radiation causes displacement damage in the bulk silicon material, as well as macroscopic effects, like an increase in Si resistivity and leakage current, both proportional to the received particle fluence [13].

A simple remote readout can be realized as so-called "forward bias", assessing the macroscopic radiation effects with a fast current pulse. Another option is to use the diodes in reverse bias mode, with "pad structures", if high sensitivity fluence measurements are required. Figure 7 shows the irradiation response of the OSRAM BPW34F diodes that were tested in forward bias operation applying a current pulse of 1 mA over 180 ms for the readout.

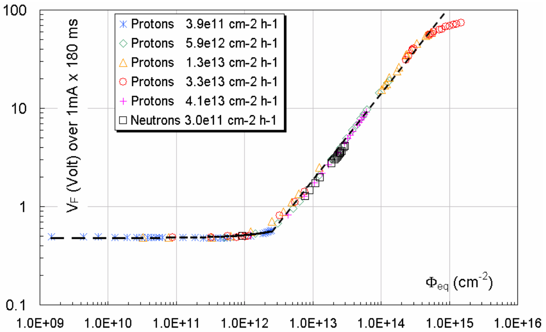

Fig. 7: Irradiation response of OSRAM BPW34F pin diodes (forward bias operation mode).

3.4 Passive sensors

For long-term radiation monitoring, several techniques are available: polymer-alanine (PAD) and radio-photo luminescent (RPL) dosimeters. Their working principle is the formation of stable free radicals (PAD) or color centers (RPL) after irradiation. For readout, they have to be removed. The necessary readout instrumentation and know-how is already in use at CERN (SC/RP department).

4 CONCLUSION

In a test beam measurement could be demonstrated, that CVD diamond is a promising sensor candidate for the LHC Beam Condition Monitor, capable of withstanding the expected radiation doses and particle fluxes.

Several sensor types are under investigation for various monitoring applications in the LHC experimental caverns. In the present state, it is worth continuing the investigation of a broad variety of sensor technologies in order to provide the experiments with all possible information they need to make their sensor choices.

5 ACKNOWLEDGEMENTS

The authors wish to thank Jens Spanggaard for having set up the fast extraction beam line for the irradiation tests, The CERN RD42 collaboration with their spokespersons H. Kagan, and

P. Weilhammer has kindly helped with advice, provided the diamond samples and granted access to its characterization stand.

6 REFERENCES

[1] L. Fernandez-Hernando, V. Cindro, Ch. Ilgner, A. Macpherson, A. Oh, H. Pernegger et al., Development of a Beam Condition Monitor for Use in Experiments ath the CERN Large Hadron Collider Using Synthetic Diamond, in preparation.

[2] F. Ravotti, M. Glaser, M. Moll, A.G. Holmes-Siedle, and Ch. Ilgner, Response of RadFET dosimeters to high fluences of fast neutrons, in preparation.

[3] http://cmsinfo.cern.ch/Welcome.html

[4] http://atlas.web.cern.ch/Atlas/Welcome.html

[5] O. Brüning, “Mechanisms for Beam Losses and their Time Constants”. *Chamonix IX*, Jan. 1999.

[6] M. Fahrer et. al., Beam loss induced electrical stress test on CMS Silicon Strip Modules, NIM A 518, pp 328-330, 2004.

[7] M. Huhtinen. “The radiation environment at the CMS experiment at the LHC”. Geneva, CERN, HU-SEFT-R-1996-14. 1996.

[8] W. Adam et. al. (The RD42 Collaboration). “Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC”. *CERN/LHCC 2002-010, LHCC-RD-001. Status Report/RD42*, March 2002 and November 2003.

[9] L. S. Pan, S. Han and D. R. Kania. “Diamond: Electronic Properties and Applications”. Kluwer Academic Publisher. 1995.

[10] M. Glaser et al., New Irradiation Zones at the CERN-PS, NIM A 426 pp 72-77, 1999

[11] M. Huhtinen et. al., Impact of the LHC beam abort kicker pre-fire on high luminosity insertion and CMS detector performance, Proceedings of the 1999 Particle Accelerator Conference, New York, pp 1231-1233.

[12] M. Huhtinen, N. Mokhov, S. Drozhdin. ”Accidental Beam Losses at LHC and impact on CMS Tracker”. *CMS General Meeting, Geneva, CERN, unpublished.* 16 March 1999.

[13] F. Ravotti, M. Glaser, M. Moll, K. Idri, J-R. Vaillé, H. Prevost, and L. Dusseau, “Conception of an Integrated Sensor for the Radiation Monitoring of the CMS Experiment at the Large Hadron Collider”, CERN-PH-EP-2004-004, NSREC Conference, Atlanta, USA, 2004.

[14] O. Missous, F. Loup, J. Fesquet, H. Prevost, J. Gasiot, “Optically Stimulated Luminescence of rare-earth doped phosphors”, Eur. J. Solid State Inorg. Chem., Vol. 28/s, pp. 163,166, 1991.

[15] A.G. Holmes-Siedle and L. Adams “RadFETs: a review of the use of metal-oxide-silicon device as integrating dosimeters”, *Rad. Phys and Chem.* 28(2), pp. 235-244, 1986.

[16] B. O’Connell, C. Connelly, C. McCarthy, J. Doyle, W. Lane and L. Adams “Electrical performances and radiation sensitivity of Stacked PMOS Dosimeters Under Bulkbias Control*”, IEEE Trans. Nucl. Sci.,* Vol. 45, pp. 2689-2694, 1998.