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Conception of an Integrated Sensor for the Radiation Monitoring of the CMS Experiment at the Large Hadron Collider

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Abstract

The concept of an active integrated dosimetric sensor for the radiation monitoring of the Compact Muon Solenoid experiment at the CERN (European Center for Nuclear Research) Large Hadron Collider is presented. The sensor, based on RadFET, OSL, *p-i-n* diode and Pad detector dosimeters, will measure both ionizing and non-ionizing energy losses in the harsh radiation environment produced by hadron interactions.

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I. INTRODUCTION

THE radiation environment encountered in the Large Hadron Collider (LHC) experiments at CERN [1] will differ completely from standard applications in which existing dosimetric technologies are used.

The mixed radiation field in the Compact Muon Solenoid (CMS) Experiment will be composed of neutrons, photons and charged hadrons. This complex field, which has been simulated by MonteCarlo codes [2], is due to particles generated by the proton-proton collisions and reaction products of these particles with the sub-detector material of the experiment itself. The proportion of the different particle species in the field will depend on the distance and on the angle with respect to the interaction point (i.e. the radiation environment is unique for each sub-detector constituting CMS). For example, in the EndCap electromagnetic calorimeter of CMS, the total integrated dose (TID) over a 10-year period is estimated to reach 100 kGy and a fast hadron fluence of about 10^{14} particle per square centimeter.

It is obvious that such an environment represents a danger to all exposed detectors and electronic components. Due to radiation damage (via ionizing and non-ionizing energy losses) and other various ageing radiation effects [3], the detectors will suffer a loss of performance over time. In addition, the risk of accidental radiation burst due to beam loss or bad beam tuning, has also to be taken into account. For these reasons it is important to constantly monitor the radiation levels.

The present concept for the radiation monitoring system of the CMS Experiment comprises of the so-called Beam Condition Monitor (BCM) [4], placed a few centimeters from the interaction point, and the sensors that are presented in this work located at larger radii.

The BCM is currently under development. It will essentially provide a measurement of the beam condition and the possibility to send a beam-abort request to the LHC machine in order to protect the sub-detectors from high radiation levels. Based on MonteCarlo simulations, it can also be used to estimate the radiation levels throughout the whole experiment.

However, to measure the CMS radiation field exactly, a set of active sensors is needed to verify the simulations and correlate the BCM readings with the radiation field in the different sub-detectors. Moreover, the sensors will accomplish the following tasks:

1) To check the integrity of the shielding,
2) To act as a long term radiation monitor in some critical locations,
3) To measure the radiation background together with the ionization chambers that will be placed in the experimental area around CMS [5].

The aim of the present work is to describe the results of our recent dosimeters characterization obtained on different existing technologies and the integration into an active sensor that ensures a complete monitoring of the radiation field parameters.

RadFET and OSL dosimeters, two complementary technologies for ionizing radiation measurement, were tested. OSRAM BPW34F *p-i-n* silicon photodiodes [6] and silicon Pad detectors were tested as monitors for non-ionizing radiation.

In the following section, the principles of the different dosimeters are reviewed. In section three, the proton and neutron Irradiation Facilities of the CERN Proton-Synchrotron (PS), used for the experiments, are described. In the fourth section the experimental results are summarized. Finally, the concept for the integration is outlined and our conclusions are given in sections five and six.

II. REVIEW OF THE DOSIMETRIC TECHNOLOGIES

II.1. Radiation-sensitive Field Effect Transistors (RadFETs)

The RadFET dosimeters are p-channel MOS transistors that are used to measure ionizing dose by the build-up of charge in the SiO_2 layer of the device. The shift of the threshold voltage V_{th} between *source* and *drain* of the transistor is proportional to the deposited dose when a constant current passes through the device [7].

RadFETs are integrating devices in which the dosimetric information is kept stored even after every read-out but they do not offer the sensitivity to measure very small doses (< cGy). Moreover the sensitivity decreases with increasing dose. Therefore these devices are used when regular measurements of doses absorbed over long periods of time are required [8], [9].

II.2. Optically Stimulated Luminescence (OSL)

The propriety of irradiated OSL material to emit visible light proportional to the received dose is extensively described in references [10], [11] and [12].

Ionizing radiation creates a large number of electron-hole pairs in the OSL material. A fraction of these carriers is trapped by dopants with energy levels located in the wide band gap of the insulator. Some of those charges will remain trapped for a period of time depending on the activation energy of the traps and the temperature. The energy necessary to release the charges is provided by an optical stimulation, and a subsequent radiative recombination may be observed. Quantifying the amount of the emitted light makes it possible to evaluate the dose [13].

The OSL has a higher sensitivity than RadFETs. The dosimetric information is however erased after every read-out and to obtain the dose absorbed over a long time it is thus necessary to add up all the readings. Complementary to the long-time integration of the RadFETs, the OSLs will therefore be used to detect very small increases of dose over short periods of time (e.g. days).

II.3. OSRAM BPW34F p-i-n Silicon diodes

The BPW34F *p-i-n* photodiodes are junction devices with a base of high resistivity (some kΩ · cm) n-type silicon with a thickness of some hundred μm. They are cheap commercial devices designed for infrared remote control [6] that are sensitive to particle fluence due to displacement damage effects. In particular, they show an increase of their leakage current when biased reversely, and a linear increase of their resistivity when powered forward [14], [15].

II.4. Pad detectors (reverse biased p-i-n diodes)

Silicon particle detectors are reverse biased *p-i-n* diodes with a very high resistivity (several KΩ · cm) n-type bulk of usually 300 μm thickness. Irradiation of such devices will produce generation/recombination centers in the silicon bulk leading to a fluence proportional increase of the leakage current if the device is kept fully depleted. It has been demonstrated that the increase of the leakage current is independent from the impurity content of the silicon base material [16]. They can be used as a NIEL proportional damage counter for a wide range of different particles and particle energies if care is taken about the rather complex annealing behavior [17]. For dosimetric purposes usually small "Pad-structures" with an active area in the order of 0.25 to 1 cm^2 protected by one or several guardrings against edge currents are used.

III. Irradiation facilities & Dosimetry

III.1. CERN IRRAD1 24 GeV/c proton facility

Since 1998 the irradiation facility IRRAD1 is operated in the East Hall Experimental Area of the CERN-PS complex.

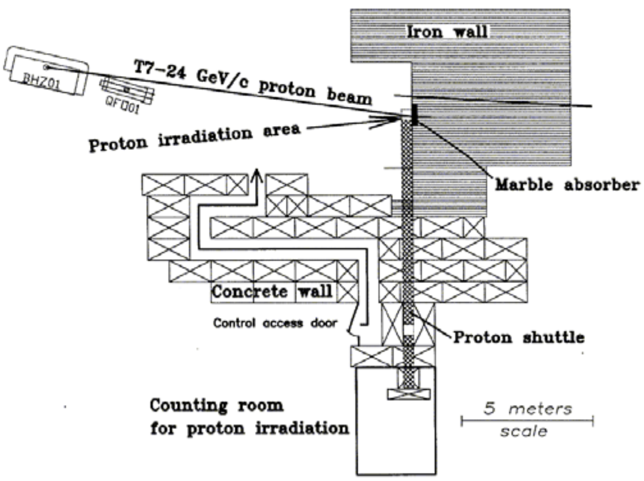

Fig. 1 Layout of the IRRAD1 Irradiation Facility.

In the T7 beam-line, the primary 24 GeV/c proton beam is directed to the irradiation area, where a remote controlled shuttle allows to place the sample to be irradiated moving them from the counting room into the irradiation area as shown in Fig. 1 [18].

The proton bursts are delivered during the 16.8 seconds supercycle of the PS in 1-3 spills of about 400 ms, with a maximal beam intensity of about 2x10^{11} protons per spill. A defocusing-scanning system is then used to spread out the beam in order to produce a uniform irradiation over a surface of several square centimeters as shown in Fig.2.

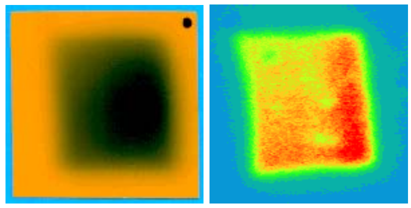

Fig. 2 Left: Beam spot on a 5x5cm^2 Gafchromic XR sensitive film. Right: High-resolution 5x5cm^2 beam profile measured by a 100μm OSL film.

The beam calibration and the dosimetry during sample irradiation are performed with Gafchromic sensitive films [19] and thin OSL films (when high resolution is needed in the determination of the dose mapping) [12]. The proton fluence is measured by evaluating the ^{24}Na activity of aluminum foils produced via the nuclear reaction ^{27}Al(p,X)^{24}Na. With the latter technique it is possible to obtain fluence measurements with an accuracy of ± 7 %. Taking into account that ionization is the main contribution to the energy loss of a charged particle and that its mean value, the stopping power (dE/dx) is given by the Bethe-Bloch law, it is possible to convert the fluence into the dose (Gy) deposited in thin samples, using the following formula:

$$D = K \times (dE/dx)_m \times \Phi \,. \qquad (1)$$

Thereby Φ is the proton fluence expressed in particles/cm^2, $K = 1.602\text{x}10^{-10}$ is a scale factor, and $(dE/dx)_m$, expressed in MeV·cm^2/g, is the minimum ionizing energy loss rate. For GeV protons it assumes values between 1.6-1.8 MeV·cm^2/g for our materials. For high-energy charged particles, the contribution of nuclear interactions and the resulting secondaries to the dose in the beam is usually small and so it can be neglected under normal circumstances [20].

III.2. CERN IRRAD2 mixed gamma/neutron facility

Fig. 3 shows the layout of the irradiation zone IRRAD2 in the T8 beam-line. The irradiation is performed in a cavity with secondary particles produced by the primary 24 GeV/c proton beam after crossing a thick beam dump constituted of carbon and iron blocks [18].

As for the IRRAD1 facility, a motorized shuttle system allows to transport the samples from the counting room to the irradiation cavity in which a broad spectrum of neutrons and gamma rays is produced as shown in the spectra obtained by MonteCarlo simulations in Fig. 4 [21].

With the remote shuttle system it is possible to set the position of the samples with respect to the beam axis. Depending on the position, the ratio of charged hadrons in the GeV energy range to neutrons and gammas can be chosen.

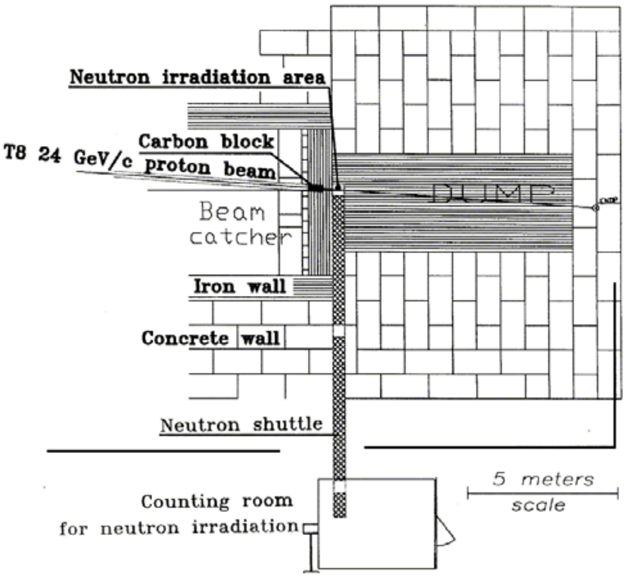

Fig. 3 Layout of the IRRAD2 Irradiation Facility.

It is thus possible to perform irradiations in a pure gamma/neutron environment (at positions far from the beam axis) or in charged hadron rich radiation environment that better represents the one expected for the inner part of the LHC experiments (at positions close to the beam axis).

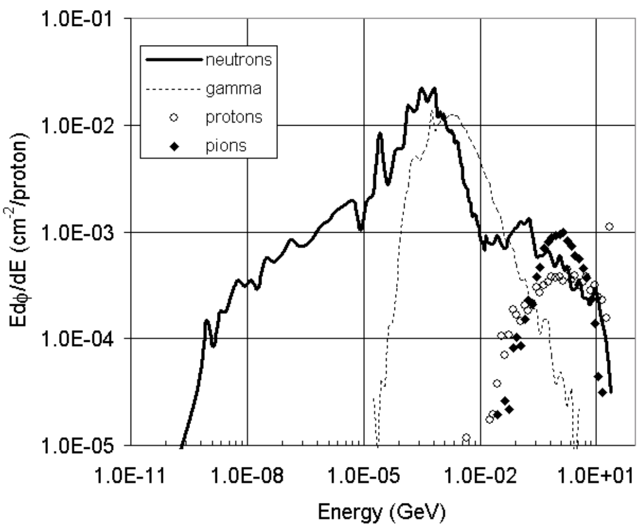

Fig. 4 Particle spectra in IRRAD2 cavity at 10 centimeters from beam axis normalized to one impinging 24 GeV/c proton.

Different dosimetry techniques are used to monitor the neutron fluence and the deposited TID in this complex environment depending on the irradiation position and upon the users request. For the present work, in which all the samples were placed in the pure neutron environment, calculations based on simulations [21], [22] as well as measurements with alanine [23] and silicon detectors [16] were used. With these techniques it is possible to obtain fluence measurements with an accuracy of ± 10 %.

IV. Results and Discussion

In the present section, the results obtained during the characterization of the various technologies are summarized separately. Integration issues of all these technologies into one module will be presented in section *V*.

IV.1. Ionizing radiation measurement with RadFETs

RadFETs from different manufacturers and with various oxide thickness (0.1 μm – 0.85 μm) are under investigation at CERN since the year 2000 [24], [25]. Our latest test campaign was instead focused on the study of devices with thicker oxide (1.6 μm) supplied by the *Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS)* of Toulouse, France.

The increase of the MOS threshold voltage under 100 μA drain current was read out in real-time at the end of 25 m cable by a PC controlled Keithley 2410 SourceMeter. The system was programmed to perform serial measurements in order to record a signal versus dose curve.

Fig. 5 shows the growth of the MOS threshold voltage versus dose (averaged over 2 to 4 identical devices measured at the same time) compared to the ^{60}Co calibration curve supplied by the manufacturer. For the IRRAD1 (24 GeV/c protons) data the dose is calculated from the proton fluence according to Eq.1. For the IRRAD2 data the presented dose is the TID as calculated from a FLUKA simulation [21], [22] including the neutron contribution to ionizing KERMA (Kinetic Energy Released in MAterial) that was estimated to be about a few percent. The maximum value of 3.0 Gy_{Si} corresponds to a 1MeV neutron equivalent fluence of 1.1×10^{12} particles per square cm.

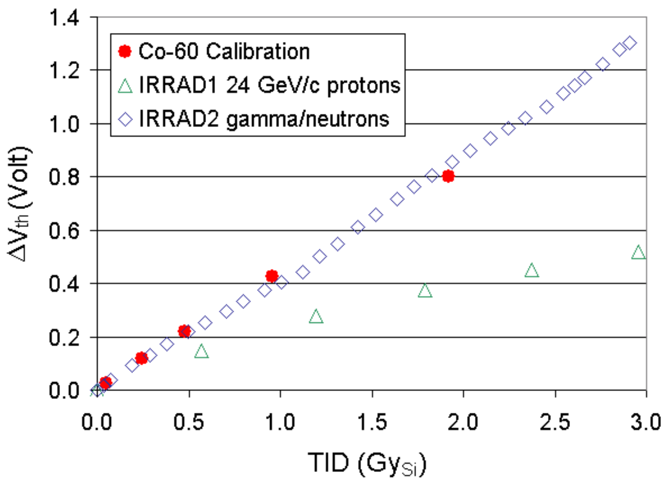

Fig. 5 Experimental results for LAAS devices obtained at CERN facilities.

The response measured in the IRRAD2 facility fits exactly the calibration curve indicating that the simulation estimates even the ionization due to neutrons correctly [26]. The measured high sensitivity of 4.2 mV/cGy, defined as the slope of the signal versus dose in its initial linear region, will allow to use these devices as high accuracy dosimeters in regions of the experiments where the expected doses will be less than 3 Gy_{Si} [27].

However, the voltage shift measured in IRRAD1 is already reduced by a factor of 2.4 at the maximum dose of 3 Gy considered here. This phenomenon, probably due to recombination processes within the SiO_2 layer [28], has to be carefully taken into account, if the devices are used in regions of the experiments that are dominated by high-energy charged particles.

IV.2. Ionizing radiation measurement with OSLs

Besides the beam profile characterization shown in section *III*, two types of experiments were run with the OSL. Different raw OSL materials were doped with boron or mixed with polyethylene in order to increase their sensitivity to a wide neutron spectrum. A preliminary characterization was performed with high-energy protons and a mixed gamma/neutron field at IRRAD1 and IRRAD2. The first results, obtained by reading the samples after irradiation with a laboratory test bench [12], are presented in Fig.6 and Fig.7.

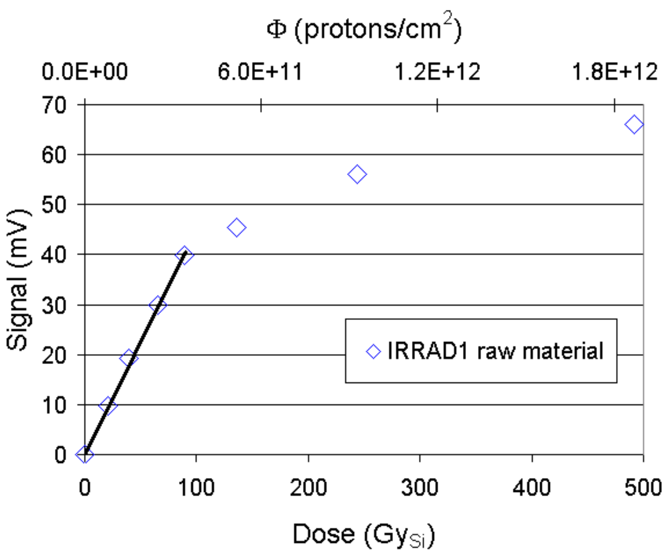

Fig. 6 Raw OSL material responses as read from the test bench at IRRAD1.

The diamond marks of Fig. 6 represent the response to the 24 GeV/c proton beam in the explored dose range up to 500 Gy_{Si}, corresponding to a fluence of 1.9×10^{12} p/cm^2. The measurements were taken with one OSL sample that was successively irradiated to the different indicated proton fluences. As expected, the response follows a linear behavior up to 100 Gy_{Si}, then becoming sub-linear due to saturation at higher doses.

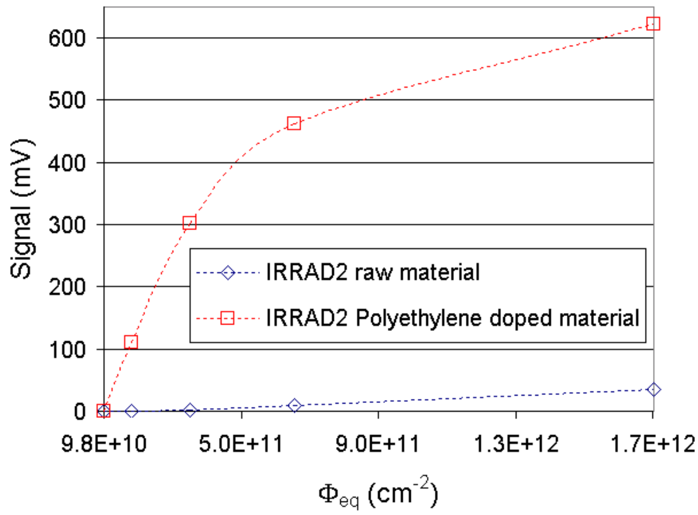

Fig. 7 OSL material responses as read from the test bench at IRRAD2.

The IRRAD2 irradiations plotted in Fig. 7 were performed with samples of different composition. For values of neutron equivalent fluence under 1.0×10^{11} cm^{-2}, the signal was below the noise level since the gain of the read out system was set to measure up to high doses. The raw OSL material (diamond marks) shows insensitivity to the neutron component of the field. The measured signal is compatible with the TID predicted by the simulation. The polyethylene-doped samples (square marks) show a factor 20 increase in sensitivity.

Furthermore, an integrated OSL sensor, developed for space applications [13], was tested. The device, placed in the beam, was connected by a 30 m long coaxial cable to the read out system. Although it was possible to record an OSL signal, it appeared that the associated electronics of the sensor, as developed for space applications, was not suited for our experiment. A new version adapted to the specifications of the CMS environment is currently under development at the University of Montpellier, France.

IV.3. Non-Ionizing radiation measurement with BPW34F

The possibility to use the BPW34F semiconductor diodes as dosimeters was investigated at CERN several years ago [29]. In order to better characterize these devices, we performed further proton and neutron irradiations, measuring the voltage drop for a fixed forward current on- and off- line (i.e. during irradiation and in the laboratory).

With the same readout electronics used for RadFETs, a short pulse of 1 mA was injected for 180 ms, and the corresponding forward voltage (V_F) was read out. This technique was applied to avoid current induced annealing phenomena. The pre-irradiation analysis shows a big temperature coefficient of about –35 mV/°C. Therefore, the temperature was monitored during the experiments and its dependence taken into account.

In Fig. 8 and Fig. 9 the obtained results are presented. Different proton fluxes from 2.2×10^9 cm^{-2} to 3.1×10^{10} cm^{-2} per spill have been used in the IRRAD1 facility. However, no differences regarding the response of the dosimeters were observed. In Fig.8 the on-line measurements are compared to the data taken after irradiation (off-line). A part of the data were taken directly after irradiation while some of the data were measured after a heating of 4 min at 80 ºC in order to simulate an annealing of the devices at room temperature. Although further experiments are needed to study the annealing behaviour in detail, this first test already indicates that the annealing is not a severe problem for off-line measurements.

To allow a comparison of the IRRAD1 data with the results obtained in the IRRAD2 facility, the proton fluence in Fig. 9 was converted into the 1MeV neutron equivalent fluence by means of the hardness factor of 0.62 [17].

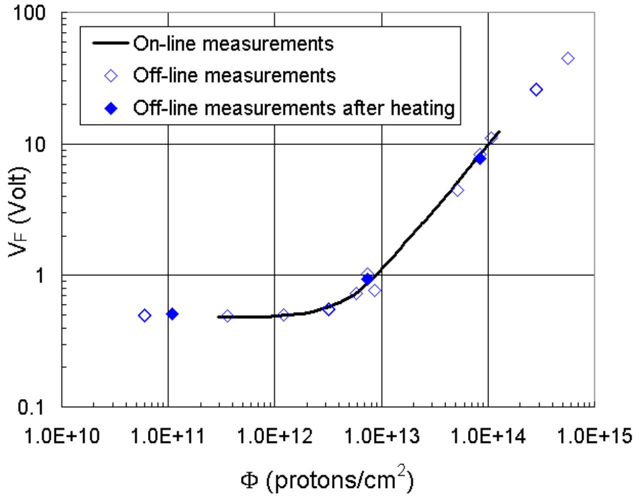

Fig. 8 Comparison between the results obtained for the BPW34F diodes in on-line and off-line mode at IRRAD1. The Forward Voltage is plotted against the proton fluence.

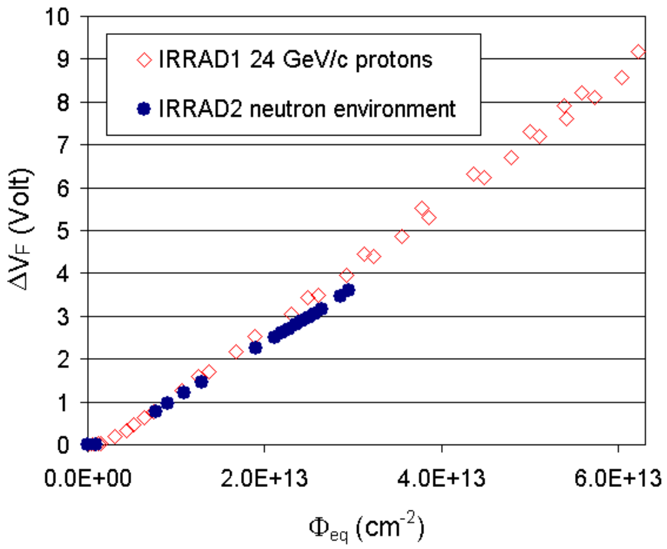

Fig. 9 Shift of the forward voltage for BPW34F devices obtained at CERN facilities and expressed in terms of 1MeV neutron equivalent fluence.

After an initial flat region up to proton fluences of 1.0×10^{12} cm^{-2}, in which the devices are not sensitive, the response is linear and in good agreement with the displacement damage scaling in silicon as shown in Fig. 9. A forward voltage shift of 1.1 V was measured for a neutron equivalent fluence of 10^{13} cm^{-2}. With the above characteristics, these devices are usable to measure high fluences, but the possibility to monitor also the reverse currents, leaves the way open to extend the sensitivity of these devices into the low fluence range. The influence of the forward current pulse length and the relatively weak annealing are currently under study.

IV.4. Non-Ionizing radiation measurement with Pad detectors

In this work 307 μm thick *p-i-n* detector test structures produced by ST Microelectronics, Italy with an active area of 0.25 cm^2 and protected on the front side by a guardring from edge currents have been used. The detectors were exposed to the different radiation fields at ambient temperature (about 27 °C) without biasing them. After irradiation the devices were annealed for 4 min at 80 °C and the leakage current at full depletion was measured and normalized to 20 °C (see e.g. [17]). The results are presented in Fig.10 and demonstrate that these devices can be used over a very wide fluence range provided that the annealing is performed carefully.

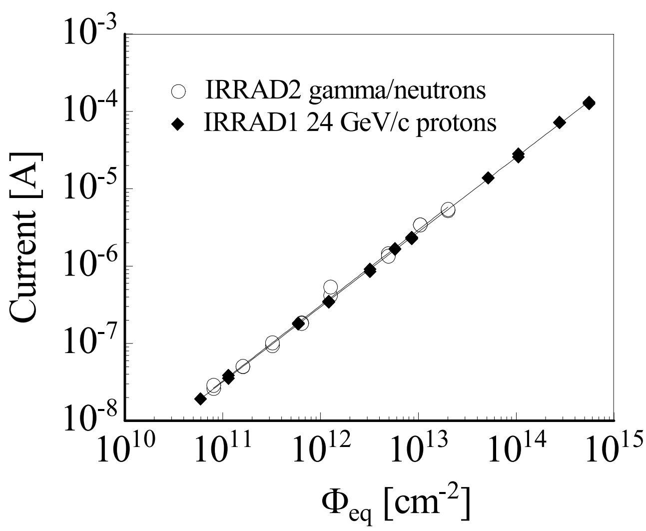

Fig. 10 Increase of the Pad detector leakage current versus the 1 MeV neutron equivalent fluence.

V. DOSIMETERS INTEGRATION

From the above results, it is clear that the four different technologies can provide a complete and quantitative map of the complex radiation environment of the CMS Experiment. Moreover, the four types of devices have the following common characteristics:

1) Limited dimensions, the sensitive areas of each device is some square millimeters;

2) In all cases resistive measurements are performed.

The dosimeters, together with a temperature probe PT100 and a DAQ electronic will be integrated on a single PCB. The preliminary design of the PCB is currently under preparation.

VI. Conclusion

The radiation monitoring of the CMS experiment at the CERN Large Hadron Collider is a challenging issue due to the complexity, intensity and composition of its radiation field.

The experimental results obtained at the CERN-PS Irradiation Facilities on the four different tested dosimeter technologies to monitor both ionizing (RadFETs and OSLs) and not-ionizing energy losses (BPW34F *p-i-n* diodes and Pad detectors), were briefly summarized. The promising results make the concept of an integrated radiation sensor an attractive approach.

VII. Acknowledgments

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