Silicon Photo-Multiplier radiation hardness tests with a beam controlled neutron source.

M. Angelone and M. Pillon

ENEA, Frascati, Italy

R. Faccini[†,*], D. Pinci[*]

[†] *Sapienza Università di Roma,* [*] *INFN, Sezione di Roma, Italy*

W. Baldini[*], R. Calabrese[*,†], G. Cibinetto[*,†],
A. Cotta Ramusino[*], R. Malaguti[*], and M. Pozzati[†].

[†] *Università degli Studi di Ferrara,* [*] *INFN Ferrara, Italy*

Abstract

We report radiation hardness tests performed at the Frascati Neutron Generator on silicon Photo-Multipliers, semiconductor photon detectors built from a square matrix of avalanche photo-diodes on a silicon substrate. Several samples from different manufacturers have been irradiated integrating up to 7×10^{10} 1-MeV-equivalent neutrons per cm^2. Detector performances have been recorded during the neutron irradiation and a gradual deterioration of their properties was found to happen already after an integrated fluence of the order of 10^8 1-MeV-equivalent neutrons per cm^2.

1. Introduction

Silicon Photo-Multiplers [1] are constituted of a large number of micro-pixels each made of a shallow n$^+$p junction (GM-APD) in series with a quenching resistance and they operate in Geiger mode. Their sensitivity to a small number of photo-electrons and their fast response make them candidate light detectors also for the extruded scintillators of the Instrumented Flux Return (IFR) of the super flavor factory experiment proposed at “Laboratori Nazionali di Frascati” (SuperB [2]). Extremely high luminosities are to be achieved at SuperB at the cost of very high backgrounds, among which neutrons impacting on the detectors. The knowledge of the impact of neutron irradiation on Silicon Photo-Multipliers is therefore critical for the project. Currently it is based on preliminary results on nuclear reactor tests [3]. Due to the impossibility to record data during irradiation and to control the neutron energy and flux, these tests can only assess that the devices are severely damaged after an integrated fluence as high as $10^{11}\mathrm{n}_{eq}/\mathrm{cm}^2$, roughly one year of SuperB data-taking without

Table 1: Device positions in a reference frame centered in the neutron generation point and with the z axis coincident with the deuteron beam axis and the total integrated fluences. The conversion to the fluence equivalent to 1 MeV neutrons on silicon (n_{eq}) is based on Ref. [8]

Device	x (mm)	y (mm)	z (mm)	tot. int. fluence ($10^{10} n_{eq}/cm^2$)
SiPM #4	5.0	0.0	3.0	1.25
SiPM #6	3.0	1.3	3.0	3.07
SiPM #7	-0.5	0.0	13	0.18
SiPM #8	-1.0	0.0	3.0	7.32
MPPC #1	-3.0	0.0	3.0	2.71
MPPC #2	1.0	0.0	3.0	7.32
MPPC #5	-0.5	0.0	2.5	4.26
MPPC #6	0.5	0.0	2.5	4.26
SiPM 2×2	-5.0	0.0	3.0	1.25

appropriate shielding. No information is available on the maximum fluence that can be absorbed, i.e. on the behavior of the devices for intermediate fluences.

2. Measurement Setup

This paper reports the results from irradiation tests on a neutron source, the "Frascati Neutron Generator" (FNG [4]), that uses a deuteron beam accelerated up to 300 keV impinging on a deuteron target to produce a nearly isotropic 2.5 MeV neutron output via the $D(d,n)^3He$ fusion reaction. The beam current at the target can be regulated in order to obtain up to a maximum neutron production rate of 5×10^8 neutrons per second on the whole solid angle. During our tests, the neutron yield was monitored online by measuring the rate of recoiling protons measured with a calibrated liquid scintillator (NE213). Pulse shape discrimination is used to reject gamma-ray events. The Monte Carlo neutron and photon transport code MCNP-5 [5] was used to performe a full simulation of the whole experimental hall and to convert the neutron yield into the flux impinging on the detector, including also secondary effects like the neutron scattering from the bunker concrete walls. An "ad hoc" source routine was also used in the MCNP code to accurate simulate the source anisotropy arising from the beam-target interaction.

Five devices (four 1×1 mm^2 and one 2×2 mm^2) produced by the Istituto di Ricerca Scientifica e Tecnologica (IRST [6]), named SiPM in the following, and four 1×1mm^2 produced by the Hamamatsu[7], named MPPC in the following, have been irradiated with neutrons. Their position with respect to the neutron generation point and the corresponding integrated fluence, delivered in six runs of shortly more than one hour each, is shown in Tab.1.

During the exposure the devices were biased and their current read in turn by a pico-amperometer driven by a relee: the SIPM were biassed between 3V and 4V above the breakdown bias, while the MPPC were partly biassed about 10V below their operating point (#1 and #2) and the rest at the operation point. At

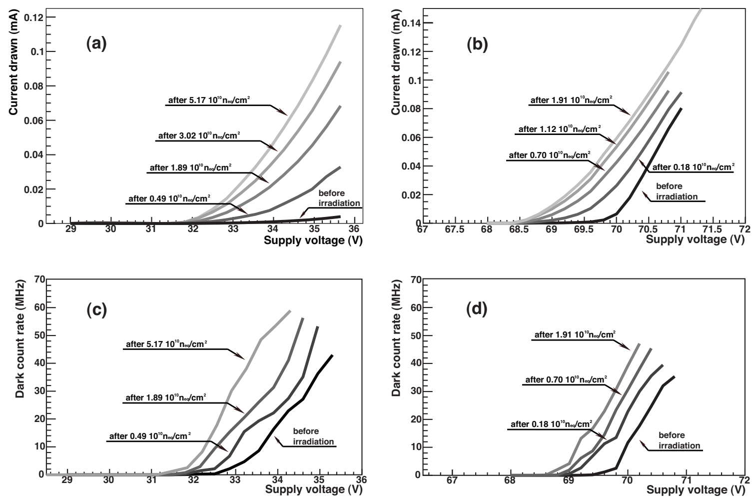


Figure 1: Behavior of the I-V characteristics and the rates for a 2.5 photo-electron threshold as a function of the bias for a SiPM (a, c) and an MPPC (b, d) after different integrated fluences.

the end of each irradiation run a scan in bias was performed in order to measure the $I - V$ characteristic. The bias voltage was distributed by the frontend cards, placed at about one meter from the neutron target, which also provided signal amplification and discrimination for the rate measurement. The data acquisition system allowed to monitor currents, rates, and biases continuously and to change the settings from remote without accessing the experimental hall. Photodetectors temperature, neutron rate and integrated fluence were also recorded for offline analysis.

3. Currents and rates

Figure 1 superimposes the measured characteristics taken after several different fluences of irradiation for a SIPM and an MPPC. It shows that the drawn current increase significantly even for relatively small fluence ($5 \times 10^9 \mathrm{n}_{eq}/\mathrm{cm}^2$). The same effect can be observed in the measured rates by setting a threshold at 2.5 photo-electrons.

Data collected during the irradiation allow to investigate the break-down fluence. The measured dark currents drawn as a function of the irradiation time show significant differences among the devices depending on the neutron flux they are exposed to. Fig. 2 shows that during the four hours of data-taking some devices worsened by a factor 30, others by "only" a factor 10.

It is then natural to look for a more general trend by considering the integrated fluence instead of the irradiation time. This is shown for the SiPMs in Fig. 3a: the dark current increases monotonously ever since $10^9 \mathrm{n}_{eq}/\mathrm{cm}^2$ for all devices and independently of the neutron fluences that are different among them. The curve of the relative increase is universal among SiPMs, including

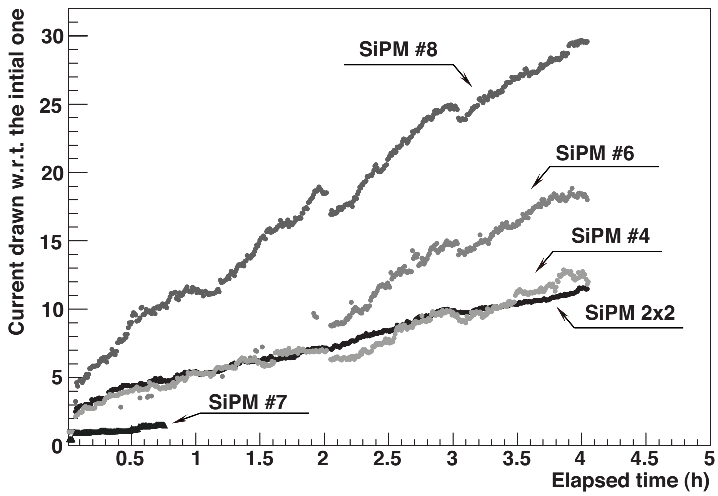
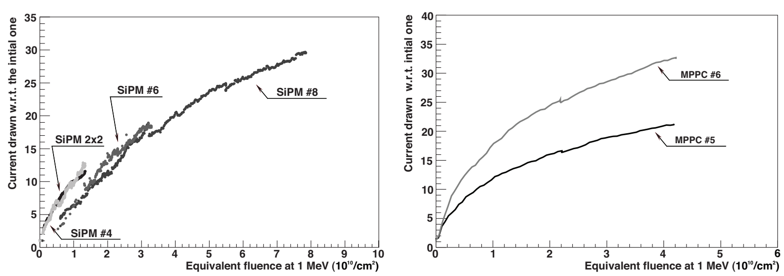


Figure 2: Increase factors of the current drawn by the SiPMs as a function of the irradiation time.

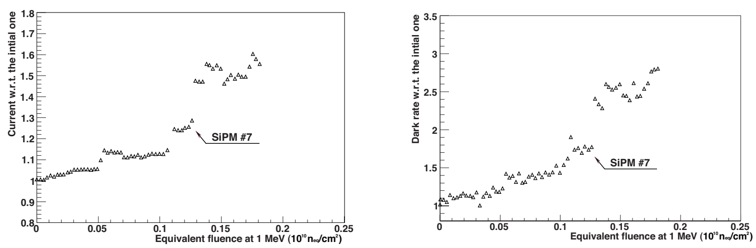


(a) (b)

Figure 3: Increase factors of the current drawn by the SiPMs (a) and the MPPCs (b) as a function of the accumulated fluence.

the larger area one: it can be fit with $f(x) = Ax^{2/3}$ where $A \sim 8.5$ and it shows that after a fluence of $10^{10}\mathrm{n}_{eq}/\mathrm{cm}^2$ ($4 \times 10^{10}\mathrm{n}_{eq}/\mathrm{cm}^2$)the current drawn is worsened by approximately a factor 10 (20). Similarly MPPCs (see Fig. 3b) show a rapid degradation with irradiation, but the slopes of the dark currents can be significantly different.

To probe the resistance of a SiPM to lower fluences, one of the devices was also irradiated at a larger distance from the source, thus reducing the flux by about two order of magnitudes. Fig.4, shows that currents and dark rates are stable up to fluences of the order of 2-4$\times 10^8\mathrm{n}_{eq}/\mathrm{cm}^2$ and then, they start to increase. No significant recovery effects appeared after a whole night without irradiation: the absolute value of the current and the increase rate, once the flux was back on, didn't change.



(a) (b)

Figure 4: Increase factors of the current drawn by the SiPM as a function of the fluence (a) and of the corresponding dark rate for a threshold at approximately 2.5 photo-electrons (b).

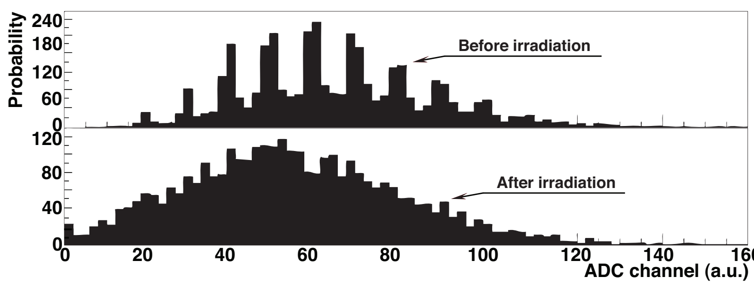


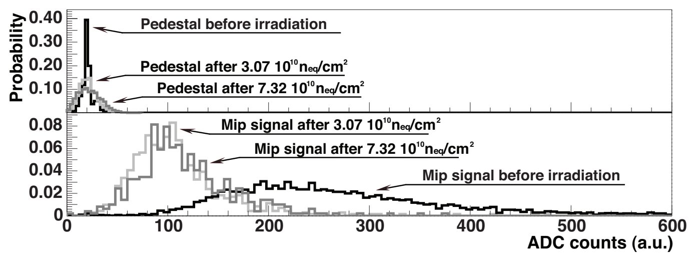
Figure 5: SiPM charge spectra for a low intensity LED run, before (top) and after (bottom) irradiation.

4. Gains

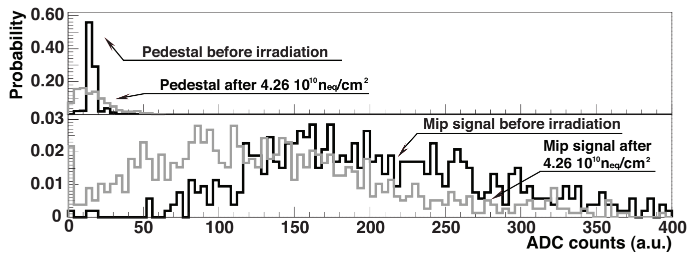
The effect of the irradiation on the gain was studied by testing the response of the Photo-Multipliers to a pulsed LED yielding a low number of photo-electrons and to the light produced by cosmic rays in a plastic scintillator, where the light yield is closer to the expected operation of the devices.

LED runs performed after irradiation show an almost complete degradation of the single-photon resolution due to the increase of the noise (see Fig. 5). Even worse is the effect during the cosmic-ray runs (see Fig.6). Pedestals broaden approximately by a factor three due to the increase of the dark rate intrinsic noise and the average gain of the irradiated devices is lower by approximately a factor two.

These effects lead in the cosmic-ray run to an important reduction of the detection efficiency of requiring a signal three standard deviations above the pedestal from more than 95% to about 70%. No evident dependence of the performance deterioration on the integrated fluence was found.



(a)



(b)

Figure 6: Pedestal (top) and cosmic signal charge spectra (bottom) for a SiPM (a) and an MPPC (b) downstream of a 150 cm long WLS fiber for different integrated fluences.

5. Conclusion

Several Silicon Photo-Multipliers have been exposed to an intense neutron flux integrating up to a total fluence of $7.32\times10^{10}\mathrm{n}_{eq}/\mathrm{cm}^2$. Their performance were for the first time studied before, during and after the irradiation thanks to the use of a controlled neutron source (the ENEA FNG). The drawn currents were found to increase up to a factor 30 while the dark counts up to 300. The detection efficiency measured with cosmic rays, drop from above 95% to around 75%. From the measurements shown we conclude that Silicon Photo-Multipliers performance would start deteriorating after an irradiation of few $10^8\mathrm{n}_{eq}/\mathrm{cm}^2$. A dedicated experiment at so low rates is being planned in order to better quantify the break-down fluence.

[1] B. Dolgoshein et al., Nucl. Instr. and Meth. A563 (2006) 368, and references therein.

[2] M. Bona et al., “SuperB A High-Luminosity Heavy Flavour Factory Conceptual Design Report” INFN/AE - 07/2, SLAC-R-856, LAL 07-15.

[3] T. Matsumura *et al.*, PoS **PD07** (2006) 033.

[4] M. Martone et al., “The Frascati Neutron Generator” Proc. SPIE Vol. 2339, p. 208-212, International Conference on Neutrons and Their Applications, George Vourvopoulos; Themis Paradellis; Eds.

[5] X-5 Monte Carlo Team, Los Alamos National Laboratory Report No. LAUR-03-1987, 2003

[6] N. Dinu et al., Nucl. Instr. and Meth. A572 (2007) 422

[7] S. Gomi et al., Nucl. Instr. and Meth. A581 (2007) 427

[8] "Standard practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Mono-energetic Neutron Fluence for Radiation Hardness Testing of Electronics", ASTM E 722 - 93.