RADIATION DAMAGE STUDIES OF SILICON PHOTOMULTIPLIERS IN NEUTRONS FIELD OF IBR-2

S.V. Afanasiev[1,2], Yu.V. Ershov[1], I.A. Golutvin[1], N.V. Gorbunov[1,2], A.I. Malakhov[1,2], V.A. Smirnov[1,2], N.I. Zamyatin[1], E.V. Sukhov[1], V.V. Ustinov[1,2]

[1] *Joint Institute for Nuclear Research, Dubna, 141980, Russia*

[2] *Dubna State University, Dubna, 141980, Russia*

E-mail: [a] afanasev@lhe.jinr.ru, [b] suhov@junr.ru, [c] ustinov@jinr.ru

The report is devoted to the study of radiation resistance of silicon photomultipliers (SiPM) produced by HAMAMATSU. SiPM was irradiated in neutron fluxes of the JINR IBR-2 reactor. The tested SiPM received fluence from 10^{12} up to $2x10^{14}$ of neutrons/cm^2. Irradiated detectors were investigated using a radioactive source and laser flashes at a temperature of -30^{o}C. The measurements showed that the SiPM remain fully functional as photon detectors up to neutron fluence $2x10^{14}$ despite a significant increase in noise.

Keywords: CMS, SiPMs, radiation hardness.

Sergey Afanasiev, Yuriy Ershov, Igor Golutvin, Nikolay Gorbunov, Alexandr Malakhov, Vitaliy Smirnov, Nikolay Zamyatin, Evgeny Sukhov, Valentin Ustinov

Introduction

A future replacement of the HE calorimeter for scintillator section of the CMS HL-LHC endcap calorimeters during the LS3 period presupposes the installation of the photo detectors (SiPM) directly on the scintillation tiles [1]. The radiation exposure of the calorimeter was estimated up to the integral luminosity of 3000 fb^{-1} at HL-LHC. There were defined areas of the detector with different levels of irradiation. A necessary condition for the modernization of the spectrometer is to ensure the operability of active detector elements.

Silicon photomultipliers (SiPM) are a new type of photodetectors. They consist of miniature diodes operating in streamer mode (APD). The detector has a high sensitivity and is able to register individual photons On the one hand, SiPM is characterized by a low supply voltage and insensitivity to the magnetic field, and on the other, by a high dependence of the gain on temperature and the destruction of the detector structure in the strong radiation fields typical for modern spectrometers.

The work is devoted to the study of radiation effects on SiPM structures.

Irradiation of SiPMs with neutrons

JINR group performs the investigation of some SiPM properties after irradiating them with neutrons at the IBR-2 reactor. The main goal of the work is to estimate the upper limit of neutron irradiation, which will lead to the impossibility of further use of SiPM in the central region of the scintillation part of CMS calorimeters cooled to -30 °C. The main criterion for the operation of SiPM is the possibility of recording by a photo detector MIP signals above the noise level.

Irradiation of 21 SiPM photo detectors with fast neutrons was carried out in two runs at IBR-2 [2]. The first run was held in November 2016 and the second one - in March 2017. Three types of Hamamatsu SiPM devices were used for irradiation with dimensions of 10, 15 and 25 μm cells: MPPC S12571-010C [3], MPPC S12571-015C [3], MPPC S13360-1325CS [3]. Each SiPM has an identification number which was used for the subsequent reference (Table 1).

Table 1. Identification numbers for the used SiPMs

MPPC S12571-010C	403, 404, 412, 413, 414, 415, 416
MPPC S12571-015C	184, 185, 188, 189, 190, 191, 192
MPPC S13360-1325CS	10327, 10328, 10355, 10356, 10357, 10358, 10359.

Three photo detectors, one of each type, were combined in a set. There were seven sets in tota. SiPMs of each set received the same neutron radiation. The sets were irradiated in the range of fluence values $1.7 \times 10^{12} \div 2.1 \times 10^{14}$ neutrons/cm^2. Table 2 shows the magnitudes of neutron fluence and the date of irradiation for each set of photo detectors.

Table 2. Magnitudes of neutron fluence and date of irradiation for each set of photodetectors

Set #	**Set composition**	**Φ, neutrons/cm2**	**Date of irradiation**
1	412, 188, 10355	$1{,}7\times10^{12}$	03.2017
2	413, 189, 10356	$5{,}3\times10^{12}$	03.2017
3	403, 184, 10328	$5{,}4\times10^{12}$	11.2016
4	414, 190, 10357	$1{,}7\times10^{13}$	03.2017
5	415, 191, 10358	$5{,}18\times10^{13}$	03.2017
6	416, 192, 10359	$8{,}14\times10^{13}$	03.2017
7	404, 185, 10327	$2{,}1\times10^{14}$	11.2016

The magnitude of neutron fluence was measured by two methods:

- The first method was standard and used at IBR-2. The technique was based on measuring the induced activity of Nickel wires irradiated together with the samples.
- The second method was based on the measurement of the quantity of defects in two silicon semiconductor detectors located near each set of SiPM devices.

Measurement of main parameters of the SiPM

All photodetectors passed test procedures to measure the main parameters after irradiation and to compare them with parameters defined in factory specifications. Table 3 presents the main parameters of the investigated devices.

Table 3. The main parameters of SiPM before and after irradiation

S12571-010C, area - 1mm^2, 10 000 of 10 μm cells								
Φ, cm^{-2}	SiPM number	Before irradiation (spec. HPK), at +25°			After irradiation, Measurement at -22°			
		Vop,V	M (gain)	F_{dark}, kHz, (0,5pix)	V_{br},V (noise)	V_{br},V (dI/dU/I)	σ_{noise}, pixels Vov=3V	F_{dark}, kHz Vov=3V
$1{,}7\times10^{12}$	412	69,86	$1{,}35\times10^{5}$	111	63.265	63.205	3.74	6530
$5{,}3\times10^{12}$	413	69,88	$1{,}36\times10^{5}$	110	63.31	63.46	7.56	9080
$5{,}4\times10^{12}$	403	69,81	$1{,}34\times10^{5}$	124	63.25	63.4	7.0	9040
$1{,}7\times10^{13}$	414	69,9	$1{,}35\times10^{5}$	115	63.41	63.46	9.6	9985
$5{,}18\times10^{13}$	415	69,87	$1{,}35\times10^{5}$	113	63.78	64.13	11.8	10530
$8{,}14\times10^{13}$	416	69,89	$1{,}35\times10^{5}$	108	63.91	64.06	12.8	10610
$2{,}1\times10^{14}$	404	69,82	$1{,}34\times10^{5}$	119	65.71	66.28	15.5	10710

S12571-015C, area - 1mm2, 4 489 of 15 μm cells								
Φ, cm^{-2}	SiPM number	Before irradiation (spec. HPK), at +25°			After irradiation, Measurement at -22°			
		Vop,V	M (gain)	F_{dark}, kHz, (0,5pix)	V_{br},V (noise)	V_{br},V (dI/dU/I)	σ_{noise}, pixels Vov=3V	F_{dark}, kHz Vov=3V
$1{,}7\times10^{12}$	188	67,96	$2{,}3\times10^{5}$	98,7	62.11	62.06	5.63	8040
$5{,}3\times10^{12}$	189	68,05	$2{,}29\times10^{5}$	118	62.05	62.3	8.92	8640
$5{,}4\times10^{12}$	184	67,99	$2{,}30\times10^{5}$	109	62.11	62.13	8.78	8517
$1{,}7\times10^{13}$	190	68,08	$2{,}32\times10^{5}$	111	62.31	62.5	12.3	8749
$5{,}18\times10^{13}$	191	68,07	$2{,}29\times10^{5}$	107	62.51	62.86	12.5	8840
$8{,}14\times10^{13}$	192	68,11	$2{,}29\times10^{5}$	125	62.96	63.3	13.1	8798
$2{,}1\times10^{14}$	185	68,02	$2{,}31\times10^{5}$	111	64.51	64.89	12.3	8989

S13360-1325CS, area - 1,69 mm2, 2 668 of 25 μm cells						
Φ, cm^{-2}	SiPM number	Before irradiation, +25°C and Vop = Vbr + 5V,		After irradiation -22°C		
		Id, uA,	Vbr, V	V_{br},V (noise)	V_{br},V (dI/dU/I)	σ_{noise}, pixels Vov=3V
$1{,}7\times10^{12}$	10355	0,029	53,72	49.41	49.35	5.85
$5{,}3\times10^{12}$	10356	0,018	52,95	49.48	49.51	-
$5{,}4\times10^{12}$	10328	0,019	52,53	49.2	49.13	8.87
$1{,}7\times10^{13}$	10357	0,028	53,13	49.61	49.8	8.84
$5{,}18\times10^{13}$	10358	0,017	51,87	49.85	50.25	8.85
$8{,}14\times10^{13}$	10359	0,016	51,94	49.85	50.0	8.8
$2{,}1\times10^{14}$	10327	0,016	51,83	49.91	50.0	8.64

The parameters of unirradiated SiPMs were taken from the Hamamatsu data sheets. All the values were specified for + 25 °C. For S12571-010C and S12571-015C amplification (M), operating voltage (Vop) and dark noise frequency (Fdark) at the threshold of 0.5 pixels are given. The breakdown voltage (Vbr) was not specified. The data sheet of S13360-1325SS specified the typical dark current as 70 kHz and the typical gain as 7.0×10^{5}. There was indicated the breakdown voltage (Vbr) and current of the detector (Id) for each device in the present paper.

Measurement the signal to noise ratio for SiPMs

All SiPM photo detectors were examined before and after irradiation. For the measurement we used a setup shown in Figure 1. The signal in the scintillator was excited by two sources:

- The first one was a ^{90}Sr radioactive source.
- The second one is a laser whose signal was as from a particle with a minimum ionizing capability (MIP).

The SiPM response was measured at room temperature and at -30 °C.

The results of measurements of SiPMs irradiated to a value of 5.38×10^{12} neutrons/cm^2 are shown in Figure 2 for the light signal excited by a radioactive source. The results of laser measurements of the same SiPM devices are shown in Figure 3. For a cooled photo detector the MIP signal is almost 12 times higher than the noise level.

The results of measurements of SiPM devices irradiated to 2.09×10^{14} neutrons/cm^2 for both sources of light are shown in Figure 4. A photo detector was cooled up to -32 °C. Measurements at room temperature were not carried out because the noise level from the photo detector was too high.

A registration of the MIP signal for SiPMs irradiated to 2.09×10^{14} neutrons/cm2 becomes problematic due to a high noise level even at -32 °C. The signal-to-noise ratio is at the level of ~ 1.

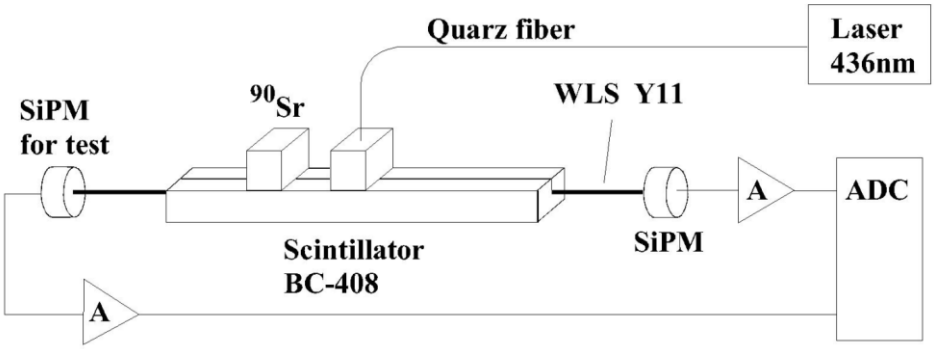

Figure 1. Setup used for measurement of SiPM response

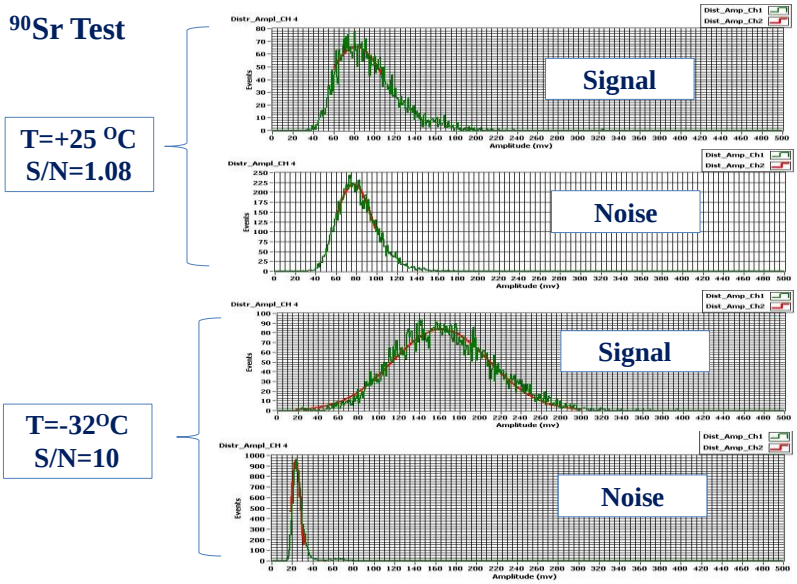

Figure 2. Results of measurements of SiPMs irradiated to a value of 5.38×10^{12} neutrons/cm^2 using ^{90}Sr as source of light

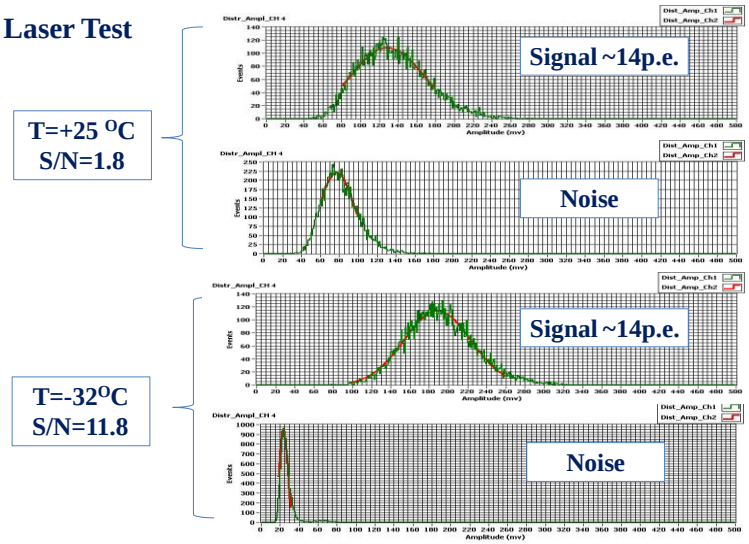

Figure 3. Results of laser measurements of SiPMs irradiated to a value of 5.38×10^{12} neutrons/cm^2

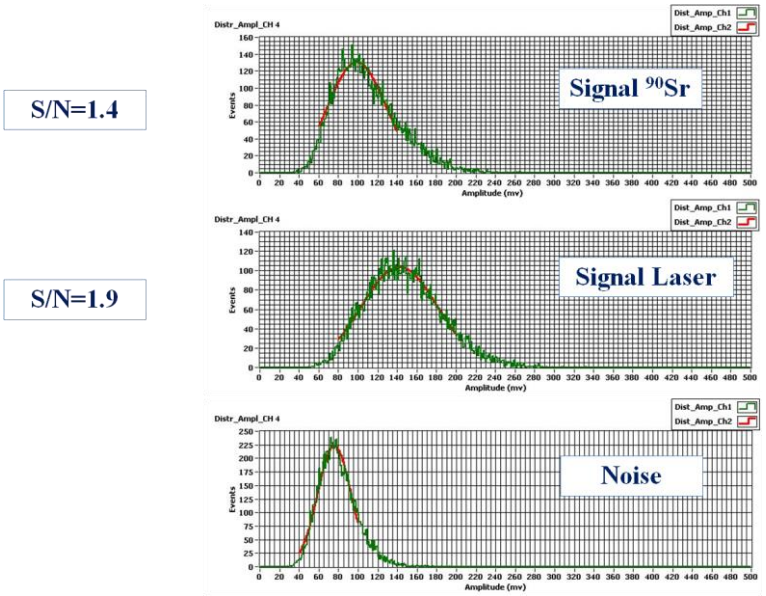

Figure 4. The results of measurements of SiPM devices irradiated to 2.09×10^{14} neutrons/cm^2 for both sources of light at -32 °C

Conclusion

JINR study shows that up to irradiation levels of ~ 5.4×10^{12} neutrons / cm^2, the above-mentioned Hamamatsu photodetectors will ensure the recording of signals from MIP particles in case of SiPM-on-tile readout in the scintillator section of the CMS HL-LHC endcap calorimeters.

References

[1] J. Mans and P. de Barbaro. The baseline readout of the scintillator section of the CMS HL-LHC Endcap Calorimeter // CMS DN-17-010.

[2] IBR-2 Reactor Parameters. Available at: http://flnph.jinr.ru/en/facilities/ibr-2/parameters (accessed 19.11.2019)

[3] MPPC. Available at: http://www.hamamatsu.com/ (accessed 19.11.2019)