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Characterisation of SiPM radiation hardness for application in hadron calorimeters at FAIR, CERN and NICA

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ABSTRACT: Silicon PhotoMultipliers (SiPM) are an excellent choice for the scintillator light readout at hadron calorimeters due to their insensitivity to magnetic fields, low operating voltages, low cost, compactness and mechanical endurance. They are already successfully utilized in Projectile Spectator Detector (PSD) of NA61 at CERN, and will be utilized soon in PSD of CBM at FAIR and Forward Hadron CALorimeters (FHCAL) of BM@N at NICA heavy-ion collision experiments. The main issue of SiPM application is their degradation due to high neutron fluence that can reach up to 2×10^{11} n_{eq}/cm^2 per year of the experiment operation. Multiple irradiation tests of SiPMs produced by Ketek, Zecotek, Hamamatsu and Sensl manufacturers were conducted at the cyclotron of NPI Řež with a broad neutron spectrum and total fluences in the wide range of 5×10^{10}–6×10^{12} n_{eq}/cm^2. Detailed characterisation of all SiPMs was performed based on dependencies of dark current on voltage, capacitance on voltage and frequency, and response to LED light on voltage. SiPM's breakdown voltage, quenching resistance, pixel capacitance, gain and signal to noise ratio were

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extracted from these measurements. Those parameters' dependence on neutron fluence and their variability are discussed. Performance of the PSD calorimeter module equipped with irradiated SiPMs in CERN during the beam scan with 2–80 GeV/c protons is briefly overviewed.

Keywords: Calorimeters; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Radiation damage to detector materials (solid state)

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Contents

1 Introduction

NA61@CERN, CBM@FAIR, BM@N and NICA heavy-ion collision experiments employ compensating lead-scintillator calorimeters to measure the energy distribution of the forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity [1]. The scintillation light is transferred via the WaveLength Shifting fibers and read out by Silicon Photo-Multipliers (SiPM). High interaction rates up to 1 MHz lead to harsh radiation conditions, namely total ionization dose up to 1 kGy and neutron fluence up to 2×10^{11} n_{eq}/cm^2 per year of the experiment operation. Only negligible changes in scintillators' light yield were observed after irradiation with this ionization dose [2]. In this article we compare changes of main parameters for various SiPMs after the neutron irradiation. The list of investigated SiPMs and their parameters, namely breakdown voltage V_{bd}, number of pixels N_{pix}, pixel pitch, gain, photodetection efficiency PDE, pixel recovery time $\tau_{recovery}$, pixel capacitance C_{pix}, quenching resistance R_q, difference between turn-on and turn-off voltage for the Geiger avalanche $V_{bd} - V_{off}$, are presented in table 1 [1].

SiPMs were irradiated at the cyclotron of NPI Řež with a "white" (from thermal up to 34 MeV [3]) and a quasi mono-energetic (peak at 22 MeV, with thermal neutron background [4]) neutron spectra and total fluences in the range of 5×10^{10}–6×10^{12} n_{eq}/cm^2. We estimated the fluence values by the activation foil method, gold foils were irradiated together with SiPMs. Fluence was further recalculated to 1MeV equivalent with damage factors $k = 1.54$ and 1.62 achieved for "white" and a quasi mono-energetic spectra, respectively. Fluence uncertainty is about 15% due to complicated neutron spectrum [3, 4].

Samples were irradiated and measured at temperature about 25 °C, covered from light. Measurements of SiPMs were performed after several months after irradiation, so self-annealing is

[1]Note, that before our measurements Zecotek MAPD-3A SiPMs were utilized at NA61 PSD for several years and were already slightly irradiated. $V_{bd} - V_{off}$ was not measured for these samples because they were unable to distinguish single photon peaks which typically happens after irradiation by fluence around 10^9–10^{10} n_{eq}/cm^2 [7].

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Table 1. Parameters of investigated SiPMs produced by various manufacturers. Most of parameters are typical and vary from sample to sample. All SiPMs have $3 \times 3\,\mathrm{mm}^2$ area. Pixel pitch for Sensl SiPMs is calculated based on number of pixels and SiPM area, so it is bigger than claimed by manufacturer. Values of C_{pix}, R_q and $V_{\mathrm{bd}} - V_{\mathrm{off}}$ are from our measurements.

	Zecotek MAPD		Hamamatsu MPPC		Ketek SiPM PM33		Sensl SiPM uF	
	3 A	3 N	S12572 -010P old	S14160 -1310PS new	15 -WB-A0	50	C 30020	B 30020
V_{bd}, V	64	88	67	38	27	23	25	25
N_{pix}	135000	135000	90000	90000	3600	38800	11000	11000
Pitch, μm	8	8	10	10	15	50	29	29
Gain	$6{\times}10^4$	10^5	10^5	10^5	$3{\times}10^5$	$6{\times}10^6$	10^6	10^6
PDE, %	20	30	10	18	22	40	24	24
τ_{recovery}, ns	2000	10000	10	10	13	2000	100	100
C_{pix}, fF	1.5	1.2	3.2	6.4	19.5	280	63	63
R_q, MΩ	2.7	2.7	2.7	1.6	0.74	0.42	0.4	0.48
$V_{\mathrm{bd}} - V_{\mathrm{off}}$, V	–	0.43	1.7	0.97	0.72	0.15	0.15	0.15

considered to be finished. Laboratory measurement setup includes Keithley 6517A Electrometer, Hioki 3532-50 LCR HiTester, Rohde&Schwarz RTO1024 Oscilloscope, custom amplifier with gain of 120 and fast 400 nm LED driven by custom pulse generator. Dedicated software was developed in NI LabWindows/CVI to automate the measurements. Voltage step was set to 0.1 V to achieve optimal measurement accuracy. Uncertainties of measured parameters for samples irradiated by different neutron fluences are dominated by sample-to-sample variability. Variability for SiPMs of same type irradiated with the same fluence was typically about 15% for dark current and 10% for LED response measurements which confirms the uniformity of the sample irradiation, see figure 6 in the end of section 4. Measurement variability for quenching resistance was typically about 8%, for capacitance it was about 1%.

2 Dark current measurements

Measurements of SiPM dark currents in reverse bias mode were used to extract the breakdown voltages as maximum of $1/I_{\mathrm{dark}} \cdot (dI_{\mathrm{dark}}/dV_{\mathrm{rev}})$. Extra measurements were performed under illumination for non-irradiated SiPMs to increase the precision of V_{bd} determination. For irradiated SiPMs V_{bd} determined with and without light do not differ. Change of breakdown voltage after irradiation did not exceed 0.5 V. Note that V_{bd} is the turn-on voltage for the Geiger avalanche and it differs from the turn-off voltage V_{off} [5]. The latter was measured with help of single photon spectra measurements for non-irradiated SiPMs and the typical difference $V_{\mathrm{bd}} - V_{\mathrm{off}}$ is presented in table 1. Unfortunately, after irradiation all the SiPMs lost the ability to distinguish single photons, so V_{off} could not be measured anymore.

Figure 1 presents dependence of dark current on fluence observed for the investigated SiPMs at different values of overvoltage $V_{\mathrm{OV}} = V_{\mathrm{rev}} - V_{\mathrm{bd}}$. Comparison of different SiPMs is provided

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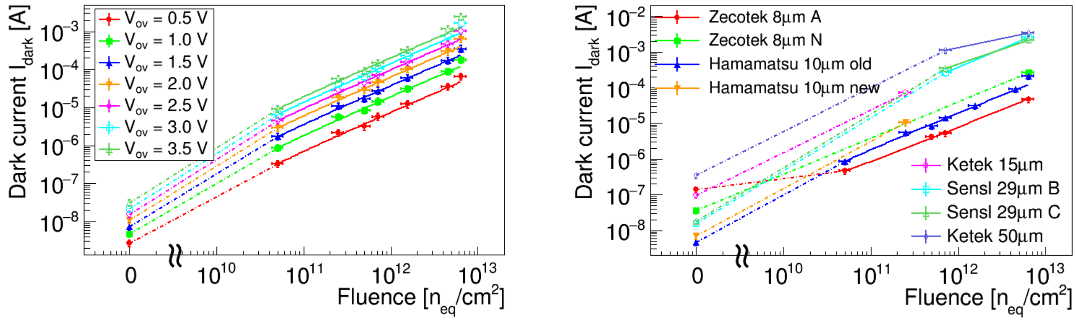
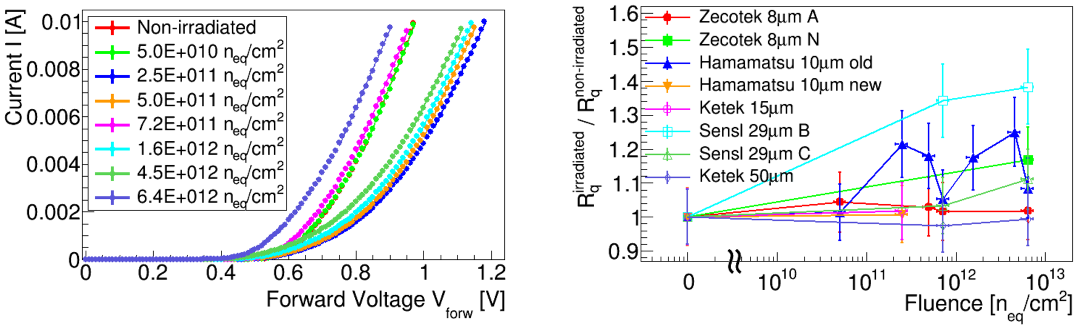


(a) **(b)**

Figure 1. Dependence of dark current on fluence for Hamamatsu MPPC S12572-010P at different overvoltages (a) and for all the investigated SiPMs at overvoltage V_{OV} = 1 V (b).

for V_{OV} = 1 V because highly irradiated Ketek and Sensl SiPMs reach 10 mA limit of electrometer right after 1 V [6]. All the SiPMs follow the trend of linear dark current increase with fluence which is typically observed for silicon sensors. Dark current increased in up to 5 orders of magnitude for highly irradiated SiPMs which resulted in huge noise and power consumption making them hardly applicable, see section 5. Analysed data suggest that value of dark current after irradiation[2] directly depend on the pixel size, i.e. the bigger the pixels — the higher the dark current.



(a) **(b)**

Figure 2. Dependence of dark current on forward voltage for Hamamatsu MPPC S12572-010P for different fluences (a). Ratio of quenching resistance after/before irradiation for all the investigated SiPMs (b).

Measurements of dark current versus forward voltage are exemplified in figure 2 (a). SiPM quenching resistances were extracted from these measurements as $R_q \approx N_{\mathrm{pix}}/(dI_{\mathrm{dark}}/dV_{forw})$ [5]. Linear fit was performed at the very end of $I_{\mathrm{dark}}(V_{forw})$ curve due to its deviation from linearity in the lower range. Changes of SiPM quenching resistance after the irradiation by $\Phi < 10^{11}$ $\mathrm{n_{eq}/cm^2}$ are below the uncertainty of 8% as shown in figure 2 (b). For higher fluences R_q seems to increase by up to 20% for some SiPMs.[3] Absolute values of R_q before irradiation can be found in table 1.

[2]Generally, data before the irradiation are not so straight forward to interpret. Note, that Zecotek MAPD-3A has quite high dark current before irradiation because before our measurements these samples were utilized at NA61 PSD for several years and were already slightly irradiated.

[3]Only single sample of Sensl uF-B30200 was measured before the irradiation and it exhibited quite strange dark current dependence which could explain the higher deviation of R_q after irradiation.

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3 Capacitance measurements

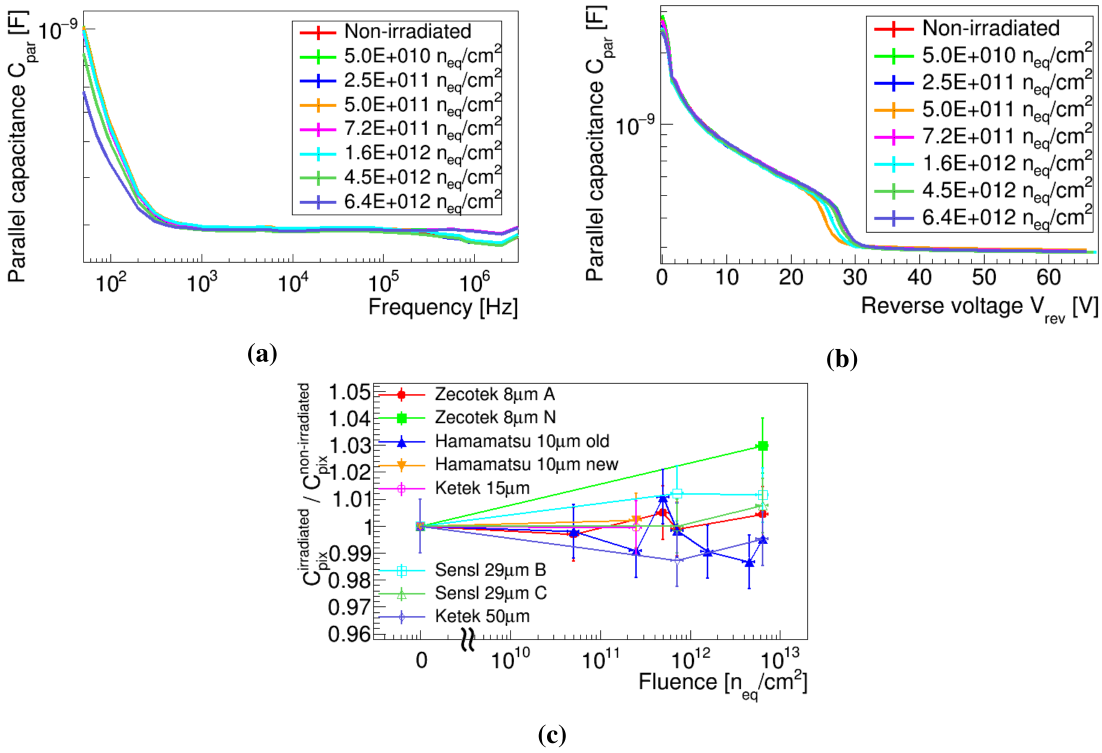

Figure 3. Dependence of capacitance on test signal frequency below the breakdown for Hamamatsu MPPC S12572-010P for different fluences (a). Dependence of capacitance on reverse voltage at 10 kHz for Hamamatsu MPPC S12572-010P for different fluences (b). Ratio of pixel capacitance after/before irradiation for all the investigated SiPMs (c).

Capacitance-frequency measurements of all SiPMs before and after irradiation biased at voltage $0.9V_{bd}$ were carried out in parallel equivalent circuit mode, for example see figure 3 (a). Based on these results, stable intermediate frequency of 10 kHz was chosen for further investigation. Pixel capacitance was calculated from parallel capacitance as $C_{pix} \approx C_{par}/N_{pix}$, which is valid for intermediate frequencies where parasitic and quenching capacitances are negligible [5]. We are interested in C_{pix} above the depletion voltage V_{dep} which is visible around 30 V for Hamamatsu SiPMs in figure 3 (b). However, for Ketek and Sensl SiPMs full depletion is not reached until the breakdown voltage and capacitance measurement in the SiPM avalanche region is not a straight forward task. We assume that the change of C_{par} above V_{bd} is not too big and determine C_{pix} at 1 V below V_{bd}.

Figure 3 (c) shows that pixel capacitances did not change after the irradiation for most SiPMs.[4] Absolute values of C_{pix} before irradiation are presented in table 1. SiPM gain is defined as $G(V_{rev}) \approx (C_{pix} + C_q) \cdot (V_{rev} - V_{off})/q_0$, where quenching capacitance C_q is typically an order of magnitude lower than C_{pix} [5]. We might assume that V_{off} only slightly change after irradiation similarly to V_{bd}. Then we can conclude that SiPM gain did not change after irradiation as well as C_{pix}.

[4]Only for Zecotek MAPD-3N C_{pix} increased by 3% which is higher than the typical uncertainty of 1%. However, this uncertainty is based on variability of other samples, while only single irradiated and single non-irradiated Zecotek MAPD-3N samples were investigated, therefore their variability might be higher.

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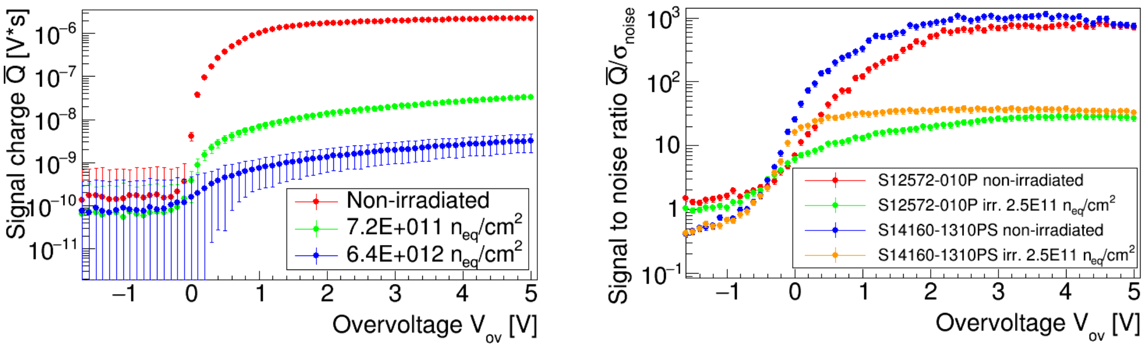
4 LED response measurements

The most important is to measure SiPM's ability to serve as a photodetector after the irradiation. For this purpose response of SiPM to LED pulses with constant amplitude and 10 ns width was measured versus overvoltage. Measured signal charge $\bar{Q}$ is defined as mean of the integral area measurement with window gate of 100 ns. Noise estimation is based on standard deviation σ_{Noise} of the measured integral without the light exposure. Both are expressed in nV·s. Signal to noise ratio is defined as $SNR = \bar{Q}/\sigma_{\text{Noise}}$ and signal resolution is defined as $Res_Q = \sigma_Q/\bar{Q}$. Signal amplitude was chosen so that non-irradiated and the most irradiated sample could still detect it. For the least radiation hard samples such as Ketek PM-3350 with the largest $50 \times 50\ \mu\text{m}^2$ pixels we had to choose such a big signal that non-irradiated sample would saturate almost immediately after the breakdown as shown in figure 4 (a). Due to this fact ratios of signal parameters are presented at overvoltage of 1 V. For lower overvoltages SiPM response is extremely dependent on variation of V_{bd}, also it can be too small for highly irradiated samples. Hamamatsu SiPMs after irradiation with $\Phi = 2.5 \times 10^{11}\ \text{n}_{\text{eq}}/\text{cm}^2$ exhibit signal to noise ratio above 10 which is considered to be sufficient for the calorimeter operation, see figure 4 (b).



(a) **(b)**

Figure 4. Dependence of LED response on overvoltage for Ketek SiPM PM-3350 before and after irradiation (a). Standard deviation of LED response σ_Q is used as uncertainty here to visualise a poor signal visibility for the most irradiated sample. Dependence of signal to noise ratio before and after irradiation for Hamamatsu 10 µm SiPMs of old S12572-010P and new S14160-1310PS version (b).

Drastic degradation of SiPMs' response to LED and consequently signal to noise ratio up to 3 orders of magnitude was observed after irradiation by $\Phi = 6.4 \times 10^{12}\ \text{n}_{\text{eq}}/\text{cm}^2$, see figure 5 (a, c). No signal degradation was observed for $\Phi < 2.5 \times 10^{11}\ \text{n}_{\text{eq}}/\text{cm}^2$. SiPM signal response to incoming light is essentially a convolution of gain, photodetection efficiency PDE and excess charge factor ECF. ECF is responsible for production of secondary correlated Geiger discharges and it is typically ≤ 1.2 [5]. Most likely, PDE decreased after irradiation due to change of internal structure of SiPM and/or due to individual pixel failures. Alternatively, SiPM gain could have decreased if indirect gain assessment based on pixel capacitance measurement presented in section 3 is not valid for irradiated SiPMs. Unfortunately, there is no direct way to measure SiPM gain and PDE after irradiation. SiPM noise increased in only 2–10 times for $\Phi < 10^{12}\ \text{n}_{\text{eq}}/\text{cm}^2$ and then saturated or even decreased, see figure 5 (b). Presented relative decrease of SiPM noise shall be regarded as the lower limit because noise of non-irradiated SiPMs at $V_{\text{OV}} = 1$ V is mostly produced by

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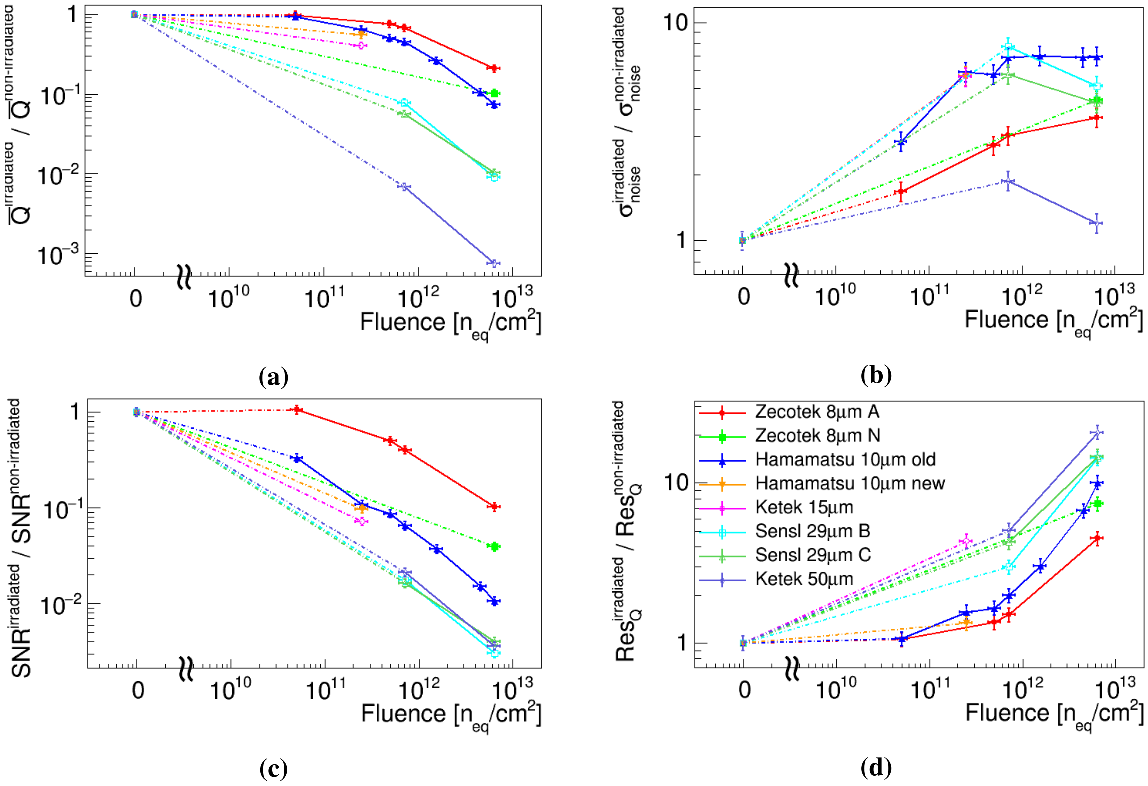

Figure 5. Ratios of LED response (a), noise (b), SNR (c) and resolution (d) at overvoltage $V_{OV} = 1$ V before/after irradiation for all the investigated SiPMs. Note, that drop of signal parameter ratios represent a lower limit for SiPMs with pixel pith > 20 µm because they exhibit partially saturated signal already at $V_{OV} = 1$ V, see figure 4 (a) for example.

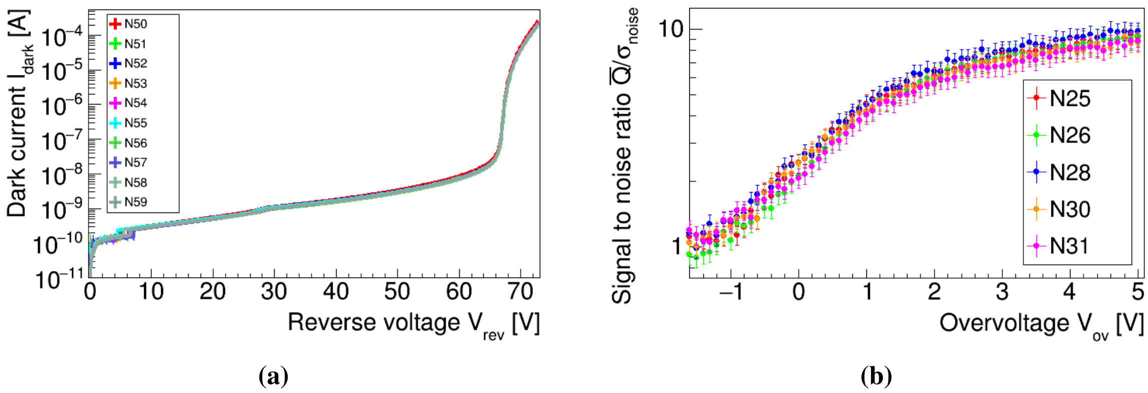

Figure 6. Dark current variability for ten Hamamatsu MPPCs S12572-010P irradiated by 2.5×10^{11} n_{eq}/cm^2 (a). Signal to noise ratio variability for five Hamamatsu MPPCs S12572-010P irradiated by 1.6×10^{12} n_{eq}/cm^2 (b).

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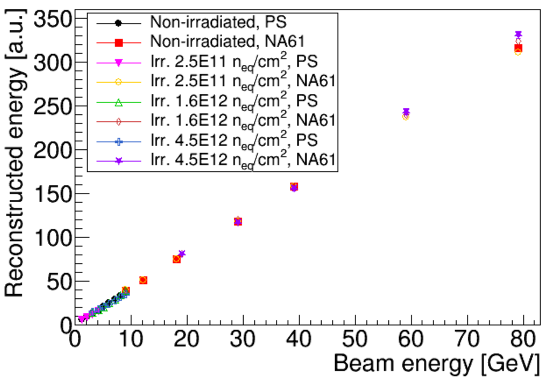
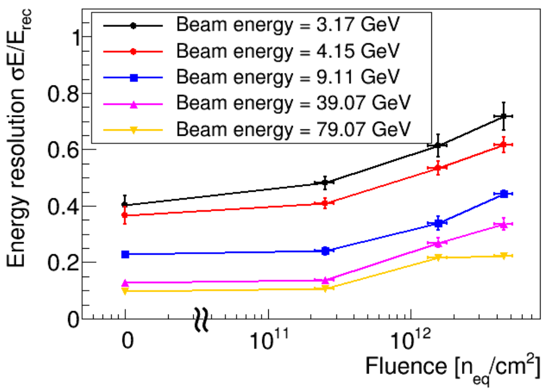
amplification and readout circuitry. Noise decrease could be explained with the decrease of SiPM gain which compensate for noise added by higher dark current. SiPM resolution degraded by more than factor 10 as shown in figure 5 (d). Relative degradation is smaller for resolution than for SNR because standard deviation of LED response σ_Q before irradiation is more than 10 times higher than standard deviation of noise σ_{Noise} but after irradiation they become comparable.[5] Similarly to dark currents, SiPM LED response and SNR after irradiation is directly dependent on the pixel size, i.e. the bigger the pixels — the more the SiPM response degrade with accumulated fluence.

5 PSD calorimeter performance

PSD single module response to proton beams was studied in the momentum range of 2–80 GeV/c, including tests at CERN PS beamline for 2–10 GeV/c and tests at CERN NA61 beamline for 10–80 GeV/c. Module was consequently equipped with 3 batches of Hamamatsu MPPCs S12572-010P irradiated by 2.5×10^{11}, 1.6×10^{12} and 4.5×10^{12} $\mathrm{n_{eq}/cm^2}$. These SiPMs were chosen for the superior radiation hardness with respect to SiPMs produced by Ketek and Sensl manufacturers. We assume that this is largely due to small pixel size of $10 \times 10\,\mu\mathrm{m}^2$ of Hamamatsu SiPMs. Moreover, small pixel size is important for us as it increases the calorimeter dynamic range. One may note that Zecotek MAPDs have even smaller pixels and better radiation hardness. Unfortunately, due to very large pixel recovery time about several microseconds they cannot withstand the high event rates up to 1 MHz and cannot be utilized at our detectors [6].



(a)



(b)

Figure 7. Single module proton energy linearity vs beam energy (a). Resolution vs fluence for different beam energies (b). SiPMs were operated at overvoltage = 3 V and room temperature. Supply voltage of each SiPM was tuned online with respect to measured temperature to keep V_{bd} and gain stable during the operation.

Figure 7 (a) shows that linearity of the calorimeter response did not suffer from the radiation. Figure 7 (b) presents the degradation of energy resolution with accumulated fluence. Only slight deterioration is observed after irradiation by 2.5×10^{11} $\mathrm{n_{eq}/cm^2}$ which is the worst case scenario

[5] σ_Q depends on Poisson statistics of light counting, so it scales with the measured charge $\bar{Q}$ which is very big before irradiation. Noise on contrary does not depend on $\bar{Q}$ and can be very small before irradiation. After irradiation $\bar{Q}$ become very small and σ_Q become dominated by σ_{Noise}, so both become comparable.

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for a one year of experiment operation[6]. Modular detector structure of our fix-target heavy-ion collision experiments allows to exchange the most damaged SiPMs every year if necessary.

6 Results discussion and conclusion

Achieved data suggest only minor changes of SiPM breakdown voltage, quenching resistance, pixel capacitance and gain after irradiation which agrees well with investigations from other authors summarized in [7]. We also observed linear dependence of SiPM dark current on neutron fluence up to 6×10^{12} n_{eq}/cm^2, same trend was presented for lower fluences up to 6×10^9 n_{eq}/cm^2 in [8, 9].

We found out that SiPMs' response to LED and signal to noise ratio decrease by 10–1000 times at $\Phi > 10^{12}$ n_{eq}/cm^2 for SiPMs with different pixel sizes. Musienko et al. measured SNR $\approx$ 5–10 for FBK SiPMs with 10–12.5 µm pixel pitch that were irradiated by 2×10^{12} n_{eq}/cm^2 which is similar to our results for SiPMs with 10 µm pixel pitch. Several authors [10–12] observed that dark current and LED response performance of highly irradiated SiPM is greatly improved when it is cooled down to −30°C. Even full recovery of PDE and single photon detection can be accomplished at cryogenic temperatures about 80 K for SiPMs irradiated up to by 10^{14} n_{eq}/cm^2 [11, 12]. However, no cooling is planned to be utilized at our hadron calorimeters.

Both dark current and LED response of irradiated SiPMs scale with the pixel size, namely the smaller the pixels — the better the radiation hardness. Such a scaling was already observed for SiPM dark currents in [9, 13, 14] and for LED response in [13]. SiPM pixel miniaturisation is beneficial because it lowers pixel capacitance resulting in the shorter charge collection time and higher collection efficiency contributing to the PDE improvement. It also generally reduces the sensor deadtime and therefore increases the total dynamic range for the high frequency signals. Decreased active volume and surface of a single pixel results in the decrease of generated dark current, and lowered probability of both the after-pulsing and the cross-talk. This suggests the use of SiPMs with the smallest available pixels for the harsh radiation environment.

PSD calorimeter performance with older version of Hamamatsu SiPMs irradiated by 2.5×10^{11} n_{eq}/cm^2 decreased only slightly. New version was proven to perform in a similar manner which suggests its use at new calorimeters which are now being assembled.

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[6]Results presented for higher fluences of 1.6×10^{12} and 4.5×10^{12} n_{eq}/cm^2 are an upper limit of resolution degradation because only first 5 sections of the module were equipped with SiPMs and external voltage supply was used due to high SiPM power consumption.

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