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Noise and radiation damage in silicon photomultipliers exposed to electromagnetic and hadronic radiation

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ABSTRACT

For the electron arm tracking system in the KAOS spectrometer at the Mainz Microtron MAMI a detector based on 2 m long scintillating fibres read out by silicon photomultipliers (SiPM) is planned. Because of the detector's close proximity to the intense electron beam a study of noise and radiation damage in SiPM has been performed. A sample of devices was exposed directly to a 14 MeV electron beam and to a mixed radiation field in the experimental area. First noticeable effects are a large increase in the dark count rate and a severe loss of the gain uniformity.

1. Introduction

Silicon photomultipliers (SiPM) are used by an increasing number of high energy and nuclear physics experiments in their detector systems due to the advantages that a solid state device presents in comparison to traditional vacuum photomultiplier: low supply voltage operation and magnetic field insensitivity [1,2]. For the electron arm tracking system in the KAOS spectrometer of the A1 collaboration at the Mainz microtron MAMI two vertical planes of fibre arrays, covering an active area of $L \times H \sim 1600 \times 300\,\mathrm{mm}^2$, supplemented by one or more horizontal planes are under construction [3]. SiPM are considered as possible read-out devices for the $\sim$300 fibres per plane of the horizontal sub-system. The diodes used in our investigation (SSPM from Photonique) have a typical bias voltage of only 18 V, can be operated without magnetic shielding in the stray field of the KAOS dipole, and introduce simplifications in the detector mechanics.

Particle detectors are often exposed to high radiation doses. It is well known that generating centers are created during irradiation which increase the leakage current [4]. The bulk leakage current is multiplied in avalanche photodiodes (APD) by the gain factor and the resulting pulses are undistinguishable from photon generated events. Consequently, an increasing rate of dark pulses as a function of the radiation dose is seen in SiPM [5]. Adverse effects of irradiation on other characteristic parameters of SiPM such as gain uniformity, after-pulsing or optical cross-talk probability would be also detrimental for a detector.

The KAOS spectrometer's electron arm detectors will operate close to zero degrees scattering angle and in close proximity to the electron beam [6]. Fig. 1 shows a schematic drawing of the set-up in the spectrometer hall at the Mainz microtron MAMI, where the spectrometer is operated by the A1 collaboration. A sophisticated trigger logic implemented in FPGA at 400 MHz clock frequency [7] will be used in order to minimize accidental trigger rates in the electron arm instrumentation. However, the radiation hardness of its photon detectors is still an open issue. In addition to a broad neutron spectrum high electromagnetic background levels are expected at the SiPM locations. It is consequently imperative to study how operative parameters of SiPM can be affected in different radiation environments. A Monte Carlo simulation containing the most relevant operational parameters can be used to extract the impact of irradiation on the SiPM performance [8]. Photonique devices with an active area of 1 mm^2 composed of 500 APD have been irradiated directly by a 14 MeV electron beam and indirectly by placing them in close proximity to the beam-line. Shielding effects and annealing have also been investigated. The results will be presented in the following sections.

2. SiPM characterization

The SiPM photon counting capabilities are a consequence of the narrow response function. Two factors contribute to this fact.

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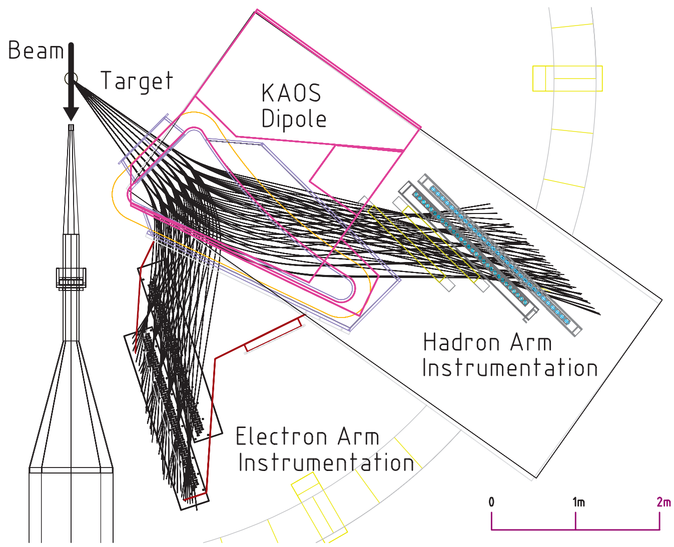

Fig. 1. Overview of the KAOS spectrometer operated by the A1 collaboration at the Mainz microtron MAMI: electrons and hadrons are detected under small scattering angles in coincidence. Charged particle trajectories through the spectrometer are shown by full lines. The electron arm tracking detector will be located close to the electron beam. High radiation levels are expected at such an exposed position.

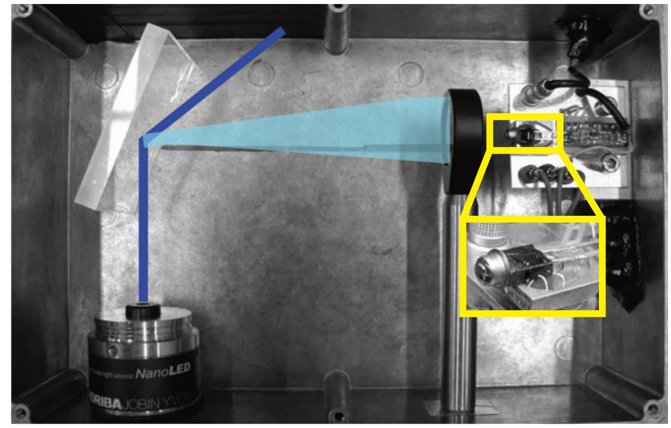

Fig. 2. Experimental set-up for SiPM characterization: a fast pulsed UV laser (100 ps FWHM) excited a plastic scintillator. Reflected UV light was absorbed in a black screen. The blue scintillation light was attenuated by a neutral density filter so that only few photons arrived to the SiPM (inset right).

Firstly the single pixel signal has a well-defined amplitude due to the low excess noise factor (smaller than 1.1 for the SiPM under study), and secondly the variation of that amplitude from pixel to pixel is small as a result of the fabrication process. Low light level detection is thus characterized by a multi-photoelectron pulse-height distribution (MPHD) with very clear peaks corresponding to the different number of activated pixels and a photon detection efficiency (PDE). It is revealing to measure with an analogue-to-digital converter (ADC) the output signal charge for a randomly generated integration window in the absence of light. SiPM characteristics such as optical cross-talk, after-pulsing and dark count rate have a direct impact on the MPHD. These contributions explain the departure of the ADC spectrum from a Poissonian distribution. Experience has shown that also irradiation effects are observed in the MPHD and Monte Carlo simulations are an appropriate tool to extract any change in SiPM working parameters. For example any increase in dark count rate will change the relative amplitude of the pedestal peak by populating the one or more pixel peaks.

A complete SiPM characterization was performed by measuring ADC spectra under low illumination levels and in addition in darkness with a randomly generated 30 ns wide window. The average width of the single-pixel signal was 9 ns. The low light level detection under reproducible conditions was realized by exciting a plastic scintillator (BC-408 from Bicron, $80 \times 50 \times 10\,\mathrm{mm}^3$) with a fast pulsed UV laser (NanoLED from Horiba Jobin Yvon, 100 ps FWHM). The measuring system can be seen in Fig. 2. Reflected UV light was absorbed in a black screen and the blue scintillation light was attenuated by a neutral density filter. The laser intensity could be regulated so that only few photons arrived to the SiPM.

3. SiPM irradiation with the electron beam

Controlled radiation dose studies are important in order to provide precise quantitative information about SiPM radiation hardness. Stage A of MAMI provides a high quality beam of 14 MeV electrons. We irradiated a sample of SSPM-0701BG-TO18 SiPM with a beam current of 10 nA. The electrons crossed a 0.3 mm thick aluminium window at 15 cm distance from the $1\,\mathrm{mm}^2$ active area of the SiPM. Fluences on the SiPM were calculated taking into account multiple Coulomb scattering in the thin exit window and ranged from 3.1×10^9 to 3.8×10^{10} electrons/mm^2. The damage in silicon devices depends on the flux, type and energy of the particle. For comparison with similar studies performed with other radiation sources and energies we quote the non-ionizing energy loss (NIEL) of 14 MeV electrons when crossing the SiPM active area being $1.1 \times 10^{-4}\,\mathrm{MeV\,cm^2/g}$ [9,10]. Heat dissipation and damage on the transparent epoxy layer protecting the silicon material were also calculated and was proved to be negligible (less than 5% for the full integrated dose). Grounding of the SiPM was provided in order to avoid damage by the sudden release of accumulated charge. Fig. 3 shows the experimental set-up. The beam position was monitored with a fluorescent screen during the SiPM irradiation.

Green sensitive Photonique SiPM (40% PDE at 560 nm) were characterized before and after irradiation by studying the noise rate and the MPHD for low amplitude signals. The PDE and the signal amplitude are linearly increasing functions of the bias voltage, as can be seen in Fig. 4. Relatively low operating voltages are advantageous for low light level detection due to the exponential increase in dark count rate with bias voltage. Too small bias voltages are, however, not suitable when the signal gain becomes insufficient. An operating voltage of 17.9 V was recommended by the manufacturer and was confirmed to be a reasonable compromise for scintillating fibre light output detection. Fig. 5 shows the MPHD of the SiPM dark pulses integrated in a randomly generated window from an irradiated SiPM operated at 17.9 V. A reduction of the pedestal amplitude relative to the one or more pixel peaks is clearly observed. Fig. 6 shows the MPHD before and after irradiation for a fixed light intensity for the same operating voltage. The pedestal shift is a consequence of the increase in leakage current. Electron–hole pairs generated in the active detector volume will give rise to a full pixel signal undistinguishable from photon generated pulses. The large increase in dark noise after irradiation results in signal pile-up with the corresponding shift in the pedestal position. The pedestal shift has not been corrected as the visible large magnitude of the shift can give rise to specific problems in particular applications. A Monte Carlo simulation was used in order to extract the changes in the characteristic parameters of the SiPM [8]. The results show

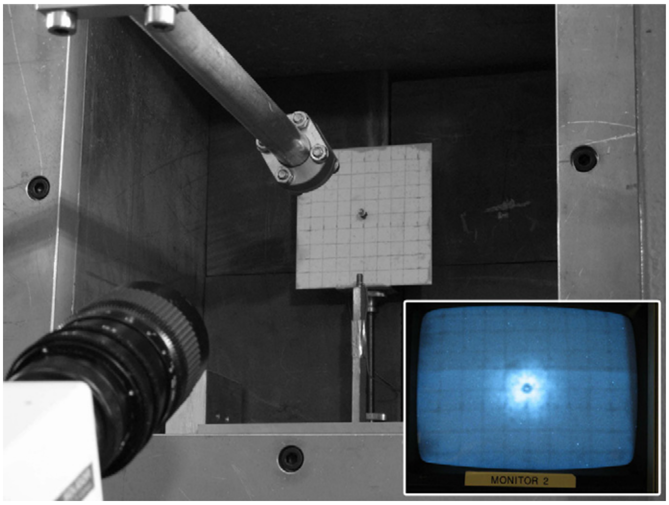

Fig. 3. Experimental set-up for SiPM irradiation. Electrons (14 MeV) left the evacuated beam-pipe through a 0.3 mm aluminum window. Multiple Coulomb scattering of the beam generated a wide spot on the fluorescent screen. The beam position could be accurately steered so that the SiPM was at the centre of the spot as can be seen in the on-line monitor picture (inset lower-right). The small SiPM active area was considered as uniformly irradiated.

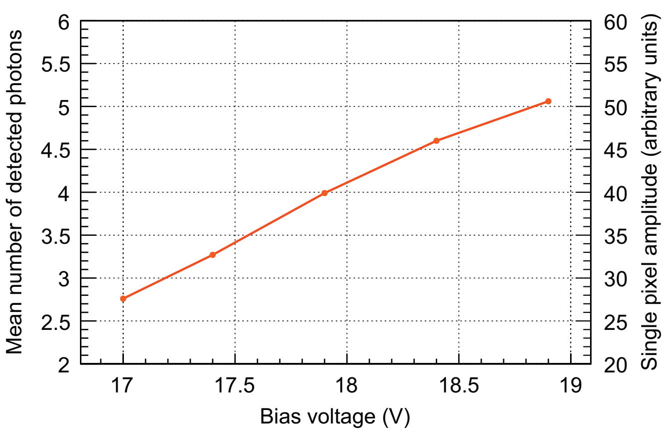

Fig. 4. Photon detection efficiency and gain as a function of the bias voltage for the green sensitive Photonique SiPM.

that the spectra of irradiated SiPM can only be reproduced with an increased noise rate and a reduced gain uniformity. A small gain reduction and increased after-pulsing probability were also observed.

For higher fluences the increase in noise rate is so large that a multi-pixel peak differentiation is no longer possible in the ADC spectrum. The detectors were still able to operate giving an output signal proportional to number of incoming photons (within the dynamical range) but the signal-to-noise ratio was considerably worse for low light levels. Monte Carlo methods are less successful for high radiation doses due to the lack of a procedure to provide approximate initial values for the parameters. Therefore, a different approach was used to extract quantitative information: the variation in the integrated pulse charge was studied by comparing the position of the maximum in the ADC spectra for large signals. The noise contribution to such a spectrum are considered irrelevant. The result of such an investigation is shown in Fig. 7. A progressive reduction of the integrated charge was observed. This fact can be attributed to the loss of a progressively larger amount of pixels which remain permanently in the off-state, to the reduction in the PDE of each pixel, to a reduction in

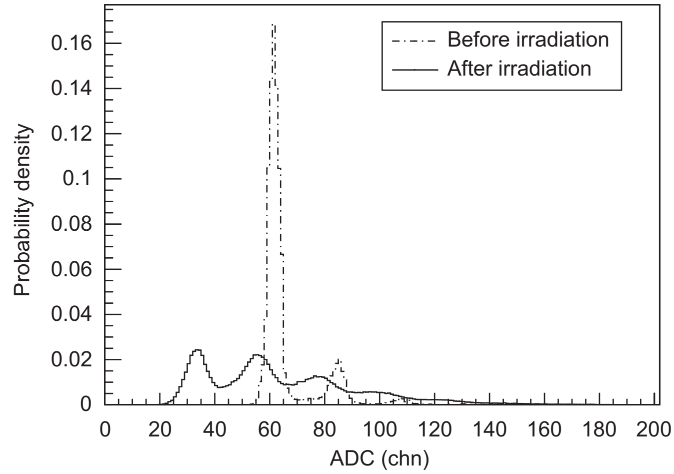

Fig. 5. Integration of dark pulses in a randomly generated window for a bias voltage of 17.9 V before and after irradiation with 3.1×10^9 electrons/mm^2. The reduction of the pedestal amplitude relative to the one or more pixel peaks and its shift in position are a result of the increase in dark count rate.

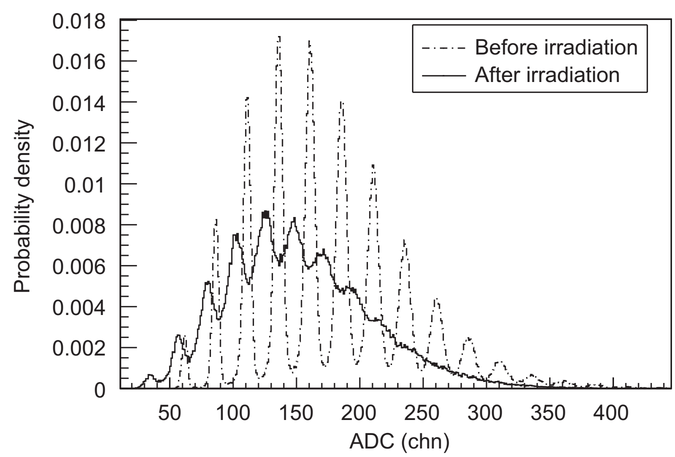

Fig. 6. ADC spectra for low amplitude signals from green sensitive Photonique SiPM before and after irradiation with 3.1×10^9 electrons/mm^2.

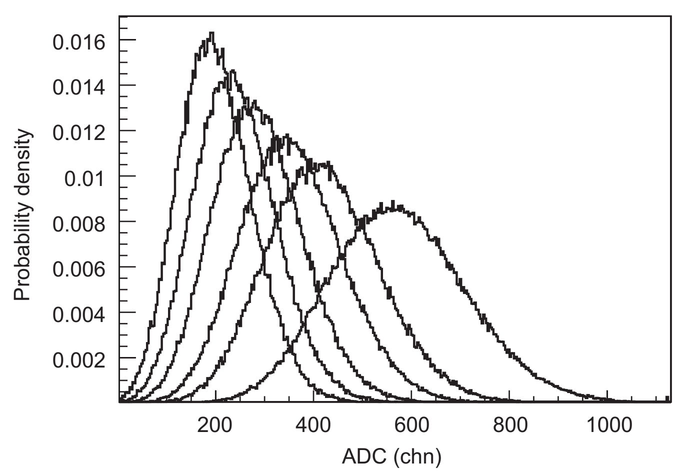

Fig. 7. ADC spectra for fixed laser intensity after irradiation with 30.8, 77.0, 123, 185, 262 and 385 $\times 10^8$ electrons. A progressive reduction of the photon detection efficiency or of the SiPM gain is suggested as an explanation for the observation of lower integrated charge with increased irradiation dose.

the single pixel amplitude or gain variation due to reduced bias voltage as a consequence of the larger voltage drop in the series resistor for increased leakage current. A combination of these factors is equally possible. No attempt is made to disentangle the different effects involved.

4. SiPM irradiation by hadronic and electromagnetic background

In a second step a more realistic situation was arranged by placing the SiPM in the experimental area close to where the actual detector will be located. A precise knowledge of the radiation field in the experimental hall for a future SiPM detector set-up is not available, as it happens to be strongly dependent on the experimental condition. As the radiation damage predictions based on the electron irradiation data (scaled appropriately) can only be approximate, it is consequently important to study the effect of the heterogeneous radiation present at the planned detector position on the SiPM performance. The blue sensitivity Photonique device SSPM-0611B1MM (16% PDE at 410 nm) was added to the sample in order to investigate possible radiation hardness differences. Noise spectra were taken for Photonique SSPM-0701BG-TO18 devices before irradiation and after 3, respectively, 7 days of normal operation with typical electron beam currents of 10 μA on a carbon target in the experimental hall.

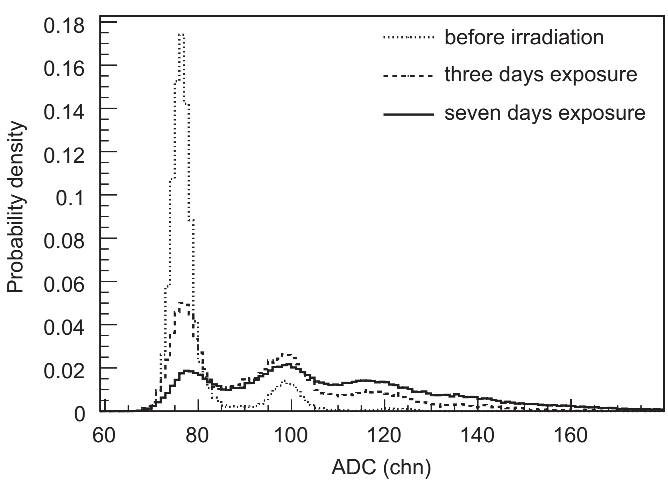

Fig. 8. Noise spectra of a green sensitive Photonique SSPM-0701BG-TO18 device that was exposed to mixed background irradiation close to the beam-line during one week of normal beam operation. Substantial damage was observed after 3, respectively, 7 days of exposure.

The electromagnetic component of the radiation field at the SiPM location was estimated by means of a digital dosimeter giving an average value of 30 mSv per day of exposure. At this relatively low level measurable effects on the SiPM due to photons or electrons will show up only after several months of exposure. Short term damage is mainly due to the large hadronic component present in the beam-dump proximity as a consequence of their much higher NIEL. The damage in silicon detectors with active areas of several mm^2 induced by protons and neutrons for fluences up to 10^{10} nucleons per cm^2 became recently available [11,12]. After irradiation an increase in leakage current and dark noise was found, but no apparent reduction in PDE. High energy neutrons are particularly dangerous due to their long range in air and the practical impossibility to provide effective shielding for them. Thermal neutrons can be easily stopped by borated polyethylene (BPE) for example. Nuclear capture of such thermal neutrons frequently results in the production of photons, that can be accounted for by a few mm of lead shielding. One of the SiPM was shielded by 3 cm of BPE and 2 mm of lead. The amount of shielding used is compatible with the space available for the actual tracking detector.

Noise spectra of an irradiated SSPM-0701BG-TO18 device are shown in Fig. 8. After irradiation a large increase in the number of one pixel pulses as compared to the pedestal peak was observed. For a randomly generated integration window this can be directly interpreted as an increase in the dark pulse rate. The variation found in the relative populations of the second and third peaks corresponding to one and two pixels before and after irradiation are a consequence of an increase in the after-pulsing probability according to the Monte Carlo simulation.

Two blue sensitive Photonique SSPM-0611B1MM devices were exposed to half of the full dose and the noise spectra with and without shielding are shown in Fig. 9. The shielding effect was apparent but the damage due to mainly high energy neutrons was still observable. The device SSPM-0611B1MM seems to have suffered from a smaller damage than the green sensitive SSPM-0701BG-TO18 device for the same irradiation period of 3 days. Further studies are being developed in order to confirm a possible radiation hardness difference.

A heat treatment (annealing) was attempted to reduce the observed damage. SiPM were kept in a controlled temperature oven at 80 °C for two weeks. The MPHD for a randomly generated window is shown in Fig. 10 for the green sensitivity device. Pedestal shifts have been corrected for comparison. Only a partial recovery was observed. A longer annealing period did not produce any further improvement.

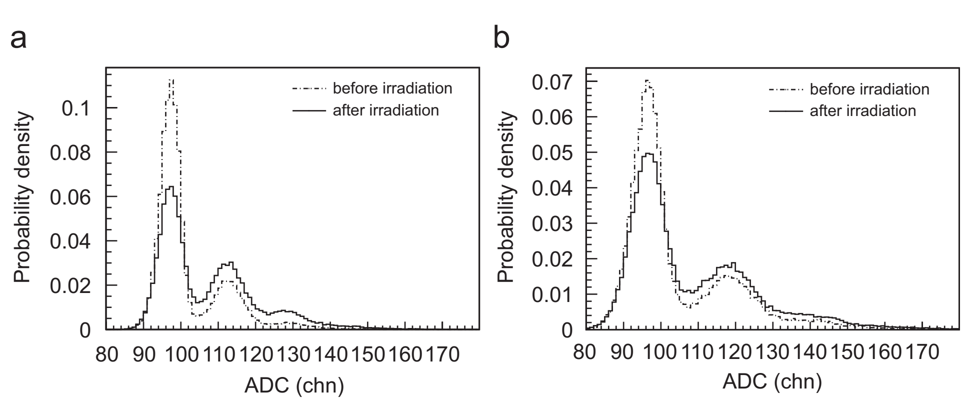

Fig. 9. Noise spectra of two blue sensitive Photonique SSPM-0611B1MM devices before and after irradiation in a mixed radiation field close to the beam-line. (a) SiPM without radiation shield. (b) SiPM shielded by 3 cm of BPE and 2 mm of lead. A reduced damage was observed for the shielded SiPM.

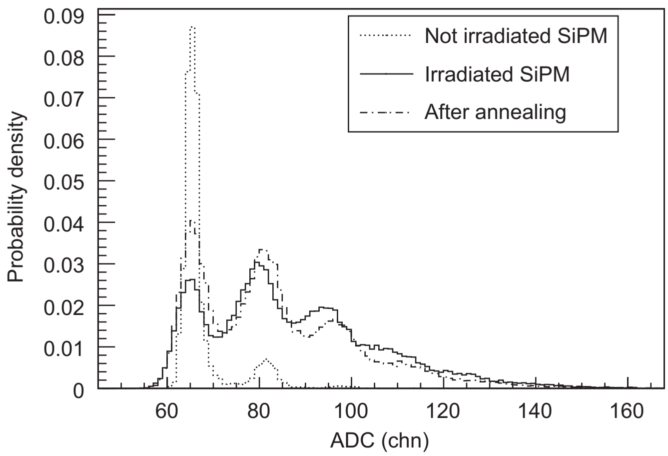

Fig. 10. Annealing at 80 °C of the SiPM exposed to the radiation field in the experimental hall resulted in a partial recovery. The ADC spectra for a randomly generated integration window of the green sensitivity SiPM are shown before and after irradiation. The same histogram is shown after the heat treatment.

5. Discussion

Low light levels are characteristics of long and thin scintillating fibres due to the low mass presented to the incident particle and the transmission and attenuation of the light. SiPM show a high dark count rate at room temperature of the order of 1 MHz/mm^2. Therefore, it is a challenge to obtain a high particle detection efficiency and low accidental trigger rates even when fibres are read out at both extremes and left-right coincidences are required. The KAOS spectrometer's horizontal tracking detector requires 2 m long scintillating fibres. A relatively large cross-section of 4 mm^2 has been chosen as the optimum value between minimal particle trajectory deflection and maximum particle detection efficiency. Detection efficiencies of 100% have been measured with an experimental prototype read out by a SSPM-0606BG4MM-PCB Photonique device at accidental coincidence rates of only a few Hertz. Any change in the SiPM performance will compromise this acceptable although fragile situation.

The well-known increase in leakage current of silicon detectors after irradiation and the high electromagnetic and hadronic background that the KAOS detectors will be exposed to needs a deeper understanding of how SiPM respond to irradiation. The electron beam irradiation has shown that a large increase in dark count rate and a partial loss of gain uniformity occur at relatively low doses. Surface effects were detected by a shift in the pedestal position. Background irradiations in the experimental area under typical beam-time conditions also show similar effects. Realistic amounts of shielding have been tested and found to have only a relatively poor performance. More massive external shielding is under discussion and radiation hardness of SiPM produced by different manufactures is under study. The observed increase in dark count rate can introduce an additional complication: low light level detection does not require SiPM with large dynamic ranges. Consequently, the number of pixels in the detector matrix can be kept relatively small, resulting in an appropriate high PDE due to the large fill factor. On the other hand spontaneous pixel activation is stimulated in irradiated SiPM giving rise to a reduced effective number of active pixels due to the time needed to charge the intrinsic capacitor through the quenching resistor. As a consequence the dynamic range of irradiated SiPM is reduced which has to be taken into account when choosing the optimum number of APD for applications in high radiation environments.

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