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Slawomir Mianowski (✉ slawomir.mianowski@ncbj.gov.pl)

National Centre for Nuclear Research

Nicolas De Angelis

University of Geneva

Johannes Hulsman

University of Geneva

Merlin Kole

University of Geneva

Tomasz Kowalski

Polish Academy of Sciences

Sebastian Kusyk

Polish Academy of Sciences

Hancheng Li

University of Geneva

Zuzanna Mianowska

National Centre for Nuclear Research

Jerzy Mietelski

Polish Academy of Sciences

Agnieszka Pollo

National Centre for Nuclear Research

Dominik Rybka

National Centre for Nuclear Research

Jianchao Sun

Chinese Academy of Sciences

Jan Swakon

Polish Academy of Sciences

Damian Wróbel

Polish Academy of Sciences

Xin Wu

University of Geneva

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Proton Irradiation of SiPM arrays for POLAR-2

Slawomir Mianowski^{1*}, Nicolas De Angelis^{2*}, Johannes Hulsman^{2*}, Merlin Kole², Tomasz Kowalski³, Sebastian Kusyk³, Hancheng Li⁴, Zuzanna Mianowska¹, Jerzy Mietelski³, Agnieszka Pollo¹, Dominik Rybka¹, Jianchao Sun⁵, Jan Swakon³, Damian Wrobel³ and Xin Wu²

^{1*}National Centre for Nuclear Research, A. Soltana 7 Street, Otwock, 05-400, Poland.

^{2*}DPNC, University of Geneva, 24 Quai Ernest-Ansermet, Geneva, CH-1205, Switzerland.

³The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152 Street, Krakow, 31-342, Poland.

⁴Geneva Observatory, ISDC, University of Geneva, 16 Chemin d'Ecogia, Versoix, CH-1290, Switzerland.

⁵Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing, 100049, China.

*Corresponding author(s). E-mail(s):

slawomir.mianowski@ncbj.gov.pl; nicolas.deangelis@unige.ch;
johannes.hulsman@unige.ch;

Abstract

POLAR-2 is a space-borne polarimeter, built to investigate the polarization of Gamma-Ray Bursts and help elucidate their mechanisms. The instrument is targeted for launch in 2024 or 2025 aboard the China Space Station and is being developed by a collaboration between institutes from Switzerland, Germany, Poland and China. The instrument will orbit at an altitude of approximately 300 km with an inclination of 42° and will be subjected to background radiation from

cosmic rays and solar events. It is therefore pertinent to better understand the performance of sensitive devices under space-like conditions. In this paper we focus on the radiation damage of the silicon photomultiplier arrays S13361-6075NE-04 and S14161-6050HS-04 from Hamamatsu. The S13361 are irradiated with 58 MeV protons at several doses up to 4.96 Gy, whereas the newer series S14161 are irradiated at doses of 0.254 Gy and 2.31 Gy. Their respective performance degradation due to radiation damage are discussed. The equivalent exposure time in space for silicon photomultipliers inside POLAR-2 with a dose of 4.96 Gy is 78.1 years (or 5.04 years when disregarding the shielding from the instrument). Primary characteristics of the I-V curves are an increase in the dark current and dark counts, mostly through cross-talk events. Annealing processes at 25 °C were observed but not studied in further detail. Biasing channels while being irradiated have not resulted in any significant impact. Activation analyses showed a dominant contribution of β^+ particles around 511 keV. These resulted primarily from copper and carbon, mostly with decay times shorter than the orbital period.

Keywords: POLAR-2, SiPM, radiation, protons, cosmic rays

1 Motivation

Gamma-Ray Bursts (GRBs) are the most energetic astrophysical events in the Universe known to man, emitting energies up to 10^{53} erg. They have a short prompt emission which is followed by a longer lived afterglow with wavelengths ranging from radio waves to TeV energies. Mergers of compact binaries were long thought to generate short GRBs, which was experimentally confirmed by the joint detection of GRB170817A by LIGO, VIRGO, INTEGRAL and *Fermi*-GBM [1]. Regarding long GRBs, growing evidence indicates that they are accompanied by supernovae events [2].

The scientific benefits through polarization measurements have spawned numerous polarimetry missions [3–6], the most dedicated of which are GAP (50–300 keV) [3] and POLAR (50–500 keV) [7]. The latter of which is the predecessor to POLAR-2 [8]. Extensive polarization analyses by POLAR are discussed in their catalogue paper [9]. Despite the scientific advances in GRB polarimetry, no analysis can compensate for the need of higher precision measurements. A mission with improved instrumentation and longer lifetime, amongst which finer time and/or energy resolved polarization analyses can be carried out, will obtain larger GRB samples. POLAR-2 is dedicated to that cause, accounting for the experiences gained from its predecessor. It will be launched towards the China Space Station (CSS) in 2024 or 2025 for a mission of at least 2 years. The CSS (and hence POLAR-2) will orbit at an altitude

of 300 km at an inclination of 42° . As a result, it is exposed to radiation from cosmic rays and solar flares (more to it in section 3).

Silicon photomultipliers (SiPMs) are chosen as photodetectors for POLAR-2. They are photon counting devices wherein multiple avalanche photodiode pixels operating in Geiger mode. Generally, SiPMs provide a high gain (10^5 to 10^7) comparable with classical photomultiplier tubes, have a fast response time, are compact, require a low bias voltage (below 100 V) and are insensitive to a magnetic field. However, when exposed to radiation, they can suffer from either bulk damage (primarily due to non-ionizing energy loss - NIEL) or surface damage (primarily due to ionizing energy loss - IEL) [10], resulting in a decreased scientific performance of the instrument. These effects are minimized (yet not prevented) through shielding of the mechanical structure of the instrument. Regardless, dedicated measurements are necessary to estimate the long term performance of such components like SiPM arrays and how this affects the science case of POLAR-2. These will be discussed in this paper.

2 Instrument Design

Polarization measurements of γ -rays can be achieved through Compton scattering, whose differential cross section is described by the Klein-Nishina formula [11]. Its azimuthal scattering angle is linked to the least populated scattering angle in the distribution (referred to as the polarization angle) as the photon preferentially scatters orthogonal to the polarization vector. This phenomenon can be exploited by developing an instrument with segmented (low-Z) scintillator bars, where a γ photon scatters in the first bar and is absorbed/scattered by a second; as illustrated in Figure 1a. The relative position between these bars allows one to derive the scattering angle. Numerous photons from a GRB will lead to a scattering angle distribution, also referred to as a modulation curve, whose shape is used to determine the polarization angle, which is related to the phase of a 180° modulation, and the polarization degree which is related to the amplitude of this modulation.

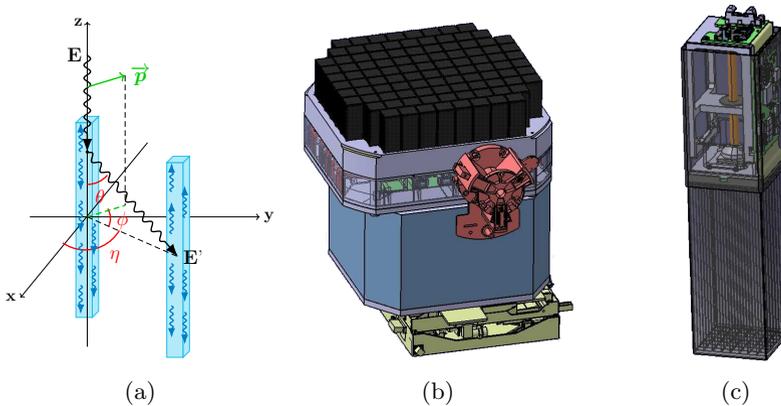


Fig. 1 a) Schematic of a photon scattering between two scintillator bars. b) A preliminary CAD model of POLAR-2 and c) the polarimeter module [8].

POLAR-2, the successor to POLAR [4], applies the aforementioned technique into its polarimetry instrument. The full instrument, as shown in Figure 1b, encompasses a total volume of about $60\text{ cm} \times 60\text{ cm} \times 70\text{ cm}$. The polarimeter consists of 100 modules facing deep space with a half-sky field of view. Each detector module, seen in Figure 1c, consists of a target of 64 plastic scintillators with dimensions $5.9\text{ mm} \times 5.9\text{ mm} \times 125\text{ mm}$. Each scintillator is read out on the bottom side by its own SiPM channel. The 64 SiPMs in turn are readout using the module front-end electronics which handles the trigger logic and communication of the detector module with the back-end electronics. The top of the scintillators is covered by a sorbothane damper system and the full module is covered in a carbon fibre socket. Additionally, all modules

together are covered by one large carbon fibre shield as shown in Figure 2¹. Below the detector modules POLAR-2 consists of a large aluminium structure which houses the back-end and power supplies as well as the communication system with the CSS.

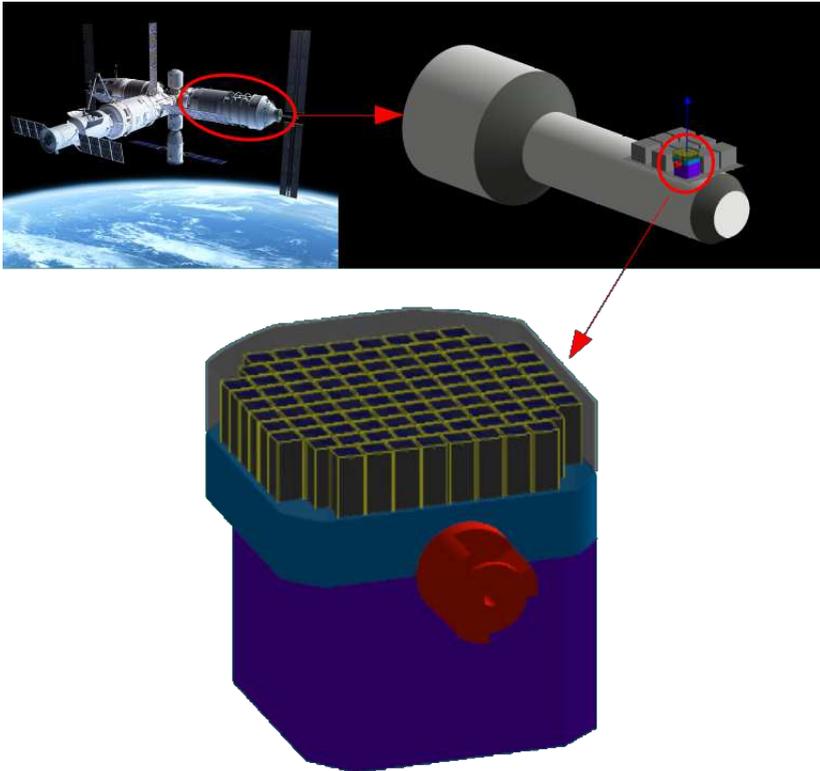


Fig. 2 **Top left** shows a 3D rendering of the CSS. **Top right** provides a simplified version of the experimental module, whereas in the **bottom** you can see the full POLAR-2 instrument in GEANT4 [12].

Contrary to its predecessor POLAR, where the scintillators were read-out using a multi-anode Photomultiplier Tubes (MAPMT), the 6400 plastic scintillators are read out by 400 16-channel SiPM arrays, also called Multi-Pixel Photon Counter (MPPC), from Hamamatsu Photonics (S13361-6075NE-04, referred to as S13361 in this paper). This change serves three main purposes. First, it allows for a more robust mechanical design, as unlike PMTs, SiPMs do not have a glass window. Second, using SiPMs (instead of PMTs) removes the need for a high voltage power supply which is complex to design and operate in space. Finally, the SiPM readout increases the sensitivity. By

¹The amount of shielding in the zenith direction is therefore 125 mm of plastic scintillator, 1 mm of sorbothane dampers, and 4 mm of carbon fiber housing

using SiPMs the number of photo-electrons (p.e.) per deposited keV in the scintillators can be increased from 0.3 p.e./keV (in the case of POLAR) to 1.6 p.e./keV. As a result, we achieve a lower energy detection threshold.

The typical downside of SiPM use over standard PMTs is the dark noise, which increases significantly for high radiation dose. This effect must be studied carefully for better low threshold energy determination. Additionally, the main challenge in polarization measurements is to achieve a high level of detection uniformity, including SiPM single channel and scintillator response. For POLAR-2 this implies a uniform response over the 6400 detector channels in order to allow to distinguish between the non-uniformity induced by a potential polarization signal and that induced by a non-uniform detector response. The scheme of the proposed polarimeter shows that one would expect the outside of the instrument to suffer more from cosmic radiation than the centre, the induced damage will therefore not be uniform, resulting potentially in a higher noise level for channels on the outside of the instrument compared to those in the centre. It is therefore important to understand in detail the deterioration of SiPMs performance in order to allow to mitigate when possible or model noise effect in detector simulations.

A dedicated POLAR-2 Monte Carlo simulation framework was developed for detector science analyses. Here, the GEANT4 framework [12], v4.10.07.p02, is used to characterize the instrument as well as its response². The following physics lists have been used for subsequent background radiation simulations: *G4EmLivermorePolarizedPhysics*, *G4EmExtraPhysics*, *G4DecayPhysics*, *G4RadioactiveDecayPhysics*, *G4HadronElasticPhysicsHP*, *G4StoppingPhysics*, *G4IonQMDPhysics*, *G4IonElasticPhysics*, *G4HadronPhysicsQGSP_BERT_HP*, *GammaNuclearPhysics* and *G4EmStandardPhysics*.

The design illustrated in Figure 2 reflects the most up-to-date design at the time of this writing. A 3D rendering of the CSS can also be seen there. As encircled, POLAR-2 is situated on one of the experimental modules of the space station (on the *Wentian* module). A simplified version of the experimental module was characterized in GEANT4 to account for the shadow cast by it³. Its wall thickness is 10 mm and is composed of aluminium (alloy 2219). 8 neighbouring instrument are also included. Their design is unknown and are therefore represented by $600 \times 600 \times 500$ mm³ solid aluminium (same alloy as the space station) boxes. At the bottom of the figure the implementation of the POLAR-2 instrument in Geant4 can be recognized. It is nearly identical to that in Figure 1b (with the exception of the missing carbon fiber shielding). For clarity, each single SiPM channel is modelled by a 100 μ m epoxy resin and 450 μ m of silicon⁴.

²This will be outlined in more details in a future publication.

³A more detailed version will be presented in the future when the CSS' design is completed

⁴Exact specification was not delivered by Hamamatsu.

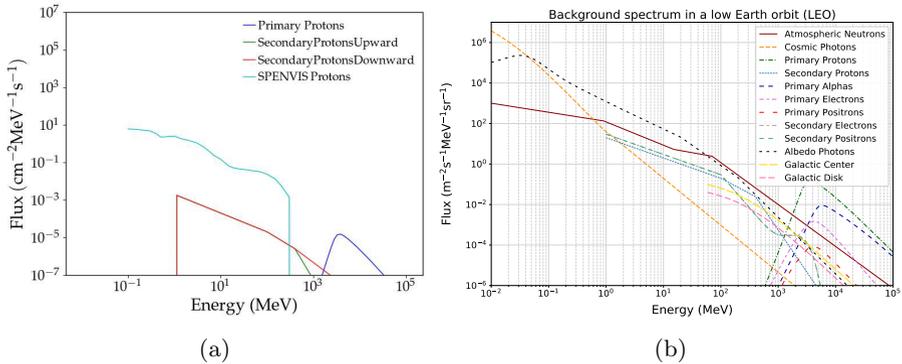


Fig. 3 **a)** Comparison between the proton energy spectrum from LEOBackground [13] and SPENVIS [14]. **b)** The spectrum of various background particles [13] expected to be seen at an altitude of 300 km and an inclination of 42° (POLAR-2 orbit).

3 LEO Background & Anticipated Radiation Doses

As mentioned in the motivation part, it is pertinent to obtain a good estimate on radiation damage from background radiation. Therefore, the POLAR-2 simulation framework was enhanced to allow for background information to be taken from LEOBackground [13] or SPENVIS [14]. The former is a summary of collected data and analyses performed by various experiments; such as *Fermi*-LAT [15], AMS-02 [16], etc. It provides information on neutrons, photons, protons and electrons. Figure 3b shows the expected flux for these particles. It is generated by setting the orbital altitude and inclination to 300 km and 42° respectively. The solar modulation potential is set to 650 MV. SPENVIS only provides information on proton and electron fluxes. However, it is more comprehensive when accounting for solar activity, natural radiation belts, plasmas and gases. Protons are among the most penetrating particles (with neutrons and gammas), whereas electrons are significantly more abundant but easily stopped by the carbon fiber shielding before reaching sensitive components. Considering penetration depth, energy spectrum and deposition it is expected for protons to be the most contributing factor to deposit energy in the SiPM array and other electronics. Accounting for the South Atlantic Anomaly (SAA), their flux is at least two orders of magnitudes higher than that of neutrons (see Figure 3b, where the proton spectrum is that from [17] (used by SPENVIS) and [16] (used by LEOBackground)). We therefore decide to use SPENVIS data to simulate the expected radiation *dose*⁵.

Figure 4 shows, the dose (normalized with respect to the dose in the less exposed detector module) in each module. As anticipated, the dose is highest

⁵energy deposit per mass of sensitive volume

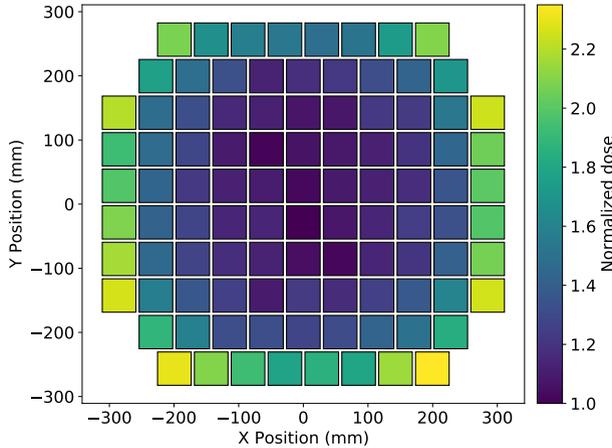


Fig. 4 Normalized dose distribution per detector module in the POLAR-2 instrument (seen from the top) due to background radiation. The asymmetry is due to shielding from neighbor instruments on the payload platform and from the robotic arm adapter piece. The bottom right corner is not facing any neighbor payload, and the adapter is installed on the bottom side.

for modules closest to the edge of the instrument. For simplicity, in this paper, the 'dose' refers to the average dose expected for all POLAR-2 modules⁶. In other words, the dose is defined as

$$dose_{\text{SiPM}}^{\text{POLAR-2}} = \frac{\sum_i E_i^{\text{SiPM-channel}}}{N_{\text{mod}} \cdot N_{\text{ch}} \cdot m_{\text{ch}}}, \quad (1)$$

where N_{mod} , N_{ch} and m_{ch} refer to the number of modules (100), number of SiPM channels (64) and silicon mass of each SiPM channel.

We use the AP-8 proton model [17] during a solar maximum for protons with energies ranging from 100 keV to 400 MeV. Other particles (such as electrons) are excluded as they are primarily blocked by the carbon fiber shielding. The proton flux is then used to set the primary proton energy (interpreting it as an 'energy distribution'). These primaries are then randomly placed on a sphere with an isotropic distribution. Their angular distribution follows Lambert's cosine-law. To obtain the doses, 35×10^6 particles were injected. Their anticipated doses are listed in the Table 1 below for 4 different scenarios. The *bare SiPM* reflects the scenario where the component is not shielded by neighbouring detector components and serves as the 'worst case' scenario, which is considered by us in this paper. The *full instrument* reflects the full POLAR-2 instrument as shown in Figure 2. The addition of *CSS* implies that the simplified description of the China Space Station is included (top right in Figure 2). This allows us to understand how much the shadow of the space station affects the anticipated radiation dose.

⁶Note that there are 100 modules, each with a 64 channel SiPM.

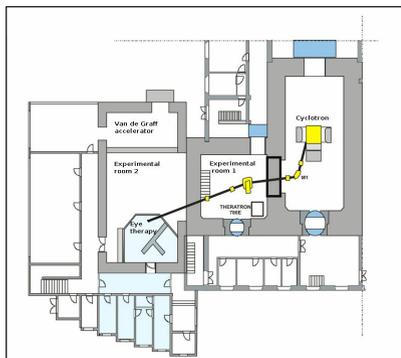
Simulation Setup	SiPM dose per year (Gy/yr)
Bare SiPM	9.84×10^{-1}
Bare SiPM + CSS	6.27×10^{-1}
Full instrument	7.65×10^{-2}
Full instrument + CSS	6.38×10^{-2}

Table 1 Radiation doses of a SiPM for four different scenarios. The most pessimistic scenario is the 'Bare SiPM', whereas the most realistic one is the 'Full Instrument + CSS'.

4 Experimental setup

All planned irradiation sessions were performed at the proton radiotherapy facility at Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Krakow. The radiation campaign was supposed to reproduce the integrated dose the POLAR-2 instrument faces during its lifetime in orbit (which includes cosmic radiation when it passes through the SAA or if there are any solar events). The total dose, activation and performance of the SiPM array is of interest. For comparison, the newer series S14161-6050HS-04 (from here on referred to as S14161) from Hamamatsu was also irradiated with doses later listed in Table 2.

To generate the proton beam, the particles were accelerated by the AIC-144 isochronous cyclotron facility at an energy of 58 MeV. They were then transported from the facility to the sample by a system consisting of bending and correction magnets, measuring boxes and quadrupole doublets. It then passes through a tantalum-aluminum collimator where it scatters on a $25 \mu\text{m}$ tantalum proton scattering foil [18]. A schematic of this facility and a photo of the exit of the beam line and setup for the samples are respectively shown in figures 5a and 5b.



(a)



(b)

Fig. 5 a) A schematic of the proton radiation therapy facility at IFJ. b) A photo of the exit of proton beam line.

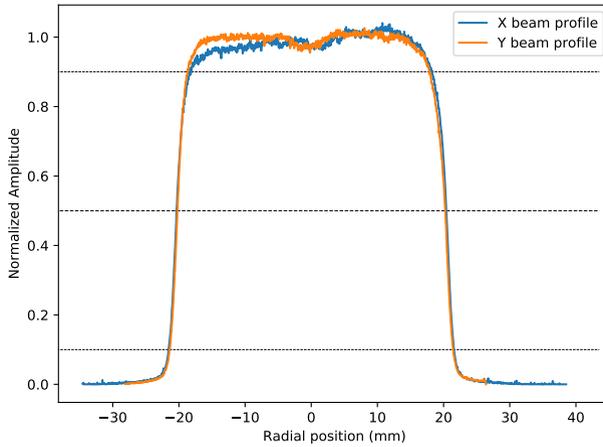


Fig. 6 Scaled beam profile (to its average) of 58 MeV protons along the x-axis and y-axis.

In Figure 6 we show the beam profile of the 58 MeV protons exiting the collimator (i.e. the profile which would arrive to the sample). It can be seen that the beam profile is mostly stable within the 5% level, consistent with recent work with the facility [18]. Depending on the sample, a 10 mm thick donut-shaped brass disk is placed to exclude neighbouring components from being irradiated. To simulate the expected dose from the aforementioned beam specification, we inject 1×10^6 protons perpendicular to the SiPM, as modelled in the POLAR-2 simulation framework, surface (pointing first into the resin). This yields the average dose per proton, later combined with the proton fluence to obtain the total irradiated dose. A simple cross-sectional schematic is shown in Figure 7. The simulations are also performed with GEANT4.

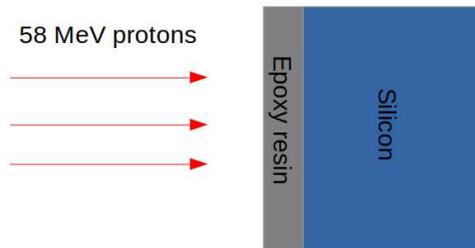


Fig. 7 The model of SiPM single channel used for different dose calculations. The first layer corresponds to $100 \mu\text{m}$ of epoxy resin, the second layer to $450 \mu\text{m}$ of silicon.

A single SiPM array was divided into two sections, noted by 'A' and 'B' as shown in Figure 8, to irradiate them with different fluences. Each section consists of a subarray of 2×4 channels, corresponding to half of the SiPM array. The arrays are mounted on a PCB, allowing us to bias and read the output signals from a chosen single channel or whole subarray. For arrays S13361-1, S13361-2 and S14161-1, during each subarray irradiation, the second half was shielded by a 7 mm thick lead cover, fully stopping the incoming protons. The whole S14161-2 array was irradiated with the same dose, while section 'A' was biased by 1 V of overvoltage⁷. Table 2 lists how the samples are irradiated, their proton fluences, calculated doses and space equivalent exposure time for a 'Full Instrument + CSS' and 'Bare SiPM' scenarios. The dose in the SiPM is computed the same way as shown in Equation 1 (where $N_{modules} = 1$).

MPPC Type	Fluence ($\frac{protons}{cm^2}$)	Total Dose (Gy)	NIEL Dose (mGy)	Equivalent Years in Space for POLAR-2 'Full Instr. + CSS'	'Bare SiPM'
S13361-1 sec. A	2.00×10^8	0.267	0.174	4.19	0.271
S13361-1 sec. B	6.10×10^8	0.815	0.532	12.8	0.828
S13361-2 sec. A	1.64×10^9	2.19	1.43	34.4	2.23
S13361-2 sec. B	3.73×10^9	4.96	3.24	78.1	5.04
S14161-1 sec. A	1.90×10^8	0.254	0.166	3.98	0.258
S14161-1 sec. B	1.73×10^9	2.31	1.51	36.2	2.35
S14161-2 sec. A and B	1.73×10^9	2.31	1.51	36.2	2.35

Table 2 An overview of SiPM elements irradiated, their corresponding dose and equivalent time in space for a 'Full Instrument + CSS' and 'Bare SiPM' scenarios (as described in section 3).

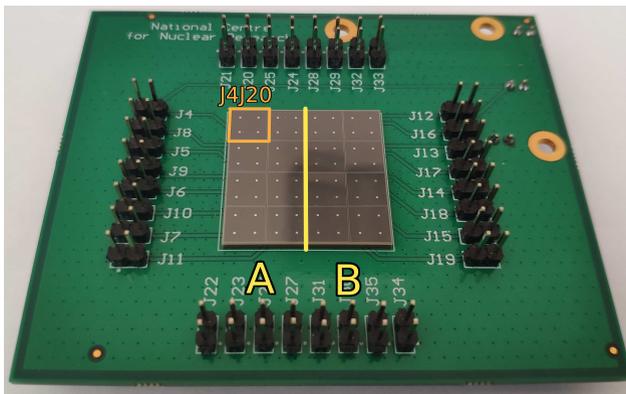


Fig. 8 The Hamamatsu MPPC S13361-6075NE-04 array mounted on PCB plate. Yellow line divide the array to two sections 'A' and 'B'. Single channel J4J20 is also marked with orange line.

⁷The excess bias voltage over the breakdown voltage, V_{bd} , is called overvoltage (V_{ov})

5 Experimental results

In order to fully characterise the behavior of SiPMs to radiation damage, the current-voltage characteristics and dark count spectra have been analysed before and after its exposure to the proton beam. Their activation products have also been studied to understand any long-term effects.

5.1 Current-voltage characteristics

All current-voltage (I-V) characteristics were measured before and after each successive irradiation session using the Keysight 2900B Source Measurement Unit. The voltage scale was chosen over the range of 40-60 V for the S13361 series and 30-50 V for the S14161 series in order to cover a wide range of V_{ov} . The current readout was limited to 100 μ A before irradiation and increased to 200 μ A for cases after irradiation. Based on the Keysight 2900B specification and chosen current range the current resolution was limited to about 60 nA.

I-V curve measurements were taken 2 h, 26 h, 8 days and 2 months after irradiation to study potential annealing effects. The only exception to this is, SiPM S13361-2, where I-V characteristics were not measured 2 h after irradiation. It was first taken to a HPGe detector to measure its activation (see later section 5.3). The former two I-V curves were taken at the IFJ experimental hall where the room temperature is (27 ± 0.8) . After completion of the radiation campaign, the SiPMs were placed inside a climate chamber where the temperature is set to 25 °C. The 2 °C temperature difference corresponds to a bias voltage (or overvoltage). The breakdown voltage describes the minimum bias voltage required (in reverse direction) which leads to self-sustaining avalanche multiplication. In other words, it is the minimum bias for which the pulses stay visible at the SiPM output. change of about 0.1 V for the S13361 series and 0.07 V for the S14461 series (based on Hamamatsu specification: 50 $\frac{mV}{C}$ and 33 $\frac{mV}{C}$ respectively). Our studies show, that the standard deviation of V_{bd} between different channels for a single array is in the range of 0.12 V. As the change in bias voltage is within 1σ , we conclude that the temperature difference is small enough for a direct comparison of the I-V characteristics.

Figure 9 shows the obtained I-V characteristics for the S13361 SiPM series for different doses and time before and after irradiation. The I-V characteristics for the S14161 MPPC series are presented in Figure 10. It is evident, when exposed to the same dose, that the current rate increase is higher for S14161 than for the S13361 series. This already implies that the S13361 type is more beneficial for POLAR-2 purposes. For both SiPM types we also observed self-annealing processes, manifesting itself through a decreasing current with respect to time after its irradiation. Further details on the annealing process of SiPM arrays will be discussed in another paper.

To discern contributions of the bias voltage on the radiation damage (through a change in the I-V characteristics or dark count rates), the S14161-2 array was irradiated with a single dose of 2.31 Gy, where only subarray 'A' was biased with an overvoltage of 1 V (while subarray 'B' remained unbiased). Figure 11 presents the obtained I-Vs for different times after irradiation. The inset in Figure 11a also shows the breakdown voltage region in logarithmic scale. Taking into account differences between the breakdown voltages for single channels, we did not observe any significant bias-dependent features. Furthermore, applying a bias voltage did not affect the self-annealing process at room temperature.

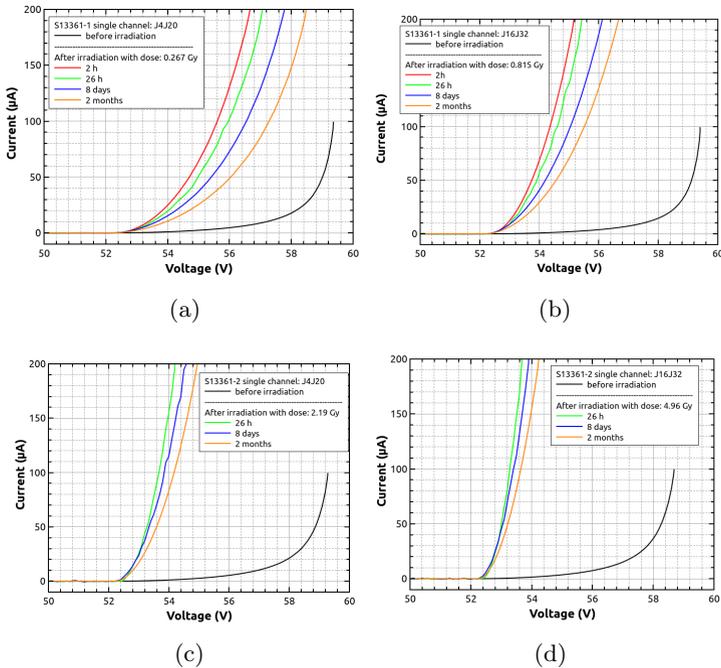


Fig. 9 Current-voltage S13361 single channel characteristics before and after its irradiation for a dose of **a)** 0.267 Gy, **b)** 0.815 Gy, **c)** 2.19 Gy and **d)** 4.96 Gy.

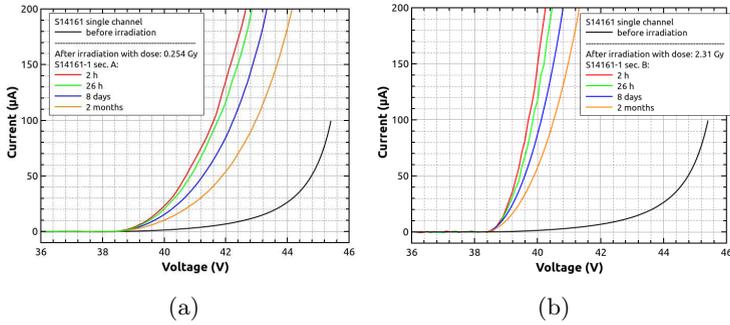


Fig. 10 Current-voltage MPPC S14161 single channel characteristics before and after its irradiation for a dose of **a)** 0.254 Gy and **b)** 2.31 Gy.

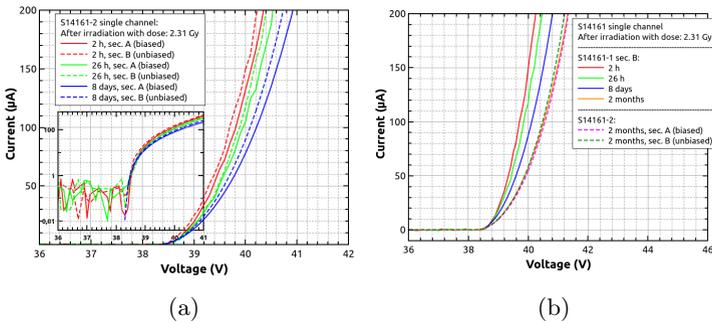


Fig. 11 Current-voltage single channel characteristics for biased (channel: J4J20) and unbiased (channel: J16J32) S14161 subarray irradiated with dose 2.31 Gy for different times after irradiation. The inset in figure **a)** shows the breakdown voltage region in y-log scale. Figure **b)** compares also two S14161 arrays (two single channels unbiased, one biased) two months after irradiation.

5.2 Dark Counts analysis

Changes in the I-V characteristics registered after proton irradiation are also reflected in the number of dark counts (DC) and the spectral shape of the output signal. To determine these parameters we adopted a method based on raw pulses analysis, originally presented by [19] and later applied by [20]. The chosen procedure eliminates the problem of high dead time for analogue and even digital data acquisition systems (like digitizers), where a few million pulses per second are expected. In our case, the direct signal from a single SiPM channel was additionally amplified by a transimpedance amplifier and then sent to a digital oscilloscope of type Keysight DSOS104-A (which has a sampling rate of 1 GSamples/s and a bandwidth of 500 MHz), where 10 ms waveforms with many single raw pulses were saved on a hard drive. In

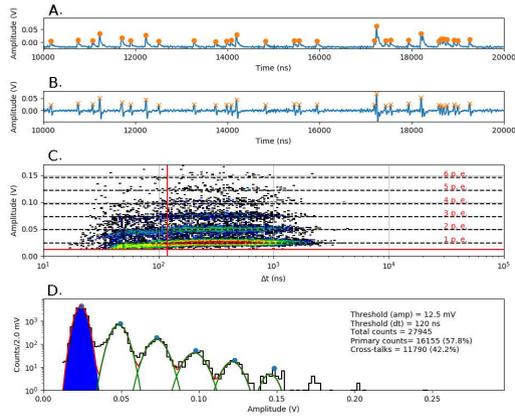
this case, each waveform was triggered based on a 0.5 p.e. threshold. Five waveforms were saved for each overvoltage and temperature, giving us an estimation of statistical uncertainties for a chosen 10 ms period time.

For the clarity, we listed below the main steps made during the off-line analysis:

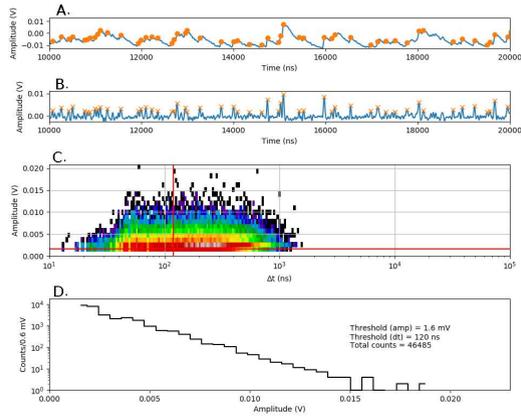
- The Savitzky-Golay filter was applied twice to each registered waveform. This filter allows to extract p.e. peaks in a DC spectrum for lower temperature ranges. Its implementation has proven to be especially useful for the S14161, which is characterized by a smaller amplitude of 1 p.e. and a longer tail;
- A copy of 10 ms waveform was created, delayed and subtracted from the original one;
- The peaks above certain thresholds (12.5 mV for S13361, 1.6 mV for S14161) were taken into account;
- The amplitude of each peak and the time difference between two consecutive pulses were determined.

The python tool *find_peak* from the *scipy 1.3.3-3* library [21] was used for the last two items. The advantage of this procedure is its speed and pile-up sensitivity, which can be controlled by *find_peak* input parameters.

An example of the aforementioned analysis steps for a non-irradiated S13361 single channel is presented in Figure 12a. Measurements were performed at 25 °C at a voltage of 55.5 V ($V_{ov}=3.5$ V). The first two upper plots show a fraction of the 10 ms waveform with many p.e. peaks and the result of the delayed waveform subtraction. Orange dots and crosses show identified peaks. The pile-up cases are also visible. The third subplot (scatter plot) presents the multiplicity of amplitudes in the unit of volts (or number of p.e.) on the y-axis and the time difference between two subsequent events on the x-axis. Finally, the bottom subplot shows the resulting DC spectrum when the amplitude and time thresholds have been applied. The structure of p.e. peaks is clearly visible in this case. A fitted multi-Gaussian function is also shown (red line), where the parametrisation was chosen to keep constant distance (gain) between the ' n 'th and ' $n-1$ 'th peak. Based on the discussion presented in [19], only the cases from the first p.e. peak (blue area) are classified as a primary counts. Similar data for the S14161 are presented in Figure 12b. Contrary to S13361, the p.e. peaks are not visible in the DC spectrum at 25 °C.



(a)



(b)

Fig. 12 An example of a single channel waveform analysis of a) S13361 b) S14161, measured at temperature 25 °C before proton irradiation. A - a part of 10 ms waveform, B - transformed waveform with peak identification, C - 3D distribution of dark pulse amplitudes as a function of time difference between two subsequent events. D - projection of the dark counts with amplitude and time cut conditions. Blue color describes 1 p.e. position and primary counts (not visible in the S14161 case).

5.2.1 Dark Counts before irradiation

Data taken before SiPM irradiation for both series are presented below. All 10 ms waveforms were collected in controlled temperature conditions inside a

climate chamber at temperatures: 25 °C, 10 °C, −5 °C and −20 °C. Figure 13 shows the typical DC spectra collected for S13361 with $V_{ov}=3.5$ V. For comparison, Figure 14 shows the case of S14161 with the same overvoltage and temperature range. The number of total counts, primary counts and cross-talks per 10 ms interval are also presented. As was mentioned before, the primary counts (blue area) were filtered using the same amplitude and time thresholds (about 0.5 p.e and 120 ns respectively). For the cross-talk it was assumed that they correspond to the total number of counts minus primary counts. No after-pulses could be distinguished, suggesting that its contributions is negligible from a statistical point of view (in this work).

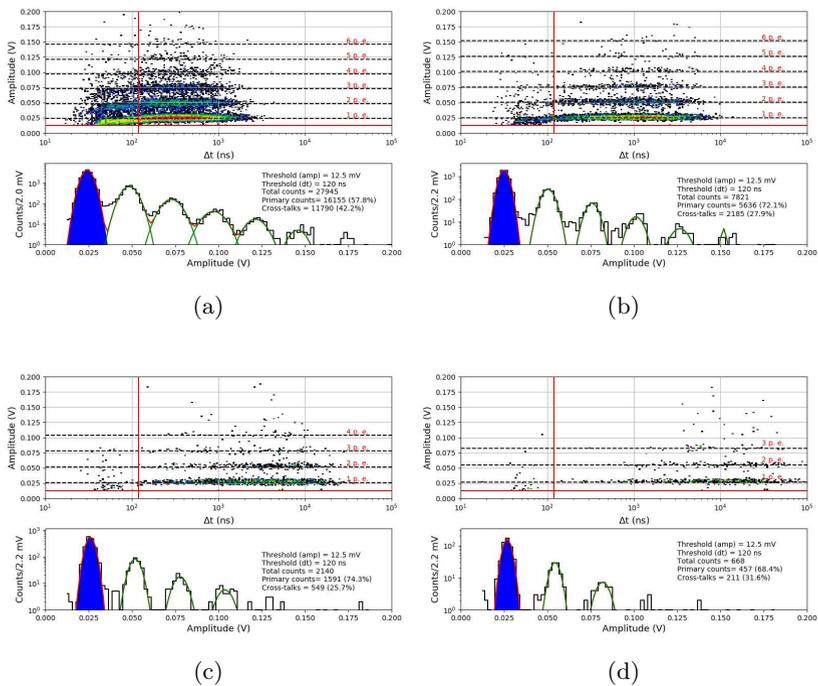


Fig. 13 S13361 single channel DC spectra measured before proton irradiation for various temperatures and the same $V_{ov}=3.5$ V: a) 25 °C, b) 10 °C, c) -5 °C, d) -20 °C.

Summarized data for both series and chosen overvoltage ranges before proton irradiation are presented in Figure 15. To stress the differences between these series, the same y-axis scale was kept. The figure shows that the DC rate is about 60% higher at 25 °C for S14161. This difference increases by a factor of 4.9 for −20 °C. The separation between p.e. peaks is also better for the S13361 for all temperature ranges. The extraction of single p.e. peak for

S14161 at 25 °C is practically impossible.

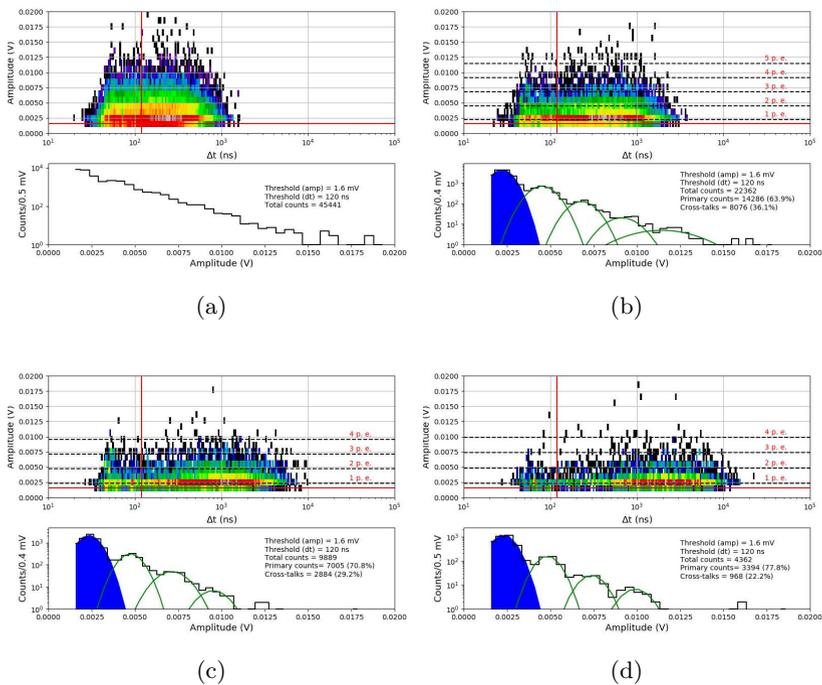


Fig. 14 S14161 single channel DC spectra measured before proton irradiation for various temperatures and the same $V_{ov}=3.5$ V: a) 25 °C, b) 10 °C, c) -5 °C, d) -20 °C.

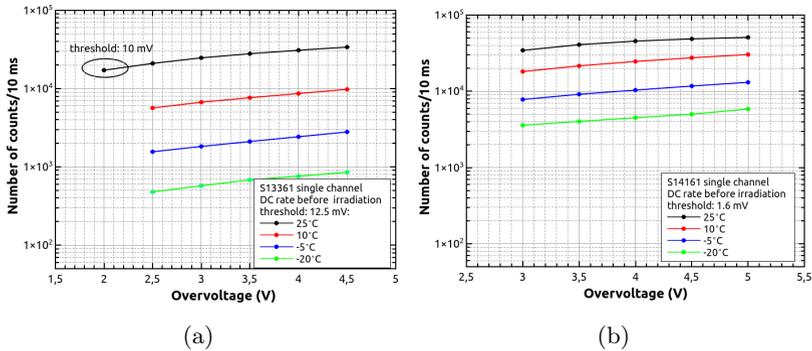


Fig. 15 The number of dark counts measured for a single channel of a) S13361 and b) S14161 array for chosen overvoltage ranges at different temperatures.

5.2.2 Dark Counts after irradiation

After the proton irradiation, as in section 5.2.1, the 10 ms waveforms were also collected at temperatures between 25 °C and –20 °C. Figure 16 shows the 3D plots and their projections to the y-axis (with the same cuts as before) of a S13361 single channel irradiated for different doses and measured at 27 °C. Due to the significantly higher number of counts the lower overvoltage region was explored. V_{ov} was set to 2.8 V in this particular case. As can be seen, it is impossible to extract any single p.e. structure in the DC spectrum. DC rate also increases.

The same studies were repeated two months after the proton irradiation (at the same temperatures). For compactness, we only present the data for near opposite temperatures (–20 °C vs. 25 °C) at a dose of 0.267 Gy (Figure 17) and 0.815 Gy (Figure 18). For higher doses of 2.19 Gy and 4.96 Gy we only present the DC spectra at –20 °C (Figure 19). It should be noted that when irradiated with a dose of 4.96 Gy, contrary to 25 °C, the p.e. peaks are still visible at –20 °C.

Figure 20a summarizes the DC rate measured 26 h and two months after the proton irradiation for different doses for S13361 at room temperature. The uniformity of two different channels (e.g. J4J20 and J9J25 here) of the S13361 is also studied and shown in Figure 20b. These channels have been exposed to a dose of 0.267 Gy at 27 °C. The number of counts between channel are consistent within a few percent.

Finally, Figure 21 shows the number of dark counts measured for different doses at different temperatures. In each case the decreasing number of counts with respect to temperature decrease is clearly visible. The direct correlation

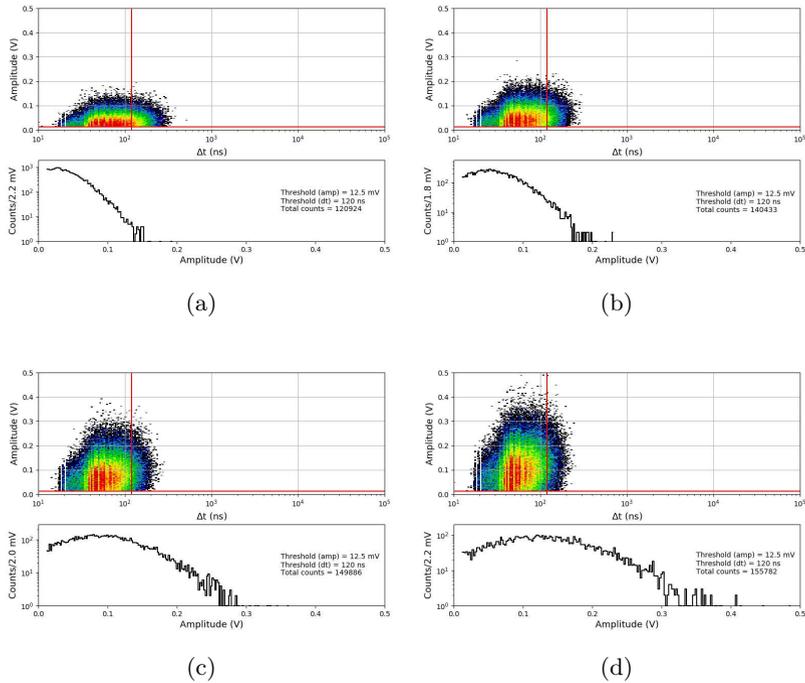


Fig. 16 An example of waveform analysis for data taken for S13361 single channel measured at 27°C for doses: a) 0.267 Gy, b) 0.815 Gy, c) 2.19 Gy and d) 4.96 Gy. The overvoltage was set to 2.8 V in each case.

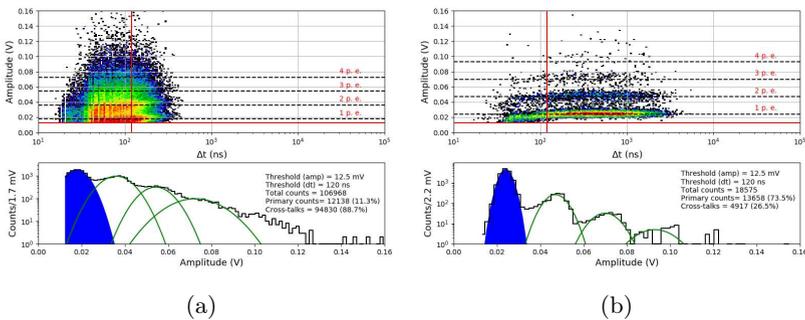


Fig. 17 An example of waveform analysis for data taken two months after irradiation with dose 0.267 Gy for S13361 single channel at a) 25°C and b) -20°C. The overvoltage was set to 2.8 V.

between DC and temperature is expected and stresses the importance of temperature control of SiPMs for POLAR-2, thus (also) minimizing the impact

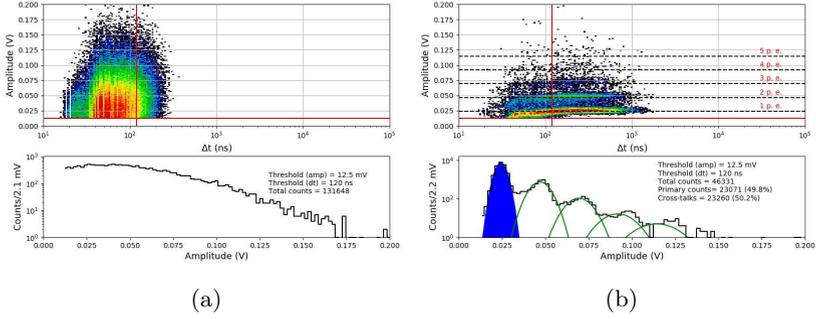


Fig. 18 An example of waveform analysis for data taken two months after irradiation with dose 0.815 Gy for S13361 single channel at a) 25 °C and b) -20 °C. The overvoltage was set to 2.8 V.

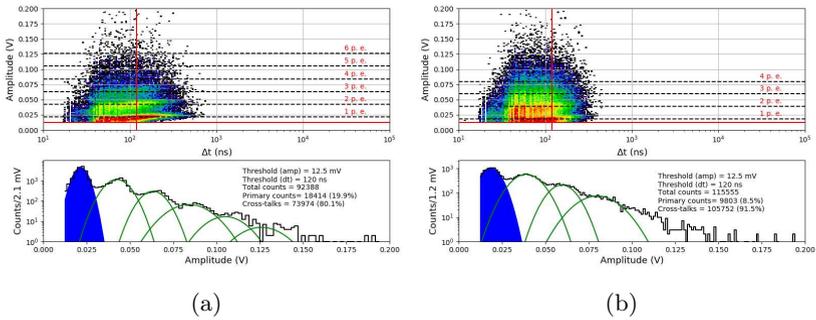


Fig. 19 An example of waveform analysis for data taken two months after S13361 irradiation with doses a) 2.19 Gy and b) 4.96 Gy at temperature -20 °C. The overvoltage was set to 2.8 V.

of radiation damage.

Similarly to Figure 21, Figure 22 summarizes the obtained data for the S14161 array. The selected irradiation scenarios are those with dose of 0.254 and 2.31 Gy. Again, the figure shows the number of counts determined for a 10 ms interval time. In general, the data signifies a good SiPM single channel uniformity. Also, considering the I-V characteristics, no bias-dependent effect during proton irradiation was observed. Finally, the number of counts is also self-consistent between different single channels (exposed to the same dose).

Figure 23 shows our estimation of DC rates (based on a simple interpolation) for 1 and 2 years in space, assuming the 'Full Instrument + CSS'

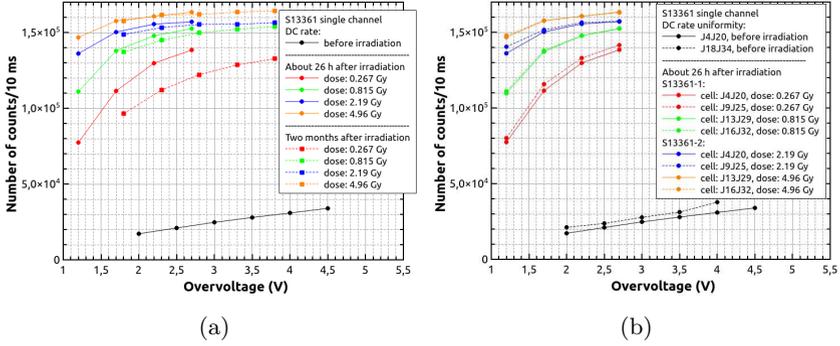


Fig. 20 The number of dark counts per 10 ms interval time measured at room temperature for S13361 a) before irradiation, 26 h and two months after b) for two different channels before and 26 h after irradiated. Different doses are presented.

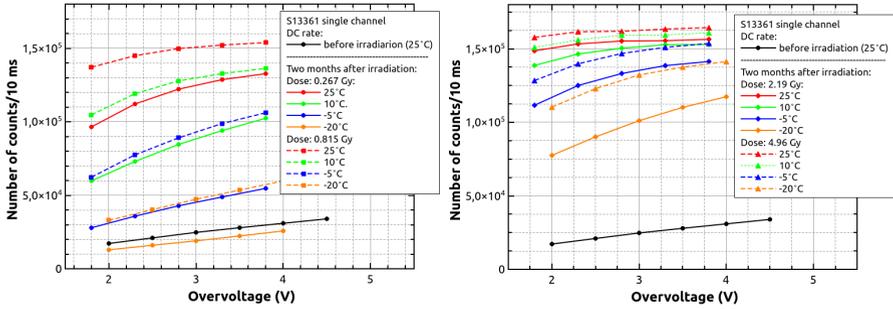


Fig. 21 The number of dark counts per 10 ms interval time measured before irradiation and two months after for S13361 for different doses and temperatures.

scenario at room temperature ($V_{ov}=2.8\text{ V}$). The presented numbers correspond to 26 h after proton irradiation. At the stage, the annealing effect and consequently the DC decreasing are negligible. We therefore conclude, that numbers of about 5.0×10^6 counts/second (cps) and 7.2×10^6 cps (one and two years equivalent, respectively) should not influence the SiPM single channel operation. Nevertheless, at the same conditions, the maximum dark pulse amplitudes increased from about 110 mV for the cases before irradiation, to about 150 mV when irradiated with a dose of 0.267 Gy. This implies that, for POLAR-2, the threshold must be carefully selected.

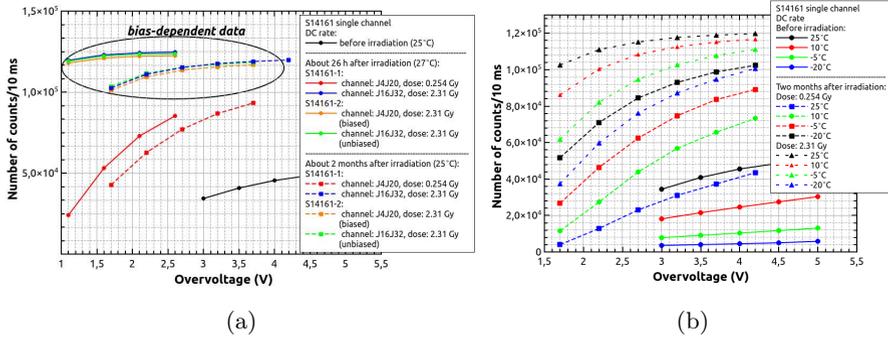


Fig. 22 The number of dark counts per 10 ms interval time measured for S14161 a) before irradiation, 26 h and 2 months after at room temperature b) for two different channels irradiated with the same dose 26 h after proton irradiation. As it is shown in a) the bias-dependent effect is not visible.

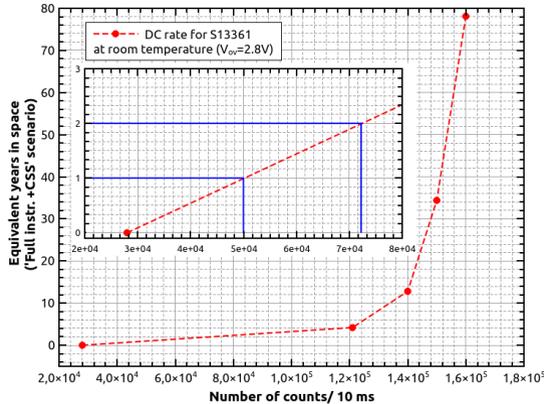


Fig. 23 The number of DC measured at room temperature and $V_{ov}=2.8V$, when 'Full Instrument + CSS' scenario is assumed (more details in the text). The inset shows expected DC rate after one and two years equivalent in cosmic space.

5.3 Activation analysis

The high energy resolution of High Purity Germanium detectors (HPGe) provide a way to identify characteristic gamma rays from proton activation products within the SiPM(+PCB) array. In the case of S13361, immediately after it was irradiated with a dose of 4.96 Gy, the SiPM array was moved to the HPGe detector to measure the most prominent gamma lines. The HPGe was placed inside a low-background lead protected chamber to decrease background radiation.

The signal readout from the HPGe detector was based on analogue NIM electronics, where the signal from the HPGe preamplifier was shaped and

amplified by an ORTEC spectroscopy amplifier. Finally, the signal was registered by a multichannel analyzer which writes the energy spectrum to file in 100 s intervals.

10 min was required to move the irradiated sample from the experimental hall and position it into the HPGe setup, introducing a non-negligible time delay between the irradiation process and the start of data acquisition. This limits our detection ability of decay products with decay times shorter than 2-3 minutes.

Many of the radioisotopes in reaction with 58 MeV protons have multiple modes of decay, where daughter nuclei mostly decay into β^+ . This explains the strong population of counts at the 511 keV line. To limit the number of decay modes, the isotopes are identified through a full-energy peak fitting of the measured HPGe spectrum. This facilitated the determination of the centroid/energy of the gamma transition inside the isotope.

The TALYS [22] software was used to simulate the nuclear reactions from 58 MeV protons. By knowing the energy of incoming protons and the main components of the SiPM array and PCB plate, such as: carbon, silicon, oxygen, potassium, etc., the tables of possible decay channels with total cross-sections were generated. Based on the highest cross-section criterion, we listed in Table 3 the most prominent decay modes and corresponding decay times [23]. The absence of silicon and oxygen in the Table 3 may be surprising. However, for silicon, the decay time is in the range of a few seconds. For oxygen, the most prominent decay channel has a decay time of 122 s. Its gamma-ray contribution is only to the 511 keV peak. As a result, to a first order, these components are neglected.

Mother nuclei	Abundance (%)	Daughter nuclei	Reaction type	Total cross section (mb)	T _{1/2} (s)	Dominant energies (keV)
Sn-120	32.6	Sb-115	(p,6n)	223.6	1926	511
Cu-63	69.0	Cu-60	(p,p3n)	27.8	1422	511, 826, 1333, 1792
Cu-63	69.0	Cu-61	(p,p2n)	92.8	12010	511
Cu-63	69.0	Cu-62	(p,pn)	167	580	511
Cu-65	31.0	Cu-64	(p,pn)	167	45724	511
Cu-65	31.0	Cu-62	(p,p3n)	117	580	511
C-12	99.0	C-11	(p,pn)	167	1222	511
K-39	93.0	K-38	(p,pn)	67.3	459	511, 2168

Table 3 Dominant reactions of 58 MeV protons on SiPM(+PCB) based elements calculated using TALYS.

Figure 24 shows a typical gamma-ray energy spectrum from the HPGe detector. The spectrum shown in Figure 24a accounts for the full energy range, whereas Figure 24b highlights the spectral structure near 511 keV. We

observe five strong gamma lines, corresponding primarily to copper and potassium activation products. It can be also seen that to the left of the 511 keV line, some additional small contributions are present. The TALYS calculations show that the sources of these lines are copper and zinc but emitted with much lower intensities. We would like to note that background contribution is negligible in the presented spectrum. Our long-time background measurement showed, that the highest contribution in energy spectrum for energies starting from 400 keV, was below 0.2 counts per 100 s.

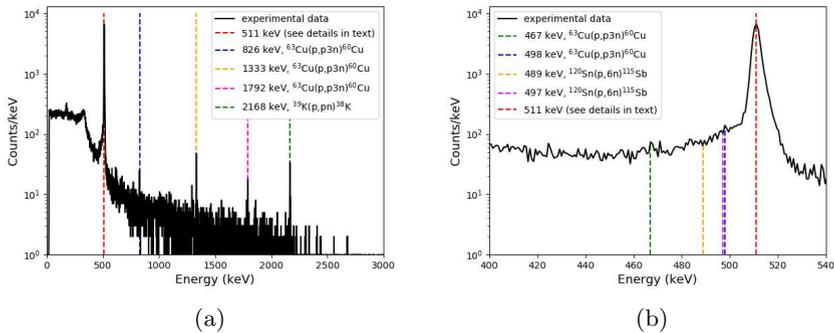


Fig. 24 The example of gamma-ray energy spectrum measured with HPGe detector after SiPM proton irradiation. Black line shows experimental data. Dashed colour lines show identified peaks.

To confirm our peak's identification the decay times for certain energies were determined experimentally. Figure 25 shows the obtained results. Due to limited count statistics, the obtained uncertainties are relatively high; over 50% in some cases. For this reason we decided to focus on two scenarios. In the first one, the decay time and amplitude were free fitting parameters (red dashed line). In the second scenario, a certain fixed decay time was taken from the Table 3 (blue dashed line) and only the amplitude was fitted. Generally, fitted curves in the second scenario are in good agreement with the experimental data. The obtained decay times are also in good agreement (within 3σ) for the lines produced by Sn-120, CU-63, Cu-65, C-12 and K-39, confirming our identification.

As is shown in Table 3, there are many potential sources for the 511 keV line. This is reflected in the shape of the decay time distribution in Figure 26 (black points), where at least two (fast and long tail) components are clearly visible. To describe the experimental data the sum of N exponential components were tested:

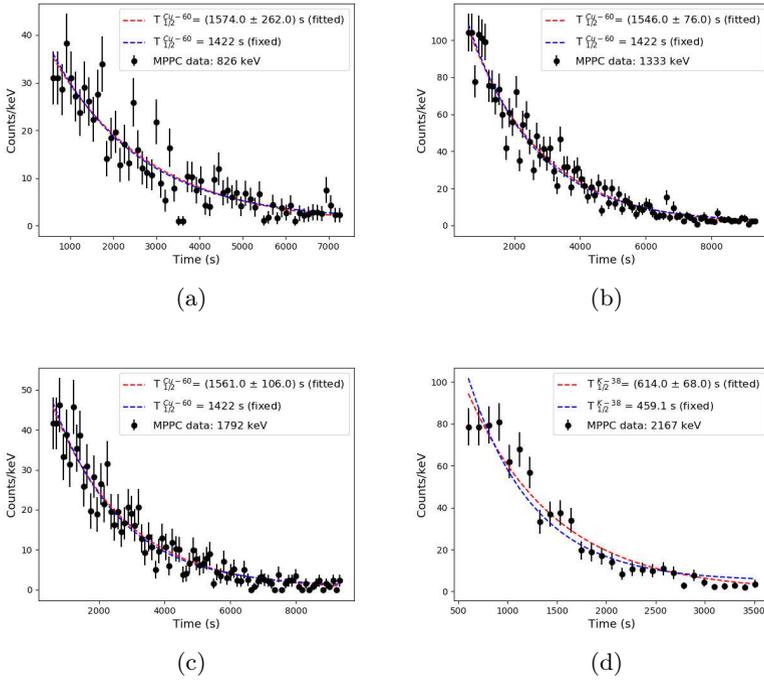


Fig. 25 Decay time distributions (black points) measured for 58 MeV proton irradiated SiPM. Subfigures corresponds to different energy gated lines a) 826 keV, b) 1333 keV, c) 1792 keV and d) 2167 keV. Red dashed lines correspond to fitting procedure, where amplitudes and decay times were set as a free parameters. Blue dashed lines describe the cases with fixed decay times (see details in text).

$$y = \sum_i^N A_i \cdot \exp\left(-\frac{t \cdot \ln(2)}{T_{1/2}^i}\right), \quad (2)$$

where A_i and $T_{1/2}^i$ refer to the amplitude and the decay time of the component respectively. To obtain a good description of the experimental data, 4 components ($N=4$) were used, resulting in 8 free parameters. The decay times obtained during the fitting procedure, presented in Figure 26a, are relatively far away from the expected values presented in Table 3 (over 3σ) for the most dominant nuclei and does not match to other potential candidates from other nuclei. This could be attributed to low statistics in the tail component, biasing towards shorter time bases, or the incorrect estimation of the number of element contributions in the 511 keV peak. The simplest approach $N>4$ increased the number of free parameters and significantly complicates the fitting procedure causing even higher uncertainties (overfitting and/or correlated parameters).

In the second approach, it was decided to use the decay times listed in table tab:activ as fixed parameters while only varying the amplitudes. Cu-63 and Cu-65 have the same daughter nuclei, Cu-62, reducing the number of components in Equation 2 by one. Next, it was assumed that the contributions of Cu-60 and K-39, which have the smallest total cross section from those presented in Table 3, are also negligible, despite seeing other gamma lines from this channel. This means that for 5 components (N=5) we only fit 5 free parameters (as opposed to 10). The result of this fitting procedure is shown in Figure 26b. It can be seen, that based on TALYS calculations, we are in good agreement with experimental data even with a smaller number of free parameters. This allows us to conclude, that our assumption about basic SiPM(+PCB) element composition is correct and we can accurately modeling the setup.

POLAR-2 will orbit with a period of 90 min, frequently passing through the SAA⁸. From the figures 26a and 26b we see that most elements have already decayed, reducing the count number by at least one order of magnitude. As the SiPM (used to derive the activation studies) was irradiated with 4.96 Gy, equating to 5.04 years of equivalent space time for the 'bare' scenario (see Table 1), we see that the number of counts already drop by more than three orders of magnitude after a day. For POLAR-2, the dose equates to 78.1 years of equivalent time in space. Furthermore, we see that the most dominating components (irrespective of fitting procedure) have decay times shorter than the orbital period. As a result, we do not expect a significant contribution of the activation of the SiPMs and the PCB to the dose to which the sensors are exposed.

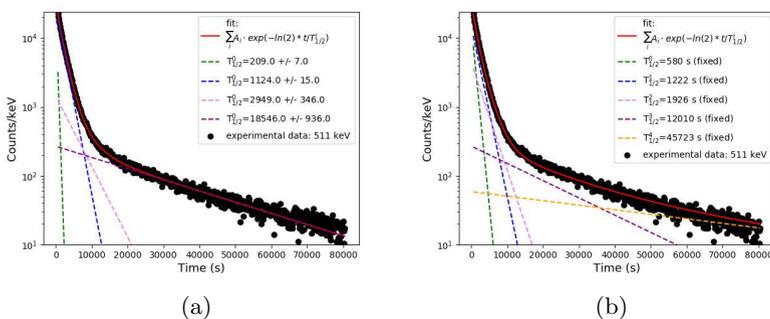


Fig. 26 Decay time distribution of 511 keV line (black points) measured for 58 MeV proton irradiated SiPM. Red lines show the results of fitting procedure for a) N=4 (8 free parameters) and b) N=5 (5 free parameters - only amplitudes). Dashed lines show each component contribution (see more details in text).

⁸Due to the orbital configuration it will pass the SAA at different regions

6 Summary and outlook

We present here the results of the irradiation of the S13361-6075NE-04 and S14161-6050HS-04 SiPM arrays from Hamamatsu. The campaign was performed for the POLAR-2 mission which is planned for launch on the CSS in late 2024 or early 2025. Two scenarios were studied: i) the 'Full Instrument + CSS' for POLAR-2 purposes and ii) the 'Bare SiPM' scenario for other instruments which may be more exposed to the background radiation.

After an exposure of 4.96 Gy, it was found that the S13361 SiPM array is still operational. For the 'Full Instrument + CSS' scenario, this equates to 78.1 years in space, whereas it equates to 5.04 years for the 'Bare SiPM' scenario. The most prominent effects after proton irradiation are the increase in dark current and dark counts, mostly by cross-talk events. The observed changes in the dark count rate, compared to data taken before irradiation, are about 4 times higher with respect to the lowest dose. Furthermore, the maximum dark pulse amplitudes for $V_{ov}=2.8$ V increased from about 110 mV (the last p.e. peak at 25 °C, before irradiation) to about 350 mV (left edge of DC spectrum, 27 °C, 4.96 Gy), showing the necessity of a well-thought threshold determination. These effects can be reduced significantly by lowering the SiPM temperature. The maximum dark pulse amplitude for the dose 4.96 Gy) and the temperature -20 °C is about 150 mV, what is close to a value before the irradiation (at room temperature).

Annealing processes were observed for DC spectra taken after 2 hours, 26 hours and 2 months. Although not the emphasis of this paper, they are later specified through a dedicated study and will be published hereafter. Neither SiPM type showed a change in performance when a single channel was biased (or unbiased) during proton irradiation as the measured I-V characteristics and DC rates did not expose significant differences in this case. Nevertheless, it is recommended, despite not affecting the radiation damage, to reduce the bias voltage in the SAA region to avoid issues with the SiPM current as well as the produced data volume.

Finally, we discussed the SiPM(+PCB) proton activation analysis. The results show a dominant contribution of the 511 keV line in the energy spectrum measured with the HPGe detector, corresponding to β^+ decay of daughter nuclei populated in proton reaction. Excluding life times in the range of seconds (due to practical limitations), the main contribution in the gamma spectrum comes from copper and carbon activation which mostly have a decay time shorter than the orbital period. As a result, we do not anticipate the activation products from SiPMs to provide a significant contribution in the polarimeter response.

In conclusion, due to the shielding in the 'Full Instrument + CSS' scenario, we do not expect POLAR-2 to greatly suffer from a rapidly degrading

SiPM through background radiation.

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Declarations

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Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Code availability

Not applicable.

Author's Contribution

The main three authors are Slawomir Mianowski, Nicolas De Angelis and Johannes Hulsman. Slawomir Mianowski is considered the primary of the three. The first draft of the manuscript was written by Slawomir Mianowski, Nicolas De Angelis and Johannes Hulsman and all authors commented on previous versions of the manuscript.

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