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Article

Study of Performances and Characterization of SiPMs (Hamamatsu S13161-3050AE-08) for the Next Generation of Telescopes in Balloon-Borne and Space-Based Experiments

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Abstract

Silicon PhotoMultipliers (SiPMs), constitute the enabling technology for a diverse and rapidly growing range of applications in experimental physics. The development of detectors based on silicon photosensors for acquisition of fast signals coming from Cherenkov and fluorescence emissions started by particle showers in the atmosphere, is the main goal of the current ASI/INFN Agreement, named *ASI/INFN_EUSO-SPB2 (Extreme Universe Space Observatory – Super Pressure Balloon 2)*, addressed to the next generation of telescopes in balloon-borne and space-based experiments. In such framework, a survey of performances of different SiPMs available on the market has been performed to identify the best sensors for space applications, where high thermal excursions and environmental radiation must be mainly taken into account with respect to ground-based experiments. In the present contribution, a characterization protocol for SiPM qualification has been applied to the (8×8) Hamamatsu S13161-3050AE-08 SiPM array in the $(-40 \div +30)^\circ\text{C}$ temperature range. The protocol is adopted for validating several key parameters: breakdown voltage, quenching resistance, gain, dark count rate and probability of cross-talk. Experimental methods and instrumental set-ups implemented for measuring them and their dependence on temperature are shown and some results are discussed.

Keywords: space-based telescopes; SiPMs; thermal excursions

1. Introduction

In the recent years, novel semiconductor photosensors, such as Silicon Photo-Multipliers (SiPMs), have been developed for fundamental science experiments, constituting an innovative technology for a diverse and rapidly growing range of applications. Especially, in the framework of the astroparticle physics, an intense investigation of using SiPMs is ongoing in order to design and implement the next generation of telescopes in ground-based, balloon-borne and space-based experiments [1,2]. In particular, the development of telescopes, with a focal surface based on SiPMs, for acquisition of fast light signals coming from Cherenkov and fluorescence emissions, started by charged secondary particles during the development of the Extensive Air Showers (EASs) in terrestrial atmosphere, represents a challenging pathfinder for indirect measurements of Ultra-High-Energy Cosmic Rays (UHECRs) from space [3]. In such context, the current Italian ASI/INFN Agreement n.2021-8-HH.2-2022, with the successive supplements and the additional Agreement n.2020-26-Hh.0., signed between the Italian Space Agency (ASI) and the National Institute of Nuclear Physics (INFN), named *ASI/INFN_EUSO-SPB2 (Extreme Universe Space Observatory – Super Pressure Balloon 2)* Project, plays a key role. It is devoted to the design, development, production and completion of a Cherenkov and/or fluorescence telescope prototype for space applications, with the ultimate purpose of enhancing the Technology Readiness Level (TRL). It intends to demonstrate the maturity of such technique for flight-qualification,

specifically of the mechanics, hardware, front-end, read-out and data acquisition electronics, of the firmware and software for triggers and slow-control systems, of the algorithms and codes for simulation, reconstruction and data analysis and also for atmospheric monitoring, with an ultimate goal of assembling and completing a telescope prototype, including all the test and integration pre-flight campaigns. The ASI and INFN (with its Divisions of Bari, Catania, Napoli, Roma 2 and Torino), as partners, and the University of Catania and University of Torino, as sub-partners, participate to the aforementioned Project. It represents the base for an implementation of Cherenkov and fluorescence telescopes of the JEM-EUSO Program [4], in particular directly connected with its recent intermediate sub-orbital SPB2 (Super Pressure Balloon 2) [5] mission and the new PBR (POEMMA Balloon with Radio) [6] balloon-borne flight, approved and funded by the NASA (National Aeronautics and Space Administration) USA Space Agency, for a launch planned in Spring 2027 from the Wanaka base in New Zealand. The PBR intermediate mission will be the closest prototype to date for the large-size space-based POEMMA (Probe Of Extreme Multi-Messenger Astrophysics) mission [7], a stereo double telescope to be considered for a NASA Probe Mission in the next decade.

2. SiPMs as Photodetectors for Space Applications

A SiPM is composed of a matrix of identical micro-cells, each one consisting of a so-called Geiger-mode Avalanche Photo-Diode (G-APD) or Single-Photon Avalanche Diodes (SPAD) and a quenching resistor (R_q) connected in series. The micro-cells are connected in parallel to a bias voltage (V_{bias}). SiPMs are also known as Multi-Pixel Photon Counters (MPPCs), naming a micro-cell as pixel. Every pixel produces the same signal when it is hit by a photon and the sum of the pixel responses gives the channel output. The typical dimension of a SiPM sensor is between $(1 \times 1) \text{ mm}^2 \div (6 \times 6) \text{ mm}^2$, the number of micro-cells per device ranges from several hundreds to several tens of thousands and micro-cells vary between $(10 \times 10) \mu\text{m}^2 \div (100 \times 100) \mu\text{m}^2$ in size. As an example the S13161-3050AE-08 Hamamatsu has channels of $(6 \times 6) \text{ mm}^2$ and micro-cell $(50 \times 50) \mu\text{m}^2$. The SiPMs as photodetectors present numerous pearls over conventional vacuum tube Photo-Multiplier Tubes (PMTs): solid-state technology and compact size; cost-effectiveness, modularity, magnetic field immunity, low voltage operation, high Photon Detection Efficiency (PDE), high Gain (G) and large output signal, wide dynamic range. Nevertheless, the SiPMs are usually more sensitive in their performances to the temperature and present also other pitfalls: higher costs for larger detection area, high Dark Count Rate (DCR), radiation sensitivity, probability Cross-Talk (pCT) leading to increased noise and reduced signal-to-noise ratio, limited dynamic range and bandwidth, not highly sensitive below 400 nm and too sensitive at higher wavelengths. The design, assembly and completion of a telescope for space applications, based on a focal surface formed by SiPM arrays, must take into account all the above-mentioned factors and meets a proper balance among pearls and pitfalls of SiPMs. Moreover, in pinpointing the best SiPM sensors for space-based experiments, the extreme ambient conditions, where high thermal excursions and environmental radiation prevail, must be carefully evaluated in contrast to ground-based experiments. In the framework of the ASI/INFN_EUSO-SPB2 Project, a specific Working Package (WP), identified as WP4400: *Characterization, selection and validation of SiPMs*, is devoted to the definition of a procedure to characterize and select the SiPM sensors that best fit experimental requirements for space applications. The most important outcome of an extensive survey on various SiPMs was a complete study of the (8×8) Hamamatsu S13161-3050AE-08 SiPM array [8], showing the best performances over a wide range of temperatures [9]. In the present contribution, the protocol adopted for validating several key parameters of SiPMs: breakdown voltage, quenching resistance, gain, dark count rate and probability of cross-talk and their dependance on the temperature excursions is introduced. The technical details and description of the experimental set-up and the procedural steps implemented for the measurements are reported to follow (Section 3).

3. Settling a Measurement Protocol for Surveying SiPM Sensors for Space Applications

Under the context of the ASI/INFN_EUSO-SPB2 WP4400 (*Characterization, selection and validation of SiPMs*), an extensive procurement, listed in Table 1), of different SiPMs available on market (Broadcom Corporation, Hamamatsu Photonics, KETEK GmbH, SensL Technologies Ltd manufacturing companies) was acquired and a preliminary survey was conducted through measurements on their basic properties at controlled temperature conditions.

Table 1. Inventory of all the different SiPM sensors procured with their basic characteristics.

Manufacturing company	Model	Number of SiPMs	V_{op} (V) ¹	V_{bd} (V) ²	Connector	Channels
Hamamatsu	S14160-1315PS	2	-	41.77	to be sold.	1
Hamamatsu	S14160-4050HS	2	37.90	40.60	to be sold.	1
Hamamatsu	S14160-1310PS	2	-	42.40	to be sold.	1
Hamamatsu	S14160-3010PS	2	-	42.66	to be sold.	1
Hamamatsu	S14160-3015PS	2	-	42.00	to be sold	1
Hamamatsu	S13360-6050CS	2	50.97	53.97	PIN A-K	1
Hamamatsu	S13360-1325CS	2	52.65	57.65 -	PIN A-K	1
Hamamatsu	S13360-6025C	2	51.87	56.87	PIN A-K	1
Hamamatsu	S13360-1350CS	2	49.49	54.49	PIN A-K	1
SensL	ARRAYJ 30035 16P PCB	1	-	-	CONN	4x4
SensL	ARRAYC 60035 64P PCB	1	-	-	CONN	8x8
SensL	MICROFC 10010 SMT TR1	6	-	-	to be sold.	1
SensL	MICROFC SMA 30035 GEVB	1	-	-	SiPM on board	-
SensL	MICROFC SMTPA 60035 GEVB	1	-	-	PIN A-K	1
SensL	MICROFC 30035 SMT TR1	-	-	-	to be sold.	-
SensL	MICROFC 60035 SMT TR1	-	-	-	to be sold.	-
SensL	no name	-	-	-	to be sold.	-
SensL	MICROFC SMA 60035 GEVB	-	-	-	SiPM on board	-
SensL	MICROFC SMTPA 10010 GEVB	1	-	-	PIN A-K	1
SensL	MICROFC SMA 10010 GEVB	1	-	-	SiPM on board	-
SensL	Arrayx BOB6 64S GEVK	-	Eval board	-	-	-
SensL	Arrayx BOB6 64p GEVK	-	Eval board	-	-	-
Broadcom	AFBR S4E001	1	Eval board	-	-	-
Broadcom	AFBR S4N44P163	1	-	-	-	-
Ketek	PA3347-WL-A0-A0-0808	1	-	-	Samtec	8x8
Ketek	PM3347-WL-A0 PIN	2	-	-	PIN A-K	1
Ketek	PM3325-WB-D0 PIN	1	-	-	PIN A-K	-
Ketek	PM3315-WL-A0	2	-	-	PIN A-K	-
Ketek	PM3335-WL-A0	2	-	-	PIN A-K	-
Ketek	PM3315-WL-A0 PIN	2	-	-	PIN A-K	-
Ketek	PM3335-WL-A0 PIN	2	-	-	PIN A-K	-

¹ V_{op} is for the operating voltage in unit of Volt (V). ² V_{bd} is for the breakdown voltage in unit of Volt (V).

In the preliminary phase, the survey was focused on a sub-set of the available inventory starting from a first comparison between Hamamatsu and KETEK SiPMs, whose specific properties are summarised in the Table 2. In addition, the wavelength spectral response range is (270 ÷ 900) nm for the Hamamatsu SiPMs with CS option while (320 ÷ 900) nm, with a peak in sensitivity at 450 nm

wavelength, for the KETEK Si photosensor. The operating temperature range is $(-20 \div 60)^{\circ}\text{C}$ for the Hamamatsu SiPMs and $(-40 \div 60)^{\circ}\text{C}$ for the KETEK SiPMs.

Table 2. Specific properties of selected Hamamatsu SiPMs versus KETEK SiPMs.

Company	Model	Number of pixels	Fill factor %	Window R-index	Active area (mm ²)
Hamamatsu	S13360-1350CS	667	74	1.41	1.3 x 1.3
Hamamatsu	S13360-6050CS	1440	74	1.41	6 x 6
Hamamatsu	S13361-3050-AE-08	3584	74	1.55	3 x 3
KETEK	PM3335-WL-A0	7396	80	1.52	3 x 3
KETEK	PM3347-WL-A0	4096	80	1.52	3 x 3
KETEK	PM3347-WL-A0-0808	4096	80	1.52	3 x 3

The primitive measurements were performed, before at room temperature and then at controlled set (25°C) temperature, by illuminating the SiPM sensor with a monochromatic LASER fixed on an optical work bench (see (a) Figure 1) and using a convergent lens to focus the LASER light pulses conducted by an adapter fiber, with the signal read by an oscilloscope. Later, the measurements were structured by putting the system in a proper large dark box (see (b) Figure 1), replacing a LED as light source, using a customized mechanical support to place SiPMs and the optical fiber conducting the light pulsed inside the dark box, by reading the signals from the SiPM sensor by means of a CAEN (DT550W) Front-End and Read-out System (FERS) Evaluation Board, a compact all-in-one, user-friendly and complete platform for the read-out of large arrays of detectors (SiPMs, Multi-Anode-PMTs, Gas Tubes, Si detectors, etc.). Successive advances were to substitute an enhanced version (DT5202) of the CAEN FERS Evaluation Board and properly to put the equipment inside a climatic chamber (specifications of all the aforementioned equipments in Table 3), as described to follow.

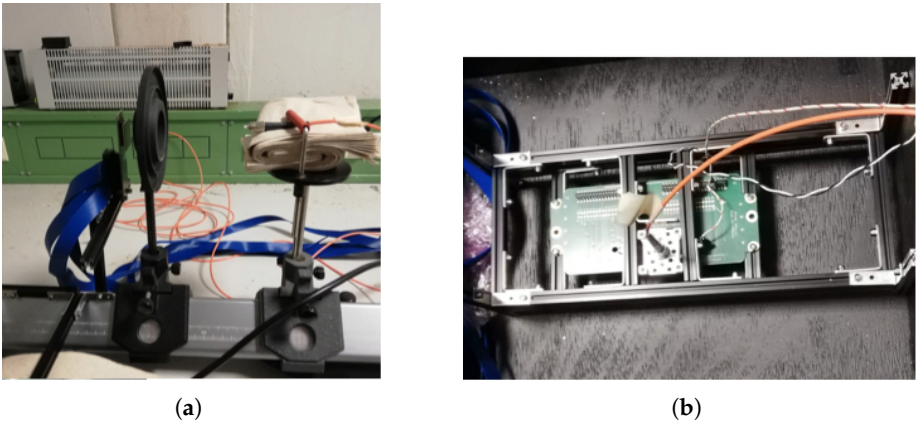


Figure 1. **a)** the optical work bench with the convergent lens used during the primitive measurements. **(b)** the customized mechanical support to house the SiPM array and the optical fiber, conducting the LED light pulses, inside a specific dark box for preliminary measurements at room temperature.

Thanks to the extended fine-tuning of the different experimental set-up prototypes and the training on various SiPMs, a definitive experimental system, organized in two configurations, and a characterization protocol were designed, optimized and finalized for the qualification of SiPMs exposed to thermal excursions. Both configurations make use of an SH-242 environmental chamber, produced by ESPEC, hosting each time the photosensor, to perform tests at controlled thermal excursions. The climatic chamber spans $(-40 \div +150)^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ temperature range; its interior size is $(300 \times 250 \times 300)\text{ mm}^3$. In order to connect the SiPMs to the instrumentations, located outside the climatic cell, proper cables (at least 1 m long) are used. A specific Printed Circuit Board (PCB) (see (a) Figure 2) has been designed and locally manufactured by the Electronics Unit of the INFN-Division of Catania (INFN-CT) in order to interface the SiPM sensor to the Front-End and Read-Out electronics. The SiPM tile is properly illuminated with light pulses at 400 nm by a LED driver (CAEN SP5601 model, 6 ns),

fed through a 40 cm CAEN AI2740 FC optical fiber. A compact mechanical structure (see (b) Figure 2), properly fitting the climatic cell dimensions, was specifically devised to support the PCB and the SiPM tile and to hang the optical fiber conducting the light source inside the climatic cell. The SiPM sensors can be illuminated, as an alternative to the LED light pulses, with a LASER light source (Picoquant PDL 800-D with LDH P-C 405B head at 402 nm and time jitter < 80 ps), which is equipment at the local Laboratory's disposal.

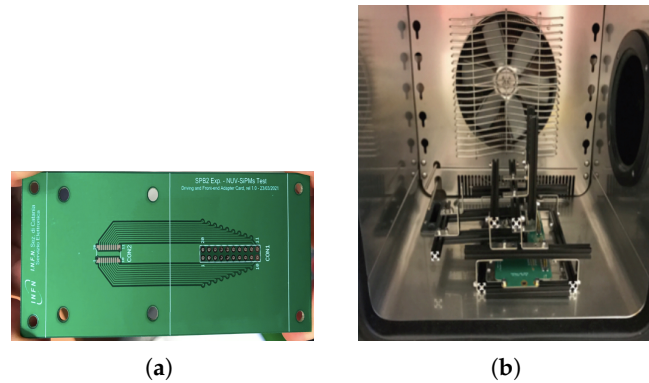


Figure 2. (a) the PCB designed and manufactured by the Electronics Unit of the INFN-CT. (b) the compact mechanical stand to house SiPM sensor, PCB and the optical fiber inside the climatic chamber.

The definitive system consists in two different experimental configurations (see Figure 3): (a) the first configuration mainly uses a pico-ammeter to measure the leakage currents accurately in order to determine two key parameters (the V_{bd} voltage breakdown and the R_q quenching resistance) by means of the direct measurement of the (I-V) curves, both in *forward-bias* and *reverse-bias* mode, (b) the second configuration mainly uses a CAEN DT5202 FERS Evaluation Board to evaluate other three key parameters (the G gain, the DCR dark count rate and the pCT probability cross-talk) by means of the direct measurement of the multi-peak spectra.

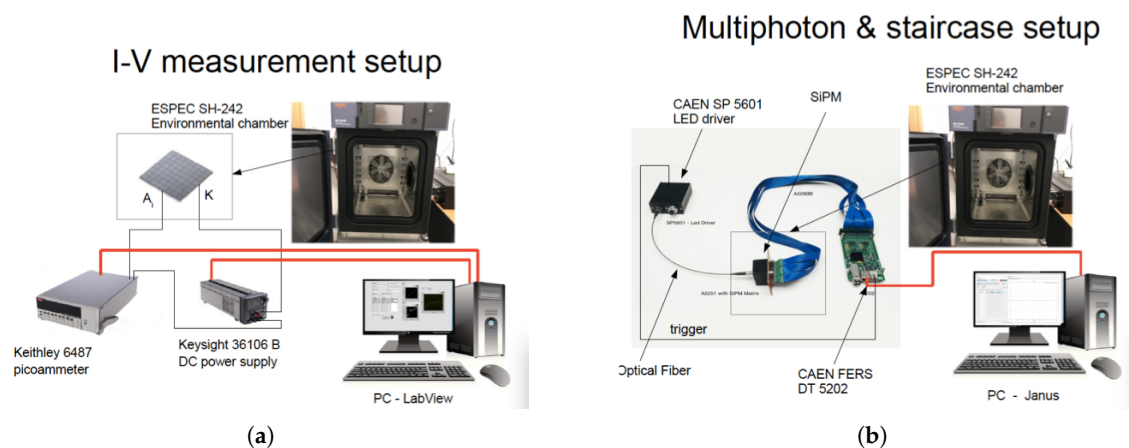


Figure 3. (a) the schematic representation of the experimental set-up configuration used for measuring the SiPM (I-V) curves at different temperatures. (b) the schematic representation of the experimental set-up configuration used for measuring the SiPM multi-peak spectra at different temperatures.

The (a) set-up allows powering individual anodes and collect the leakage current from the cathode in the *reverse-bias* measurement, and viceversa in the *forward-bias* one. A Keysight e36106b DC power supply was used to power the SiPM sensors while a Keithley 6487 pico-ammeter has been adopted for precise current measurements. Both devices were automatically operated using a specifically developed LabView program that allows setting the voltage range for supplying the photosensors, the stabilization time, used for stabilizing the SiPM after each voltage change, and the measurement time,

the time interval during the current is acquired. In the (b) set-up, the photosensor is directly connected to the CAEN DT5202 FERS device based on 2 Citiroc-1 A chips produced by Weeroc. The device permits carrying out photon counting, saving the signal Time Stamp and the Time over Threshold for each signal, accepting an external trigger (in such case, from the LED driver). The data acquisition is automatically operated using Janus software, an open source software specifically developed for the control and read-out of FERS-5200 boards. The specifications of all the aforementioned equipments are reported in Table 3.

Table 3. Specifications of different equipments used in different stages of the evolution of an experimental system for qualification of SiPMs and to this day at disposal in the local Laboratory .

Equipment	Manufacturing company	Model	Main specifications
SiPM sensors	(see Table 1)	(see Table 1)	(see Table 1)
Climatic chamber	ESPEC	SH-242	(−40 ÷ +150)° C ± 0.5° C (300 × 250 × 300) mm ³
FERS	CAEN	DT5550W	2 Petiroc WeeROC ASICs on-board power supply 64 ch, 80MS/s, 14bit ADC
FERS	CAEN	DT5202	2 Citiroc-1A WeeROC ASICs on-board power supply 64 ch, 80MS/s, 14bit ADC
DC Power supply	Keysight	e36106b	0 ÷ 100 V
pico-ammeter	Keithley	6487	2 nA ÷ 20 mA
LED driver	CAEN	SP5601	400 nm, 6 ns
optical fiber	CAEN	AI2740	40 cm
LASER driver	Picoquant	PDL 800-D	time jitter < 80 ps
		LDH P-C 405B head	monochromatic 402 nm
oscilloscope	Lecroy Wafesurfer	3024z	200 MHz, 4 GS/s
cables/connectors	miscellaneous	LEMO, BNC, SMA, MCX	4 channels, 10 Mpts/ch miscellaneous
convergent lens			f = 100 mm

The measurement protocol specifies measurements of all the characterizing parameters as a function of temperature at fixed V_{ov} overvoltage for each channel of each SiPMs. After a visual inspection in clean room by using a microscope (for identifying possible scratches, bubbles and other manufacturing defects or incidental damages), measurements at temperature variations in a climatic chamber are accomplished. The protocol is based on the premise that the breakdown voltage V_{bd} is the most important parameter characterizing a SiPM sensor, from which the G and the PDE derive. It is best specified by the overvoltage V_{ov} , defined as the difference between the bias voltage V_{bias} (e.g. the actual applied or operating voltage) and the V_{bd} as $V_{ov} = V_{bias} - V_{bd}$. To determine the V_{bias} , a compromise should be reached between gain and noise, knowing that both of them increase for high overvoltage values. To define a convenient value, a few multi-photon spectra in the dark conditions are acquired at a room temperature and different overvoltages. The protocol foresees that all the measurements are performed at a fixed $\bar{V}_{bias}$ and at a fixed $\bar{T}$ temperature, for each channel of a selected SiPM array. The

- 1) I-V (I current-V voltage) curves, in
 - a) *reverse-bias*
 - b) *forward-bias* mode;
- 2) multi-photon spectra (in technical jargon, named *finger plots* or *light spectra*), when the SiPM is properly illuminated by a controlled light source (LED or LASER), at different V_{ov} ;
- 3) multi-photon spectra (in technical jargon, named *staircase plots* or *dark spectra*), without illuminating it, at different V_{ov} voltages

are measured and the corresponding key parameters are extracted:

- 1a) V_{bd} ,
- 1b) R_q ,

- 2) G and $G(V_{ov})$ as function of V_{ov} voltage at a fixed $\bar{T}$,
- 3a) DCR and DCR(V_{ov}) as function of V_{ov} at a fixed $\bar{T}$,
- 3b) pCT and pCT(V_{ov}) as function of V_{ov} at a fixed $\bar{T}$.

Lastly, in order to characterize the SiPM key parameters completely, all the measurements are repeated at different T temperatures in a predetermined excursion range for each channel of the selected SiPM array, so the evolution in temperature of key parameters, e.g. $V_{bd}(T)$, $R_q(T)$, $G(T)$, DCR(T) and pCT(T) is extracted. Obviously, the temperature range can be selected on demand, only depending on the effective operating temperature range of the climatic chamber, and also the V_{ov} range or the fixed temperature $\bar{T}$. A complete procedure, e.g. acquisition of (I-V) curves and multi-peak spectra for all the channels of a given SiPM matrix under thermal excursions, needs a long duration, approximately (10 ÷ 16) hours. Clearly, it depends on the number of channels forming the SiPM array and to be tested and on the selected width and single interval of T and V_{ov} ranges. Nevertheless it derives also from the required dead-times due to the climatic chamber for ranging from higher to lower temperatures and viceversa.

4. Results

4.1. Foundation of a Local Laboratory for Qualification of SiPMs in Space Applications

In the course of time, all the equipments procured, the know-how and the expertise acquired, the enabling technology achieved in the implementing experimental set-ups, and the enabling methodology in applying an operational protocol, optimized for the characterisation of photosensors exposed to thermal excursions, provided the foundation of a local Laboratory (named *Laboratory of Photosensors for Astroparticle Physics*) for qualification of SiPMs in space applications and, in general, in a variety of applications in experimental physics. At present, that Laboratory is an important and unique facility in the testing of SiPM sensors for space applications. Nevertheless, the experimental set-up configurations currently adopted do not represent the ultimate system and the methodologies (and the subsequent protocol) to date followed are not definitive, but rather they are constantly developing. Possible enhancements are under study with concrete upgrades of the experimental set-ups. In particular, two integrating spheres (2P4M Thorlabs 50 mm) with their own accessories have already been procured and available at the Laboratory in order to enable an uniform illumination of the SiPM sensor and measure with accuracy an additional and important SiPM key parameter: the photon detection efficiency (PDE). Moreover, a methodology for the measurement of the after-pulse parameter is also under study. Furthermore, a remarkable development in performing the thermal excursions is also under consideration by means of using a bigger and powerful climatic chamber with larger dimensions ($600 \times 801 \times 694$) mm³ and a wider temperature range ($-75 \div +180$)° C, available at the INFN-Division of Catania. Additionally, for the time being, a fine-tuning of tools for electronics data archiving and sharing and of algorithm codes for data analysis is ongoing and an automatisation of the whole experimental protocol, for making possible massive SiPM characterization, with a proper optimization of timings is underway.

4.2. The Case Study of the (8 × 8) Hamamatsu S13161-3050AE-08 SiPM Array

The whole protocol of measurements, described in (Section 3), executable by means of the two experimental set-up configurations, has been totally and successfully applied to a specific SiPM sensor as a case study: the (8 × 8) Hamamatsu S13161-3050AE-08 SiPM array [8] (see Figure 4). The (8 × 8) channel SiPM array, having the pixel pitch of 50 μm, is equipped with connector and is manufactured by the Hamamatsu Photonics company as S13361 series for precision measurements in astrophysical applications. It is characterized by a reduced cross talk and dark count (compared to previous products), low after pulse, extended photon counting capability and exceptional photon detection efficiency. Moreover, it presents a COB (Chip On Board) package with minimal dead space, a special tiling forming a large sensitive area, an excellent uniformity and low voltage operation.

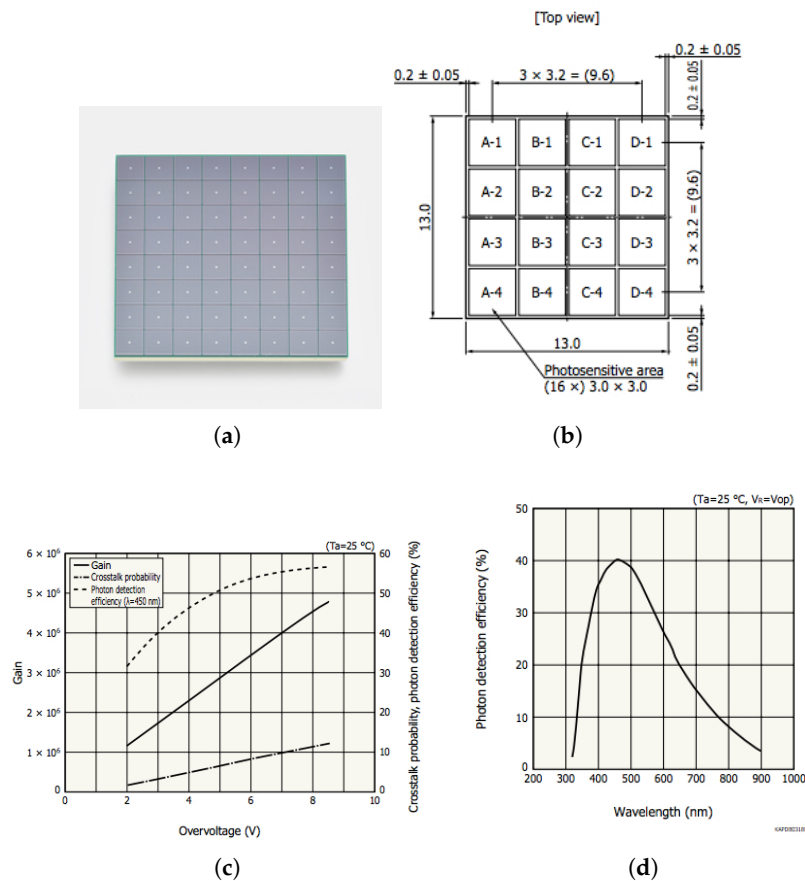


Figure 4. The (8 × 8) Hamamatsu S13161-3050AE-08 SiPM array: (a) photograph of the SiPM sensor. (b) A schematic top view of its geometry and dimensions. (c) Overvoltage specifications of gain, cross talk probability and photon detection efficiency. (d) Photon detection efficiency as a function of the wavelength at $\bar{T}=25^\circ\text{C}$, from the Hamamatsu datasheets [8].

The most important outcome of the application to this case study was a complete qualification of the SiPM sensor in question, by measuring the key parameters V_{bd} , R_q , G , DCR, pCT, having chosen the T range equal to $(-40 \div +25)^\circ\text{C}$, with $\Delta T = 5^\circ\text{C}$, the fixed temperature $\bar{T} = 25^\circ\text{C}$ and the selected V_{ov} range equal to $(0 \div 5\text{ V})$, with $\Delta V_{ov} = 0.5\text{ V}$. To determine the V_{bias} , a few dark spectra were acquired at $\bar{T} = 25^\circ\text{C}$ and different overvoltages (typical values range from 0 V up to 5 V), in the end by selecting the +3 V value as the best choice for the V_{bias} . Instead of fixing the same bias voltage for all temperatures, it is more convenient to keep constant the overvoltage. Details and conclusions can be found in a published paper [9], the main results can be summarised as follows:

- the V_{bd} voltages, measured at the same temperature for all 64 channels, are almost constant and 94% of them show a value within 1σ from the mean value;
- the observed homogeneity is better with respect to what reported in the literature for the same SiPM array,
- V_{bd} decreases as the temperature decreases,
- R_q seems almost independent of the temperature,
- the G and pCT are stable,
- the DCR level decreases as the temperatures decrease.

4.3. Application of the Measurement Protocol to the Balloon-Borne PBR Mission

In the framework of the JEM-EUSO Program, the intermediate PBR mission is an ideal model of the next generation of telescopes in balloon-borne and space-based experiments. The PBR Mission [10] is a scientific mission involving an instrument designed to be carried by a NASA suborbital Super

Pressure Balloon (SPB) with a projected duration of up to 100 days, circling over the Southern Ocean. The PBR instrument consists of a 1.1 m aperture Schmidt telescope with two photo-detectors in its hybrid Focal Surface (FS): a Fluorescence Camera (FC) [11] and a Cherenkov Camera (CC) [12], both mounted on a frame that can be tilted to point from nadir up to 13 degrees above the horizon. The CC uses 32 Hamamatsu SiPMs, each SiPM is a S13161-3050AE-08 array, consisting of (8×8) 64 channels of (3×3) mm² pixels, totaling 2048 channels for the entire camera. The experimental set-ups and the measurement protocol, here described for qualifying SiPM sensors in space applications, find natural application to the PBR CC detector. Working along the same lines, a measurement protocol for a massive characterization and calibration of the 32 SiPM photosensors in the $(-40 \div +30)^{\circ}$ C temperature range has been properly customised and the experimental set-up conveniently adapted, as reported in detail in [13] reference.

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Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ASI	Agenzia Spaziale Italiana (Italian Space Agency)
EAS	Extensive Air Shower
EUSO-SPB2	Extreme Universe Space Observatory – Super Pressure Balloon 2
G-APD	Geiger-mode Avalanche Photo-Diode
INFN	Istituto Nazionale di Fisica Nucleare (National Institute of Nuclear Phsyics)
JEM-EUSO	Joint Exploratory Missions towards an Extreme Universe Space Observatory
MPPC	Multi-Pixel Photon Counter
NASA	National Aeronautics and Space Administration
PMT	Photo-Multiplier Tube
POEMMA	Probe Of Extreme Multi-Messenger Astrophysics
PBR	POEMMA Balloon with Radio
SiPM	Silicon Photo-Multiplier
SPAD	Single-Photon Avalanche Diode
SPB2	Super Pressure Balloon 2
TRL	Technology Readiness Level
UHECR	Ultra High Energy Cosmic Ray
WP	Working Package

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