Published by IOP Publishing for Sissa Medialab

Received: *November 29, 2025*
Accepted: *January 8, 2026*
Published: *April 17, 2026*

17th Topical Seminar on Innovative Particle and Radiation Detectors
Siena, Italy
15–19 September 2025

2026 JINST 21 C04052

DAQ and electronics development and characterization for the multiPMT prototype for the SWGO experiment

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Abstract: The Southern Wide Field Gamma-ray Observatory (SWGO) is a next-generation ground-based experiment based on the Water Cherenkov technique for very-high-energy gamma-ray detection. In this context, the definition of a suitable photosensor for the outer array is still under study. In this work, we investigate the use of a multiPMT module as a possible photosensor solution. The module consists of a sealed, waterproof vessel hosting seven 3″ photomultiplier tubes together with the associated front-end and acquisition electronics. A first prototype has been deployed in a Water Cherenkov detector unit in Rio de Janeiro, where it has been operating under real environmental conditions and has successfully recorded self-triggered events, allowing validation of the acquisition chain and monitoring of system stability. A second prototype has been installed in Milan in a controlled laboratory setup, enabling complementary studies under different water purity and tank geometry conditions. The results from these deployments demonstrate the feasibility of the multiPMT approach and provide essential input for its potential application in the SWGO outer array.

Keywords: Cherenkov detectors; Performance of High Energy Physics Detectors; Front-end electronics for detector readout; Detector design and construction technologies and materials

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SWGO full author list: `https://www.swgo.org/SWGOWiki/lib/exe/fetch.php?media=wiki:the_swgo_collaboration.pdf`.

https://doi.org/10.1088/1748-0221/21/04/C04052

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1 Introduction

Ground-based detectors for γ-ray observation, such as HAWC [1] and LHAASO [2], have demonstrated the capability of the Water Cherenkov technique to achieve the highest sensitivity above a few TeV and to observe phenomena in the PeV range [3, 4]. Their wide field of view and nearly 100% duty cycle make these experiments ideally suited for continuous sky monitoring, enabling the observation of transient phenomena and the mapping of extended sources. This makes them a key component of multi-messenger astronomy.

The optimal configuration for continuous all-sky coverage would involve detectors in both hemispheres, allowing full spatial and temporal monitoring of the γ-ray sky. The current absence of a wide field-of-view instrument in the Southern Hemisphere to complement the northern experiments and the Imaging Air Cherenkov Telescopes (IACTs) has motivated the proposal for a next-generation detector.

The Southern Wide-field Gamma-ray Observatory (SWGO) will be a wide field-of-view, high duty-cycle, ground-based water Cherenkov detector array surveying the γ-ray sky in the ≈ 100 GeV to PeV range [5]. It will be located in South America, at the Atacama Astronomical Park in Chile, at an altitude of 4470 m.

The SWGO layout will consist of an array of independent Water Cherenkov Detector (WCD) units arranged in a three-zone configuration: the innermost with a high fill factor ($\approx 65\%$), the intermediate one with $\approx 4\%$ and the outermost with $\approx 1.7\%$. The inner zone will be dedicated to the study of low-energy events, while the two outer zones, forming the outer array, will extend the instrumented area to about $\approx 1\text{km}^2$ to reach the PeV scale, see figure 1.

The baseline WCD unit of the inner zone is a double-layer cylindrical steel tank, 4.1 m in height and 5.2 m in radius, with a bladder and a Tyvek reflective inner surface. The lower volume is designed for muon tagging and will be equipped with an 8″ or 10″ PMT, while the upper volume will host a 10″ PMT [5].

For the outer array, different designs are under evaluation. The proposed alternatives are undergoing an optimization process to improve hadronic background discrimination, and they must also be cost-effective to cover large areas. One possibility is to adopt a configuration similar to that of the inner array. Another promising alternative involves smaller High-Density Polyethylene (HDPE) roto-molded plastic tanks, based on a redesigned version of those used at the Pierre Auger

Observatory [6]. These tanks could host a new proposed photosensor system, the multiPMT, which is already employed in other experiments such as KM3NeT [7], Hyper-Kamiokande [8], and IceCube [9].

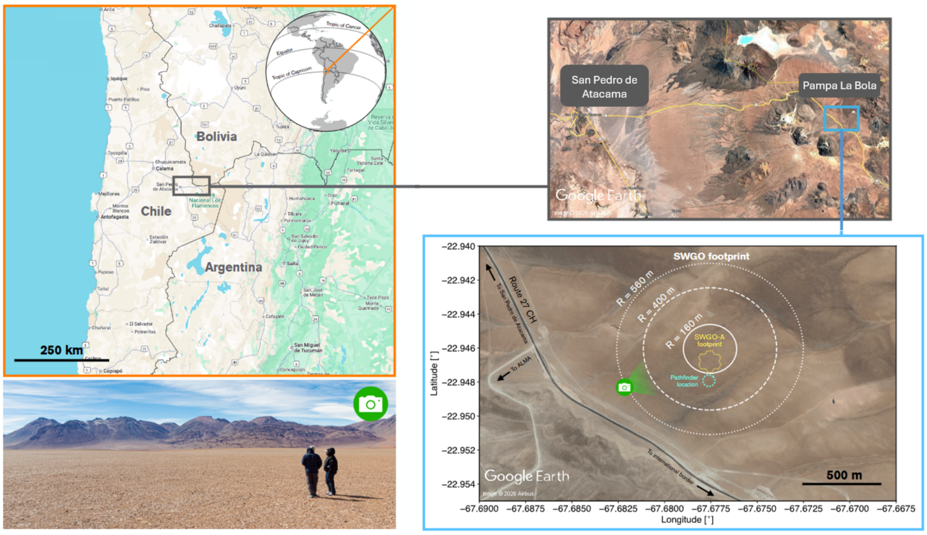

Figure 1. SWGO location and layout footprint. Reproduced with permission from [5]. Map data: Google 2025. Google Earth images: © 2026 Airbus.

2 The multiPMT module

Thanks to the experience gained at the INFN section of Naples in the development of multiPMT modules for the other experiments mentioned above, especially in the fields of electronics and mechanics, a multiPMT module has been proposed as the detection element within the WCD units of the SWGO experiment. This proposal is conceived as an alternative to using large area PMTs, aiming to offer improved performance.

The multiPMT, figure 2, is a composite photosensor made up of seven 3″ Hamamatsu R14374 [10] PMTs enclosed in a waterproof vessel. Owing to the large number of tubes produced for the KM3NeT collaboration, the 3″ Hamamatsu PMTs are extremely reliable and uniform in terms of performance and stability. One PMT is vertically oriented upward, while the other six are tilted by 45 degrees relative to the vertical one and spaced 60 degrees apart. This configuration is highly versatile, as it allows all the electronic components to be hosted inside the vessel itself, close to the PMTs. Because of that, this design requires only a low-voltage power supply for the detector, as the high voltage is generated within the module itself. Only two cables are needed to power the system and handle data acquisition, thus reducing overall costs.

The module is enclosed in a UV-transparent acrilyc dome, similar to that used in the Hyper-Kamiokande detectors [11], with a ≈ 90% transmittance peak in the UV region. The dome, 4 mm thick, is sealed to a stainless steel backplate and secured by a clamping ring.

The PMTs are held in place by a plastic holder, which also serves as a support during the pouring phase of the optical gel. The holder is designed to accommodate aluminum reflectors to increase the effective area, as shown in figure 3.

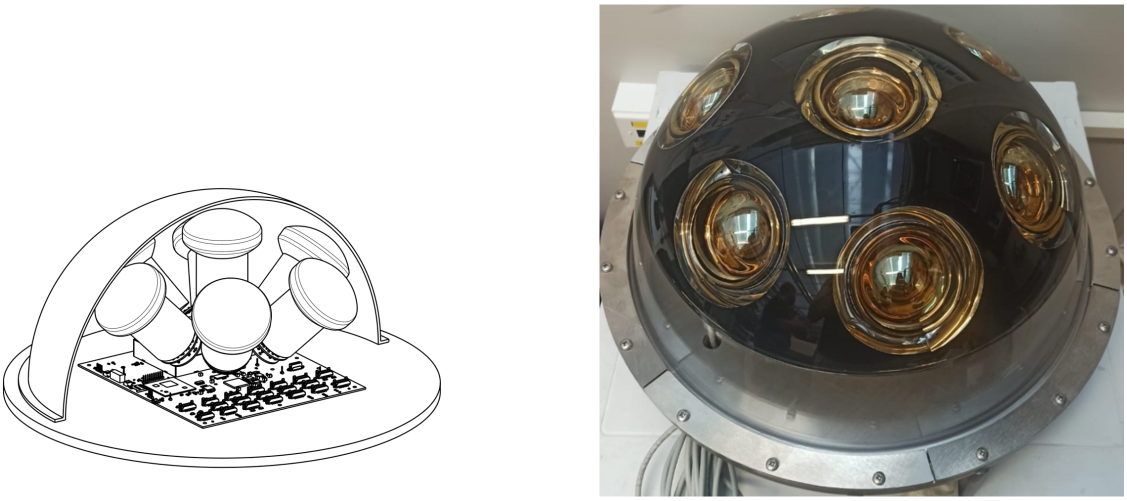

Figure 2. multiPMT conceptual design (*Left*) and a multiPMT prototype (*Right*).

Figure 3. multiPMT holder with reflectors and PMTs installed.

An 8″ PMT and a multiPMT, in the configuration described above, have been simulated in Geant4 [12–14] to compare their light collection efficiency, revealing complete equivalence between the two configurations, figure 4, thus validating the detector design concept.

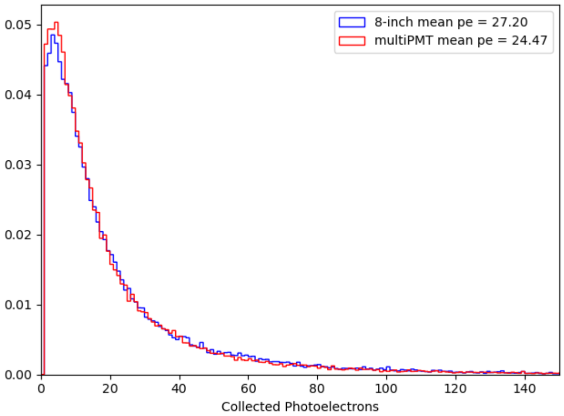

Figure 4. Collected photoelectrons for the 8″ PMT and for the multiPMT for the same events.

Additional advantages of this configuration include the intrinsic directional sensitivity resulting from its geometric structure; an extended dynamic range, as the event rate is distributed across multiple PMTs each with its own readout channel; improved reliability, since redundancy ensures that a detection unit remains operational even if a single PMT fails; and a better timing resolution compared to 8″ and 10″ PMTs.

In particular, this solution is highly flexible and can be applied to different possible tank configurations, both single- and double-layer, see figure 5.

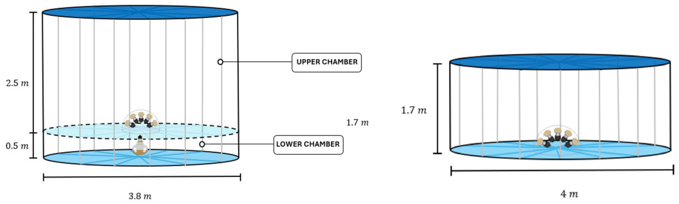

Figure 5. Possible SWGO WCD configurations using multiPMTs as photosensors.

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3 The electronics chain

The electronic readout chain for the multiPMT is derived from that already developed and implemented for the Hyper-Kamiokande experiment [15], and it has been appropriately modified and optimized to meet the requirements set by the SWGO collaboration.

The proposed electronic chain for the multiPMT consists of three interconnected blocks:

- The High Voltage Board (HV);
- The Front-End Board (FEB);
- The Main Board.

Thus, each PMTs is equipped with its own HV and FEBs, while the Main Board is unique for each module and is connected to all FEBs of the PMTs in that unit, see figure 6.

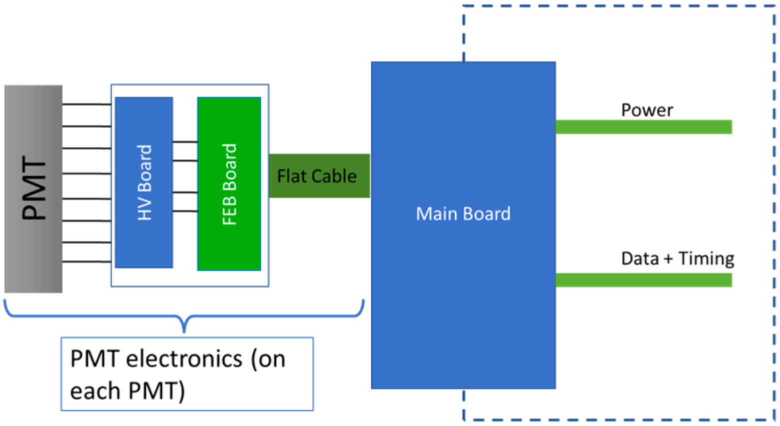

Figure 6. Schematic representation of the electronic readout chain proposed for the multiPMT.

3.1 The HV board

The voltage for the cathode and the dynode stages of the Hamamatsu R14374 3″ PMTs is obtained through an active divider based on the Cockcroft-Walton voltage multiplier. The board is equipped with an embedded current and voltage monitor to check the power supply and the absorbed current to detect the state of the PMT. This monitoring is in place to manage any potential overcurrent, allowing the PMT to be turned off and preventing any damage. The board is equipped with a 5 V power supply and is controlled by an analog input that sets the high voltage and a digital input that controls the ON/OFF state of the board. Additionally, two analog outputs provide the voltage and current values absorbed by the board, figure 7.

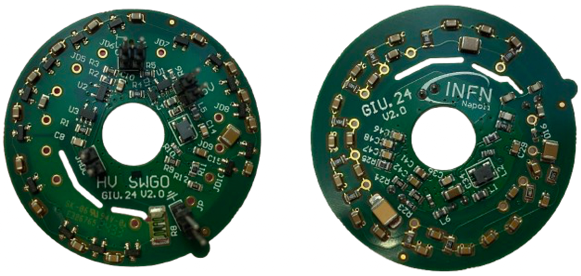

Figure 7. The HV board realised for the SWGO multiPMT.

To meet the requirements of the SWGO experiment, it is necessary to extend the linearity of the 3″ PMTs from Hamamatsu. Studies done in the SWGO Naples group demonstrated that linearity can be maintained from single photoelectrons up to ≈1000 photoelectrons (p.e.) within 5% per pulse at the gain of 3.5×10^6 if the voltage divider is modified in a tapared voltage divider. The one suggested by Hamamatsu is:

$$3 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1, \tag{3.1}$$

while the one defined in Naples for SWGO is

$$3 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 2 : 2. \tag{3.2}$$

During tests, the boards showed excellent voltage stability, on the order of 0.05%, and a power consumption at 1500 V of around 3.2 mW.

3.2 The FE board

The high voltage board contains only the circuits that generate the power supply voltage, but it does not include any control logic. This is embedded in the Front End Boards thanks to the presence of a low-power Micro-Controller Unit (MCU), figure 8.

The board collects the signal from the PMT and performs timing and charge measurements. It acts as the interface between the individual channel of the multiPMT and the main acquisition and management system constituted by the Main Board.

The FEB is designed to be placed as close as possible to the PMT to minimize the contribution of electronic noise. It is powered by two voltage supplies, one at 5 V and the other at 3.3 V, and is controlled via the Modbus protocol, implemented on a UART line [16]. The charge measurement

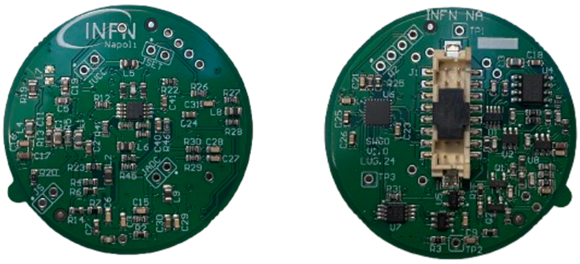

Figure 8. The FE board realised for the SWGO multiPMT.

is transferred from the ADC to the Main Board via the Serial Peripheral Interface (SPI), while the trigger signal is transmitted as a differential pair, enabling event timestamping on the Main Board with a time resolution corresponding to a least significant bit of approximately 270 ps.

The measured power consumption is 40.5 mW and linearity is established up to 400 photoelectrons at a PMT gain of 3.5×10^6.

3.3 The Main Board

The Main Board is the heart of every multiPMT unit. It provides power to multiPMT, manages data acquisition from the channels and synchronization to the global time of the experiment, figure 9.

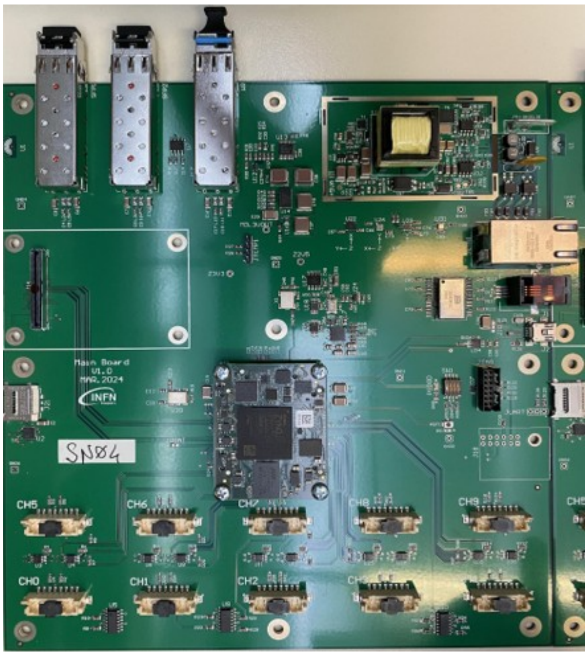

Figure 9. SWGO Main Board.

The Main Board is divided into two main sections: the power supply section and the data processing section. The first section is further composed of three modules: the Power over Ethernet Plus (PoE+) module, the DC-DC converters, and the switches to turn on and off individual channels.

The second one is divided into two stages: an FPGA that acquires and processes the data and generates a 128 bits output per event; an ARM chip embedded in a Xilinx System on Chip (SoC) that transfers via Ethernet the data of the event.

The Main Board was designed with the idea of integrating various options based on possible future decisions taken by the collaboration, especially regarding different possible links:

- Copper link to an external field node with PoE power supply and a custom timing link on copper;
- Fiber links for DAQ and Timing based on a custom link with clock recovery;
- White Rabbit node functionality. It provides sub-nanosecond accuracy and picosecond precision of synchronization for large distributed systems. It also allows for deterministic and reliable data delivery. White Rabbit enables precision time-tagging of measured data and allows triggering data acquisition in large installations while simultaneously using the same network to transmit data [17]. The circuitry needed to use White Rabbit is already embedded in the Main Board to accommodate this choice. We are now developing the firmware to make our board compliant to White Rabbit.

The FE also includes the option to transmit the pure analog signal from the PMT to the Main Board, allowing the integration of a faster ADC to acquire the full waveform of the signal when needed. To accommodate this feature, a high-reliability, high-density connector has been implemented on the Main Board, with all pins routed to the SoC. This design enables the development of a Flash ADC mezzanine that can be directly plugged into the new custom Main Board.

Power consumption is 4 W, thus the total consumption of the complete multiPMT unit remains below 5 W.

4 First tests: Milan and CBPF

The Naples group assembled four prototypes: two are, respectively, in Milan, at University Politecnico di Milano, and in Rio De Janeiro, at CBPF, and they are actively taking data. The other two will be sent to the SWGO site to be part of the Pathfinder in San Pedro de Atacama, Chile. These first tests are extremely valuable as they allow us to understand how the detector responds in realistic environments and to monitor its functionality. We are still learning and data analysis is ongoing. Various improvements and upgrades, both from a mechanical and electronics point of view, are planned in the future.

Each PMT is independently self-triggered at a threshold of 2 p.e. In both cases, we do not have an external trigger to select specific events. To better understand how the system works, we designed a software trigger. Specifically, given one channel event, we then open a 10 ns time window looking for other channels that have triggered within the window. We then aggregate all the useful data of the channel interested, time and p.e., to construct a coincidence event. In this way, we can analyze the data by varying and selecting different multiplicities, that is, the number of PMTs interested in a specific coincidence event.

For both Milan and Rio de Janeiro multiPMTs, we realized the charge spectra by plotting the total number of p.e. per coincidence event, even highlighting the contribution of each multiplicity, see figure 10.

The two responses differ significantly due to several factors: the tank in Milan is about 1 m higher and filled with ultra-pure water, while the one in Rio uses tap water; one channel in the Rio setup is not working; and the Milan module is equipped with a newer version of the electronics. We are currently working to disentangle these effects in order to better compare and understand the two conditions.

The charge centroid distribution built with coincidence events responds to expectations of particle uniformity at ground, see figure 11.

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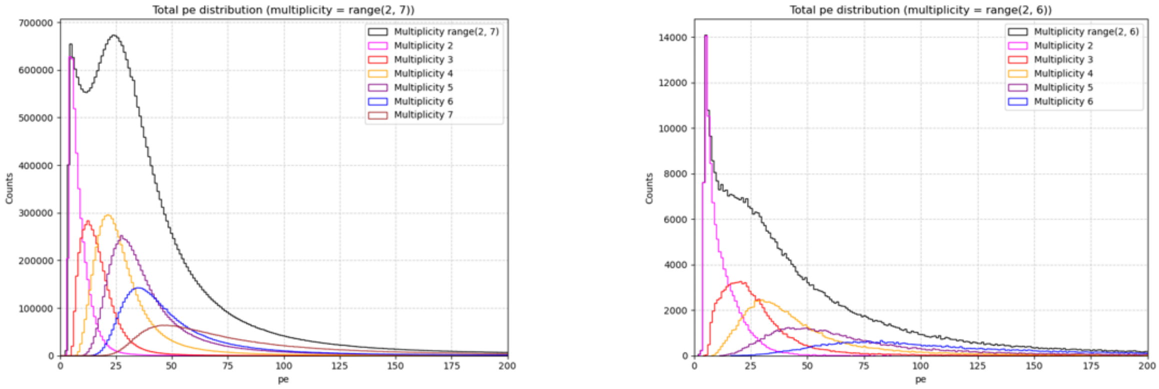

Figure 10. Charge spectra acquired in Milan (*left*) and Rio (*right*) with multiplicity contributions highlighted. In the figure titles, *multiplicity = range(2,7)* indicates that all events with multiplicities from 2 to 7 PMTs within a 10 ns window were considered in the analysis.

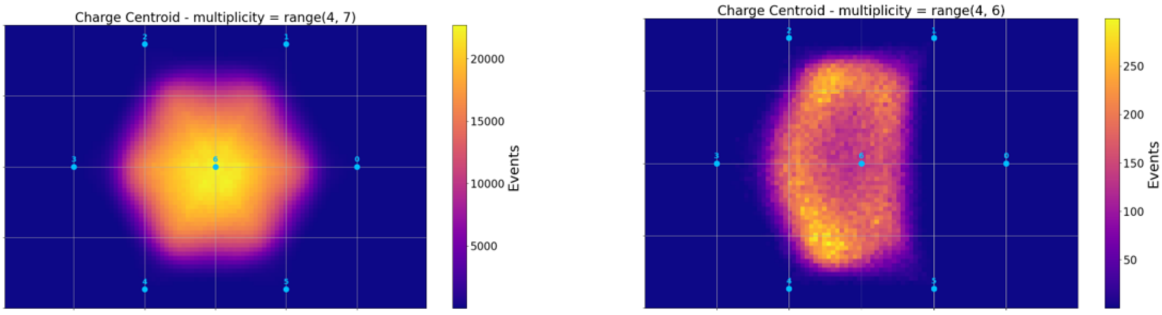

Figure 11. Charge centroids from multiPMT data acquisitions performed in Milan (*left*) and Rio (*right*). In the figure titles, *multiplicity = range(2,7)* indicates that all events with multiplicities from 2 to 7 PMTs within a 10 ns window were considered in the analysis.

An interesting result is the time distribution of the duration of coincidence events from the first hit in the event, with a clear peak at 3 ÷ 4 ns, figure 12. Connected to this is the clear possibility to study the evolution of the signal in an event looking to the different timestamp of the PMTs and the collected charge.

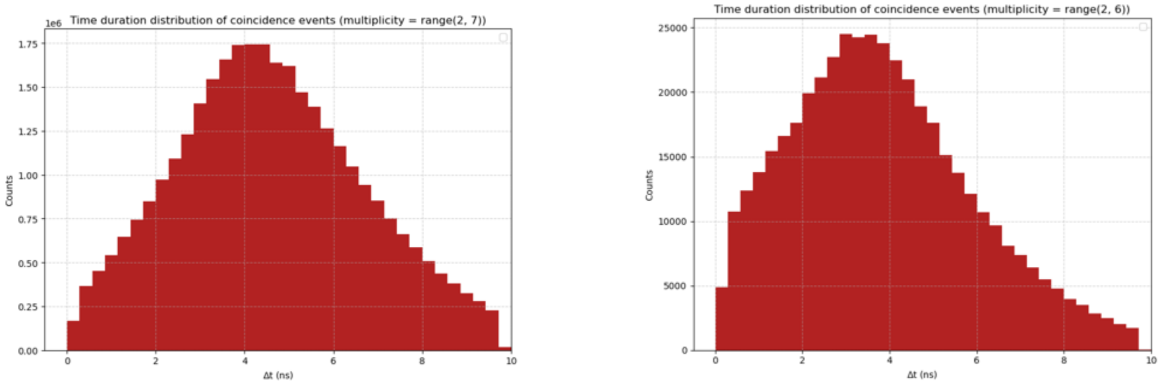

Figure 12. Time duration distributions of coincidence events for Milan (*left*) and Rio (*right*) multiPMTs. In the figure titles, *multiplicity = range(2,7)* indicates that all events with multiplicities from 2 to 7 PMTs within a 10 ns window were considered in the analysis.

5 Conclusions

These first results highlight the potential of the multiPMT as a possible photosensor for the SWGO experiment. In particular, this initial phase of performance monitoring at low altitudes represents a fundamental step, not only for the validation of the detector but also to test different configurations of Water Cherenkov Detector (WCD) units and water purities. The next key step will be the installation of a tracking system, in order to select events associated with muons and gain a better understanding of the information currently provided by the multiPMT. In the same perspective, of crucial importance will be the implementation in the firmware of the White Rabbit synchronization system, the introduction of fiber communication, and the use of real-time hardware triggers to define the selected events.

Acknowledgments

The SWGO Collaboration acknowledges the support of the following agencies and organizations for the ongoing R&D work towards SWGO: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina; Agencia Nacional de Promoción de la Investigación, el Desarrollo Tecnológico y la Innovación (Agencia I+D+i), Argentina; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil; Ministry of Science, Technology and Innovation (MCTI), Brazil; Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ Thematic Project E-26/211.342/2021), Brazil; Agencia Nacional de Investigacion y Desarrollo (ANID), Chile; Croatian Science Foundation (HrZZ) Project IP-2022-10-4595; Czech Science Foundation, Czech Republic; The Ministry of Education, Youth and Sports (MEYS), Czech Republic; Deutsche Forschungsgemeinschaft (DFG), Germany; Max-Planck-Gesellschaft (MPG), Germany; Ministry of Education, Universities and Research (MIUR), Italy; National Research Foundation of Korea, Korea; Consejo Nacional de Ciencia y Tecnología (CONACyT), Mexico; Universidad Nacional Autónoma de México (UNAM), Mexico; Fundação para a Ciência e a Tecnologia, I.P. (FCT); Fundação para a Ciência e a Tecnologia, Portugal; National Science Foundation (NSF), U.S.A.; The Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory, U.S.A.

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