A multiPMT for SWGO water Cherenkov detectors

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Abstract. Water Cherenkov detectors are playing a central role in neutrino physics, gamma-ray astronomy, and cosmic-ray research. These detectors usually rely on the use of large area photomultiplier tubes (PMTs) to detect Cherenkov radiation emitted by particles moving faster than the speed of light in water. Recent studies suggest that using multiple small area PMTs in a compact structure enhances the performance of these detectors. Such a solution has been adopted in several experiments. This work focuses on the design and optimization of a hemispherical module with several 3" PMTs, called multiPMT, and related electronics for possible use in the water Cherenkov detectors of the SWGO Experiment. This study shows that such devices have promising features in terms of both cost and performance compared to large-area PMTs. The cost per area of photocathode is similar to large PMTs even including the additional channels of electronics. Dividing the signal into multiple PMTs reduces requirements on the electronics max rate and max dynamic range. The enclosure which keeps the PMT face dry provides convenient housing for the electronics and allows for easy access in case of repair. Finally, the intrinsic directionality may prove useful for shower reconstruction and to the discrimination of gamma initiated showers against the hadron background.

1 Introduction

Observing the sky for ultra-high-energy and low-energy gamma rays has been explored through various techniques, both direct and indirect. Direct observation can be space-based, while indirect observation is ground-based. For indirect observation, Imaging Atmospheric Cherenkov Telescopes (IACT) techniques are exceptional for pointing resolution and sensitivity [1]. However, the ground array Water Cerenkov Detectors (WCD) technique is prominent because it offers a large field of view with a 100% duty cycle. This WCD technique has been utilized by various experiments in the Northern Hemisphere, including HAWC [2] and LHAASO [3]. These experiments are located at high altitudes of about 4000 meters above sea level—HAWC at Sierra Negra in Mexico and LHAASO on the eastern Tibetan plateau in China. Both experiments feature large arrays of Water Cherenkov Detectors.

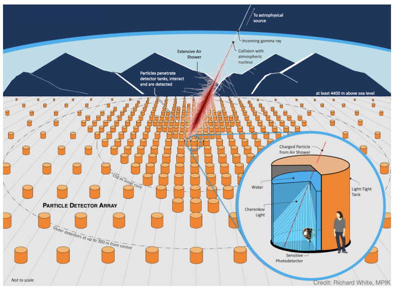

Figure 1: A diagram illustrating the ground-based methods for high-energy gamma-ray detection. Richard White, MPIK, and the SWGO Collaboration are acknowledged.

Recent results from the HAWC experiment have provided measurements of the all-particle cosmic ray energy spectrum from 10 to

500 TeV and insights into gamma-ray sources [4, 5]. LHAASO has discovered an "elbow" feature in the cosmic ray spectrum and detected gamma rays above 0.1 PeV, enhancing our understanding of high-energy cosmic phenomena [3]. Thus, a similar experiment in the Southern Hemisphere could be valuable for probing the Galactic Centre.

The Southern Wide-field Gamma-ray Observatory (SWGO) [6] is proposed to be a high-altitude observatory based on Water Cherenkov Detectors. It is designed to enhance and extend the capabilities of existing experiments. It is planned to be located in Pampa La Bola, within the Atacama Astronomical Park, Chile, at an altitude of 4770 meters and a latitude of 23 degrees south, featuring a high fill-factor core detector with enhanced sensitivity and a low-density outer array. This observatory will cover energies from hundreds of GeV to PeV, offering a near 100% duty cycle and a wide field of view 1.

SWGO objectives [6] include mapping large-scale gamma-ray emissions, accessing the Galactic Center, and supporting transient and multi-messenger astronomy, with significant potential for cosmic ray research and anisotropy detection.

SWGO (for an overview on status and prospects, see [7]) is investigating several detector technologies based on their performance to enhance directional sensitivity and muon identification. Ongoing studies show promising results for double-layered tanks with two separate compartments 2: the larger upper chamber for electromagnetic particle detection and the shallow lower chamber for muon identification [8].

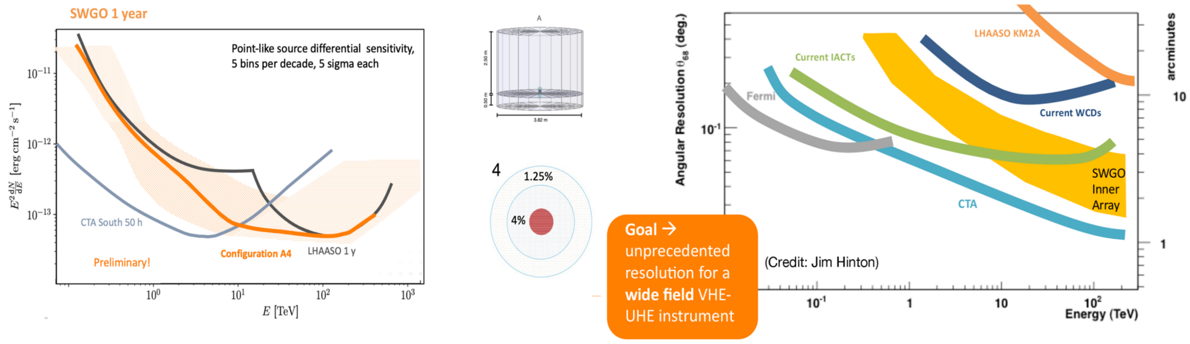

Figure 2: (left) The expected sensitivity to a point-like source after 1 year of SWGO observations (orange curve) [9, 10], as compared with LHAASO (black) sensitivities for the same observing time. The sensitivity with current IACT facilities CTA South (blue) after 50 hours of observations is also shown for comparison [11]. (right) Improved Angular resolution as compared to other experiments of WCDs and including space-based Fermi and IACT facilities of CTA [6].

The use of single large area PMTs is common in these experiments because of a large photocathode area [12, 8].

2 multiPMT Prototype Proposal

Traditional experiments [13, 2] typically rely on large area PMTs for detection. We are proposing an alternative solution to these large area PMTs which is multiPMT 3. The proposed configuration uses seven R14374 3-inch Hamamatsu PMTs [14] arranged in a hemispherical module. These PMTs are operated within a dry environment, with all electronic components securely enclosed using an acrylic dome and a steel base plate. Each PMT is individually connected to an active voltage divider and is equipped with a front-end board to ensure precise signal processing 5.

The main board for the data acquisition (DAQ) process, is strategically located at the bottom of the module 5. This setup ensures that each of the seven PMTs has its own dedicated channel for data acquisition, allowing for highly detailed and accurate detection capabilities.

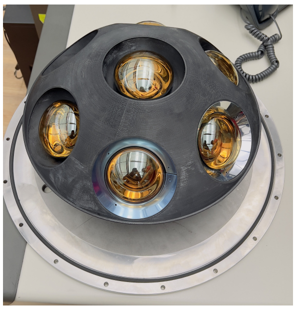

Figure 3: MultiPMT prototype finalised figure

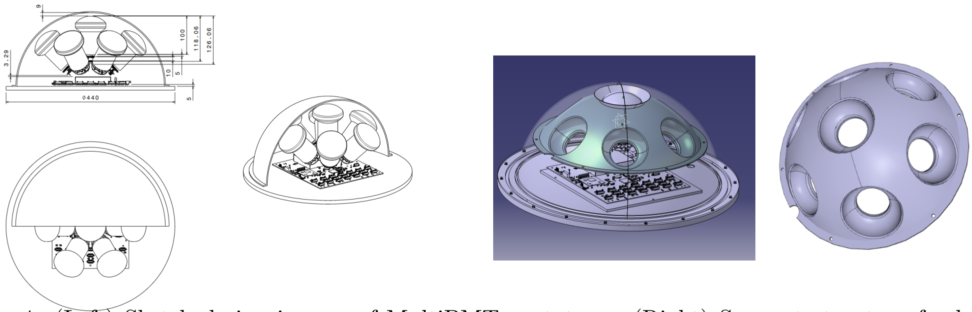

Figure 4: (Left) Sketch design images of MultiPMT prototype. (Right) Support structure for holding optical gel and reflectors for MultiPMT prototype.

The design of the multiPMT is highly flexible and has intrinsic directional sensitivity, as the PMTs cover all angles within the hemispherical configuration. This modular approach not only enhances the dynamic range and resolution but also provides significant advantages in terms of reliability and maintenance. In the event of a failure in one PMT, the modular nature ensures that the rest of the system remains unaffected, thereby preventing critical failures and ensuring continuous operation. Additionally, the multiPMT offers an dynamic range and performance at a competitive cost equivalent to single hamamatsu R5912 8-inches PMT, making it an efficient and robust solution for integration into SWGO tanks. This advanced design promises to elevate the capabilities of water Cherenkov detectors, providing equivalent timing resolution and overall improved detection performance.

Moreover, this design can be fully integrated into SWGO tanks, significantly improving their functionality through the use of integrated electronics. The multiPMT solution promises better overall performance compared to traditional large area PMTs. The results and further insights are discussed in next section, which includes a multiPMT electronics details and its test performed.

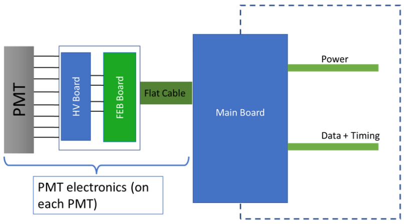

Figure 5: Schematic layout of the system showing the full chain from the PMT to the cabling. Ethernet connections from the Main board, as other critical components, are redundant for improved reliability

3 multiPMT Electronics

The multiPMT system's electronics consist of three main components: the High Voltage (HV) Active Board, the Front-End Board (FEB), and the Main Board. The HV Active Board uses the Cockcroft-Walton voltage multiplier to supply 11 different voltages required for the Hamamatsu R14374 3" PMTs [14]. This board is capable of generating up to 1500V with a power consumption of less than 4 mW.

The divider voltage drop has been optimized with respect to Hamamatsu specifications to increase PMT linearity. We made the optimization on a passive base, where it was easy to replace the resistors. A voltage drop configuration of 1-2-2 for the last three dynodes has been adopted, extending the linearity from single to 2000 photoelectrons at a gain of 3.5×10^6 as shown in figure 6. Subsequently, we implemented the active version, which we confirmed works the same, as shown in figure 8 in comparison with the large ones.

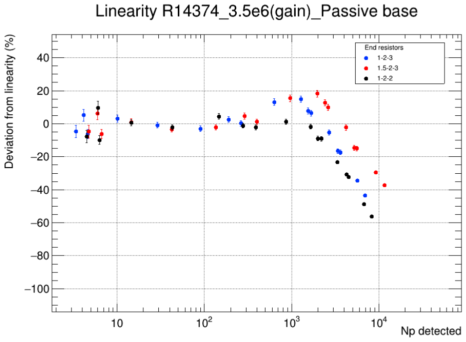

Figure 6: Linearity comparison of Hamamatsu standard divider with the optimized divider at a gain of 3.5×10^6.

With the active board, the charge spectrum of a single photon is well separated from the pedestal by a double Gaussian fit at a gain of 3.5×10^6, as seen in figure 7.

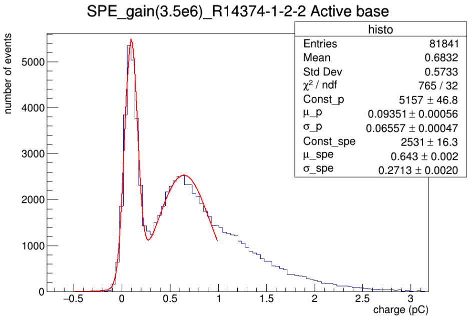

Figure 7: Charge spectrum of a single photon at a gain of 3.5×10^6, observed for the R14374 3-Inch Hamamatsu PMT with an optimized active divider having a voltage drop configuration of 1-2-2 at the end dynodes.

The observed performance in terms of linearity and TTS are compared to what obtained with commonly used large area PMTs from Hamamatsu. The comparison plot of the optimized divider for the R14374 is shown in figure 8, alongside other large area PMTs tested. With this end dynode configuration, the active board preserves transit time spread, achieving a TTS of 1.5 ns for 1 pe, as shown in figure 8.

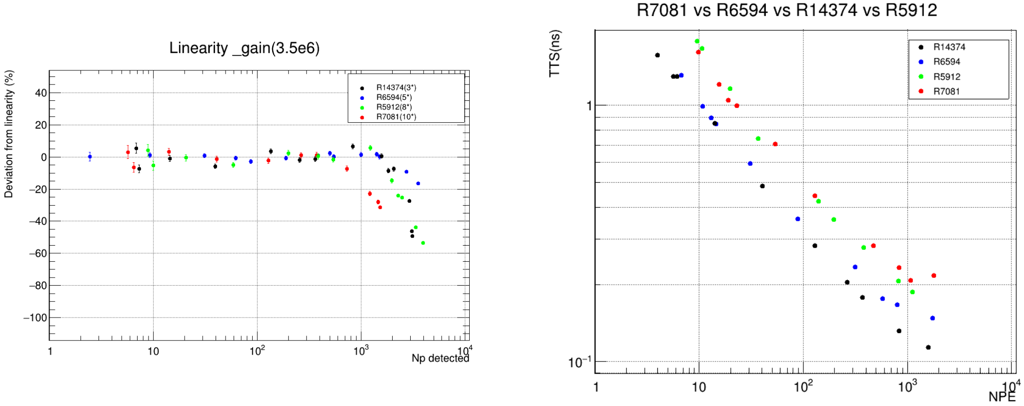

Figure 8: (Left) Linearity comparison of Hamamatsu PMTs [14] at a gain of 3.5×10^6: R14374 3-Inch (black), R6594 5-Inch (blue), R5912 8-Inch (green), and R7081 10-Inch (red). The 3-Inch PMT was tested with an optimized active divider, resulting in increased dynamic range up to 2000 pe. (Right) Transit time spread comparison of the same Hamamatsu PMTs at the same gain. The 3-Inch PMT preserves TTS with the optimized divider, achieving a linear fit TTS of 1.5 ns for 1 pe.

The Front-End Board handles fast timing and pulse charge measurements, and data transfer to the Main Board. It offers an adjustable charge dynamic range around 700 photoelectrons at a gain of 3.5×10^6 as seen in figure 9.

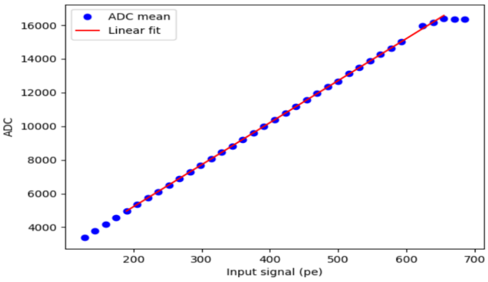

Figure 9: Front-End Board linearity observed up to 700 pe.

The Main Board, shown in figure 10, manages all front-end boards, providing time synchronization and network connections. It is designed to acquire up to 10 channels.

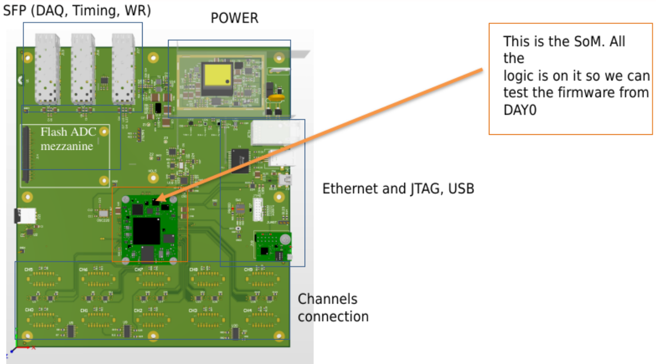

Figure 10: Diagram of the Main Board designed for the multi-PMT prototype.

4 multiPMT Performance

Expected performance of multiPMT has also been analyzed through GEANT4 [15] simulations using the HAWCSim framework [9]. The results are shown in figure 11. The multiPMT performs equivalently to the large area Hamamatsu R5912 8" PMT. Key features such as the optical gel and aluminum-based reflectors were beneficial.

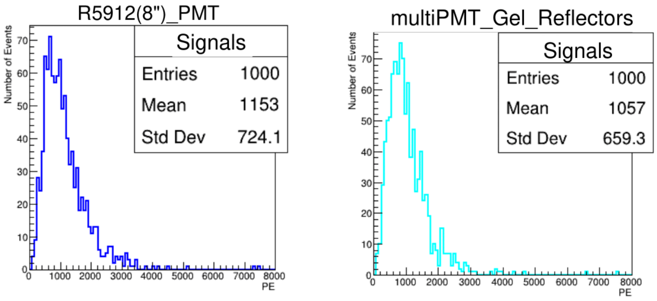

Figure 11: Performance comparison: (Left) Single R5912 8-Inches PMT, (Right) multiPMT with optical gel and reflectors, using GEANT4 simulations

Another critical aspect of the multiPMT's performance is its ability to distinguish between gamma and hadron shower particles. Identifying muons, which are significant constituents of hadronic showers, is essential for this differentiation. To assess the muon tagging capabilities, we injected particles using cosmic shower data from CORSIKA [16] into a tank equipped with a single multiPMT. Our preliminary results in figure 12, enhanced by machine learning techniques, demonstrated that the electromagnetic component of showers produces a uniform light emission, while muons produce an asymmetric emission pattern, leading to more light being detected on certain parts of the matrix. This distinct asymmetry in light distribution allows the multiPMT to accurately identify muons and effectively discriminate between different types of shower particles, thereby enhancing the overall performance of the detection system

Figure 12: Output of a CNN algorithm for muon identification at tank level exploiting muon directionality.

5 Conclusion

The multiPMT configuration offers several advantages over traditional large area PMTs, including enhanced detection capabilities, reliability, and cost-effectiveness. Its integration into the SWGO tanks promises to improve the overall performance of water Cherenkov detectors significantly.

Acknowledgements

For a complete list of acknowledgements, please refer to the SWGO Acknowledgements page: SWGO Acknowledgements.

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