Wavelength Shifting Plates with Smaller Photomultiplier Tubes for the Southern Wide-Field Gamma-Ray Observatory

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SWGO The Southern Wide-field Gamma-ray Observatory

1) Abstract:

The Southern Wide-Field Gamma-Ray Observatory (SWGO), a proposed ground-based particle detection instrument, represents an exciting development in the field of high-energy astrophysics. Its primary goal is to map transient and variable multi-wavelength and multi-messenger phenomena, which will allow us to develop our understanding of high-energy events in the universe. SWGO's proposed configuration with 6000-8000 water Cherenkov tanks, arranged in inner and outer arrays, allows for the capture of gamma-ray induced particle showers with precision. The detector array will be located at high altitudes at around 4.4km or higher, likely in South America, with a wide field of view, high duty cycle and higher sensitivity. As no Gamma-ray observatories of such scale or kind currently exist in the southern hemisphere, it would allow for a unique perspective of the southern sky, particularly in observing phenomena demonstrating large scale gamma-ray emissions such as the galactic centre and Fermi Bubbles. Such information would complement data from existing instruments such as HAWC, LHAASO and the future CTA in developing our understanding of high-energy phenomena in the universe.

This proposed detector configuration aims to replace larger photomultiplier tubes (PMTs) with ones of a smaller size, with the integration of wavelength shifting (WLS) plates to enhance sensitivity and optimize efficiency, to ultimately save costs. Monte Carlo simulations are being developed to investigate the performance of different WLS plate geometries, while a prototype is being built for further testing.

2) Water Cherenkov Detectors:

- High-energy gamma-rays decay into particle showers in the atmosphere.
- Water Cherenkov detectors (WCDs) at Earth's surface are used to detect these particles, via the emitted Cherenkov radiation in the tank.
- Traditionally large PMTs are used, however the proposal of smaller PMTs with WLS plates can cut down on costs.
- SWGO will have an array of WCDs each with two light-tight layers.
- The upper chamber is equipped with a large upwards facing PMT, for time-sensitive particle detection.
- The lower chamber houses a smaller PMT with the proposed WLS plates, for characterising cosmic-ray induced showers via muon-tagging.

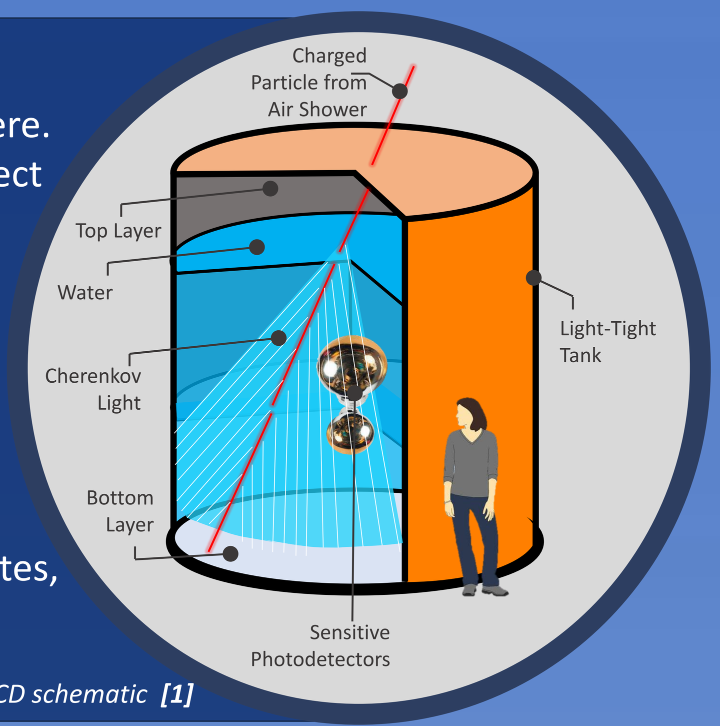


Figure 1 – SWGO WCD schematic **[1]**

3) Detector Design:

- 3-inch PMT embedded in the centre of a WLS plate.
- WLS edges are polished and reflective.
  - Only the top surface of the WLS plate is reflective.
- PMT is potted in a tube, which supports the WLS plate collar.
- There will be a < 1mm gap between the PMT and WLS edges, maintained via spacers.
- The unit is adjustable and secured facing downwards.

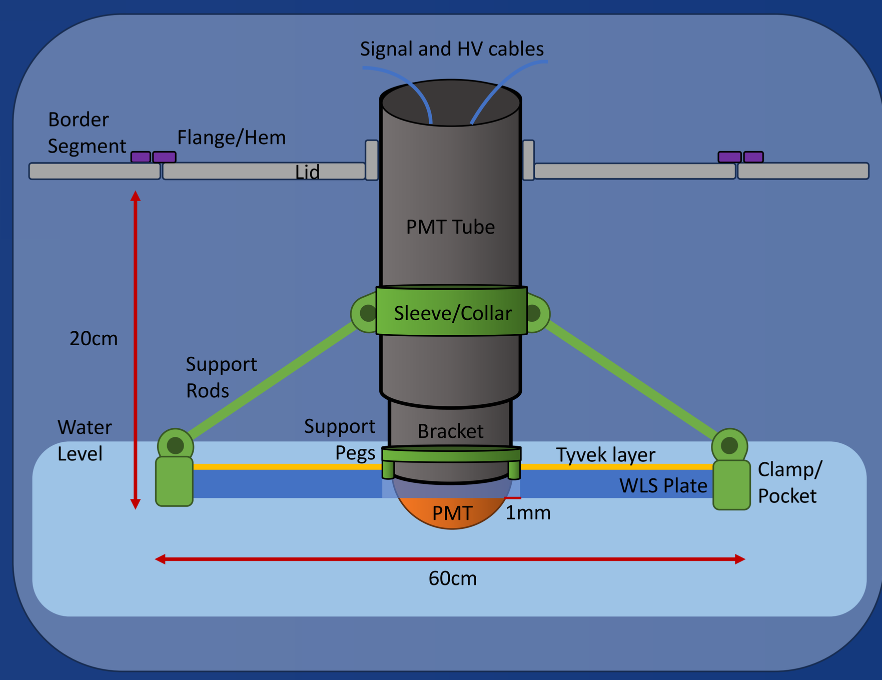
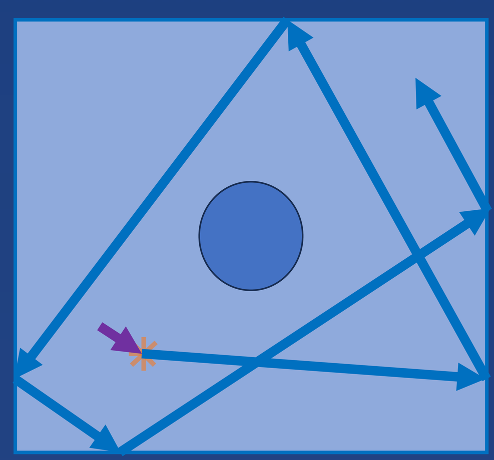


Figure 2 – WLS plate mechanical support schematic

4) Wavelength Shifting Mechanics:

- WLS plates absorb incoming photons, usually at a shorter UV wavelength, and re-emit at longer wavelengths in the blue.
- The WLS plate has short and long attenuation lengths, for the UV and blue light absorption respectively.
- This is dependant on the dopant / fluor used in the WLS plate.
- Upon absorption the blue light is isotropically re-emitted, and will reflect off the plates' reflective edges or via internal reflection, until either being re-absorbed, refracting out, or being detected by the PMT.
- The geometry of the WLS plate can also affect how long the photons path length is.



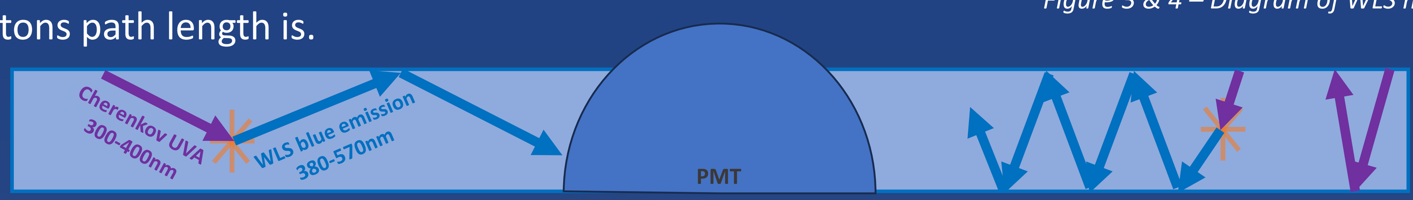


Figure 3 & 4 – Diagram of WLS mechanics

5) Monte Carlo Simulation:

- A Monte Carlo Simulation in Python has been developed to test different WLS plate geometries, as well as other properties, to investigate its performance.
- The simulation uses the Beer-Lambert law to determine the absorption lengths based on random probabilities.

$$I = I_0 \times e^{-\mu x}$$ [2]

- 10000 photons are randomly distributed uniformly across one quadrant of the plate.
  - Representing a constant Cherenkov flux.
- The PMT hit efficiency is scaled to the area of the plate used in the run.
- The same random seed is used for all the results below, for easier comparison.
- The simulation loops through varying attenuation lengths, sizes and thicknesses and compares the performance with a 3-inch PMT as the detector.
- The hit efficiency per run is measured with respects to the plate size/area, as well as the timing distributions.

6) Attenuation Lengths :

- Long attenuation length (LAtL) affects the blue light absorption and short attenuation length (SAtL) for UV absorption.
- The results shown below are measured with a 60 cm plate of 10 mm thickness.
- Timing distributions in Figures 5 and 6, as well as hit efficiency in Figure 7 show that longer LAtLs and shorter SAtLs result in more hits for this plate size.
- The SAtL does not affect the timing distribution significantly

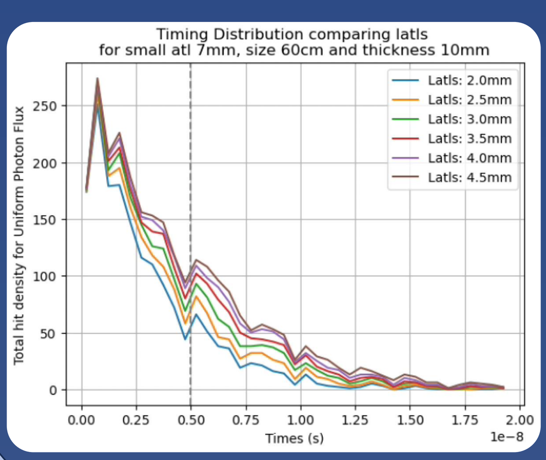


Figure 5 – Timing distribution for LAtLs

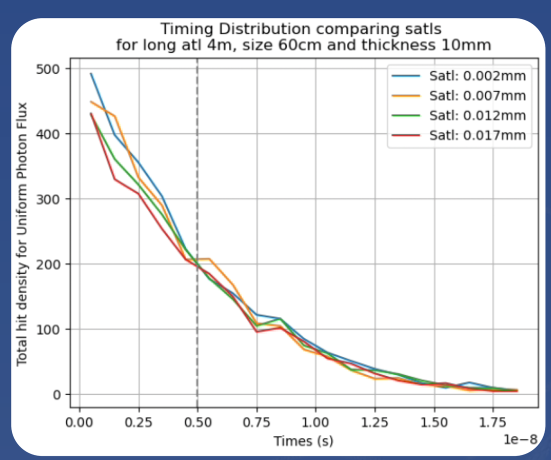


Figure 6 – Timing distribution for SAtLs

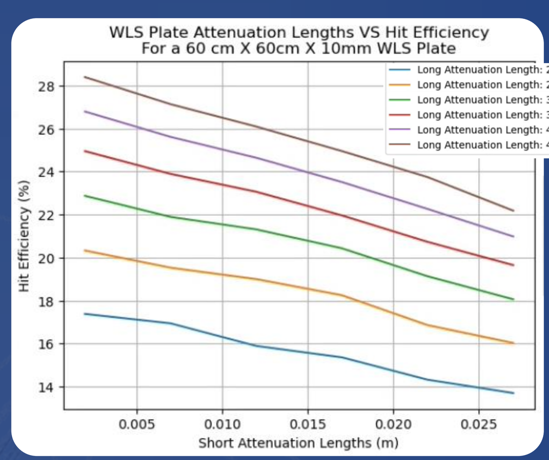


Figure 7 – SAtLs VS Hit efficiency

7) WLS Plate Geometries:

- The timing distribution in Figure 8 shows that smaller plates have a better timing resolution.
- Figure 9 shows how sensitive the LAtL is to the number of hits within 5 ns for each plate size.
  - Figure 10 shows a similar plot but for each plate thickness, resulting in a peak at a thickness of 10 mm.
- Figure 11 shows that for a constant SAtL and LAtL, larger plates result in a higher hit efficiency, due to the larger area.

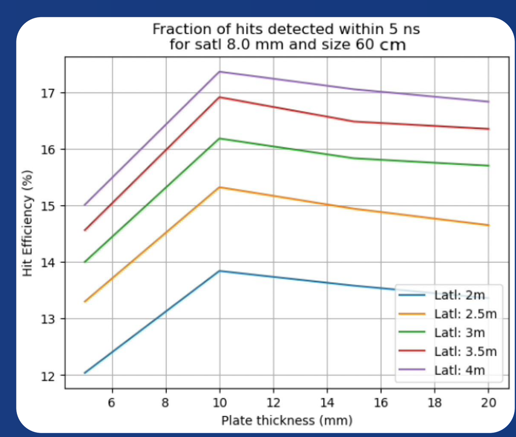


Figure 10– Number of hits detected VS thickness in 5 ns

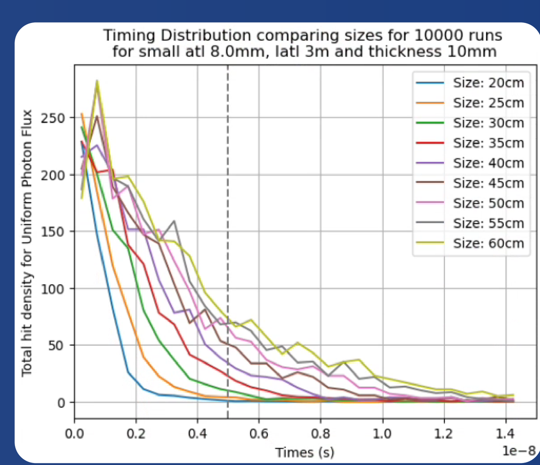


Figure 8 – Timing distribution for plate sizes

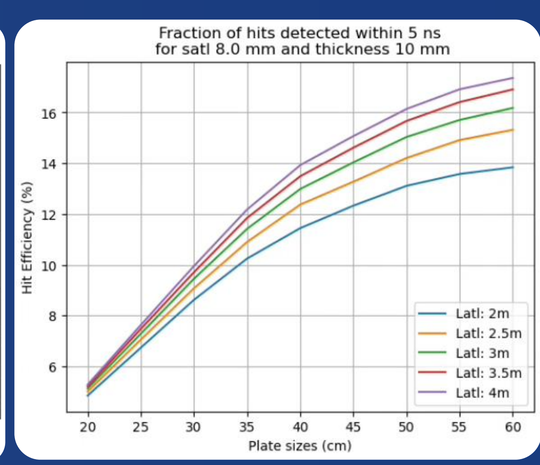


Figure 9 – Number of hits detected VS size in 5 ns

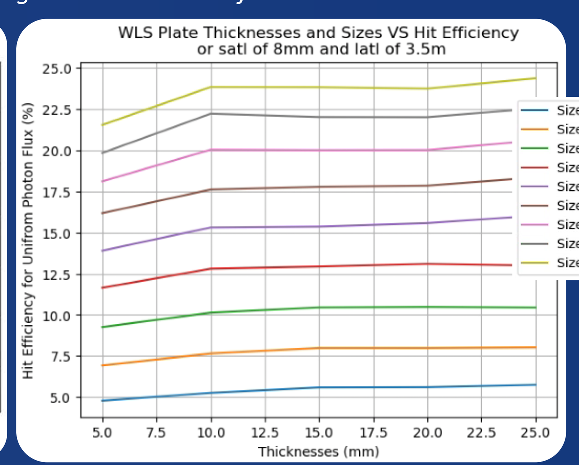


Figure 11– Plate thicknesses VS Hit efficiency

8) Simulation Analysis

- Based of these preliminary results, a WLS material with a small SAtL and long LAtL would result in a higher hit efficiency.
- The hit efficiency also improves with larger plate sizes, however the timing resolution worsens.
  - For accurate muon detection, a time delay of < 5 ns is necessary [3].
- A WLS plate thickness of around 10 mm is shown to provide the best hit efficiency within 5ns.
  - As the thickness of the plate increases, the time delay increases.
- Longer attenuation lengths result in detection of more photons with longer time delays.

9) Leicester Cherenkov Detector:

- WLS plate mechanical support structure is currently being constructed and tested (Figure 12).
- A $1m^3$ Intermediate Bulk Container (IBC) filled with de-ionized pure water and lined with Tyvek for photon reflection, houses the prototype (Figure 13).

Figure 12 – WLS support structure

Figure 13 – Black IBC WCD tank

Figure 14 – WLS plate spacers

- A 3-inch Hamamatsu R14374 PMT is potted into a PVC tube, to which the WLS support system is attached to via a collar.
  - The Microbase V2.4 is used to supply the high voltage to the PMT.
- The small gap between the PMT and WLS plate is maintained with a 3D printed spacer (Figure 14).
  - The pocket clamps, collar and support rods are also 3D printed using water safe polypropylene plastic.
- A fibreglass flange/hem is constructed on the lid to provide a light tight boundary for the tank.

10) Future work:

- Dry runs of the PMT and WLS plate will be conducted in the IBC tank, before filling the tank with de-ionised water.
- Measurements with and without the WLS plates in water will be collected for comparison with a large 8-10-inch PMT.
- Different plate sizes, thicknesses and materials will be tested experimentally and compared to simulation results.
- Tests will be conducted on potential SWGO electronics, which include the MicroBase—a PMT HV PSU and preamplifier developed by IceCube collaborators **[4]** —using the prototype and tank.

References:

[1] SWGO (2019) The Southern Wide-field Gamma-ray Observatory(SWGO) Available at: https://www.swgo.org/SWGOWiki/doku.php (Accessed: 04 April 2024).
[2] Wavelength shifting fibers (1990) kuraray. Available at: http://kuraraypsf.jp/psf/ws.html (Accessed: 04 April 2024).
[3] Muon detection at the LHC (1990) Pieter Duinker, Karsten Eggert, Available at: https://cds.cern.ch/record/220520/files/p452.pdf (Accessed 4th April 2024).
[4] Kelley, J.L. and Wendt, C. (2021) 'Evolution of the IceCube data acquisition system for IceCube-GEN2', Journal of Instrumentation, 16(09). doi:10.1088/1748-0221/16/09/c09017. (Accessed 5th April 2024).

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