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EXECUTIVE SUMMARY OF THE THESIS

Design of a Cherenkov detector for very-high-energy gamma rays

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

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1. Introduction

In the last decade there has been an important development of multi-messenger astronomy: the coordinated observation and interpretation of information from photons, cosmic rays, neutrinos and gravitational waves. In this context, very-high-energy (VHE) gamma rays (from 100 GeV to 100 TeV) are an element of particular interest for research since they can carry information about many extreme astrophysical objects and high-energy phenomena.

Due to the declining flux emitted by cosmic sources with increasing energy, photons in this energy range can not be studied with direct measurements, therefore they are detected indirectly from ground-based instruments, by observing the particle cascades they produce in the atmosphere: the so-called Extensive Air Showers (EASs). Two types of instruments are used to observe VHE photons: Imaging Atmospheric Cherenkov Telescopes (IACT), which detect the light produced by the shower particles as they traverse the atmosphere, and ground Extensive Air Showers (EAS) detectors, which directly sample the shower particles at ground level.

Until recently, IACTs dominated the field of ground-based gamma-ray astronomy with three major facilities providing coverage of both hemispheres: H.E.S.S., MAGIC and VERITAS. EAS detectors were typically composed by sparse arrays of scintillation detectors distributed over large areas at moderate altitudes, which sampled only a small fraction of the shower particles.

The first observatory to change the role of EAS detectors was Milagro (1999-2008) by introducing water Cherenkov technology: in a water detector, EAS particles generate Cherenkov light by moving in the water at relativistic speed, providing an amplification effect and therefore making the particle detectable also by light sensors that do not intersect their trajectory. This innovation, combined with its large field of view and high duty cycle allowed Milagro to be the first EAS array capable of continuously monitoring the overhead sky for sources of TeV gamma rays and to discover new sources in that energy range. Milagro's success was in fact followed by the construction of of two larger facilities: HAWC first (Mexico 2015) and then LHAASO (China 2019) situated over 4 km altitude and therefore capable of detecting a higher number of shower particles.[4]

Both HAWC and LHAASO have achieved very important results in the field of gamma rays and cosmic rays research, but both facilities are situated in the Northern hemisphere. The Southern hemisphere has a privileged view of the galactic center (GC) region, where most galactic accelerators and astrophysical sources in general are located, therefore a detector placed in the Southern hemisphere would be an important tool for research and its observations would complement the ones of HAWC and LHAASO.

An international Southern Wide-field Gamma-ray Observatory (SWGO) collaboration has therefore formed to develop the plans for a ground-level particle detection based observatory, aiming for a performance at VHE comparable to that of LHAASO, and possibly better in the $\sim 100\ GeV$ region. The observatory will be located in South America at a latitude of -30° to -10° and an altitude of 4.4 km or higher.[1]

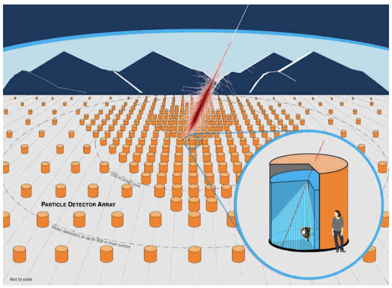


Figure 1: Qualitative representation of SWGO's layout.

The detector will be based primarily on water Cherenkov units (fig. 1), for the realization of which there are several variables that have to be studied, such as the type and position of the photosensors that will detect the Cherenkov light and the materials used. To study all these variables, both analytical and experimental means are being used by SWGO. Istituto Nazionale di Fisica Nucleare (INFN) and the other Italian SWGO partners are working on the construction of a prototype Cherenkov detector in Politecnico di Milano's labs to test them.

2. Methods

2.1. Study on particle detection as a function of the water level

Structural studies determined that the floor of Bovisa's B6 labs (the first installation site considered) could handle safely a pressure of 2.0 t/m^2 for long periods of time, equivalent to a water level of 2.0 m, inferior to the originally planned 2.7 m. It has therefore been decided to study the detector's performance as a function of the water level. This could be useful to determine whether it was worth installing the tank in B6 labs with a lower water level with respect to the one originally considered (at least for single layer tests), or it would be preferable to find a different location; but it could also give important information for the studies on tank geometries.

An analytical study has been carried out using the HAWC observatory simulation software known as HAWCSim. Two showers of 12000 muons have been generated in a disc over the tank, with an azimuth angle ϕ in the range 0 - 360° and zenith angle θ extracted from the distribution $\cos^2\theta$: the first shower's particles had an energy of 1 GeV, and the second with 10 GeV energy. Each shower's interaction with the tank has been simulated for five water levels: 1.65 m, 2.00 m, 2.35 m, 2.70 m and 3.05 m and the first 10000 particles to enter the water have been analyzed.

The main difficulty with this study was that the reference configuration of sensors that had to be simulated was composed by one 10" photomultiplier tube (PMT) and four 5" PMTs: the 10" PMT was already implemented in HAWCSim, as well as an 8" PMT and a 3" PMT, but a 5" PMT was not available. To bypass this problem, 8" PMTs have been used, and then scaled to 5" during the analysis phase.

HAWCSim carries out the simulation of the particles' interaction with the tank and the photosensors and it gives an output file that can be converted in .root. To analyze it and extract the relevant data from it, the implementation of a macro in C++ was necessary, where the selection of the first 10000 particles has been implemented, as well as the area scaling for the PMTs.

Three parameters have been assessed to study the behaviour of the tank's detection capability as a function of the water level[2]:

- detection efficiency (how many particles have been detected by a PMT configuration with respect to the total number entering the water)
- number of photoelectrons (PE) detected
- standard deviation (SD) of the first photon time (it gives an idea of how the detection precision varies with the water level)

An analogous study has been performed on electrons (1 GeV energy) to verify the model's reliability: electrons in fact would loose energy faster with respect to muons and so, with the increase of the water level, they should produce a lower number of photons. If the model was correct, this should be seen in the number of PE detected and in the efficiency values.

2.2. Design of the PMT holder

In order to fulfill the goals of the prototype tank, it must be possible to test different types of sensors inside it, and to adjust the configuration following the tests' results, changing the sensors' position may be needed frequently. For this reason a structure was needed, capable of holding different sizes and shapes of detectors in as many configurations as possible and with a simple mechanism so they would be easy to move.

Maintaining high water purity in the tank is a primary requirement: it guarantees the lowest possible attenuation for UV Cherenkov light and, in addition to that, its properties can be well known and constant. A study on materials compatible with purified water and suitable with the structure's requirements has been carried out as a first design step. At the end, stainless steel (AISI 304) has been selected for its good mechanical properties and availability on the market.[3]

A large structure, able to handle all the proposed photosensors' configurations (fig. 2) has been designed in SolidWorks and the load simulations demonstrated that it could handle the PMTs' weight.

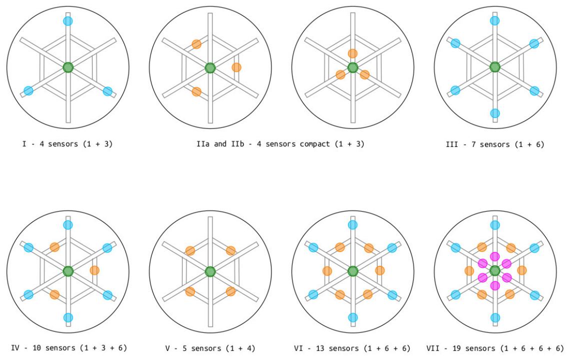


Figure 2: Possible PMT configurations assessed for the hexagonal holder, configuration V is the reference one.

That structure's construction however has been postponed in favour of a smaller more economic one (fig. 3) that allows to start the tests with the reference configuration (1x 10" PMT + 4x 5" PMT). Its pieces will be recycled for the larger one afterwards, when other sensors will arrive for testing.

For the structure's realization, stainless steel perforated flat bars (1000 mm x 50 mm x 1 mm) have been acquired, from which all the pieces have been manufactured in Politecnico's workshop. The structure is composed by three types of parts:

- flat bars (the arms of the cross, fig. 4a)
- C-profiles (reinforce elements used to keep the structure's shape and hold the PMTs, fig. 4b)
- L-profiles (raise the structure from the tank's floor, fig. 4c)

The use of C-profiles to hold the photosensors allows easy placement and removal, which is a key requirement for the prototype tank's project. Rubber gaskets will be installed around the PMTs, for better holding, and under the L-profiles, to protect the tank's internal PVC cover.

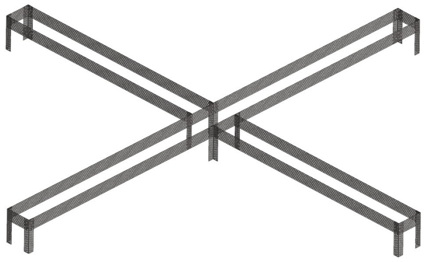
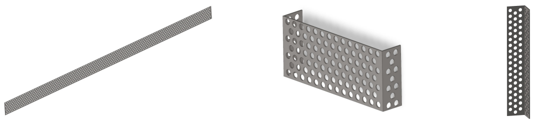


Figure 3: 3D model of the cross holder



(a) Part a (b) Part b (c) Part c

Figure 4: Parts composing the cross holder: part a is the base piece bought from the supplier (1000 mm x 50 mm x 1 mm perforated flat bar) from which part b and part c can be obtained.

3. Conclusions

The construction of the prototype tank in the new site is now in progress and it will be com-

pleted in the next months. The simulation work on the tank with different water levels in fact, proved that the detection performances improve with a higher water level for muons: a linear increase of detection efficiency with the water level has been obseerved, as well as an increase of the number of photoelectrons (PE) detected and a reduction of the SD of the detection time of the first photon. Results are very similar between 1 *GeV* and 10 *GeV* muons, although performances are generally slightly better for the higher energy level. These results led to the change of the installation site from the original one inside a lab to an open-air site able to handle a higher pressure in order to fill the tank up to a higher water level and maximize the detector's capabilities.
The plots reported here are for the central 10" PMT (which ID number is 1), considering the coincidence parameter: a particle's detection is considered valid only if at least two produced PE are detected by a PMT in an interval of 30 *ns*.

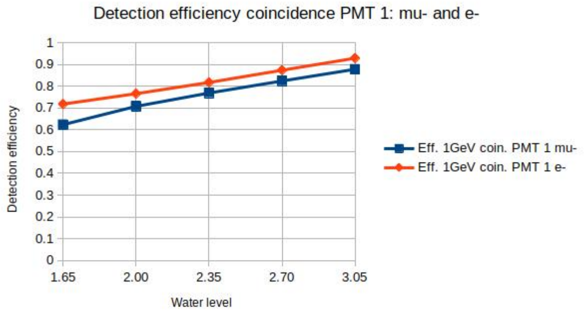


Figure 5: Detection efficiency of the 10" PMT, with coincidence parameter, for $\mu-$ and $e-$ of 1 GeV energy.

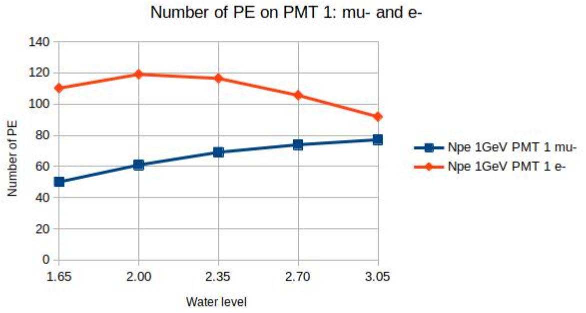


Figure 6: Number of PE detected by the 10 " PMT, with coincidence parameter, for $\mu-$ and $e-$ of 1 GeV energy.

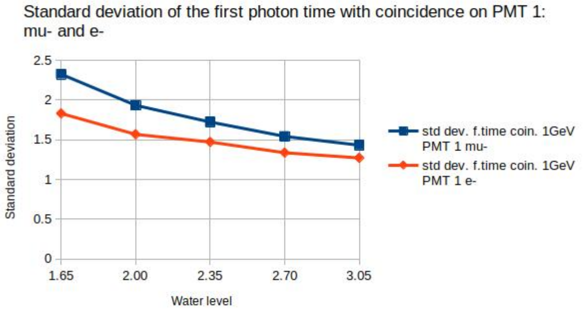


Figure 7: Standard deviation of the first photon time on the 10 " PMT, with coincidence parameter, for $\mu-$ and $e-$ of 1 GeV energy.

The additional study on electrons, done to verify the model's reliability, showed that the detection efficiency increases but at a lower rate with respect to muons (fig. 5), while the number of PE increases up to 2.00 *m* of water and then decreases (fig. 6); the SD decreases, as for muons, but at a lower rate (fig. 7).

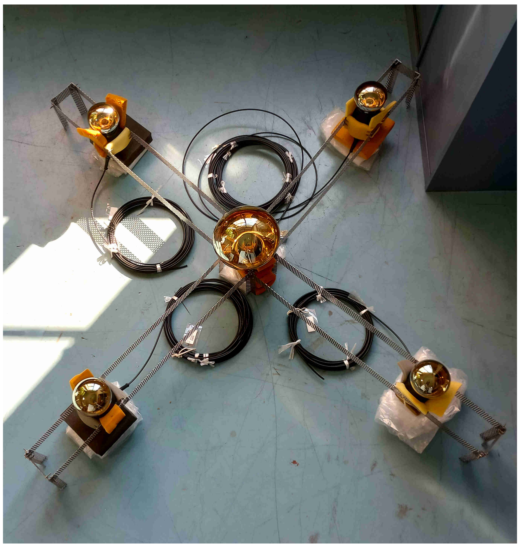


Figure 8: Holding test of cross holder using the 5 PMTs of the reference configuration (before reinforcement of the cross arms).

The PMT holder has been assembled and the installation of the 5 reference configuration PMTs has been tested successfully (fig. 8). The structure has also been manually lifted after mounting the PMTs to test its robustness and it has been decided to add two more C-profiles on each arm of the cross as further reinforcement.

3.1. Future development

The next step in the prototype tank project development will be the design of the lifting system for the PMT holder. The materials have already been selected but a system of pulleys over the tank will have to be designed, as well as a method to control it precisely from the lab.
The data acquisition from the light sensors will have to be tested too: the PMTs' cables will have to be connected to a station inside the lab, which will have to be equipped for receiving signals from all the types of sensors that will be used.
A procedure to regularly assess water's purity will have to be instituted, but most importantly, a suitable cover for the tank will have to be designed, so that the water is kept clean. The sensors' cables will of course need to pass through it.
After all these steps are concluded and the prototype tank is fully completed and operative, the tests with the reference configuration will start. As soon as the detector is calibrated, it will be ready to be used for testing new types of sensors.

References

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