Light collection optimization studies of HAWC water Cherenkov detectors by means of simulations

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***Abstract*. The High Altitude Water Cherenkov (HAWC) is a large field of view gamma-ray observatory and will locate in Mexico at an elevation of $4100m$ (lat. $19°$ and long. $97°$). The detector initial design considers about 900 cylindrical shape water tanks with a centered Hamamatsu PMT (R5912) at the bottom. In this study the local large surface light collectors around the PMT have been designed to increase the number of detected optical photons, which will reduce the energy threshold of the detector and allow to obtain clearer muon signatures as this is important for the hadron/gamma separation. We find that the use of light collector will not significantly worsen the timing resolution (due to the geometry properties), that is important for the precise reconstruction of the primarys direction. The simulation study is performed by means of GEANT4 program for the different design of PMTs, light collector geometries and optical properties of its surface. The simulation results demonstrate that the signal can be increased up to factor 2 using relatively small light collectors ($\simeq 1m$ in diameter).**

***Keywords*: Water Cherenkov detector, Monte-Carlo simulation, Light collectors**

I. INTRODUCTION

The water Cherenkov detectors have been in large use during the last 20 years in high energy and Cosmic Ray physics [?],[?],[?]. Dependent on the requirements of physics different types of light collectors have been used for the water Cherenkov detectors. For an uniform response the diffuse reflectors covering the water volume or a wave length shifter (WLS) material dissolved in water [?] can be considered optimal. This cant be considered a good solution if temporal characteristics are important. For a large water volume if a fast response is important, only local (around the PMT) reflectors should be considered optimal. In this case one should expect some loss of uniformity due to the specific Cherenkov light emission. The local reflectors with specular and diffuse surfaces were also of great interest (see [?] and references therein). Well established light collectors (Winston cone and small angel cones, which have good efficiency of light collection for small aperture angles [?],[?]) are not optimal due to the Cherenkov large emission angle in the water. For the EAS detectors the light collection system should be optimal for both the muon and electromagnetic components. These two components have different light emission topology and the optimization should include some compromise. The specular collectors though have better collection power but are sensitive to the light source topology and also exist the stable surface material problem in the water. The diffuse collectors have less collection power but are easier for construction and cheaper in price. In this study the optimization of local light collectors have been done by means of simulations. The production and transport of optical photons have been performed using GEANT4 [?] program.

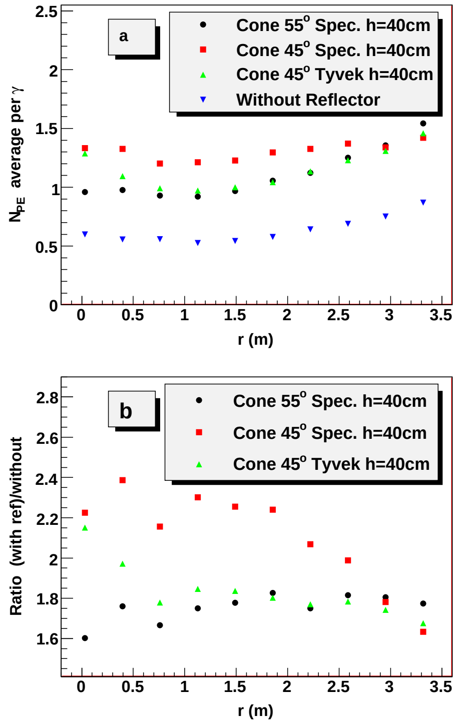

Fig. 1: N_{PE} dependent on radial distance from PMT for $designI$ and for different light collectors (a). N_{PE} ratios with and without a light collector (b)

II. GENERAL DESCRIPTION

For the vertical muons the number of the photoelectrons (N_{PE}) produced by the optical Cherenkov photons approximately (neglecting the optical photon scattering

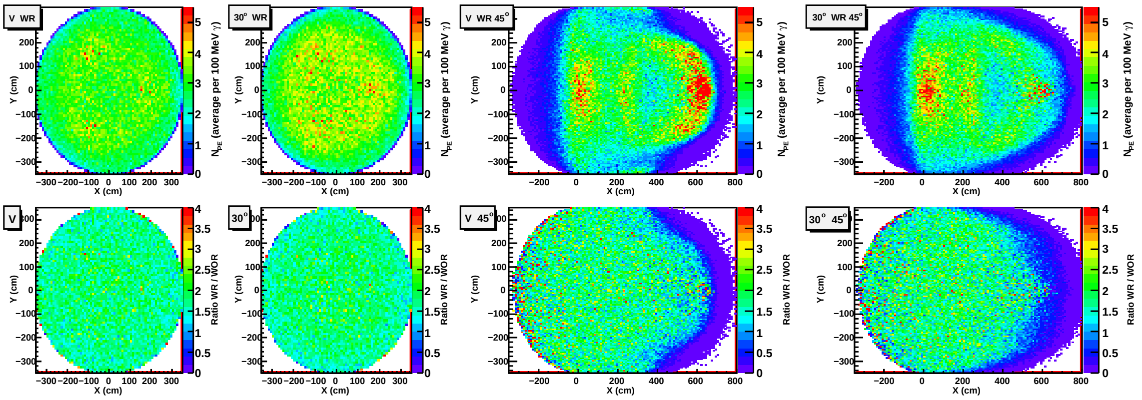

Fig. 2: N_{PE} per $100MeV$ γ dependent on the Cartesian coordinates of gamma incidence at the top of the tank for the $designII$. Upper row with conic $45°$ ($h = 40cm$) diffuse reflector and the bottom row are the corresponding ratios with and without the reflector. Leftmost two are for the vertical γ and rightmost two for the zenith angle $45°$. The first and the third columns are for vertcal orientation of PMTs and the second and the fourth for $30°$ orientation.

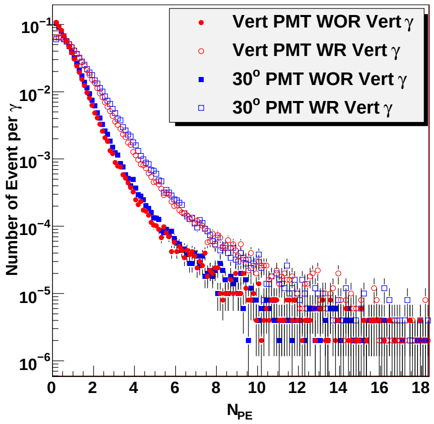

Fig. 3: N_{PE} normalized distributions of single PMT for $100MeV$ γ and for $designII$.

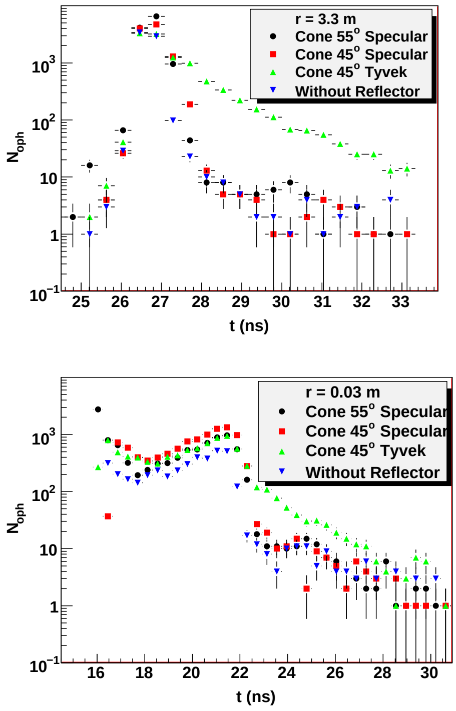

Fig. 4: The time distributions of optical photons for two different positions and for $designI$

and the surface geometry of PMT) is:

$$N_{PE} = \int \frac{2C(\lambda)Q(\lambda)\arcsin\left(\frac{r_0}{r}\right)\exp\left(\frac{-r}{L_0 \sin\theta}\right)d\lambda}{\pi \tan\theta} \tag{1}$$

Where λ is the wave length of the optical photon, $C(\lambda)$ is the spectrum of Cherenkov photons, $Q(\lambda)$ is the quantum efficiency of PMT, L_0 is the absorption length in the water, r_0 is the radius of PMT, r is the distance of the muon track from the PMT and θ-is the Cherenkov angle. It is difficult to give an approximate analytical expression for the gammas. Dependent on the energy of gamma it can include two parts: one similar to (**??**) due to shower high energy electrons and the other more chaotic conditioned by the low energy electrons.

There are different options to increase N_{PE}: the use of PMT with large cathode surface; multiple PMTs; local light collectors; WLS material dissolved in water or combination of all of them. Detector volumes having cylindrical symmetry are good enough for particles having direction parallel to cylinder axes (in our case vertical). For non vertical particles some part of volume can be less sensitive (see (1)). This part will increase with the increase of the zenith angle and somehow can be reduced using all the above-mentioned options. To optimize the light collector design two simulation setups are considered: one includes a cylindrical water volume having $7.3m$ diameter (maximum possible diameter of water tank that is now in consideration in HAWC collaboration) and $\simeq 5m$ height with centered upward facing

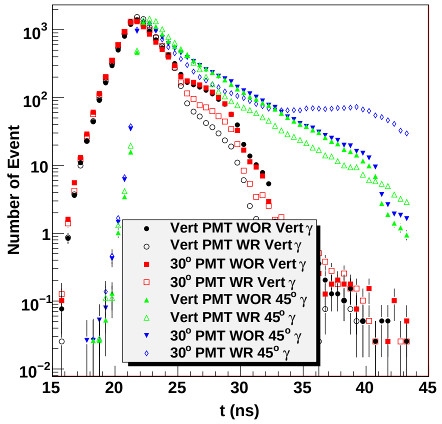

Fig. 5: Time spread of sum signal for $designII$ and for the same combinations mentioned in Fig 2

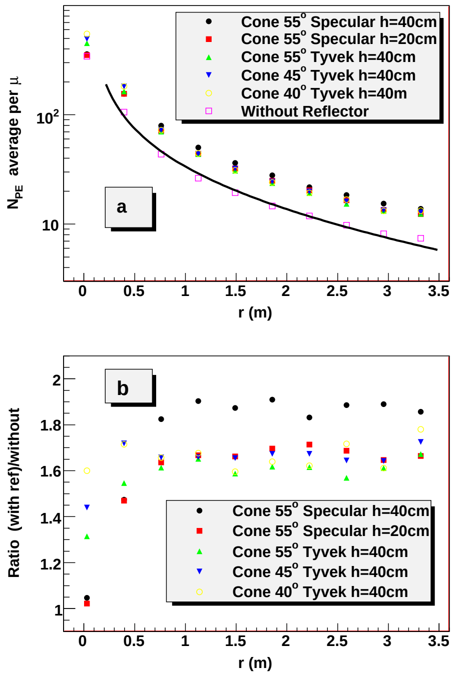

Fig. 6: N_{PE} dependent on radial distance from PMT for vertical muons and for $designI$ (a)(line is the fit result using Eq 1) and (b) the ratios of N_{PE} with and without light collectors.

20cm R5912 PMT at the bottom [?] ($designI$) and the second one includes 3 R5912 PMTs at the bottom located in the vertices of the equilateral triangle having the same circumcenter as the tank cylinder ($designII$). The distance of each PMT from the center of the tank is half of the tank radius. For the $designII$ two different orientations of PMT are considered: first, upward facing PMTs; second, they have an angle with the vertical of 30° (the distribution of optical photons on surface PMT clearly shows that the non vertical orientation can be preferable). To estimate the light collector efficiency for each design two simulations with (WR) and without (WOR) light collectors have been performed. For the light collectors specular and diffuse materials have been used. Different geometries have been tried and for the final simulations only conic shape is used due to the simplicity of the construction. In the presentations of the results the light collector sizes are given by the half angle of the cone vertex and its height. The small aperture diameter is equal to the PMT diameter. For the estimation of the coordinate and angular dependences of the light collector efficiency, monoenergetic gammas and muons have been used in the simulations. The increment of the light collection efficiency due to the usage of light collectors is presented as the ratio of simulation results with and without collectors to cancel the possible uncertainties in the simulation of PMT properties. For the PMT an uniform photocathode response is used. For the reflection coefficient of specular reflectors $0.6-0.8$ interval is used for the corresponding λ interval $300-600nm$. The aluminized surfaces can provide an average reflectivity about 0.77 [?] or better [?] for Cherenkov like spectrum. For the diffuse (Tyvek) reflectors the interval $0.80-0.93$ of reflection coefficient is used[?] for the above mentioned λ interval. An experimental study demonstrate that there are diffuse materials like Lumiror and Goretex with better reflectivity for the Cherenkov light[?]. For the other required parameters of GEANT4 UNIFIED model the used values are from the report [?]. In the simulations $100MeV$ energy for gammas and $2GeV$ for muons have been used to estimate the coordinate uniformity of the detector.

III. RESULTS

The detector average response per vertical gamma incident for the $designI$ with and without light collectors dependent on the radial distance is shown in Fig 1a. As it can be seen from the figure the detector uniformity is within $\pm 15\%$ up to radius values $3.5m$. The signal increment conditioned by the usage of light collectors is within $1.6-2.2$ (see Fig 1b) and depends on the reflector type. Using diffuse reflector with the aperture diameter $\simeq 1m$ one should expect the signal increment about the factor of $1.6-1.7$. For $designII$ the light collector gain is approximately the same as in case of $designI$ (see Fig 2 down row), though for the zenith angle 45° of gamma for some part of the active area this gain is smaller than 1. The uniformity of the response is good enough for the vertical gammas (see Fig 2 upper row) and for the zenith angle 45° is not as good as for the vertical one. Non vertical orientation of PMTs (30° in the vertical plane that is crossing the tank and corresponding PMT centers) increases the signal value as it was expected. This increase is of order of $\simeq 10\%$. It is also clear from the figure that for the azimutal symmetric effective area of the tank the distance between the tanks should be $\simeq 4m$ if the zenith angle aperture is smaller than 45°. In fig 3 is represented the distribution of N_{PE} for the single PMT for $100MeV$ energy vertical

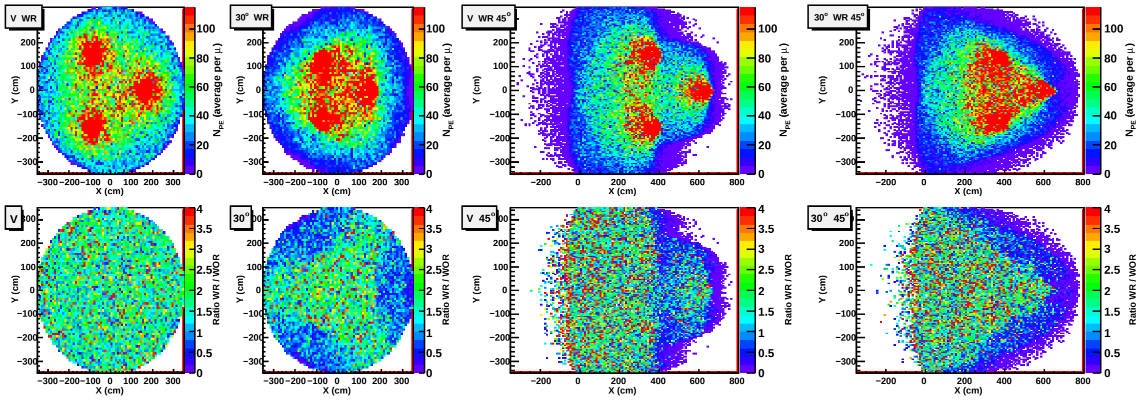

Fig. 7: N_{PE} dependent on the muon coordinate at the top of the tank for the $designII$. Notations are the same as in Fig 2.

gammas normalized per gamma incident for the different orientations of PMTs. As it can be seen even using the reflector, the efficiency of the detection $100MeV$ gamma is low($\simeq$ 30% for $1PE$ threshold). The time distributions of the optical photons for the single gamma, for design I and for two different positions of gamma incident with and without light collectors are shown in Fig 4. The increase of the distribution width is of order of ($\simeq$ 20%) when the diffuse light collector is used. For $designII$, which does not provide radial symmetry, the time spread of the first arrived optical photon at any PMT for each gamma is shown in Fig 5. As is expected, the large time spread has non-vertical gammas due to larger effective area (see Fig 2). So to improve the detector time characteristics one should reduce the effective area for the non-vertical gammas (for example, using compact filling of the tanks). For the vertical muons the coordinate dependence for $designI$ has approximately the shape given by (1) (see Fig 6a). The light collector in fact doesnt changes significantly the position dependence. The signal increment conditioned by the usage of light collectors is within $1.5 - 1.9$ (see Fig 6b). 2D uniformity plot for $designII$ and for vertical and zenith angle $45°$ muons is shown in Fig 7. The use of light collectors improves a little the uniformity response. It only increases the signal value by a factor of $\simeq 1.5$ that is less a little than for the gammas. The linearity of N_{PE} from the energy of gamma is shown in Fig 9. For the best fit a small quadratic member is required. For the muons the energy threshold has coordinate dependence (see (1)).

IV. CONCLUSION

Conic shape light collector ($\simeq 1m$ aperture diameter) can provide the signal increase by a factor of up to $\simeq 2$ dependent on the zenith angle, reflection and PMT photocathode properties. For the exact estimations of the light collector efficiency the knowledge of the coordinate map of PMT photocathode sensitivity is required. The specular reflectors provide better light collection and time resolution. Although the use of the light collectors increases the signal it is not able to solve the non-uniform response problem. The worsening of the detector temporal characteristics using the local light collector is relatively small. A compact placement of the tanks will reduce the detector effective area, but it improves the time resolution.

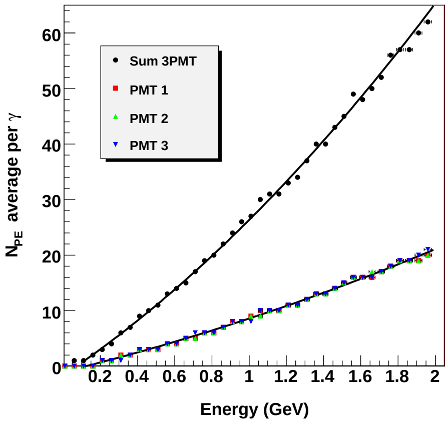

Fig. 8: N_{PE} dependent on the energy of gamma for $designII$. Lines are polynomial fit results for single PMT and the sum signal of 3 PMTs

V. ACKNOWLEDGEMENTS

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