Simulation of a Compton-pair imaging calorimeter and tracking system for the next generation of MeV gamma-ray telescopes

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Abstract. The astrophysical community is currently focusing its efforts in the development of a new generation of gamma-ray telescopes to detect low-energy photons in the MeV-GeV energy range, operating both in the Compton and pair conversion regimes. The reconstruction of the incident photons energy and direction is not straightforward, as the range of secondary particles produced by photon interactions is usually short. We propose a detector consisting of a tracker system based on scintillating fibers and of a Compton-pair imaging calorimeter made of CsI(Na) crystals coupled to wavelength shifting (WLS) fibers read out by Silicon Photomultiplier (SiPM) arrays. We have developed a dedicated simulation code to study the performance of this detector. The simulation takes into account the optical photon production and propagation inside the fibers and is used to optimize the fiber geometrical and optical properties and the design of the readout system.

1. Introduction

The recent observations of a short gamma-ray burst in coincidence with a gravitational wave from a neutron star merger and the latest constraints on WIMP dark matter obtained from the stacked analysis of dwarf spheroidal galaxies have awakened the interests of the scientific community for gamma-ray astronomy in the sub-GeV energy region. Gamma-ray telescopes operating in this energy range should work in both the Compton and pair production regimes, with a large effective area and a wide field of view. Several detectors have been proposed in the last years [1, 2, 3] based on different technologies.

The Advanced Particle-astrophysics Telescope (APT) [4] is a very large Compton and pair telescope, that makes use of scintillating fibers readout by Silicon Photomultipliers (SiPMs) and of a distributed imaging CsI(Na) calorimeter (ICC). The instrument, which will have a cross section of 3×3 m^2 and a height of 2.5 m, will consist of 20 $x - y$ tracker and ICC planes. Each tracker plane will include 2 layers of round scintillating fibers oriented along the x and y

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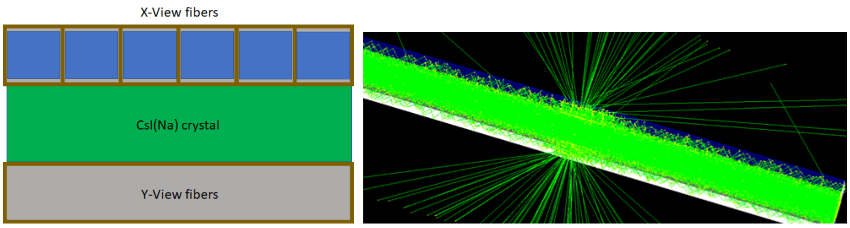

Figure 1. Left panel: Schematic view of the ICC module simulated (not in scale). Right panel: Event display showing the tracks of optical photons produced by a 1 GeV muon crossing the tile at its center. The light yield is reduced of a factor 10 to make the tracks visible.

axes and equipped with SiPMs at the ends. The ICC will consist of 5 mm thick CsI(Na) tiles, sandwiched between two planes of square wavelength shifting (WLS) fibers with 2 mm side, oriented along the x and y axes. The WLS fibers collect the UV/blue scintillation light exiting from the CsI tiles and deliver a fraction of the re-emitted light to the SiPMs connected at their ends. The signals from the SiPMs can be used to infer the coordinates of the interaction in the CsI crystal. The detector has a total thickness of 5.8 radiation lengths, for a total weight of approximately 7200 kg. APT is expected to provide more than on order of magnitude larger effective area and twice the field of view of the Fermi LAT.

2. Simulation setup

We have developed a GEANT4-based simulation to study the performance of the ICC. An ICC module consists of a 5 mm thick CsI(Na) crystal tile with a cross section of 20×20 cm^2, sandwiched between two layers of WLS fibers with square cross section. The fibers of the two layers are oriented orthogonally each other, in order to reconstruct the $x - y$ coordinates. Two configurations have been simulated, respectively with fibers of 1 mm and 2 mm side. All fibers are coupled with SiPMs at both ends. A schematic view of the module is shown in Fig. 1.

In our simulation we have set the scintillation yield of the CsI(Na) to 41000 photon/MeV with an emission spectrum according to ref. [5]. The WLS fibers consist of a polystyrene core (refractive index 1.59) surrounded by a PMMA cladding (refractive index 1.49). The thickness of the cladding has been set to the 2% of the total thickness of the fiber. The absorption spectrum of the fiber cores as a function of the photon wavelength has been taken from ref. [6]. All scintillation photons produced in the CsI(Na) crystal absorbed in the WLS are re-emitted with a shifted wavelength from blue to green (100% conversion efficiency). Finally, the light production and decay time in WLS fibers was set to 8.5 ns.

All individual optical photons are tracked inside the detector volumes. Photons reaching the interface between two different materials are propagated according to Snell's law. The four lateral surfaces of the CsI(Na) are treated as perfect absorbers. The simulation allows to study the response of the system in terms of hit fibers (spatial resolution) and collection time (electronic read out). Fig. 1 (left panel) shows the event display of a simulated 1 GeV muon crossing the ICC vertically. The green line indicate the tracks of the optical photons, which include the scintillation photons produced in the CsI(Na) crystal and the shifted photons emitted by the WLS.

3. Simulation results

We have simulated a set of 1 GeV vertical muons crossing the module. In Fig. 2 the spectra of all photons produced and escaped from the module are shown. About 24% of primary scintillating photons reach the WLS fibers, as expected from considerations based the critical angle for total internal reflection, which is given by $\theta_0 = \sin^{-1}(n_{clad}/n_{crystal})$. About 8.6% of photons will

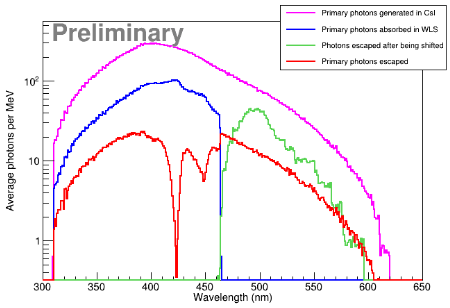

Figure 2. Spectra of all photons tracked by the simulation code. The purple line indicates the primary scintillation photons produced inside the crystal after the muon energy release; the blue line indicates the photons that are absorbed in the any fiber plane; the red line indicates primary scintillation photons escaping outside the ICC; the green line indicates photons escaping outside the ICC after being absorbed and re-emitted by the WLS fibers.

escape outside the detector (light loss), and their spectrum is indicated by the red curve in Fig. 2.

WLS fiber size	**1** mm	**2** mm
Shifted Photons per MeV and per view	$\sim$ 4400 ($\sim$ 11%)	$\sim$ 5000 ($\sim$ 12%)
Collected Photons per MeV and per side	$\sim$ 140 ($\sim$ 3.2%)	$\sim$ 180 ($\sim$ 3.6%)
RMS (number of fibers hit)	2.83 (2.83 mm)	2.13 (4.26 mm)

Table 1. Summary of the results in terms of hit fibers and light collected by the modules for the 1 mm and 2 mm fiber side configurations.

Figs. 3 and 4 show the average number of photons absorbed by the fibers and the average number of photons collected by the SiPMs as a function of the fiber number, for both the x and y views, in the two configurations with 1 mm and 2 mm fiber sides respectively. A summary of the results obtained, in terms of hit fibers and light collected by the fibers for both the 1 mm and 2 mm side configurations is shown in table 1. We see that the number of collected photons is slightly larger in the configuration with 2 mm side fibers. Both values are consistent with the expected trapping efficiency, which can be evaluated from geometrical considerations based on Snell's law.

Fig. 5 (left panel) shows the distribution of collection times (black histogram) and the corresponding cumulative distribution (red histogram). We see that almost all photons are collected in about 2 μs, as expected since the light decay time of the CsI(Na) is of about 630 ns.

Our simulation results can also be compared with the experimental results obtained when testing an ICC prototype equipped with 2 mm side WLS fibers with cosmic-ray muons [4]. The display of an event is shown in Fig. 5 (right panel), where the pulse height in individual SiPMs are shown together with the time profiles of the signals in the central SiPMs. We see that the distribution of hit fibers (in terms of read-out channels) is consistent with the results of our simulation.

Finally, we studied the dependence of the collected light on the position of energy deposition inside the module. The position of the energy deposition is reconstructed from the centroid

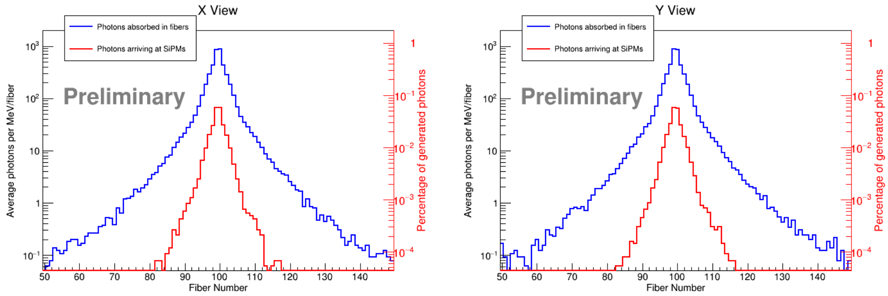

Figure 3. Results with 1 mm side fibers. The blue histograms show the average number of absorbed photons by the fibers in the x-layer (left panel) and y-layer (right panel); the red histograms show the average photons collected by the SiPMs. Fibers are numbered starting from 0 to 199 (fibers 100 and 101 are the central ones).

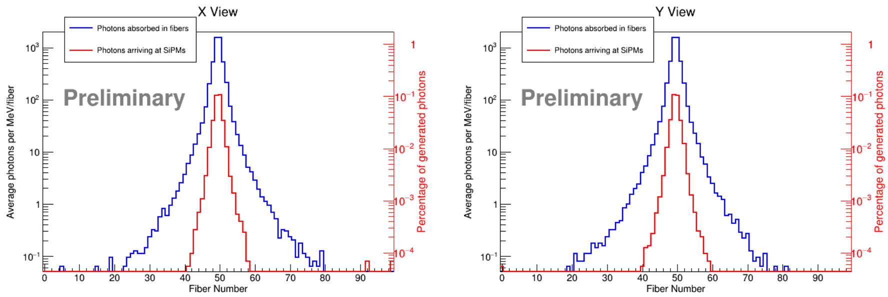

Figure 4. Results with 2 mm side fibers. The blue histograms show the average number of absorbed photons by the fibers in the x-layer (left panel) and y-layer (right panel); the red histograms show the average photons collected by the SiPMs. Fibers are numbered starting from 0 to 99 (fibers 50 and 51 are the central ones).

of the hit fibers and the spatial resolution can be evaluated by the RMS of the distribution. We have simulated a set of point-like energy deposits across the crystal at different positions with a step of 0.5 mm from the CsI(Na) crystal center along the z-direction. For each set of simulations we have studied the distributions of the hit fibers in the two views (like those shown in Fig. 3 and Fig. 4). The plots in Fig. 6 show the distribution of the hit fibers and the collected photons/MeV as a function of the position of the energy deposition. As expected, both histograms are symmetric and the RMS of the distribution increases with the distance of the energy deposition from the reference fiber plane.

Conclusion

We have developed a GEANT4-based simulation with optical photon tracking capability to study the performance of the ICC of the APT detector. We have investigated two different WLS fiber configurations, with 1 mm and 2 mm side.

The simulation framework takes into account of all optical properties of the materials and allows to evaluate the number of escaped and absorbed photons and their energies. This information can be used to better understand the optical photon collection process, to study the performance of the APT module in terms of spatial resolution and to evaluate the photon collection times.

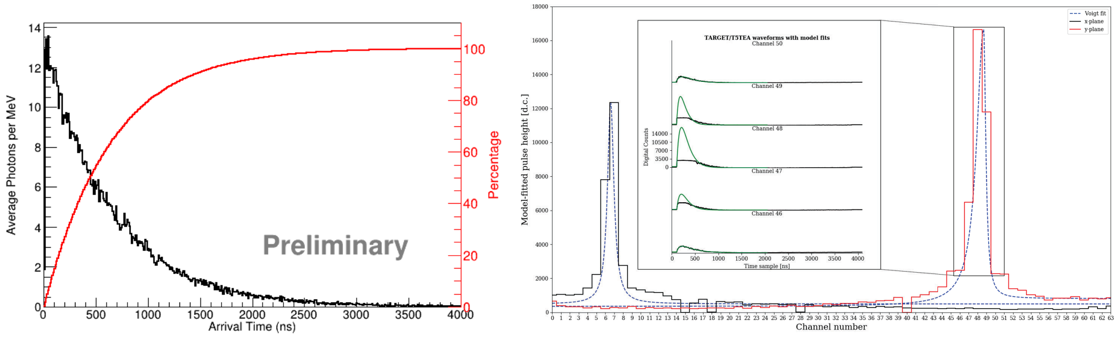

Figure 5. Left panel: Global (black) and cumulative (red) collection time distributions of detected photons. Right panel: Event display of a cosmic-ray muon event in a ICC module equipped with 2 mm side WLS fibers (taken from Ref. [4]).

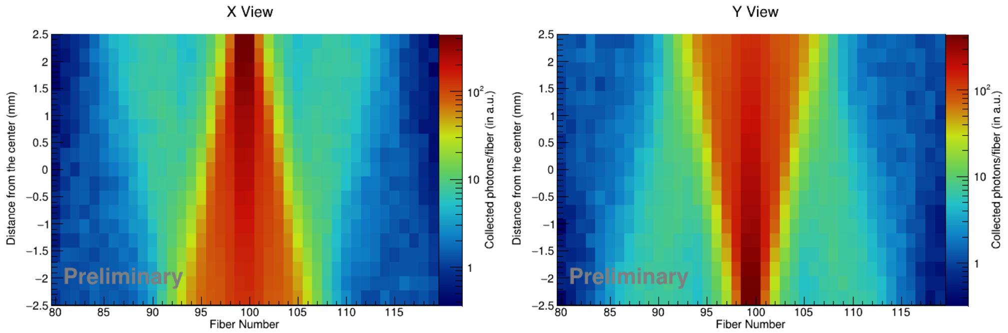

Figure 6. Distribution of hit fibers and collected photons/MeV as a function of the position of the point-like energy deposition for the x-view (left) and y-view fiber planes (right). The plot refer to the configuration with 1 mm side fibers. The coordinate on the y-axis of the histograms is referred to the center of the CsI(Na) crystal; the x-view fibers are located above the crystal ($z > 2.5$ mm) and the y-view fibers are located below the crystal ($z < -2.5$ mm).

Acknowledgments
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