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Geant4 Comparative Study of Affecting Different Parameters on Optical Photons Related to the Plastic Scintillation Detector

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Abstract: In this research, different parameters of plastic scintillator detector were investigated by Geant4 simulation toolkit. These parameters consisted of radius, length and position of PMT as well as surface reflective type and finish options. Furthermore, response time distributions of two organic plastic materials were studied. The results indicated that collecting optical photons has a linear relationship with PMT radius head. Also, the vertical location of PMT has a non-linear relationship with the optical photons collection. However, the collection decreased by increasing PMT length or moving PMT head horizontal position. The response functions of two plastic scintillator materials were in good agreement with experimental published results. Also, Geant4 radiation transport code can simulate incident radiation photon and predict subsequent events to the PMT head very well. The results indicated that BC-404 has faster scintillation properties versus BC-400 organic scintillator materials. Comparison between Geant4 outputs illustrates that the best reflector material and surface finish type for optical photons is ground TiO_2.

Key words: Geant4 Monte Carlo Code, optical photon collection, plastic scintillator, reflector material, surface finish.

1. Introduction

Nuclear detectors are used in a wide range of applications throughout the world. There are different kinds of detectors e.g. gaseous and scintillation detectors with the aim of measuring surface radioactive contamination [1]. Plastic scintillation detectors have been compared to other detectors previously [2]. In plastic detectors, each incident particle produces a different number of optical lights, which are proportional to the deposited energy of the particle. Organic plastic scintillation detectors have some notable advantages over proportional gas sealed or gas flow detectors: relatively low weight, gas independence, no warm-up time (in comparison to gas flow detectors), high detection efficiency, ability of identification of particle radiation type, better spectroscopy, no sensitivity to moisture, less temperature dependency, low repair cost, and easy construction of large area detector (for instance in the case of whole body contamination monitoring) [3, 4].

We produced Pars-HFM 01[1] using MWPC[2] in Pars Isotope Co. [5] and then tried to develop this device using plastic scintillation detectors. Optimization of gas detector design can be obtained from Garfield and MCNP simulations [6] and for plastic scintillation detector, Geant4 tool was used. Generally, construction of a scintillation detector depends on investigation of optical characteristic effects of different parameters on optical yield and detector's response time [7]. Geant4 is able to simulate optical photon transport characteristics of both bulk and sheet scintillation materials [8].

In this research, considering Geant4 simulation tool

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[1] Hand, Foot and Clothes Monitor.
[2] Multi-Wire Proportional Counter.

capabilities in simulating nuclear interactions, scintillation interaction modeling, transportation of visible photon and simulation of response time curve, we will study the effects of various components of a plastic scintillation detector.

2. Materials and Method

2.1 Optical Physics

The main three phenomena of an incident light photon to a media surface are reflection, transport (refraction) and absorption. All these three behaviors are included in Geant4 tool-kits. R and T are two parameters which describe the portion of reflected or transported OP [9].

$A\,cos\theta_i$, $A\,cos\theta_r$ and $A\,cos\theta_t$ are cross sections of incident, reflection and transport of optical photon (OP), respectively, and subsequently I_i , I_r and I_t are their related flux densities. Thus, the probabilities of incident OP, reflection OP and transport OP are due to the surface A are $I_i A\,cos\theta_i$, $I_r A\,cos\theta_r$ and $I_t A\,cos\theta_t$, respectively. Reflectance R and transmittance T are given by Ref. [9]:

$$R \equiv \frac{I_r A\,cos\theta_r}{I_i A\,cos\theta_i} = \frac{I_r}{I_i} \qquad (2.1)$$

$$T \equiv \frac{I_t A\,cos\theta_t}{I_i A\,cos\theta_i} = \frac{I_t\,cos\theta_t}{I_i\,cos\theta_i} \qquad (2.2)$$

where, θ is the light photon incident angle.

2.2 Geant4 Monte Carlo Tool-Kits

Geant4 is a C++ programming language tool for simulating particle behaviors with the help of Monte Carlo method. This toolkit has multi-classes for simulating scintillation detectors, particles transportation, and passage of particles through matter and this code has applications in different fields of particle physics, nuclear physics and space engineering as well medical physics [10, 11].

Geant4 code requires some input data including: geometrical configurations, radiation source specifications, definition of primary and secondary particles, description and registration of physical interactions and cut-off energy [12]. Geant4 is able to simulate scintillators because of its flexible and reliable Monte Carlo optical photon simulations [13]. This code is an object oriented code for simulating particle trajectory continuously. This software is an open source code allowing for defining any new particle and even virtual particle. In radiation measurements, the signal pulse generated by the detector has valuable information about an incident photon. Also Geant4 code can emulate emission decay curve and arriving time distribution at the PMT photocathode [14].

2.2.1 Geant4 Software Features

In this paper, for exploring different components of the scintillation detector, Geant4 version 10.1 (released December 2014) was used for simulation of optical photon tracking. These parameters are location of the PMT (photomultiplier tube), reflection specifications related to the internal detector surface as well as plastic scintillation characteristics. In our work, we used PhysicsList class which includes reference classes of G4EmStandardPhysics, G4DecayPhysics, G4RadioactiveDecayPhysics, G4IonPhysics, and G4OpticalPhysics. The assumed incident particle is beta particle with an average energy of 196 keV (from common ^{90}Sr radioactive source). The other features of the simulation project considered for this study are as follows:

The area of thin plastic scintillation sheet, which was simulated by Geant4, was about 29 × 15 cm^2 with a thickness of 1.5 mm. Time constants of two scintillation plastics were about 2.4 and 1.8 ns for BC-400 and BC-404, respectively. Other optical properties of these scintillators were introduced to the software from BICRON plastic scintillation data sheet [15].

2.3 Reflector Characteristics

The internal surface of the detector's geometry and top window of the detector should reflect produced optical photons in the housing to the PMT head. The desired simulated geometry of the detector and its dimensions are shown in Fig. 1. The trapezoidal shape of the geometry helps better light guidance toward PMT head position on side (a).

For description of optical surface properties, pre-assumptions of RealSurface1.0 library were used [16]. Visualization of an incident β particle with produced lights and consequence reflections to the PMT are depicted in Fig. 2. Then, the effects of reflective properties of internal surfaces on collected OP were studied. In this stage, five different reflective materials with three surface finish options polished, etched and ground were simulated by Geant4 software. The simulated reflective window was EJ-590 (Eljen Technology) aluminized polyester film (Mylar) with a thickness of 2.0 μm [17].

2.4 PMT Description

The radius of PMT and its optimal location in the housing of the detector geometry have specific effects on total light photon counts. These two important parameters have been studied by Geant4 Monte Carlo code.

2.4.1 Simulation of PMT Radius

For investigation of PMT radius effect, the fixed location of PMT was 1 cm away from side (a), and

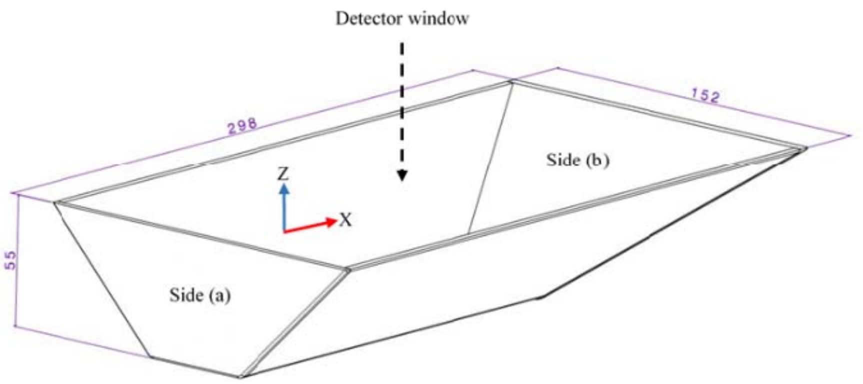

Fig. 1 Trapezoidal geometry of the simulated detector's housing.

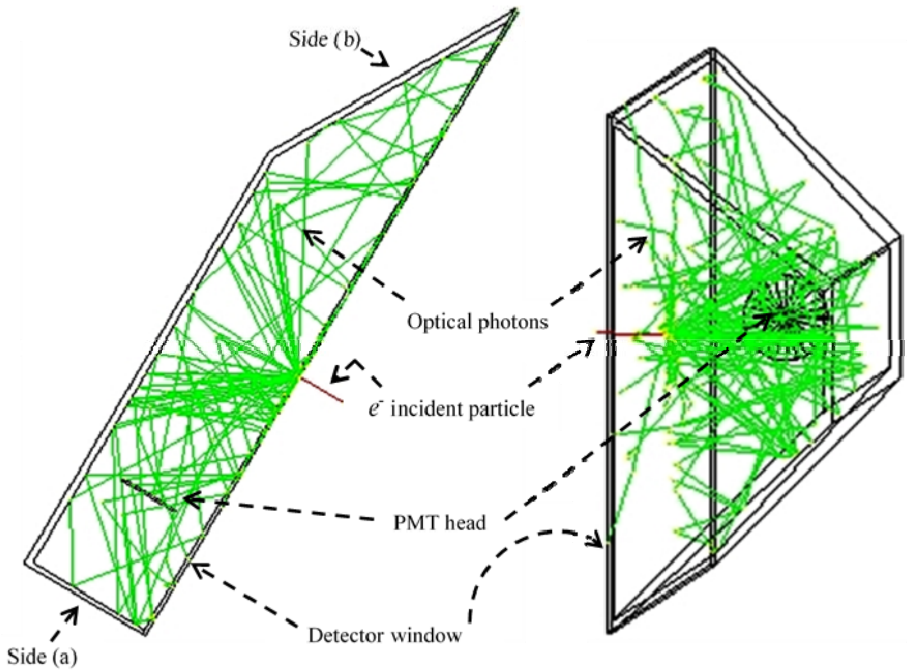

Fig. 2 Visualization of beta particle radiation event (red line) and its OPs (green lines) behavior in the reflector housing of the detector.

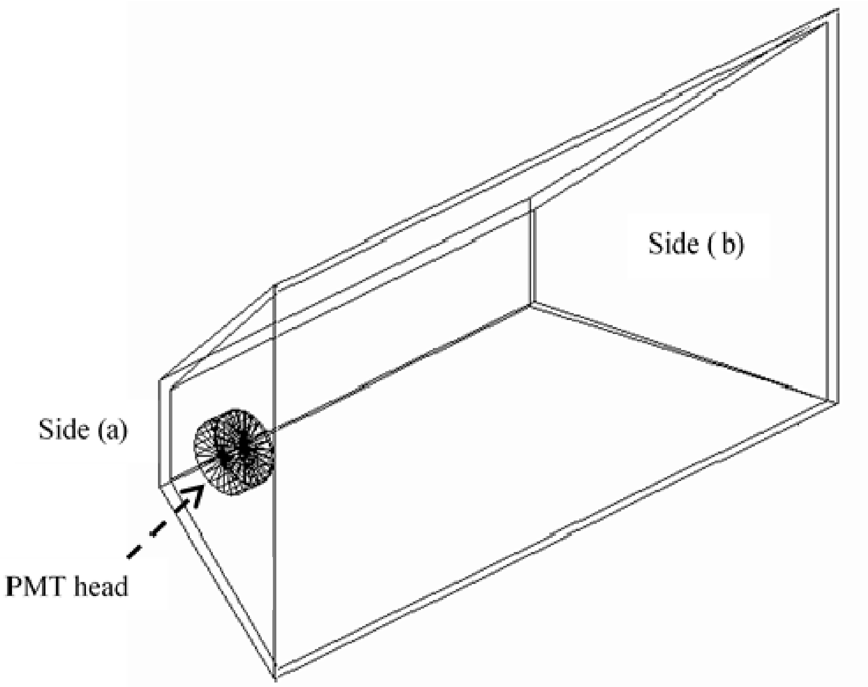

Fig. 3 Light entry side to PMT module.

different PMT radiuses were studied including 0.5, 1, 1.5, 2 and 2.5 cm. As Fig. 3 reveals, the entrance direction to PMT head is from side (a), which is the end of detector.

2.4.2 Simulation of PMT Horizontal Location (x Axis)

The position of PMT head inside the detector can also be named as PMT length. The initial location of the PMT head was 0.25 cm away from the right angle side (a) (Fig. 1). Then, the location of PMT moves on x axis from side (a) toward side (b) in Geant4 code as well as from length of 0.25 to 3.5 cm by the step of 0.25 cm. In this simulation, a constant PMT radius of 1.5 cm was assumed and the entrance location of PMT was in the center of side (a).

2.4.3 Simulation of PMT Vertical Location (z Axis)

The vertical position of PMT on side (a) shows the distance of PMT from top scintillation material. For better light photon collection, optimal z location of PMT should be studied by the output of simulation code. For this, the vertical location of PMT head on side (a) was altered on z axis from -1 to +1 cm by the step of 0.125 cm. The center of side (a) was defined as the zero point of this investigation. Regarding this part of simulation, constant assumptions were radius of PMT and its length which were both 1.5 cm.

3. Results and Discussion

3.1 Effects of Surface Type and Reflector

Five different simulated reflectors were evaluated by Geant4 including Lumirror, Teflon, TiO_2, Tyvek and VM2000. The effects of reflective properties of internal surface finishes of detector's enclosure on the amount of collected OPs were also studied by Geant4 simulation tool. Comparison between the effects of reflector properties and surface finishes consisting of 15 graphs are illustrated in Fig. 4.

It is deducted from Fig. 4 that for Tyvek reflective material, the number of collected OPs for both polished and ground surface finishes are approximately equal to each other. It means that for Tyvek reflector surface, polished finish can be replaced with ground finish. But the number of collected OPs for Tyvek etched finish is relatively higher than that of the two surfaces mentioned above. Equivalent reflector materials with their optical surface finishes are tabulated in Table 1.

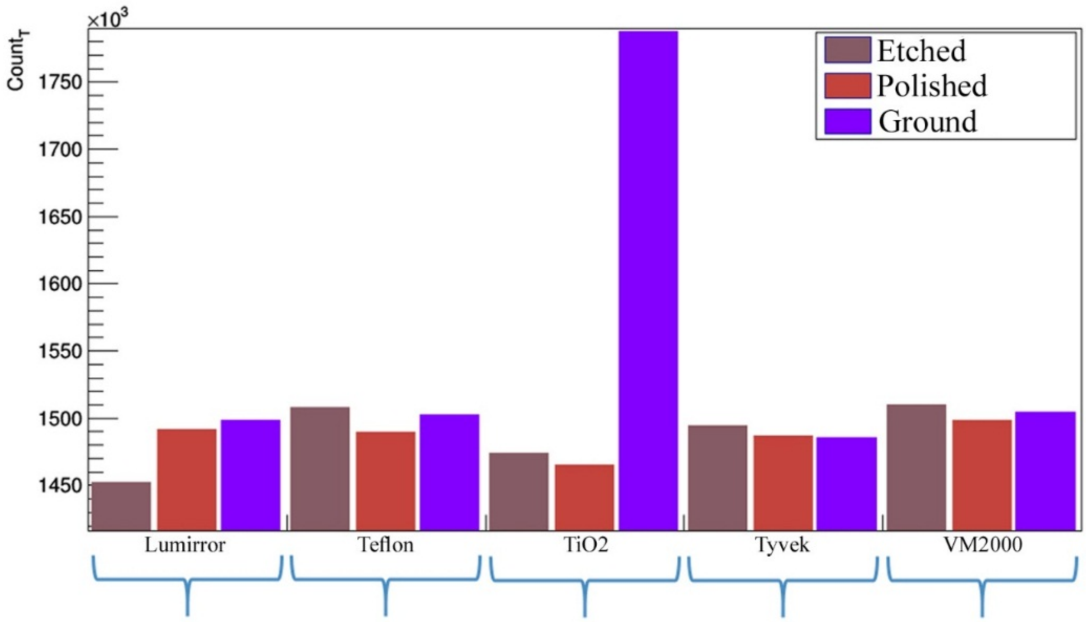

Fig. 4 Different reflection materials with different surface finishes.

Table 1 Substitutable surface reflectors for simulated geometry.

Equivalent reflectors		
Polished Tyvek	=	Ground Tyvek
Polished Lumirror	=	Polished Teflon
Ground Lumirror	=	Polished VM2000
Ground Teflon	=	Ground VM2000
Etched Teflon	=	Etched VM2000

Table 2 Sorting of reflectors based on better reflecting attributes.

Sorting materials based on high reflective properties
Ground TiO_2
Etched VM200
Etched Teflon
Ground VM2000
Ground Teflon
Ground Lumirror~Polished VM2000
Etched Tyvek
Polished Lumirror
Polished Teflon
Polished Tyvek
Ground Tyvek
Etched TiO_2
Polished TiO_2
Etched Lumirror

According to the simulation results, sorting of effective reflector materials is also compiled in Table 2 from high to low regarding reflective properties. Based on this table, for the purpose of light reflection properties, ground and etched surface finishes are more efficient than polished surface. Apart from ground TiO_2 in Table 2, VM2000 and Teflon with etched and ground surface finishes are two very good materials for the aim of reflecting optical photons.

3.2 Effects of Scintillation Material on the Response Time

For the aim of studying the effects of two plastic scintillators, BC-400 and BC-404, on the response time, the detector's selected properties are: ground surface TiO_2 reflector material, PMT with a radius of 1.5 cm and arbitrary position of the PMT at the distance of 3.5 cm off side (a). The radioactive source type is negative beta emitter wide area source (12 × 20 cm^2) with an average energy of 196 keV and located in the center of detector's window. This e^- plane source with the surface uniform distribution was placed in contact to the surface of Mylar foil and perpendicular to the window of the detector. The response function curves for two plastic materials are demonstrated in Fig 5.

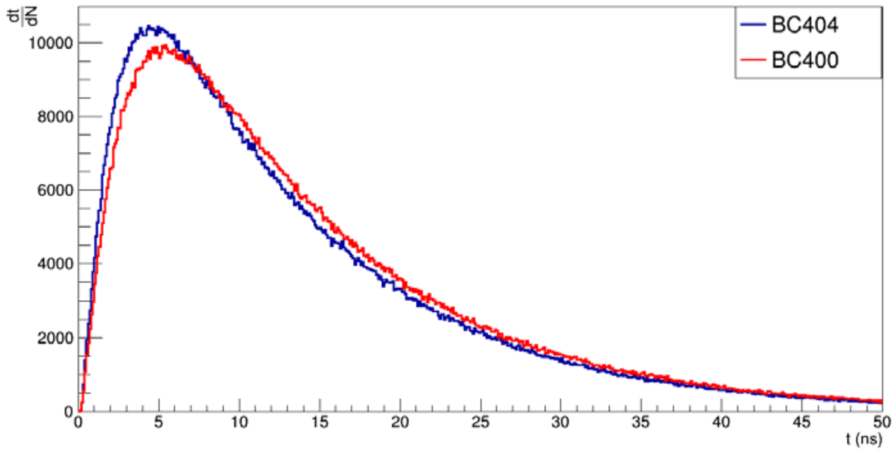

Fig. 5 Response time spectrum of detected photons from BC-404 and BC-400.

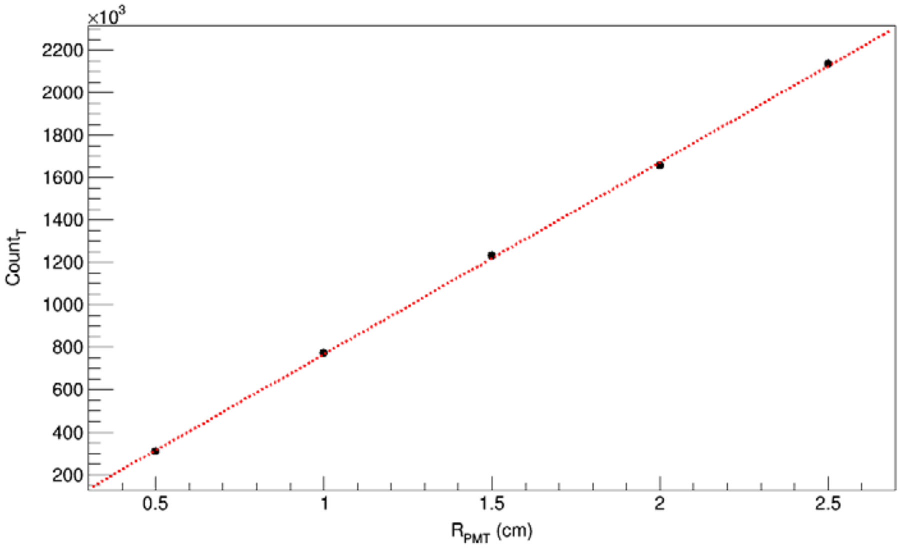

Fig. 6 Linear fit curve of PMT radius length.

As is clear from time distribution spectra in Fig. 5, BC-404 has a shorter rise/fall time in comparison to the BC-400 plastic scintillator. So, BC-404 is a suitable scintillator for fast counting applications. Considering time constants of two selected scintillators, this approach can approve correct modeling of simulated scintillation process and true time sampling by Geant4 software. Also, this graph confirms the validity of simulation code outputs when compared to the experimental plastic scintillators data sheet [15].

3.3 Effects of PMT Radius on Light Photon Collection

Fig. 6 shows that with the help of linear fit curve, by increasing the radius of the PMT, accumulation of OPs will increase linearly. However, because of the detector geometry limitations, PMT radius has not increased more than 2.5 cm and has not been investigated by Geant4 code.

3.4 Effects of PMT Location on Light Output

The best position of PMT head has a significant effect on collecting optical photons. Two man locations were studied by simulation tool and results as depicted in Fig. 7. One position is a location of PMT head inside the detector housing toward to the side (b), i.e. PMT length, with the results indicated in Fig. 7a. Another is vertical PMT location on side (a),

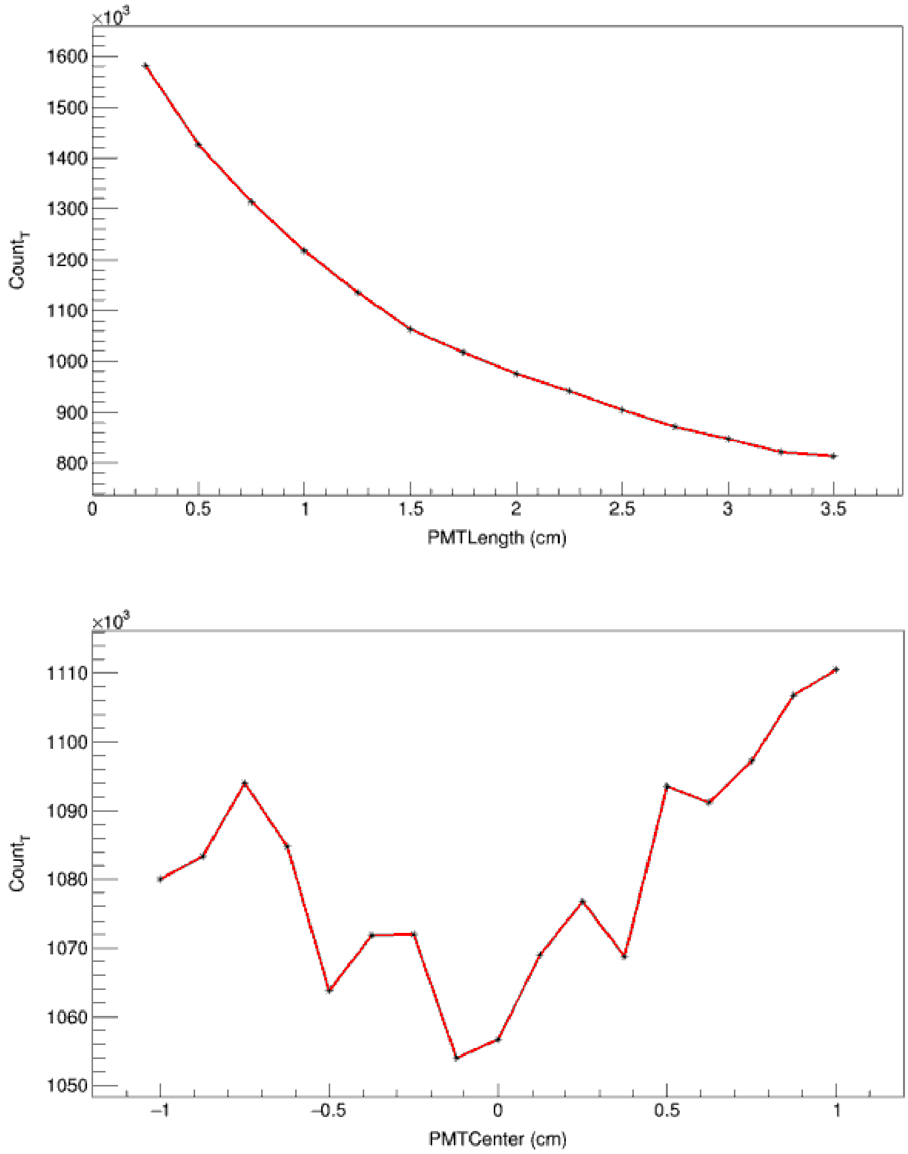

Fig. 7 Investigation of PMT head location (a) horizontal location on x axis (b) vertical location on z axis.

i.e. PMT center, with the results demonstrated in Fig 7b.

As Fig. 7a shows, the OP collection is somewhat hindered by changing the PMT position on x axis from side (a) to the side (b), which reduces the collection of light. This reduction is most likely due to the slope of side (b) which deviates reflected OPs orientations which should reach the PMT head. Considering Fig. 7b, it can be deduced that there is a non-uniform relationship between collection of optical photons and vertical movement of PMT head (the results are in agreement with the Machaj's results [2]). However, due to direct OPs registration on PMT head, collected count rates are a little higher at shorter distances between PMT head and plastic scintillator.

4. Summary

In this study, different parameters affecting the total light output were investigated by Geant4 well-known simulation tool. These parameters included scintillator properties, reflector type and reflective surface finish, PMT location, and radius of PMT, which had influence on light collection. Geant4 based simulation software can model radiation source, detector components, scintillation phenomena and physical processes accurately.

The response times spectra of two plastic scintillators were in good agreement with experimental results previously published. The results show that organic BC-404 plastic scintillator has fast scintillation properties. Various reflector materials and detector's internal reflective surfaces were also studied by the simulation tool. According to Geant4 outputs, internal surface covered by TiO_2 reflector layer with the Ground finish has had the best optical reflective properties, while Etched Lumirror has had the worst optical reflectance characteristics.

Simulation of OPs behavior and intensity can give optimized position of PMT end module. Simulation of PMT shows that by increasing PMT radius, optical photon collection will increase linearly. Regarding PMT head horizontal position in the detector, by extending PMT length for finding optimal PMT location, total OPs decreased exponentially. Therefore, the most appropriate position of PMT head is the one that has shortest distance from side (a). However, for PMT distance from scintillator (vertical position), dependency of collection of OPs on the z axis movement is non-linear and the proper position is the one which is closer to the scintillation material.

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