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Study Through Geant4, for Time Resolution Characterization of Different Detectors Arrays Coupled with Two SiPMs, As a Function of: The Scintillator Plastic Material, its Volumetric Dimensions and the Location of the Radiation Emission Source

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ABSTRACT

The *high time resolution detectors* are relevant in those experiments or simulations were the particles to detect, have a very short time of flight (TOF), and due this it´s required that the detections times are ranged between *ns.* & *ps*.
Using Geant4 software, it was made thirty simulations of coupled detectors to plastic scintillators with two silicon photomultipliers (*SiPMs*) located on the scintillator's central sides. To characterize the time resolution, it was required to quantify the optical photons that reach the *Score* in a certain time, which are generated by muons on the surface of the plastic scintillator. Different configurations of *muon beams* were simulated at energy of *1 GeV*, to interact with the configuration of the scintillator material of its corresponding arrangement. The simulations were made varying three parameters: the scintillator material "*BC404 & BC422*", its size, and the location of the radiation source. Fifteen simulations correspond to *BC404* material & fifteen simulations to *BC422* material respectively. The first five simulations consisted in varying the scintillator's volumetric size and collocate the *muons beam* guided *randomly distributed* over it, the next five simulations differentiate from setting up a *directly centered beam*, and the last five simulations for guide the *beam on the left lower corner* of each scintillator.
The best time resolution achieved was $\sigma = 8.67 +/- 0.26$ ps., reported by the detector with *BC422* scintillator material which has a volume of 20x20x3 mm^3.

1. Introduction

The *high-time resolution detectors* are relevant in those experiments or simulations where it's required that the detection times are in the order of *ns. and ps.,* due this the particles to be detected arrive to the photomultiplication device with a short *time of flight (TOF)* [8, 14].

The time resolution is an important parameter to study in topics related with particle detection. For e.g., in systems which are designed for *"Triggers"* or for *"coincident events"* with others similar detectors [6, 14, 16]. The improvement of capacity of the detectors pretend to determinate the particle time of flight *(TOF)*, and with that identify which kind of particle is detected.

The development and implementation of this type of detectors is important for the construction and improvement of particle detection systems. These types of detectors are integrated with other detectors for the optimization in the identification of particles, in particles and ion collider projects such as *LHC & JINR ("Large Hadron Collider" and "Joint Institute for Nuclear Research" respectively)*. The implementation of high resolution detectors not only transcends the field of research in particle physics, and high energies [1, 2, 17], they also stand out in some industrial security systems *(dosimetry, spectrometry, X-rays)* [7, 15]; these detectors can also be found in hospitals, within some medical imaging equipment, such as *X-Rays (XR)*, *Fluoroscopy (RF)*, *Computed Tomography (CT), Positron Emission Tomography (PET)* and Scanning Microscopy [5, 13, 14].

By using *Monte Carlo* techniques, it is possible to perform simulations of the behavior of the design of new detectors. Through Geant4 software were simulated [19], thirty detectors coupled with two silicon photomultipliers *(SiPMs),* referred to as *"Score",* and two scintillator materials *BC-404 & BC-422* [10, 11]. This set of simulations were carried out, varying its volumetric dimensions 100x100x20, 50x50x10, 40x40x5, 20x20x5, 20x20x3 mm^3 and the location of the radiation source over the different types of

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scintillator. Through the simulations previously described, the parameters associated with the arrival time of the optical photons at the *Scores (SiPMs)* were obtained, which were generated by the *"muons"* when interact with the plastic scintillator in a determined area, which serves as a photodetection electronic system.

For the statistical treatment after the simulations, the programming *frame-work* called *ROOT* was used, this in order to characterize the time resolution of the detectors, based on the aforementioned parameters.

2. Motivation

Modernity, in most cases, leads to innovating what already exists in terms of science and technology; *"Do more with less"*, which means: improve the operating ranges and precision of the devices, in this case we refer to detectors, using different materials and designs that allow improving their characteristics without significantly increasing their costs, and thereby make them more accessible.

One of the most used devices to detect photons are photomultiplier tubes *(PMTs),* which emerged in the *1930's and* almost *one hundred years later* are still used in areas such as microscopy, medicine, high-energy physics, particles, etc.; since they have a combination of low electronic noise, a large bandwidth and a high gain that allows the accurate detection of photons. Compared to Silicon Photomultipliers *(SiPMs), PMTs* have a fairly high operating voltage, a low quantum efficiency *(QE)*, and manufacturing costs are generally considered to be higher. On the other hand, *"SiPMs"* being made of silicon allow low manufacturing costs compared to vacuum tubes, high damage thresholds, low operating voltage, sensitivity within the infrared spectrum and easy portability [5, 16]. For these advantages it is considered pertinent to simulate arrays of *plastic scintillator coupled to SiPMs*, analyze their response and evaluate the manufacturing plausibility of the *complete detector*.

In our particular case, it is relevant to simulate the interaction of muons with arrays of detectors, and by doing this it's possible to compare the studies with the experiments related to the calibration of detection of atmospheric muons, or cosmic ray traces. These studies could help the growth of areas such as particle physics, high energy, etc. [1, 9, 17].

In addition, deepening in researches that allow the creation and innovation of high-time resolution detectors can generate tools for their adaptation and implementation in medical equipment, which would lead to less irradiated people who are subjected to radiation studies [3, 12], contributing to the development of areas such as biomedical engineering and medical physics [13, 16].

3. Methodology

Thirty simulations were carried out, through which it was desired to characterize the time resolution of the aforementioned detector arrays. For this, it was required to quantify the optical photons that reach the *Score* in a certain time, which are generated by the interaction of *muons* on the surface of the *plastic scintillator*. In the *Geant4* software, different configurations of *muon beams* were simulated at energy of *1 GeV*, to interact with the configuration of the scintillator material of its corresponding arrangement. Every time a *muon* is launched it is known by the name of an *event.* The simulations carried out between 1000 and 2500 events, this in order to generate a sample that allows it to be statistically analyzed.

These simulations were carried out varying three parameters: the scintillator materials *BC-404 & BC-422, which are manufactured and simulated based on Polyvinyltoluene (PVT)* [4], its dimensions $100\times100\times20$, $50\times50\times10$, $40\times40\times5$, $20\times20\times5$, $20\times20\times3$ mm^3 and the interaction zone on the scintillator. Fifteen simulations correspond to the *BC-404* material and fifteen simulations to the *BC-422* material respectively. The first 5 simulations consisted of varying the volumetric size of the scintillator and directing a beam of muons randomly distributed on the surface of each of the aforementioned geometries, the next five simulations only differ in directing the beam right to the middle of the scintillator, and the last five are differentiated by directing the beam towards the lower left corner of each geometry. For all the simulations the radiation source was considered to be *1mm* away from the front of the surface of the scintillator material. In Figure 1 & 2. The regions where the beam interacts in the scintillating geometry are illustrated, in *green* where the muon beam is randomly distributed, *red* where it is directed right to the middle, and *yellow* for the low left corner. Front view of the scintillator *(Left box)*, edge view of the scintillator *(Right box).*

Figure 1 & 2 Geometry (20x20x3 mm^3) simulated in Geant4, corresponding to a plastic scintillator coupled with two SiPMs located at the central sides. (Left box) geometry seen from the front. (Right box) same geometry rotated 90 degrees. The green points represent the randomly distributed muon beam, red points correspond to the beam directed to the middle and in yellow points, the beam directed to the lower left corner.

For the statistical treatment after simulations, the programming frame-work called *ROOT* was used, this in order to obtain the distributions of the arrival times of the optical photons to the *Score,* and characterize the *time resolution* of the detectors (which is described in the next section), as a function of the scintillator material, its dimensions and the zone of interaction of the scintillator with the *muon beam*.

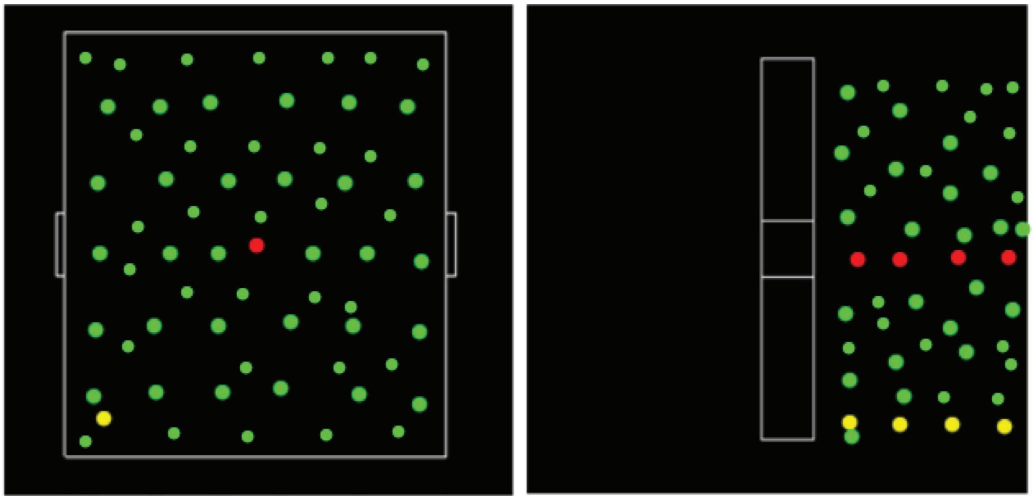

Figure 1 & 2: Geometry (20x20x3 mm^3) simulated in Geant4, corresponding to a plastic scintillator coupled with two SiPMs located at the central sides. (Left box) geometry seen from the front. (Right box) same geometry rotated 90 degrees. The green points represent the randomly distributed muon beam, red points correspond to the beam directed to the middle and in yellow points, the beam directed to the lower left corner.

4. Results & Analysis

The thirty simulations carried out in *Geant4* allowed obtaining physical parameters associated with the optical photons, which are generated by each *event*. These parameters were: position in the three spatial coordinates, kinetic energy, wavelength and the arrival time of these photons at the respective *Scores.*

The arrival times of the photons to the *Scores* were used to analyze them statistically. In *ROOT* these arrival times were processed, by event, to fit them to Landau distributions. The statistical mean (μ) of each *Landau fit* distributions, refers to the arrival average time of the photons in each event; these average times referring to each event, allow to construct a new distribution. The variance (σ) of this last distribution is precisely the time resolution.

The results of the time resolution of each detector array are shown in the following Tables.

Table 1: "BC 404 & BC-422" time resolution, randomly distributed muon's beam.

Arrays (mm^3)	BC−404 Time Resolution (ps.)	BC−422 Time Resolution (ps.)
100x100x20	295.29 +/− 14.20	367.022 +/− 0.69
50x50x10	67.68 +/− 2.59	70.375 +/− 2.85
40x40x5	64.78 +/− 2.87	56.04 +/− 3.85
20x20x5	22.23+/− 0.44	27.13 +/− 1.31
20x20x3	23.87 +/− 0.37	16.36 +/− 1.68

Table 2: "BC 404 & BC-422" time resolution, muon beam directed to the scintillator's center.

Arrays (mm^3)	BC−404 Time Resolution (ps.)	BC−422 Time Resolution (ps.)
100x100x20	161.804 +/− 3.91	181.920 +/− 4.61
50x50x10	79.174 +/− 2.10	80.670 +/− 2.06
40x40x5	45.463 +/− 1.11	45.442 +/− 1.13
20x20x5	16.953 +/− 0.41	16.58 +/− 0.76
20x20x3	13.146 +/− 0.38	11.06 +/− 0.30

Table 3: "BC 404 & BC-422" Time resolution, muon beam directed to the scintillator's left lower corner.

Arrays (mm^3)	BC−404 Time Resolution (ps.)	BC−422 Time Resolution (ps.)
100x100x20	201.14 +/− 10.28	270.04 +/− 8.47
50x50x10	70.24 +/− 1.23	74.50 +/− 1.21
40x40x5	67.96 +/− 1.29	67.84 +/−1.13
20x20x5	14.27+/− 0.24	11.28 +/− 0.20
20x20x3	16.55 +/− 0.27	8.67 +/− 0.26

The previous tables show the time resolutions of the arrangements referring to the *BC-404 & BC-422* materials, with the *muon beam randomly distributed over the scintillator*

(Table 1), with the *muon beam directed towards the middle of the scintillator* (Table 2) and with the *muon beam directed to the lower left corner of the scintillator* (Table 3) respectively.

It is possible to see in each of the tables that the time resolution of the 100x100x20 & 50x50x10 *mm³* arrangements belonging to the *BC-404* material have a lower time resolution value than the *BC-422* material. On the other hand, the arrangements corresponding to 40x40x5*, 2*0x20x5 *& 2*0x20x3 *mm³* associated with the *BC-422* material, have a lower time resolution values compared to the *BC-404* material, with the exception of the *2*0x20x5 *mm³* arrays in which the beam is *randomly distributed* over the scintillator (Table 1). It is plausible to affirm, in general terms, that *BC-404* material presents a better time resolution in arrays with measures equal to and greater than 50x50x10 *mm³*, while *BC-422* material performs with a better time resolution in arrays equal to or less than 40x40x5 *mm³*

Figure 3 illustrates the time resolution of *BC-404 & BC-422* materials as a function of the volumetric size of the scintillators, showing its appropriate legends, that allow the curves to be related to their respective beam interactions. The largest values of time resolutions *(worst performance)* belong to both materials with the array size of 100x100x20 *mm³* with *randomly distributed beam* (Table 1), these arrays can be seen in *yellow* and *royal blue color* (Figure 3). The smallest value of time resolution *(best performance)* achieved in these simulations, corresponds to the *BC-422* material, with the scintillator size 20x20x3 *mm³* with a beam directed to its left corner (Table 3). The value of this time resolution is σ = *8.67 +/- 0.26 ps*. Figure 6, which competes with the reported values in the article *"Reaching time resolution of less than 10 ps. with plastic scintillation detectors"*. In this article, Jianwei et al, mention that the best time resolution achieved was σ = *5.1 ps.*; however, the scintillator material corresponding to that time resolution was *EJ-232Q* which has *0.5% benzophenone*, in similarity with the *BC-422* material, which also contains it [11]**.** Regardless the performance of the *BC-422* material has been evaluated with a computational simulation, and the *EJ-232Q* material has been evaluated by an experiment [6**,** 18]**,** the values of the physical parameters that are entered to run the simulations *(photon's energy, refractive index, scintillation, etc.)* reflect the actual *chemical character of the material*. In general terms, it can be perceived that *the composition and chemical structure of the scintillator material is linked to its performance*, which can contribute to improve time resolution, probably due to *aromatic structures that benzophenone possesses*. These *aromatic structures* generally present *phosphorescence or fluorescence phenomena*, which are the consequence of *metastable states of condensed matter; those phenomena* are necessary conditions for the generation of photons which contributes to scintillating, and allow to keep a count of the *events* and thus characterize the *time resolution.*

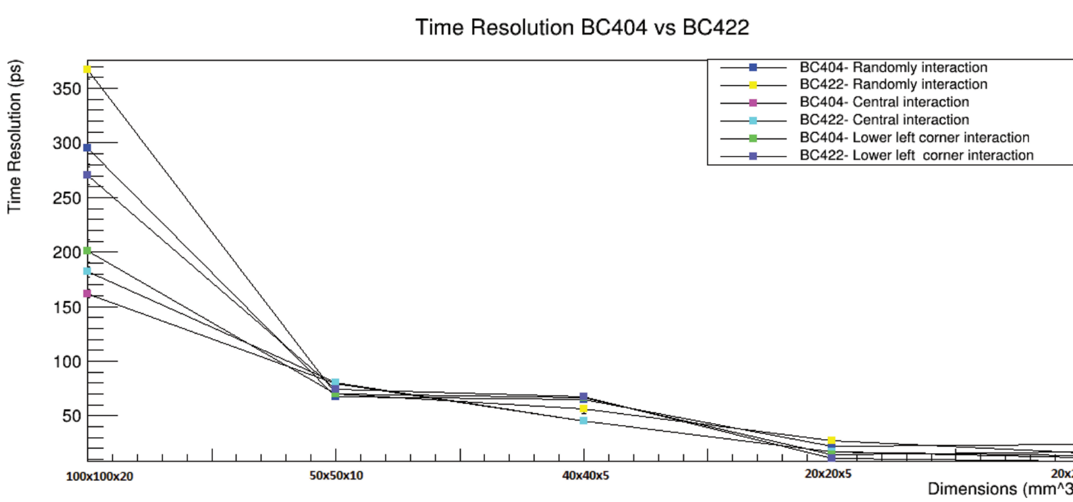

Figure 3: Time resolution of scintillator BC-404 vs BC-422 coupled with 2 SiPMs with different beam interactions.

Representative distributions corresponding to the smallest scintillator material arrangments (20x20x3 mm³), configured with randomly distributed, middle and corner beam are shown in Figures 4, 5 and 6, respectively. It should be noted that the data of all the arrays referring to the randomly distributed beam were fitted using a distribution called *Crystalball* which is identify by having a bias to the right *(Figure 4 and 7),* this bias becomes more prominent as the scintillator volumetric dimensions decreases *(Figure 7).* In contrast, the data belonging to the arrangements with the beam directed to the middle and to the left lower corner of the scintillator, behaved under a *Gaussian/normal Fit distribution (Figures 5 and 6).*

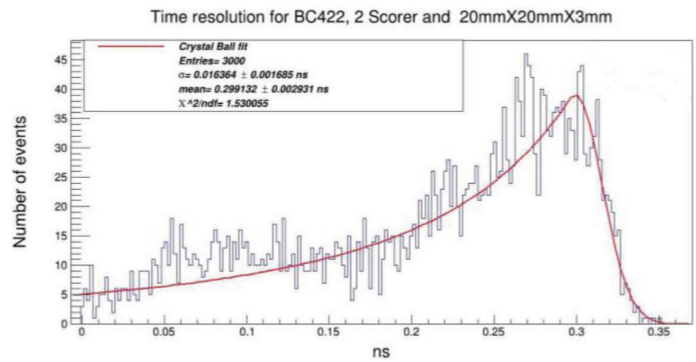

Figure 4: Crystalball Fit distribution of time resolution for the *2*0x20x3 mm³ array with randomly distributed muon beam on the scintillator.

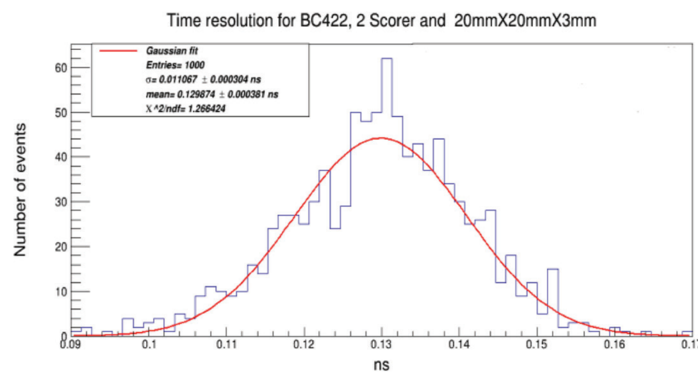

Figure 5: Gaussian Fit distribution of time resolution for the 20x20x3 mm³ array with a muon beam directed to the center of the scintillator.

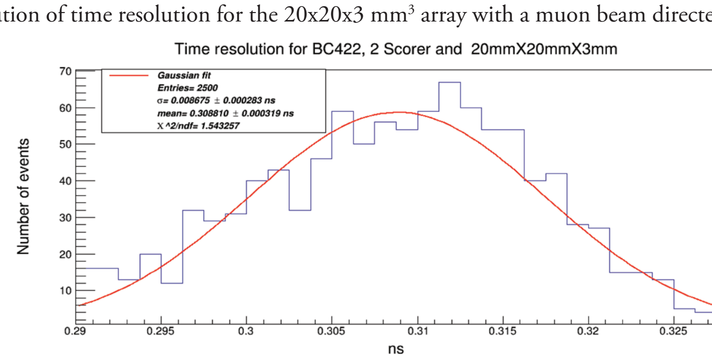

Figure 6: Gaussian Fit distribution of time resolution for the 20x20x3mm³ array with a muon beam directed to the lower left corner of the scintillator.

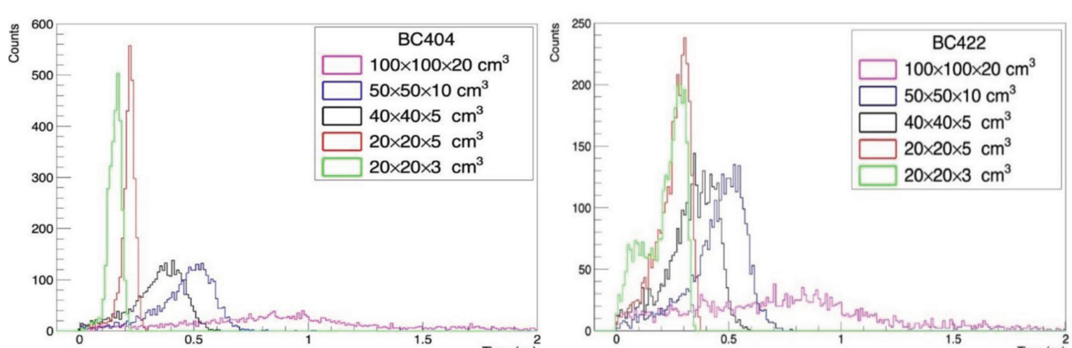

Figure 7: Arrival times distributions corresponding to materials BC-404 & BC-422 with randomly distributed beam configuration. (Left box) material BC-404. (Right box) Material BC-422.

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Conclusions

According to the *Saint Gobain* manufacturer the *BC-422* material has small percentages of benzophenone, which helps to improve the scintillator performance, which is superior to *BC-404* in scales lower than 40x40x5 mm^3 with respect to our arrangements. The manufacturer also mentions that *BC-422* scintillator plastic is designed for uses with *"ultra-fast timing"* and "ultra-fast counting" applications; in addition, it is recommended to be used with dimensions smaller than 100 mm**.** With this information we can contrast and better interpretate the performance difference between *BC-422 & BC-404*, and thus confirm that the results obtained are consistent with the *physical-chemical* reality of the scintillators.

It is also prudent to conclude that, the way in which a beam is configured to interact with the scintillator, will contribute to define the *statistical distribution* in which the data will behave. This is due to the differences in the optical path that the photons travel towards the *Score*, which are generated at particular distances from the *SIPM*, emphasizing the case of the *randomly distributed beam* on the surface of the scintillator, which was observed in this study.

Future Works

It is planned to return to the previously exposed beam configurations and to add others, to carry out simulations, and with them evaluate the performance of detectors with different geometries, sizes and scintillator materials, varying the particles with which they are irradiated.

On the other hand, it is desired to carry out this type of studies at an experimental level to compare the corresponding results with those of the previous simulations, and thus have more scientific arguments that allow the simulations to be validated with rigor and certainty. Specifically, it would be pertinent to evaluate at a simulation and/or experimentation level the scintillator materials *BC-422, BC-422Q, EJ-232 and EJ-232Q* [11,18], which are formed with a *PVT* base and contain different percentages of *benzophenone;* this with the purpose of observing how these percentages contribute to the improvement of *time resolution***.**

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