

Time Resolution Simulation Measurement for the Configuration Plastic Scintillator Material+SiPM and its Application to Medical Physics

C H Zepeda

Cátedra CONACyT, 03940 Ciudad de México, Mexico, Facultad de Ciencias Físico-Matemáticas, Benemérita Universidad Autónoma de Puebla, EMA 3 building, Office 206, University City, Puebla, Puebla, Mexico.

E-mail: hzepeda@fcfm.buap.mx

Abstract. The Silicon Photomultipliers (SiPMs) have been used more frequently in the last years compared to Photomultiplier Tubes (PMT), due to its low cost, lower bias operation voltage and its smaller size, which can be up to $1 \times 1 \text{ mm}^2$. In this work, it is shown the time resolution simulation results for two scintillating materials: BC404 and BC422 ($20 \times 20 \times 3 \text{ mm}^3$ of size)+ SiPM ($3 \times 3 \text{ mm}^2$ of size). The studies of this configuration can replace the PMT and crystals, commonly used in a Positron Emission Tomography (PET). The time resolution can be improved to be able to make the greatest data collection, to use an isotope with less life time and thus perform less damage to the patient by radiation.

1. Introduction

The low time resolution of detectors is very important for data collection. There are several types of detectors, the most used are gaseous or solid. To show an example of them, it can be observed the employees in the MPD experiment [1]. The Mexican group “MexNICA” will contribute with a detector called BEam-BEam Monitoring Detector (BE-BE) [2], with an expected time resolution of 45 ps, to be implemented in stage 2. From the results of the simulation part, the time resolution decreases with a greater detection area (number of photosensors) or scintillator size. The simulation made in this work are considering a Silicon Photon-multiplier (SiPM) Hamamatsu (S10985-050C) [3], with the purpose that due to its size (1 to 36 mm^2 of effective area), more than one can be easily coupled to the scintillator for the electronic part.

The detectors are not used only for scientific research, for example, they can be used in airport surveillance system or in medicine. In the hospitals are used in tomography, Magnetic Resonance Imaging (MRI) or Positron Emission Tomography (PET) [4]. The configuration of a PET is scintillator crystals and Photon-multiplier Tubes (PMTs). 64 scintillation crystals of approximately $2 \times 2 \text{ cm}^2$ (of frontal area and 3 cm long) are commonly used per each PMT (64 cm^2 of effective area), therefore, it is not possible to distinguish between these scintillators. On the contrary, it is possible to have the configuration of one scintillator for a SiPM and have information of each one, then, an image can be reconstructed with a larger number of pixels. Using this configuration, there will be a higher spatial resolution [5]. Finally, the operating

voltage of a PMT is in the range of 500-3000 V, while for a SiPM the operating voltage can be in 30-70 V, then, a low voltage source can be used.

The common scintillator material used in a PET is the LYSO crystal [6]. However, the implementation of a LGSO:Ce crystals are used lately [7]. The configuration scintillator material + SiPM has been studied before [5], [7], [8]. The relevance of this work is to use a plastic scintillator instead of a crystal, which is cheaper and it is possible to obtain a low time resolution to be implemented in a PET. The work is distributed as follows, in Section 2 is described our simulation method to find the intrinsic time resolution of a $20 \times 20 \times 3$ mm³ of plastic scintillator and we compare two commercial plastic scintillator materials: The BC404 and BC422. In Section 3 is shown the results and the discussions. Finally, in Section 4 our conclusions.

2. Simulation

Using Geant4 we simulated the four configurations shown in Fig. 1. In this program is complicated to simulate the electronic part, then, we used the black squares as the SiPMs (scorers) and we added two characteristic. The first one is that the photons stop when they arrive to the scorers and the other one, is that the scintillator was simulated with a reflection rate of 95% between it and the environment. The scorers are located in the opposite face of the interaction points and we simulated π^+ of 0.5 GeV as incident particles. The method we used is listed below.

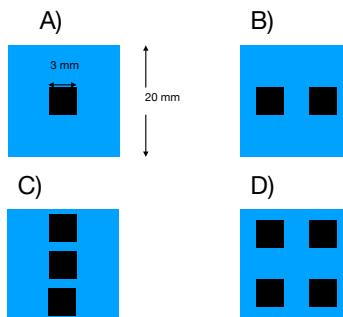


Figure 1. The four configurations we simulated to find the one with the lowest time resolution.

- (i) We simulated all the optical characteristics for BC404 and BC422 scintillated materials. These plastics have the same refractive index (1.58), however, they differ in the absorption length, 1.2 m for BC422 and 1.4 m for BC404. In Fig. 2 are shown the relative light output spectrum we simulated for each material. There are other amounts in which they differ as Rise Time and Decay Time [9], [10]. One of the objectives is to select the best material to obtain the lower intrinsic time resolution.
- (ii) The interaction was done covering the entire front face (2,000 events).
- (iii) For each event, we obtained the Landau Fit distribution of the time of flight of photons in each scorer. An example, the case for two scorers is shown in Fig. 3. We kept the minimum mean value of the Landau Fits. It represents the first photosensor to give the signal. Clearly for the case of 1 sensor it will have just 1 distribution.
- (iv) We obtain the Gaussian Fit distribution with the set of all minimums, being σ the intrinsic time resolution, independent of the electronics. The same shape distribution is obtained for the other cases.

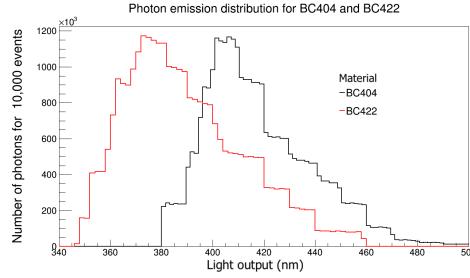


Figure 2. Photon emission simulation for BC404 and BC422.

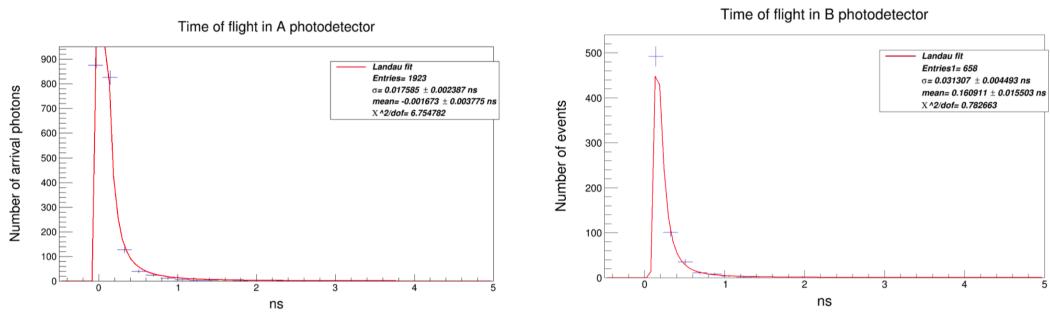


Figure 3. An example of time of flight Landau Fit distribution in each photosensor for one event. It is shown the results for B configuration of Fig. 1.

3. Results and discussion

As an example, in Fig. 4 is shown the lowest time of flight value distribution, i.e., the minimum mean value of Landau distributions for each event, for the configuration of 4 scorers. For the other configurations, the same shape is obtained (two Gaussians). The first Gaussian in each case represents the first signal pulse. For the four configurations (1, 2, 3, and 4 scorers), the intrinsic time resolution is around 8 ps. The two Gaussians represent the minimum time of flight value associated with the interaction points.

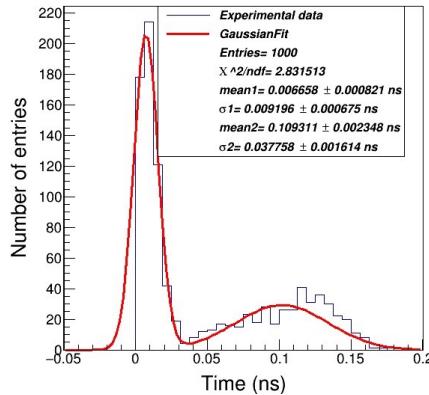


Figure 4. The set of minimum mean time of flight for scintillated photons. It is shown the results of D configuration of Fig. 1.

To understand the above described shape, we made three simulations, in which, a particular interaction point was chosen. These interaction points are shown in Fig. 5, we refer to them as corner, up and center. The time of flight distributions are shown in Figs. 6, 7 and 8, respectively. Clearly, a single Gaussian is obtained. Then, the distribution obtained in Fig. 4 is due to the average of all interaction points. It can be seen that the center interaction has a bigger time resolution due to the larger photon optical way. Opposite case of corner (up) interaction. In other words, the case of the corner (up) interaction, the photons are reflected immediately and then the variance is shorter than the center case. However, the mean distribution for the center has a lower value than the corner (up) case. The results are the same for the other three configurations of Fig. 1.

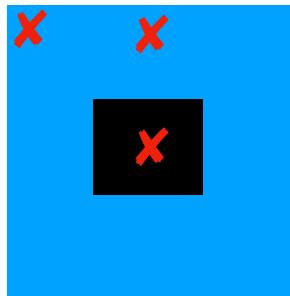


Figure 5. The three interaction points for the three simulations. It is shown the case of 1 scorer. We refer to the upper left as *corner*, the middle top as *up* and the central as *center*.

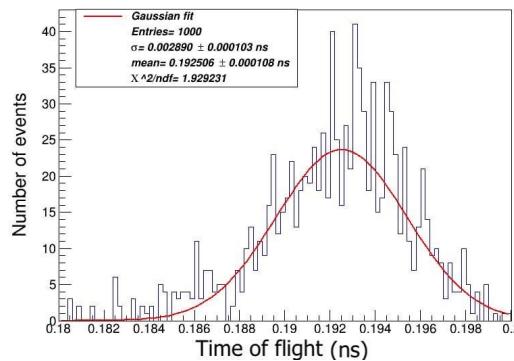


Figure 6. The time of flight distribution for the corner interaction point, relating to configuration of Fig. 5.

We repeated the method for the BC422 scintillator material. In Tables 1 and 2 are shown the results for 1 and 4 SiPMs configurations for BC404 and BC422 materials, respectively.

As an estimate of the experimental value, consider the analysis and results of [2]. Taking that the time resolution of the Front end electronics (σ_{FEE}) is 100 ps. To calculate the time resolution measured, it is used

$$\sigma_M^2 = \sigma_P^2 + \sigma_{FEE}^2, \quad (1)$$

where σ_M is the time resolutions measured considering the electronic and plastic scintillator and σ_P is the plastic intrinsic time resolution (8 ps). The PET time resolution will be of the order of

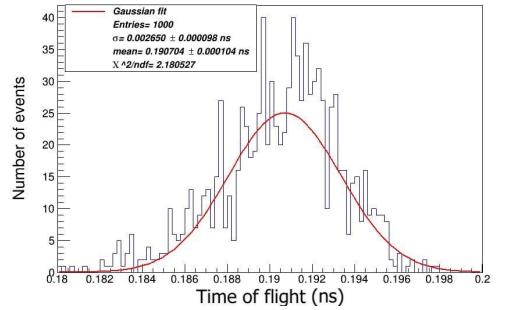


Figure 7. The time of flight distribution for the top interaction point, relating to configuration of Fig. 5.

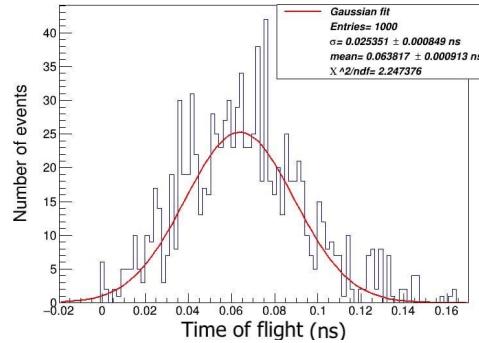


Figure 8. The time of flight distribution for the center interaction point, relating to configuration of Fig. 5.

100.32 ps. Note, that the greatest contribution is due to electronics. Compared this result with a PET using a PMT [11] where is reported a time resolution of 484 ps, a better time resolution would be obtained using our configuration. Values reported are on the order of hundreds of picoseconds, even using SiPMs [12].

Table 1. BC404 intrinsic time resolution for 1 and 4 configuration-scorers.

# of Scorers	All Area (ps)	Corner (ps)	Up (ps)	Center (ps)
1	7.76 ± 0.87	2.89 ± 0.10	2.65 ± 0.09	25.35 ± 0.85
4	9.29 ± 0.67	0.72 ± 0.10	1.81 ± 0.10	26.6 ± 0.10

Table 2. BC422 intrinsic time resolution for 1 and 4 configuration-scorers.

# of Scorers	All Area (ps)	Corner (ps)	Up (ps)	Center (ps)
1	7.76 ± 0.87	2.54 ± 0.12	2.74 ± 0.08	24.56 ± 0.85
4	9.29 ± 0.75	0.68 ± 0.06	1.89 ± 0.06	26.58 ± 0.82

4. Conclusions

The time resolution of a plastic scintillator material with size $2 \times 2 \times 0.3 \text{ cm}^3$ is in the range of 2.5 and 25 ps for 1 scorer and 0.7 and 27 ps for 4 scorers, the cases of 2 and 3 scorers are in the same range. In average, the intrinsic time resolution obtained is around 8 ps, remains constant for both materials (BC404 or BC422) and the number of photosensors. Whereby, using one photosensor the results are the same than using 4 photosensors, then, the cost of production is cheaper. Using this configuration, it is possible to construct a PET with more number of pixels (or cells, which are the proposals in this work), and therefore, a more defined image acquisition. The time resolution is very important for data acquisition in the case of brain or heart, in which, the life time of the isotope is 2 minutes. As a conclusion, the configuration shown in this work can improve the time and spatial resolution of a PET, due the small size of the cells, allows to use a small photosensor per cell, as well as, it can have more pixels and therefore an improvement in image construction. Finally, more data will be collected, because the time resolution improves using a SiPM than a PMT [2].

Other interesting SiPM that can be used is a SensL (C-60035-4P-EVB) [13]. This SiPM has the characteristic to obtain two pulses: Standard and fast. The fast pulse is very useful for our goal. It has a less rise time than the standard (1 ns and 4 ns, respectively) and it can give a fast response. The total time resolution is divided in the intrinsic part and the electronic part, then, the selection of the right SiPM also depends of their high photon detection efficiency [14]. The experimental analysis can help to this selection.

The analysis shown in this work is for one cell of the complete PET. The time resolution is the first important amount, for the reasons mentioned above. The second important amount is the Coincidence Time Resolution (CTR), which contemplates the detection gamma ray time of flight coincidence in two opposite cells. To complete the analysis shown in this work, will have to be calculated the CTR and compare it with previous results [7]. Recently a 10 ps of CTR has been achieved [15]. Comparing the simulation results in this work, will be in the order with those already mentioned.

References

- [1] Golovatyuk V, Kekelidze V, Kolesnikov V, Rogachevsky O and Sorin A 2016 *Eur. Phys. J. A* **52** 212
- [2] Alvarado M et al. 2020 *Nucl. Instrum. Methods Phys. Res. A* **953** 163150
- [3] Hammamatsu MPPC (multi-pixel photon counter) Datasheets 360 powered by IEEE GlobalSpec
- [4] Vansteenkiste J, Deroose C and Dooms C 2016 *21-Positron Emission Tomography* ed Courtney V et al. (Philadelphia) chapter 21 360
- [5] Daoming Xi et al. 2012 *Phys. Procedia* **37** 1497
- [6] Alva-Sánchez H et al. 2018. *Sci Rep* **8** 17310
- [7] Cates W J and Levin C S 2016 *Phys. Med. Biol.* **61** 2255
- [8] Otte N et al. 2006 *Nuclear Physics B (Proc. Suppl.)* **150** 417
- [9] CRYSTALS SAINT-GOBAIN 2018 BC400 BC404 BC408 BC412 BC416 Data Sheet
- [10] CRYSTALS SAINT-GOBAIN 2016 BC418 BC420 BC422 Data Sheet
- [11] Chen Z 2013 arXiv:1309.3736 [physics.ins-det]
- [12] Conti M, Bendriem B 2019 *Clin Transl Imaging* **7** 139
- [13] SensL sense light. C-Series Low Noise, Blue-Sensitive Silicon Photomultipliers DATASHEET
- [14] Cattaneo P W et al. 2014 *IEEE Trans. Nucl. Sci.* **61** 2657
- [15] Harmon E S, Thompson M O, Ross Schmidlein C R, Turner J N and Krol A 2020 *Medical Imaging 2020: Biomedical Applications in Molecular, Structural, and Functional Imaging. SPIE International Society for Optics and Photonics* 72