Deposited charge estimation from Fast signal on SensL SiPM, using plastic organic scintillators

A Preprint

C.H. Zepeda-Fernández
Facultad de Ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla
Av. San Claudio y 18 Sur, Ciudad Universitaria 72570, Puebla, Pue.
Cátedra CONACyT, 03940 Ciudad de México, México.

L.F. Rebolledo-Herrera *
Facultad de Ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla
Av. San Claudio y 18 Sur, Ciudad Universitaria 72570, Puebla, Pue.
fidel.rebolledo@inaoep.mx

M. Rodríguez-Cahuantzi
Facultad de Ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla
Av. San Claudio y 18 Sur, Ciudad Universitaria 72570, Puebla, Pue.

E. Moreno-Barbosa
Facultad de Ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla
Av. San Claudio y 18 Sur, Ciudad Universitaria 72570, Puebla, Pue.

June 1, 2020

ABSTRACT

The silicon photo-multipliers (SiPMs) are commonly used in the construction of radiation detectors such as those used in high energy experiments and its applications, where an excellent time resolution is required for triggering. In most of this cases, the trigger systems electric charge information is discarded due to limitations in data acquisition. In this work we propose a method using a simple radiation detector based on an organic plastic scintillator $2 \times 2 \times 0.3$ cm$^3$ size, to estimate the electric charge obtained from the acquisition of the fast output signal of a SensL SiPM model C-60035-4P-EVB. Our results suggest a linear relation between the reconstructed electric charge from the fast output of the SiPM used with respect to the one reconstructed with its standard signal output. Using our electric charge reconstruction method, we compared the sensitivity of two plastic scintillators, BC404 and BC422Q, under the presence of Sr90, Cs137, Co60 and Na22 radiation sources.

Keywords Scintillators · Trigger detectors · PET PET/CT

*corresponding author
**1 Introduction**

Silicon Photomultipliers (SiPM) have been widely used during the past two decades in different areas like high energy physics [2][1], and its medical applications. A clear example is the development of Positron Emission Tomography (PET)[3] where the typical photomultiplier tube (PMT) is being replaced by the SiPM technology with the aim to improve its time and spatial resolutions [6][5][4][7]. Since 2013 SensL corporation has developed SiPMs with two signal outputs: Standard and fast [8]. For a 6 × 6 mm$^3$ of SensL C-series SiPM, the standard signal output is characterized by a raise time of 4 ns and a pulse width of 100 ns, while the raise time of the fast signal output is 1 ns with a pulse width of 3.2 ns [9].

Several works have reported the use of SiPMs [3][12][10][1][11], where the standard output is commonly used to reconstruct the deposited electric charge using the acquired photo current from the anode which is related with the deposited energy in the sensitive material of a radiation detector [14][13][5][11]. In recent years, the fast signal output has been used to improve the pulse shape discrimination of gammas and fast neutrons [15][2]. It has been also shown that exists an equivalent coincidence resolving time (CRT) between the fast and standard output signals of the SensL SiPM [16]. An application for this fast pulse, is on a detector development with high time resolution as described in [17]. In this work we use a simple radiation detector based in organic plastic scintillator to study the relation of the reconstructed electric charged using both SensL SiPM output signals.

This work is organized as follows. In Section 2 the methodology of this work is described. In Section 3 we present the analysis and discussions of the results. Finally, in Section 4 we present our conclusions.

**2 Materials and method**

**2.1 Instrumentation**

A MicroFC-60035 SiPM from SensL with a cell size of 35 µm, peak wavelength of 420 nm and package size of 6 × 6 mm$^2$ was used. In order to acquire the two signals from this SiPM, we developed a homemade printed circuit board (PCB) of 3 × 4 cm, specifically designed for the described SiPM model. The schematic diagram is shown in Figure 1, where $V_s$ and $V_f$ refers to the standard and the fast output signal, respectively. As described in [9], an overvoltage of $V_{br}+5$ V was used to maximize the photon detection efficiency (PDE) of the SiPM.

![Figure 1: Basic front-end electronics for polarization and acquisition of standard and fast signals.](image)

We choose BC404 and BC422Q plastic scintillator as radiation sensitive materials, with a volume of 20 × 20 × 3 mm$^3$. Some scintillation characteristics are shown in Table 1[18]. The BC422Q material was selected with a weight percentage of benzophenone of 0.5%.

The experimental setup is shown in Figure 2. The SiPM was attached to the center of each plastic scintillator and a radioactive source was located in the opposite face. Four radiation sources are used: Sr90, Na22, Cs137 and Co60. The description for these radioactive sources is shown in Table 2.
Table 1: Scintillator material properties. [18]

|                  | BC404 | BC422Q |
|------------------|-------|--------|
| Rise Time (ps)   | 700   | 110    |
| Decay Time (ns)  | 1.8   | 0.7    |
| Pulse Width, FWHM (ps) | 2,200 | 360    |

Figure 2: Experimental setup scheme, showing the fast and standard outputs.

A Tektronix DPO7054 digital oscilloscope was used for signal acquisition, with a 50 Ω of coupling impedance and a sampling rate of 10 GS/s. For each radioactive source, $10^4$ events were recorded. Each event consists of $2 \times 10^4$ samples to reconstruct the pulse. The reconstruction and the data analysis was made offline with CERN ROOT software [19].

2.2 Method

We reconstruct the electric charge from the fast ($Q_F$) and standard ($Q_S$) output signals, using the integrals given in the follow equations:

$$Q_S = \int_{t_i}^{t_f} i_s(t) dt = \frac{1}{50} \int_{t_i}^{t_f} V_s(t) dt$$

(1)

$$Q_F = \int_{t_i}^{t_f} i_f(t) dt = \frac{1}{50} \int_{t_i}^{t_f} V_f(t) dt$$

(2)

If we assume a linear relation between fast and standard signal outputs, we can introduce a correlation coefficient given by

$$R_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y},$$

(3)

where $\sigma_{xy}$ is defined as the covariance between random variables $x$ and $y$, while $\sigma_x$ and $\sigma_y$ correspond to the standard deviation of $x$ and $y$ variables, respectively. After the described correlation test, a regression line can be adjusted to obtain a linear model based on statistical moments for each stochastic process, as described by the following equation

$$y - \bar{y} = \frac{\sigma_{xy}}{\sigma_x^2} (x - \bar{x}).$$

(4)

Table 2: Radiation sources properties.

| Source | Radiation [µCi] | Gamma 1 [keV] | Gamma 2 [keV] | Beta [keV] |
|--------|-----------------|---------------|---------------|------------|
| Co60   | 1.00            | 1173          | 1332          | -          |
| Cs137  | 0.25            | 662           | -             | -          |
| Na22   | 1.00            | 511           | 1275          | -          |
| Sr90   | 0.10            | -             | -             | 546        |
It can be rewritten in terms of the correlation coefficient as

$$y = \frac{\sigma_y}{\sigma_x} R_{xy}(x - \bar{x}) + \bar{y},$$

(5)

which is a standard equation of a straight line

$$y = ax + b$$

(6)

with

$$a = \frac{\sigma_y}{\sigma_x} R_{xy}$$

(7)

$$b = \bar{y} - a\bar{x}$$

(8)

In this case, $x$ was defined as the charge $Q_f$ measured from the standard signal and $y$ as the charge $Q_s$ from fast output signal. Therefore, equations 6 and 7 can be rearranged in terms of charge,

$$Q_s = aQ_f + b,$$

(9)

$$a = \frac{\sigma_s}{\sigma_f} R_{sf},$$

(10)

$$b = \bar{Q}_s - a\bar{Q}_f,$$

(11)

where $\sigma_f$ and $\sigma_s$ refer to standard deviation of fast and standard signal charges, respectively. While $R_{sf}$ is the correlation coefficient between $Q_s$ and $Q_f$.

## 3 Analysis and results

To determine the relation between standard and fast charges, the correlation coefficient was calculated for each radiation source (Co60, Cs137, Na22 and Sr90) and each plastic scintillator (BC404 and BC422Q). As the probability distribution functions for deposited charge from a SiPM are non Gaussian, Pearson correlation index cannot be accurate; thus, Spearman [20] correlation index was calculated as reported in Table 3.

| Source  | BC404 Pearson | BC404 Spearman | BC422Q Pearson | BC422Q Spearman |
|---------|---------------|----------------|----------------|-----------------|
| Co60    | 0.9686        | 0.9489         | 0.9783         | 0.9611          |
| Cs137   | 0.9484        | 0.9157         | 0.9367         | 0.9111          |
| Na22    | 0.9549        | 0.9414         | 0.9767         | 0.9320          |
| Sr90    | 0.9658        | 0.9522         | 0.9856         | 0.9660          |

Correlation coefficient was estimated, resulting on indexes close to one as observed on Table 3 which confirms the linear relation hypothesis for fast and standard reconstructed electric charge. Therefore, the described linear regression in Equation 4 can be applied to reconstruct the charge distribution for the standard output from the fast signal. This relation is depicted in Figure 3, where, the estimated charge correlation for each radioactive source was graphed.

Two orders of magnitude from fast and standard charge can be observed, which is related to the difference of charge deposition among the two variables of interest. Also, it is possible to qualitatively distinguish between the four sources for the case of BC404 scintillator, giving an opportunity for future development of classification algorithm implementation. In particular, Sr-90 and Cs-137 can be clearly separated from Na22 and Co60. For the case of BC422Q scintillator, this source separation seems to be harder to accomplish.

The mean and standard deviation are the required statistical momenta for the linear regression model. To exemplify and obtain these parameters from the charge distribution, in Figure 4 is shown the charge distribution for the Na22 and Sr90 radioactive sources. Doing a Gaussian fit in the part of the peaks, it is possible to get the required momenta. A particular case is observed for Na22 source, two peaks can be appreciate in fast and standard charge. One of these
peaks can be associated to the original gamma from the source and the other can be associated to a gamma from the pair annihilation from positron emission. For the other two sources, the charge distribution has one peak, similar to Sr90.

The charge distribution deposited in the BC422Q scintillator for the Na22 and Sr90 sources are shown in Figure 5, in order to compare the charge distribution with Figure 4. In this arrangement, a single peak is observed for Na22 on the contrary of the reviewed case of BC404 scintillator material. The other two sources have the same shape of one peak.

Once the linear relation between fast and standard charge has been established, all parameters required in the model were calculated. For each random variable, the correlation index \( R_{sf} \), the mean \( \bar{Q}_s \) and \( \bar{Q}_f \) and standard deviations \( \sigma_s \) and \( \sigma_f \) were estimated. To exemplify this relation, in Figure 6 is shown the linear dependence for Na22 source from BC404 and BC422Q scintillator materials. For a complete reference about the the resulting parameters, the measurements are listed in Tables 4 and 5 for BC404 and BC422Q scintillators, respectively.

Based on results from Tables 4 and 5, the linear regression parameters for each source and material are shown in Tables 6 and 7 for BC404 and BC422Q scintillator, respectively.

Using the respective linear regression from Tables 6 and 7, the reconstructed charge distribution for the cases of Na22 and Sr90 are shown in Figure 7.
Figure 6: Relation between the fast and standard charge for BC404 (up) and BC422Q (down).

Table 4: BC404 scintillator material linear regression estimated parameters

| Source | $Q_f$ \(10^{-12} C\) | $\sigma_f$ \(10^{-12} C\) | $Q_s$ \(10^{-10} C\) | $\sigma_s$ \(10^{-10} C\) |
|--------|-----------------|-----------------|-----------------|-----------------|
| Na$_{22}$ peak1 | 2.910 | 0.338 | 2.784 | 0.374 |
| Na$_{22}$ peak2 | 3.431 | 0.482 | 3.194 | 0.594 |
| Sr90 | 5.492 | 0.314 | 5.127 | 0.373 |
| Cs137 | 2.450 | 0.345 | 2.297 | 0.355 |
| Co60 | 3.648 | 0.259 | 3.464 | 0.433 |

Table 5: BC422Q scintillator material linear regression estimated parameters

| Source | $Q_f$ \(10^{-12} C\) | $\sigma_f$ \(10^{-12} C\) | $Q_s$ \(10^{-10} C\) | $\sigma_s$ \(10^{-10} C\) |
|--------|-----------------|-----------------|-----------------|-----------------|
| Na$_{22}$ | 0.311 | 0.099 | 0.258 | 0.068 |
| Sr90 | 0.323 | 0.116 | 0.262 | 0.074 |
| Cs137 | 0.333 | 0.131 | 0.269 | 0.082 |
| Co60 | 0.323 | 0.120 | 0.263 | 0.080 |

Table 6: Linear regression(BC404).

| Source | a \(10^{-3}\) | a (error) \(10^{-5}\) | b \(10^{-12} C\) | b (error) \(10^{-12} C\) |
|--------|-------------|-----------------|-------------|-----------------|
| Co60 | 7.75 | 6.3 | 1.14 | 0.03 |
| Cs137 | 6.18 | 9.9 | 1.06 | 0.22 |
| Na$_{22}$ | 8.43 | 9.3 | 0.69 | 0.02 |
| Sr90 | 9.06 | 5.5 | 0.95 | 0.03 |

Table 7: Linear regression(BC422Q)

| Source | a \(10^{-2}\) | a (error) \(10^{-5}\) | b \(10^{-12} C\) | b (error) \(10^{-12} C\) |
|--------|-------------|-----------------|-------------|-----------------|
| Co60 | 1.16 | 5.3 | 0.014 | 2.30 |
| Cs137 | 1.01 | 9.4 | 0.052 | 3.10 |
| Na$_{22}$ | 1.13 | 5.5 | 0.017 | 2.22 |
| Sr90 | 1.17 | 4.3 | 0.004 | 2.11 |
Figure 7: Charge reconstruction compared with standard output for (a) Na22 and (b) Sr90 for BC404 and (c) Na22 and (d) Sr90 for BC422Q scintillator.

The charge reconstruction from fast data was also developed for Co60 and Cs137 radiation sources, obtaining similar results as those described for Na22 and Sr90. It was possible to obtain a relation between the mean and $\sigma$ parameters from the Gaussian Fit. It is shown in Figure 8. The difference between this two scintillator configurations, is that for BC404, it is possible to make a distinction between the sources. Note that for BC422Q, the Cs137 apparently has the greatest mean, however, by the error values they are consistent. Then, the configuration with the BC422 scintillator does not allow us to distinguish between sources.

Figure 8: Mean-$\sigma$ relation from the Gaussian Fit for studied radiation sources with BC404 (up) and BC422 (down) scintillators.

4 Conclusions

We could find the relation between fast and standard pulses, i.e., given the fast pulse from a SensL SiPM, it is possible to reconstruct the standard pulse. Then, it is possible to estimate the deposited charge, instead of the standard output. In average, the factor conversion among fast and standard charge is $0.008 \pm 0.001 \times 10^{-12}$ for BC404 and $0.012 \pm 0.001 \times 10^{-12}$ for BC422Q. Whence, $Q_{S404}/Q_{F404} = 128.205$ and $Q_{S422}/Q_{F422} = 85.106$, which means that the charge deposition in the BC404 scintillator is 1.506 times the one for a BC422Q scintillator. Therefore (using these thin materials [11]), BC404 scintillator is 1.506 more sensitive than BC422Q scintillator for Sr90, Co60, Cs137 and Na22 radiation sources. This result gives the possibility to use the fast pulse from the detectors, where time resolution is an important restriction [17] and for fast triggering systems in Time of Flight (TOF) applications.

The continuity of this work is to obtain the time resolution of the configurations and select the lowest value. Using a
plastic scintillator, we plan to use this configuration in a PET, which usually use a LYSO crystal. The time resolution is a very important parameter in the data acquisition, for example, in the hospitals, the life time of the isotopes used for images of brain or heart is around 2 minutes, then, it is necessary to use fast detectors. This small configuration and using the fast pulse can improve the time and spatial resolution of a PET, the latter amount allows to have more pixels in a PET and therefore an improvement in image reconstruction. Finally, the sensibility of BC404, could be distinguish between the cosmic rays and the gamma particles, allowing to debug the background from the signal.

Acknowledgements

We thank Dr. José Alejandro Ayala Mercado (Instituto de Ciencias Nucleares, UNAM), Dr. María elena Tejeda-Yeomans (Universidad de Colima) and Dr. Luis Manuel Montaño Zetina (CINVESTAV) for their support in acquiring the SensL-SiPMs, scintillating plastics BC404 and BC422Q, respectively. With which it was possible to carry out this experiment.

References

[1] E. Garutti, *Silicon photomultipliers for high energy physics detectors*, J. Instrum. 6 (2011) 10 pg. C10003-C10003.
[2] F. Simon, *Silicon photomultipliers in particle and nuclear physics*, NUCL INSTRUM METH A 926 (2019) pg. 85-100.
[3] M. Pizzichemi et al., *On light sharing TOF-PET modules with depth of interaction and 157 ps FWHM coincidence time resolution*, Phys. Med. Biol 64 15 (2019) 15 pg. 155008.
[4] E. Ebru and C. Celiktas, *Effects of the positions of scintillation detectors with fast scintillators and photomultiplier tubes on TOF–PET performance*, Pramana 94 (2020) 1.
[5] W. Krzemien et al., *A novel TOF-PET detector based on plastic scintillators*, in 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), October 2015.
[6] L. Raczyński, *Reconstruction of signal in plastic scintillator of PET using Tikhonov regularization*, in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), August 2015.
[7] A. Wieczorek et al., *Novel scintillating material 2-(4-styrylphenyl)benzoxazole for the fully digital and MRI compatible J-PET tomograph based on plastic scintillators*, PLoS One 12 (2017) 11 pg. e0186728.
[8] K. O’Neil et al., *SensL New Fast Timing SPM - High-Speed Silicon Photomultiplier Signal Output for High-Performance Timing Applications*, doi: 10.22323/1.158.0022, May 2013 pg. 022.
[9] SensL Technologies Ltd., *Product Selection Guide*, http://sensl.com/products 2013.
[10] T. Cervi et al., *Characterization of SiPM arrays in different series and parallel configurations*, NUCL INSTRUM METH A 912 (2018) pg. 209-212.
[11] E. Lamprou, *Exploring TOF capabilities of PET detector blocks based on large monolithic crystals and analog SiPMS*, PHYS MEDICA 70 (2020) pg. 10-18.
[12] M. Nemallapudi, *Single photon time resolution of state of the art SiPMs*, J INSTRUM 11 (2016) 10.
[13] K. Kuper, *On reachable energy resolution of SiPM based scintillation counters for X-ray detection*, J INSTRUM 12 (2017) 01 pg. P01001-P01001.
[14] P. Lv, *A low-energy sensitive compact gamma-ray detector based on LaBr <sub>3</sub>&gt;3</sub>&gt; and SiPM for GECAM*, J INSTRUM 13 (2018) 08 pg. P08014-P08014.
[15] Y. Junhao, *Pulse shape discrimination based on fast signals from silicon photomultipliers*, NUCL INSTRUM METH A 894 (2018) pg. 129-137.
[16] D. Sergei, *Timing resolution performance comparison for fast and standard outputs of SensL SiPM*, IEEE Nuclear Science Symposium Conference Record (2013).
[17] M. Alvarado et al., *A beam–beam monitoring detector for the MPD experiment at NICA*, NUCL INSTRUM METH A 953 (2020) pg. 163150.
[18] AMCRYS, *Plastic Scintillators for n and gamma discrimination*, http://www.amcrys.com/details.html?cat_id=146&id=4302.
[19] R. Brun, *ROOT — An object oriented data analysis framework*, NUCL INSTRUM METH A 389 (1997) 1-2 pg.81-86.
[20] Ma. Rubao, *Asymptotic Properties of Pearson’s Rank-Variate Correlation Coefficient under Contaminated Gaussian Model*, PLoS One 9 (2014) 11 pg. 1-15.