Performance study of Philips digital silicon photomultiplier coupled to scintillating crystals

Z. Liu,¹,† M. Pizzichemi,¹ E. Auffray,² P. Lecoq² and M. Paganoni³

¹University of Milano-Bicocca, Piazza della Scienza 3, 20126, Milano, Italy
²European Centre for Nuclear Research (CERN), 1211, Geneva 23, Switzerland

E-mail: zheng.liu@cern.ch

Abstract: Silicon photomultipliers (SiPMs) and scintillators are often arranged in the shape of arrays in Positron Emission Tomography (PET) systems. Digital SiPMs provide signal readout in single photon avalanche diode (SPAD) level. From the photon count rate measurement of each SPAD cell of digital SiPM, we found that the output scintillating photons distribute in an area larger than the scintillator physical coupling area. Taking advantage of the possibility to enable/disable individual cells of the digital SiPM, a group of Lutetium-yttrium oxyorthosilicate (LYSO) crystals with different dimensions coupled to a digital SiPM was used to study the influence of using different SiPM active area on the number of photons detected, energy resolution and coincidence time resolution (CTR). For the same crystal coupled to the digital SiPM, the larger the active area of digital SiPM, the higher the number of photons detected. The larger active area of the digital SiPM also results in a better energy resolution after saturation correction. The best energy resolution full width half maximum (FWHM) obtained for the 2×2×5 mm³, 2×2×10 mm³, 2×2×15 mm³, 2×2×20 mm³ LYSO crystals was 10.7%, 11.6%, 12.1%, 12.5%, respectively. For crystals with different cross sections coupled to the digital SiPM, we found that the larger the cross section of coupling area, the more photons were detected and thus a better energy resolution was obtained. The CTR of crystals fully wrapped with Teflon or without wrapping was measured by positioning two identical crystals facing each other. A larger area of digital SiPM improves the CTR and the CTR reaches the plateau when the active area is larger than 2.2×2.2 mm² with both two configurations of wrapping. The best CTR value for the 2×2×5 mm³, 2×2×10 mm³, 2×2×15 mm³, 2×2×20 mm³ LYSO crystals was 128.9 ps, 148.4 ps, 171.6 ps, 177.9 ps, respectively. The measurements performed lead us to conclude that optimising the coupling between crystal and SiPM to extract more scintillating photons can improve the energy resolution and CTR.

Keywords: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA)

†Corresponding author.
1 Introduction

Silicon Photomultipliers (SiPMs) are foreseen to be widely utilised in near future by Positron Emission Tomography (PET) scanners, thanks to their compactness, insensitivity to magnetic field and low operation voltage. Time of Flight (TOF) information has been shown to improve the performance of PET scanners. Analog SiPMs and digital SiPMs have already shown excellent timing performance when coupled to scintillators. A coincidence time resolution (CTR) of 108 ps full width half maximum (FWHM) has been achieved with 2×2×3 mm$^3$ LSO:Ce codoped 0.4%Ca coupled to Hamamatsu MPPC (S10931-050P) and read out with the NINO ASIC [1], [2]. The digital SiPM produced by Philips has been shown to provide CTR of 134 ps FWHM when coupled to 3×3×5 mm$^3$ Lutetium-yttrium oxyorthosilicate (LYSO) crystals [3].

In PET systems, scintillators and detectors are often arranged in the shape of arrays. In these configurations, the scintillating light produced by each crystal can be detected by multiple channels of the detector array [4], [5]. In general, because of the large angular distribution of light emitted by a scintillator [6], the photons produced by a single crystal have a chance to hit the detector over an area larger than the cross section of the crystal itself. Digital SiPMs have the advantage of allowing the user to select the active area of the detector, by enabling or disabling the single photon avalanche diodes (SPADs). In this paper, we present a study on the influence of choosing different active areas on the energy resolution and CTR for the Philips digital SiPM.
Figure 1. Photo of Philips DPC-3200-22 sensor.

Figure 2. Layout and dimension of digital SiPM developed from Philips [7].

Figure 3. Layout and dimension of single die composed of 4 pixels. Each pixel consists 3200 SPAD cells.

2 Philips digital photon counter device characterisation

Two DPC-3200-22 sensors are provided in the Philips digital photon counter (PDPC) Technology Evaluation Kit. A photo of DPC-3200-22 sensor is shown in figure 1. The DPC-3200-22 sensor consists of 16 independent die sensors arranged in a 4×4 array, as shown in figure 2. A die sensor contains four pixels, arranged in a 2×2 array, and each pixel consists of 3200 SPAD cells [7]. The size of each SPAD cell is 59.4×64 µm². As shown in figure 3, the dimension of each die is 7.15×7.8775 mm² and each pixel of a die has an area of 3.2×3.8775 mm². A pair of time to digital converters (TDCs) is coupled to each die and generates a single time stamp. The timestamp generation is determined by the configured trigger threshold, which can be set to the level of the first photon or, alternatively, to higher photon thresholds. We have performed a threshold scan for the CTR with LYSO crystals coupled to digital SiPM and found that the best CTR was provided by a trigger threshold set to 1 photon. Based on this, we choose to use first photon trigger level during our measurements, in order to get the best timing performance.

2.1 Breakdown voltage

The PDPC kit itself provides a method to measure the breakdown voltage, based on the current as a function of bias voltage. The breakdown voltage of sensor 1 (Tile 1) was found to be 22.65 V at 18°C, while for sensor 3 (Tile 3) the value obtained was 22.62 V at 18°C.
2.2 Dark count rate

The mean value of dark count rate (DCR) for each die of tile 1 at 3.3 V over bias voltage was measured to be 24.5 MHz at 18°C, while under the same conditions a mean DCR value of 23.9 MHz was measured for each die of tile 3. The DCR value of most single SPAD cells operated at 3.3 V over bias voltage is below 1 kHz. In the energy and CTR measurements, only pixel 1 of die 3 (3200 SPAD cells) of each sensor was coupled to a crystal. The DCR of that pixel, measured for the two DPC-3200-22 sensors with temperature kept stable at 18°C, was 5.8 MHz and 5.6 MHz respectively, at 3.3 V over bias voltage. By disabling 5% of SPAD cells with highest DCR, the DCR of the pixel for the two sensors measured at 3.5 V over bias voltage was decreased to 3.2 MHz and 3.0 MHz respectively, at 18°C.

3 Setup

The performance of digital SiPM was investigated by means of the experimental setup shown in figure 4, developed at CERN in the frame of the Crystal Clear group in PH-CMX. Two sets of LYSO crystals produced by Crystal Photonics, Inc. (CPI) were tested. The crystals of one set have the same cross section of 2×2 mm², but different lengths of 5 mm, 10 mm, 15 mm and 20 mm. The crystals of another set of have the same length of 15mm, but different cross sections of 1.5×1.5 mm², 2×2 mm², and 3×3 mm². Each crystal was glued to the digital SiPM by means of Dow Corning RTV 3145 [8], and can be either fully wrapped with Teflon or left without any wrapping. All crystals were glued in the centre of pixel 1 in die 3 of the digital SiPM as shown in figure 3. In order to measure CTR, two crystals were placed facing each other at a distance of 5 cm, and a $^{22}$Na source, 3 MBq activity, was placed halfway between the two crystals. In the energy and CTR measurements, to suppress the DCR of the digital SiPM, only the pixel 1 directly coupled to the crystal was enabled, while other areas of the digital SiPM were disabled.

4 Crystal position identification and active area selection

The position of the crystal coupled to the digital SiPM was identified by the photon count rate map recorded by the digital SiPM itself. A $^{22}$Na source was positioned in front of the crystal and 2 V over bias voltage was applied to the digital SiPM. The photon count rate was measured on
Figure 5. Photon count rate map for a single LYSO crystal, dimensions of $2\times2\times15$ mm$^3$, glued on the digital SiPM. The crystal was fully wrapped with Teflon. The measurement was performed at 2 V over bias voltage and at a temperature of 18°C.

Figure 6. Plot of photon count rate map for one pixel of the digital SiPM. A single $2\times2\times15$ mm$^3$ LYSO crystal, fully wrapped with Teflon, has been glued on the SiPM. The measurement was performed at 2 V over bias voltage and at a temperature of 18°C.

SPAD-by-SPAD basis. We sequentially enabled single SPAD cells of the chip, one after the other, and measured the number of photons detected by each SPAD during the same amount of time. There was no crosstalk in these measurements since only one SPAD cell was activated during each data take. As shown in figure 5, from the photon count rate map it is straightforward to identify the position of the crystal coupled to the detector (red area). At the same time, it is clear that some optical photons interact with the digital SiPM also outside of the area of physical coupling between crystal and detector, as an effect of the large angular distribution of the photons emitted by the scintillator.

Figure 6 shows the dimensions of one pixel and the dimensions of the crystal. As mentioned before, the pixel dimension for the digital SiPM is $3.2\text{ mm} \times 3.8775\text{ mm}$, while the cross section of the crystal is $2\times2\text{ mm}^2$, corresponding to the red square in figure 6. In our study we selected 7 different areas of SPAD activation, all centred on the crystal position, with the following dimensions: $1.6\times1.6\text{ mm}^2$, $1.8\times1.8\text{ mm}^2$, $2\times2\text{ mm}^2$, $2.2\times2.2\text{ mm}^2$, $2.5\times2.5\text{ mm}^2$, $2.8\times2.8\text{ mm}^2$, and the entire pixel 1 of die 3. An example of a $2.5\times2.5\text{ mm}^2$ square selection area is also shown in figure 6.
Energy resolution and light yield output

The variation of energy resolution and number of photons detected as a function of the different active areas of the digital SiPM has been studied. From the measurements we found that, without saturation correction, the energy resolution reaches the best values when over bias voltage is set to 3.3 V and 100% of the SPAD cells are enabled, which is in agreement with measurements reported by other groups [9]. Also, the energy resolution was found to be better in teflon wrapping configuration with respect to no wrapping condition. Therefore, for the purpose of the energy resolution investigation, the over bias voltage was fixed at 3.3 V and 100% of the cells in the selected digital SiPM area were activated, and the crystals were fully wrapped with Teflon.

Figure 7. Left: \(^{22}\text{Na}\) spectra with 2×2×15 mm\(^3\) LYSO crystal at 3.3 V over bias voltage with 100% cells activated. Right: Saturation corrected energy spectra of left \(^{22}\text{Na}\) spectra. The measurements were performed at 18°C.

Figure 8. Light output of a 2×2×15 mm\(^3\) LYSO crystal coupled to digital SiPM with 2.5×2.5 mm\(^2\) active area, for different gamma source energies. The measurements were performed at 3.3 V over bias voltage and a temperature of 18°C.
The left plot of figure 7 shows the $^{22}$Na spectrum of a $2\times2\times15$ mm$^3$ LYSO crystal. Both 511 keV peak and 1270 keV peak can be clearly identified. The energy resolution for 511 keV in this plot is 6.7%, as can be deduced from a gaussian fit of the peak itself. However, this value of energy resolution has not been corrected for the saturation effect due to the finite number of cells available in the digital SiPM. In order to perform such a correction, we acquired the data with the same setup exciting the scintillator with three different gamma sources, $^{57}$Co, $^{22}$Na and $^{137}$Cs. Then we extracted the mean number of photons detected by the digital SiPM for the four different gamma peaks provided by the sources, i.e. 117 keV, 511 keV, 667 keV, and 1270 keV. For digital SiPMs, under the assumption that each SPAD cell cannot detect more than one photon during the acquisition of a single scintillation event, a simple equation can be used to describe the saturation effect [10]:

$$N_{\text{detected}} = N_{\text{cells}} \left(1 - e^{-\frac{N_{\text{photons}}}{N_{\text{cells}}}}\right) \quad (5.1)$$

where $N_{\text{detected}}$ is the number of photons detected by the digital SiPM and $N_{\text{photons}}$ is the real number of photons that would interact with the digital SiPM if there was no saturation effect. $N_{\text{cells}}$ represents the total number of active cells of the digital SiPM. If we express the number of photons emitted by the crystal, per unit energy of the incident radiation, as $LY$, the probability of a photon hitting the detector to be actually detected as photon detection efficiency ($PDE$), and we introduce a factor $\eta$ taking into account the optical coupling efficiency between the crystal and the detector, we can express $N_{\text{photons}}$ as

$$N_{\text{photons}} = PDE \times LY \times \eta \times E_{\gamma} \quad (5.2)$$

where $E_{\gamma}$ is the energy of the gamma source. Equation (5.1) therefore becomes

$$N_{\text{detected}} = N_{\text{cells}} \left(1 - e^{-\frac{PDE \times LY \times \eta \times E_{\gamma}}{N_{\text{cells}}}}\right) \quad (5.3)$$

The parameters $PDE$, $LY$ and $\eta$ remain constant for a given experimental setup, so they can be collectively grouped in a factor $C = PDE \times LY \times \eta$, yielding to

$$N_{\text{detected}} = N_{\text{cells}} \left(1 - e^{-\frac{E_{\gamma}}{C}}\right) \quad (5.4)$$

By inverting this equation, it is easy to find a relation to derive $N_{\text{photons}}$ when a given number $N_{\text{detected}}$ is detected by the SiPM

$$C \times E_{\gamma} = N_{\text{photons}} = -N_{\text{cells}} \times \ln \left(1 - \frac{N_{\text{detected}}}{N_{\text{cells}}}\right) \quad (5.5)$$

Equation (5.4) can be used to derive the parameters $C$ and $N_{\text{cells}}$, by fitting to the experimental points in plots like the one in figure 8, where the number of photons detected by the SiPM is plotted against the energy of the gamma source. In this measurement, the detection area enabled on the SiPM is $2.5\times2.5$ mm$^2$. The $N_{\text{cells}}$ parameter can then be used with eq. (5.5) to derive the value of impinging $N_{\text{photons}}$ for each recorded event, enabling to plot non-saturated energy spectra like the one shown in the right plot of figure 7, for a $^{22}$Na source.

The number of photons detected and number of photons impinging on the SiPM as a function of different active areas of the digital SiPM, for crystals of different lengths, are shown in figure 9 and
Figure 9. Number of photons detected as a function of different active areas of the digital SiPM, for crystals of different lengths. The measurements were performed at 3.3 V over bias voltage and at a temperature of 18°C.

Figure 10. Number of photons impinging on the detector as a function of different active areas of the digital SiPM, after saturation correction, for crystals of different lengths. The measurements were performed at 3.3 V over bias voltage and at a temperature of 18°C.

Figure 11. Energy resolution without corrections as a function of different active areas of the digital SiPM, for crystals of different lengths. The measurements were performed at 3.3 V over bias voltage and at a temperature of 18°C.

Figure 12. Energy resolution with saturation correction as a function of different active areas of the digital SiPM, for crystals of different lengths. The measurements were performed at 3.3 V over bias voltage and at a temperature of 18°C.

Table 1. Energy resolution for different cross sections of LYSO crystals. The energy resolution, with and without saturation correction, shown in this table are the best value obtained when choosing the optimal active area of digital SiPM for the glued crystals. The number of photons detected and the number of photons impinging on the SiPM shown in this table are referred to an active area equal to the total pixel area.

| Dimension of CPI-LYSO (mm³) | 1.5×1.5×15 | 2×2×15 | 3×3×15 |
|-----------------------------|------------|--------|--------|
| Energy resolution not corrected (FWHM)(%) | 5.0         | 4.0    | 4.8    |
| Energy resolution saturation corrected (FWHM)(%) | 15.1        | 13.0   | 10.3   |
| Energy resolution measured with PMT (FWHM)(%) | 11.5        | 12.1   | 10.8   |
| Number of photons detected | 1045        | 1754   | 2180   |
| Number of photons detected saturation corrected | 1757        | 3138   | 3882   |
Both with and without saturation correction, the number of photons detected by the SiPM increases when the active area is increased. Figure 11 and figure 12 show the variation of the energy resolution as a function of different active areas of the digital SiPM, for crystals of different lengths. The energy resolution without saturation correction shows an improvement when the active area of the digital SiPM is decreased. On the other hand, the energy resolution after saturation correction does not follow the same trend. For instance, the 2x2x5 mm$^3$ crystal achieves the best energy resolution value of 11.7% when the active area is 2.8x2.8 mm$^2$. For the scintillators we measured, the active area that optimises the energy resolution was found to be neither the physical coupling area, nor the largest area of digital SiPM, but an area close to the average between the two. The values of energy resolutions obtained with the digital SiPM were also compared to measurements carried out with photomultiplier tubes (PMTs). All crystals investigated in this study, fully wrapped with Teflon, were measured coupled to an Hamamatsu PMT R2059 [11] by means of RTV 3145. The energy resolution (FWHM) obtained with the PMT for crystal lengths of 5 mm, 10 mm, 15 mm, 20 mm was found to be 10.7%, 11.6%, 12.1%, 12.5%, respectively. These values are comparable to the energy resolutions measured by the digital SiPM in the best active area configuration (see figure 12).

**Figure 13.** Correlation plot of number of photons impinging on the SiPM and energy resolution after saturation correction, for different LYSO crystals. The measurements were performed at 3.3 V over bias voltage and at a temperature of 18°C.

The variation of energy resolution as a function of the cross section of the LYSO crystal was also investigated. We obtained the best energy resolutions, after saturation correction, with the same optimal active area that was found in the previous part of this study. Table 1 summarizes the measurement results for digital SiPM and PMT. As shown in the table, the energy resolution measured by digital SiPM after saturation correction improves when the cross section area of the crystal is increased. This reflects the increasing number of photons detected when the section of the crystal becomes larger. However, the energy resolution measured by the PMT shows little variation when the cross section of crystals is increased, and the values obtained for 1.5x1.5x15 mm$^3$ and 2x2x15 mm$^3$ crystals are consistently better with respect to the ones measured by the digital SiPM.

For the same crystal, without saturation correction, activating a smaller area of the digital SiPM improves the energy resolution. This can be explained by considering that most of the scintillating photons are impinging on the detector inside the area of physical coupling between crystal and SiPM.
where the saturation effect is larger, resulting in an spurious compression of the photoprobe. The energy resolution with saturation correction is however the most important parameter to be taken into account, as it reflects the real energy discrimination capability of the system. This is shown to improve when the active area is larger than the area of physical coupling between crystal and detector, because more cells of digital SiPM are involved in the detection and therefore more photons from the scintillating light are collected, as shown in figure 13, improving the statistical contribution to the energy resolution. After having reached the best energy performance, the energy resolution is then limited by the noise of digital SiPM and by crosstalk, which explains the degradation of energy resolution when the active area is further increased.

6 Coincidence time resolution

Figure 14. Coincidence time resolution plot of two $2 \times 2 \times 20$ mm$^3$ LYSO crystals coupled to digital SiPM. The measurement was performed at 3.3 V over bias voltage and at a temperature of 18°C.

Figure 15. Coincidence time resolution for different over bias voltage with a $2 \times 2 \times 15$ mm$^3$ LYSO crystal. The measurements were performed when 100% of the cells of one pixel are enabled. The temperature was 18°C.
Figure 16. Coincidence time resolution for different percentages of activated cells with a $2\times2\times15$ mm$^3$ LYSO crystal. The measurements were performed at 3.5 V over bias voltage and at a temperature of 18°C.

Figure 14 shows a typical energy spectrum and a coincidence time difference histogram for two identical LYSO crystals with dimensions of $2\times2\times20$ mm$^3$ coupled to the digital SiPM. All the events within one sigma of the gaussian fit of the photon peak were selected and their coincidence time differences were histogrammed in the time spectrum. A gaussian fit was performed on this resulting histogram and the CTR was extracted. CTR measurements with different bias voltage and different percentage of active cells were performed to find the optimal configuration for the timing study. The results are shown in figure 15 and figure 16. As the two plots indicate, the CTR improves with increasing over bias voltage and reaches a plateau when the over bias voltage becomes larger than 3 V. The CTR reaches the best value when 95% of cells are activated. For CTR measurements with LYSO crystals, the over bias voltage was fixed at 3.5 V and 5% of the cells with high DCR values were disabled.

Figure 17. Coincidence time resolution for a LYSO crystal with dimensions $2\times2\times5$ mm$^3$, with different sizes of digital SiPM active area. The measurements were performed at 3.5 V over bias voltage and at a temperature of 18°C.

Figure 18. Coincidence time resolution for a LYSO crystal with dimensions $2\times2\times10$ mm$^3$, with different sizes of digital SiPM active area. The measurements were performed at 3.5 V over bias voltage and at a temperature of 18°C.

The variation of CTR with crystal length, for crystal cross section of $2\times2$ mm$^2$, is shown in figures 17 to 20. In the configuration without Teflon wrapping, to make sure no photon exiting from the lateral faces of the crystal impinges on the digital SiPM, a black holder with $2\times2$ mm$^2$
square hole was attached to the crystal itself. The CTR deteriorates when the length of the crystal is increased, for both teflon wrapping and no wrapping configuration. This is the same trend that was found in analog SiPMs [2]. For different dimensions of crystals, the CTR reaches the best values when the active area is larger than $2.2 \times 2.2 \text{mm}^2$, improving by 8–10 ps with respect to the condition where an active area of $2 \times 2 \text{mm}^2$ is set. This can be explained by recalling, as shown in figure 9 and figure 10, that the number of photons detected increases when a larger area of digital SiPM is activated. Photo-statistics can greatly impact the timing resolution, and a strong correlation between the crystal light output and timing resolution has already been demonstrated in our previous study [12]. However, when the active area is increased further than $2.2 \times 2.2 \text{mm}^2$, little effect on the CTR can be detected.

![Figure 19](image1.png)  
**Figure 19.** Coincidence time resolution for LYSO crystal with dimension of $2 \times 2 \times 15 \text{mm}^3$ with different sizes of digital SiPM active area. The measurement were performed at 3.5 V over bias voltage and at a temperature of 18°C.

![Figure 20](image2.png)  
**Figure 20.** Coincidence time resolution for LYSO crystal with dimension of $2 \times 2 \times 20 \text{mm}^3$ with different sizes of digital SiPM active area. The measurement were performed at 3.5 V over bias voltage and at a temperature of 18°C.

![Figure 21](image3.png)  
**Figure 21.** Schematic of the Geant4 simulation model.

The CTR of 15 mm length LYSO crystals was also measured as a function of different crystal cross sections. The best CTR obtained for each cross section, when the active area of digital SiPM is optimised, is shown in table 2. As the difference in CTR between the cross sections investigated is negligible, we can conclude that CTR is independent on the physical coupling area between crystal and digital SiPM.
Table 2. CTR for different cross sections of LYSO crystals.

| Crystal dimension (mm$^3$) | CTR (FWHM)(ps) |
|----------------------------|----------------|
| 1.5x1.5x15                 | 172.6±2.4      |
| 2x2x15                     | 171.6±2.2      |
| 3x3x15                     | 170.7±1.9      |

Table 3. Properties of LYSO crystal simulated. The parameters are taken from [12], [14].

| Intrinsic light yield (ph/MeV) | Rise time (ps) | Decay time (ns) |
|-------------------------------|----------------|-----------------|
| 40000                         | 100            | 40              |

Figure 22. Simulation results of $2 \times 2 \times 20$ mm$^3$ LYSO crystal. The plot shows the mean number of photons detected during the first 200 ps for different active areas.

Figure 23. Simulation and measurement results of $2 \times 2 \times 20$ mm$^3$ LYSO crystal. The plot shows the mean number of photons detected during the total scintillation process for different active areas.

Figure 24. Simulation result of $2 \times 2 \times 20$ mm$^3$ LYSO crystal. The plot shows the position distribution scintillation light impinging on the detector.

Figure 25. Simulation result of $2 \times 2 \times 20$ mm$^3$ LYSO crystal. The plot shows the position distribution scintillation light impinging on the detector during the first 200 ps.
We performed a Geant4 [13] simulation study in order to understand the behaviour of CTR when using different active areas of digital SiPM. A physical volume of silicium, 3.2×3.8775 mm$^2$ to simulate the digital SiPM together with a LYSO crystal are included in the simulation geometry, as shown in figure 21. X-axis and Y-axis are oriented along the plane of the SiPM, while and Z-axis is oriented along the main axis of crystal. The LYSO crystal surfaces were defined as optically polished, and the crystal can be either fully wrapped with Teflon or left without any wrapping. The properties of simulated LYSO material are shown in table 3. The intrinsic light yield here represents the number of optical photons created per unit of deposited energy and corresponds to the light output corrected by the light transfer efficiency. As shown in figure 23, the number of photons output from simulation is quite close to the value we measured with the digital SiPM. In our simulation the rise time and decay time of the scintillation pulse are also taken into account. A glass volume of 0.2 mm thickness is placed between the crystal and SiPM and is coupled with them by means of with optical glue. A source of gamma, 511 keV energy, is placed approximately 10 cm from the crystal, on the opposite side of the SiPM. $10^5$ gamma interactions with the scintillator are simulated for each configuration of LYSO crystal coupled to digital SiPM previously studied. Saturation effects are not considered and we consider the PDE of digital SiPM as 28%, based on the values reported in [10].

Figure 22 to figure 26 show the simulation results for a $2 \times 2 \times 20$ mm$^3$ LYSO coupled to the digital SiPM, without any wrapping. As it is very well known, the first photons arriving on the SiPM give rise to the most important contribution to the timing resolution. In figure 22 and figure 23, the number of scintillating photons detected during the first 200 ps increases when the active area is increased from 1.6×1.6 mm$^2$ to 2.2×2.2 mm$^2$, and reaches a plateau for areas larger than 2.5×2.5 mm$^2$. The same trend can be seen also for the number of photons impinging on the SiPM. This is in good agreement with the experimental measurements of CTR reported in figure 20.

Moreover, in figure 24, a histogram of the impact position on the digital SiPM along the Y-axis of the optical photons is shown, for events in the 511 keV photopeak. Figure 25 shows an histogram of the impact position on the digital SiPM along the Y-axis of the optical photons arriving in the first 200 ps of every detection process.

Both these plots show, as expected, that most of scintillating light impinges on the SiPM in the area of physical contact between crystal and detector. Outside this area, the number of collected
photons has a sharp decrease. Figure 26 shows that most of the photons reaching the SiPM in the first 200 ps are contained in a range going from -1.05 mm to 1.05 mm.

Furthermore, we separated the SiPM into the different regions based on the active area, as shown in figure 27. Region A is the area included in a square with dimensions 1.6×1.6 mm², region B is the area between region A and a square of dimensions 1.8×1.8 mm², and so on. The ratio of the number of photons detected in the first 200 ps to the number of photons detected in the total scintillation process for these different regions of the SiPM is shown in figure 28. The ratio in regions A, B and C is at the level of 0.25%, and decreases from D to G. Since the CTR is strongly related to the first photons arriving on the SiPM, the CTR resolution is dominated by the regions that present a high ratio in figure 28, while the remaining regions have little effect on the CTR. Simulations performed on the other crystal lengths show similar results to the ones obtained for a 2×2×20 mm³ LYSO crystal. We can therefore conclude that collecting the photons that impinge on the SiPM outside of the area of physical coupling between crystal and detector can improve the CTR.

7 Conclusion

A set of LYSO crystals with different dimensions have been studied using different active area of the digital SiPM produced by Philips. We have found active areas larger than the area of physical coupling between crystal and detector can improve the energy resolution, because of the increased number of optical photons collected. We have also found that the cross section of the crystal has an impact on the energy resolution, with larger areas yielding better results. Moreover, the digital SiPM coupled to LYSO crystals with 2×2 mm² and 3×3 mm² cross section, can reach energy resolution levels comparable to the ones recorded by PMTs. The CTR measured with the digital SiPM coupled to LYSO crystals reached the same values that were previously reported with analog SiPMs. We found that the CTR can be improved by 8–10 ps when an active area of 2.2×2.2 mm² is used for the digital SiPM, rather than a 2×2 mm² active area matching exactly the LYSO crystal.
cross section. This can be explained by an improved collection of the first optical photons impinging on the detector, as was shown by Geant4 simulations. This leads to our conclusion that the energy resolution and CTR can be improved by optimising the coupling between crystal and SiPM to extract more scintillating photons.

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