Development of a new PET detector module with improved Depth of Interaction and Time of Flight capabilities

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It has been showed that the time difference between the signal observed in two detectors for a given positron annihilation depends on the depth of interaction (DOI) in case of long crystals, as the ones used in Whole Body PET. The aim of this study is the development of a detector module where the DOI information is extracted and used as a correction factor for the timing depth dependence, improving the time resolution. The detector module is a matrix of 4×4 LYSO scintillator pixels, each 3×3×20 mm³ with the 4 sides unpolished. The crystal pixels are in one-to-one coupling with the SiPM pixels and readout by PETsys TOFPET2 ASIC. With a DOI resolution of 6.523±0.135 mm FWHM the CTR was improved from 362 ps FWHM to 298 ps FWHM. By performing a top irradiation the detector module performance was tested for real PET scanner conditions, where the 176Lu decay intrinsic radiation was used for depth calibration. This method showed a DOI resolution of 7.565±0.271 mm FWHM that resulted in a CTR improvement from 380 ps FWHM to 334 FWHM ps.

I. INTRODUCTION

Over the past years, Positron Emission Tomography (PET) has revealed an enormous growth in clinical applications. Being a molecular imaging technique that provides images of physiologic processes rapidly became one of the most important resources in detecting, staging, restaging and monitoring therapeutic responses of a large number of malignant diseases [1]. Although photomultiplier tubes (PMT) have been the most used devices for decades, the progresses made over the years in semi-conductors technologies came with alternatives as the Avalanche Photodiodes (APDs) and more recently the Silicon Photomultipliers (SiPMs). Characteristics as high gain and fast response make the SiPM a great candidate for Time of Flight (TOF) applications [2, 3]. Today commercial, state of the art, full-body TOF-PET scanners can reach time resolution (CTR) values around 500-600 ps FWHM and some research options improved this value to around 200 ps which corresponds to spatial resolution along the Line of Response (LOR) of 30 mm [3, 5]. With TOF-PET being a reality the research community started to focus in another source of information to reduce the area around the lesion, γ-emission point, resulting in higher imaging precision - the Depth of Interaction (DOI).

The DOI is more commonly associated with the parallax errors, a geometry consequence that affects the PET spatial resolution and derives from annihilations that occur at off-center locations [6]. Although the parallax errors due to the lack of DOI information are always present, they have greater impact on small ring PET scanners since also the LORs are smaller. In whole body PET systems the most important parameter is the timing resolution and due to this the DOI information is used to improve the scanners time performance. The γ-rays, emitted particles that will reach the radiation detector, and the scintillation photons that result from the scintillation process after a γ-interaction, travel at different speeds inside the scintillator. Due to this, the time between the entrance of the γ ray and the detection of a light photon in the photodetector depends on the depth of interaction [7, 8]. This effect is enhanced by the use of long crystals, a characteristic of whole body PET scanners.

The aim of this study is the development of a detector module with TOF capabilities where the DOI information is used for timing depth dependence correction.

II. MATERIALS AND METHODS

The detector module consists in a matrix of 4×4 LYSO scintillator pixels, each 3×3×20mm³ and 4 sides unpolished. The LYSO matrix is coupled to a 4×4 SiPM array Hamamatsu S13361 with pixel dimensions that enable the one-to-one coupling between the LYSO and SiPM matrices pixels. The readout is performed by the PETsys TOFPET2 ASIC. From the readout system point of view and due to the one-to-one coupling, each LYSO pixel is identified by a channel number. For this reason during this work the designation channel will be used to refer to a particular LYSO pixel with the respective data collected by the SiPM pixel that is directly coupled.

The detector module uses a single-ended readout system and the DOI information is extracted by the combination of the innovative method of light sharing associated with the depolishing of the crystal long surfaces. The process is described in Fig. 1.

The DOI tagging setup used to perform the side irradiation of the LYSO matrix is shown in Fig. 2 and an illustration with the representation of the distances between the scintillators and the 22Na source is exhibit in Fig. 3.

Scintillating photons are emitted isotropically which means that some of them are emitted in the opposite direction of the photodetector. To avoid the loss of this massive amount of information, a reflector is placed at the top of the matrix so that light photons that travel...
in this direction can be redirected to the photodetector side. Between the crystal matrix and the reflector, a glass (light guide) with the same dimensions as the matrix is placed. This glass allows the passage of light photons from the crystal where the interaction occurred to neighbor crystals. This technique adds very useful information from adjacent SiPM pixels by collecting light photons that were produced in a different crystal than the one to which it is directly coupled. This information from neighbor crystals is fundamental for DOI extraction due to the definition of the DOI variable $R$ as:

$$R = \frac{E_{\text{max}}}{\sum E}$$  

(1)

where $E_{\text{max}}$ is the maximum energy deposited in the SiPM and $\sum E$ is the sum of the energy collected in all the SiPM pixels, both per $\gamma$ interaction.

The impact of the surface finish is shown in Fig. 1 by the different angles after and before a light photon hit the crystal wall. Microscopic irregularities due to the walls polishing show a variation of the normals along the surface which result in a diffuse reflection. The light propagation will be delayed in each collision with the walls, resulting in an enhanced depth dependence.

The 511 keV photons emitted in opposite directions by the $^{22}$Na source will be detected by the LYSO matrix and the reference scintillator, from now referred as single pixel, making an electronic collimation setup to scan the matrix along the depth. The single pixel has the same characteristics as the LYSO matrix and is glued to a pixel of an identical SiPM. The distance between the source and the single pixel (33 cm) and between the source and the matrix (4 cm), together with the pixel width (3 mm) and the diameter of the radioactive compound encapsulated in the source (1 mm), result in a beam spot of $\approx 1.5$ mm diameter that allows us to irradiate different depths without the need of external collimation. The matrix scanning will be performed by the irradiation of six points along the vertical direction equally spaced by 3 mm, starting closer to the glass (top) in direction of the SiPM (bottom). Each irradiation point corresponds to a different depth. The DOI tagging setup includes a pair of axes which allow the automatic matrix scanning and the exact point of irradiation definition. An illustration of the group of coordinates for the xOz motion is shown in Fig. 4.

To test the detector module performance in real PET scanner conditions, an irradiation from the top was performed. Both scintillators and photodetectors remained the same only in a different configuration. The setup that allowed us to simulate the real conditions is showed
in Fig. 6.

FIG. 5. Setup to simulate real PET scanner irradiation conditions.

The whole setup is placed in a light tight box where temperature is kept constant at 18°C by a cooling system.

III. RESULTS

The detector module development started with the performance study of two matrices with different depolishing: one matrix with 4 sides unpolished and another with 2 sides unpolished. During this study the detector module was readout by TOFPET1 ASIC, the readout system available at the moment. Is known that the depolishing of the long surfaces enhances the depth dependence but at the same time degrades the CTR, with matrices with all sides polished showing the best time resolution. The study of the two matrices allowed us to conclude about the best option for the detector module after a balance between CTR and DOI information is made.

The matrix with 4 sides unpolished showed a DOI resolution of 7.315±0.229 mm FWHM and a CTR improvement from 382.4 ps FWHM to 318 ps FWHM, while the matrix with 2 sides unpolished showed a DOI resolution of 11.97±0.83 mm FWHM and the CTR was improved from 322.1 ps FWHM to 289.2 ps FWHM. As expected the matrix with only 2 sides unpolished showed a better time resolution when compared with the matrix with 4 sides unpolished. However, in a matrix with crystals 20 mm long, a DOI resolution of ≈ 12 mm is not acceptable for depth information extraction. Due to that the matrix was not considered for further analysis and the study proceeded only with the matrix with 4 sides unpolished. With the launch of TOFPET2 ASIC the detector module transited to this new readout system with first reports showing better time performance and energy resolution when compared with the latest ASIC version. Both improvements were in the best interest of this work. A full description of the PETsys TOFPET2 ASIC can be found in [10].

A. DOI tagging setup

1. Coincidence Time Resolution

For each pair of coincidence events that contributes to the photopeak of both scintillators, which already demands for an energy selection, is calculated the difference between the time of arrival at each photodetector. The time difference \( \Delta t \) is defined by \( t_1 - t_2 \) where \( t_1 \) is the time of arrival to the SiPM coupled to the LYSO matrix and \( t_2 \) to the SiPM glued to the single pixel. From this is obtained a \( \Delta t \) distribution per channel and per depth as shown in Fig. 6.

FIG. 6. Example extracted from channel 928 and depth 5 (≈ 18 mm). Charge [a.u.] plots with photopeak selection in each scintillator spectrum. \( \Delta t \) distribution with Gaussian fit in the center.

Since the distance between the source and the single pixel is fixed, the arrival time of events collected in the SiPM pixel glued to this scintillator will not change. However, the matrix scanning is performed by starting at the top with each next depth being closer to the SiPM than the previous one. With the distance between the irradiation point and the SiPM becoming smaller, the arrival time of events in this SiPM will also be changing in a consistent way. This effect results in a shift of the \( \Delta t \) distribution mean value, \( \mu \), along the depth. This shift reflects the timing depth dependence. To obtain a \( \Delta t \) distribution per channel that accounts with the distributions from each depth and, at the same time, reflects only the dispersion from each depth distribution, the shift needs to be corrected. By extracting the function that describes the relation between \( \Delta t \) mean value and depth is possible to shift back each distribution in a way that the \( \mu \) from each depth distribution is now coincident around 0. The correction function for the timing depth dependence is shown in Fig. 7. An example for the \( \Delta t \) distribution per channel, with and without depth correction, is shown in Fig. 8.

As one can see by comparing both Fig. 8 (a) and (b) the correction for the timing depth dependence results in a \( \Delta t \) distribution per channel with a lower \( \sigma \) which rep-
FIG. 7. $\Delta t$ mean value along the depth with linear fitting function ($y = [a_0] x + [a_1]$ with $y$ being the $\mu$ from each distribution, $x$ the depth of irradiation and $[a_0]$ and $[a_1]$ free parameters).

FIG. 8. $\Delta t$ distribution per channel - (a) without depth dependence correction; (b) with depth dependence correction.

FIG. 9. CTR distributions for the 16 pixels of a matrix with 4 sides unpolished with TOFPET2 ASIC - (a) without depth dependence correction; (b) with depth dependence correction.

From each channel spectrum is extracted the position of 5 peaks: 31 keV, 81 keV and 356 keV from $^{133}$Ba, 511 keV from $^{22}$Na and 662 keV from $^{137}$Cs. With the position of each photopeak assigned to the respective energy was obtained the relation between charge a.u. and energy for the full spectrum, as shown in Fig. 10.

2. Depth of Interaction

The first step before start with the data treatment for the depth extraction is to perform an energy calibration. To convert the ADC counts (or arbitrary units [a.u.] of charge), output of the charge integrator after ADC conversion, small acquisitions with the sources $^{137}$Cs, $^{133}$Ba and $^{22}$Na were performed with each source placed at the top of the LYSO matrix to have an homogeneous irradiation of the 16 channels. The use of these sources is due to the previous knowledge of the energy of each photopeak.

FIG. 10. Calibration function that correlates Charge [a.u.] and Energy [keV]. The fitting function corresponds to the function that describes the SiPM: $y = -[p_2] ln \left(1 - \frac{[p_1]}{[p_1]}\right)$, with $[p_1] = \frac{ADC \times N_{\text{rad}}}{P_{\text{tot}}}$ and $[p_2] = \frac{N_{\text{rad}}}{P_{\text{tot}} \times \text{keV}}$. The parameter $[p_0]$ is an offset parameter assigned with 0 as initial value.
After several attempts, the SiPM saturation function resulted in the best approximation for the correlation between charge a.u. and energy. However, the $\chi^2/ndf$ implies the low fit quality which means that the energy information given by this calibration function can be shifted from the reality for some charge a.u. values. This will have an impact in the DOI resolution due to its dependence on the energy information from the whole spectrum.

One obtains for each channel the energy spectra of the six depths after converting the data with the energy calibration function. An example from channel 928 is shown in Fig. 11.

![FIG. 11. Energy spectra obtained for the six different depths of channel 928. Highlighted with red is the Gaussian fit to the photopeak.](image)

From the spectra represented in Fig. 11 one can see a shift of the photopeak along the depth. This shift is due to the proximity of the interactions to the SiPM as the depth increases, which results in more light collected by the SiPM pixel coupled to the matrix pixel where this interaction occurs. The shift of the photopeak is a factor with a major impact in the selection of photopeak events by an energy window. As one can see if the energy selection is applied per channel with a range that covers the photopeak position in all the depths, the energy window needed will include Compton events specially from interactions that occurred closer to the SiPM. This Compton events, due to their additional arrival time, will contribute to the CTR degradation. To avoid this effect the energy selection should be made per channel and per depth.

With the calibration performed is possible to follow with the DOI data treatment that starts with the DOI variable R calculation. To extract the quantities presented in Eq. 4 for each $\gamma$ interaction we run through all the channels and search for the maximum energy that was deposited. The maximum energy is defined as $E_{\text{max}}$ and the channel where it was deposited is defined as $c_{\text{max}}$. For the same $\gamma$ interaction, if $E_{\text{max}}$ is within the energy window that defines the photopeak position for the $c_{\text{max}}$ in the respective depth of irradiation, the energies collected in all the channels are summed. With the $E_{\text{max}}$ and the $\sum E$ is calculated the DOI variable per $\gamma$ interaction. This results in a DOI variable distribution per channel and per depth as shown in Fig. 12.

![FIG. 12. DOI variable distributions of the six consecutive depths highlighted in different colors (channel 928).](image)

By extracting the value of the DOI variable in each depth, which means the extraction of the mean value from each distribution represented in Fig. 12 is possible to obtain a function that correlate both quantities and is able to assign a depth of interaction to each R value in a continuous range. The function that describes the relation between the variable R and the depth is shown in Fig. 13.

![FIG. 13. DOI variable mean value along the depth and respective linear calibration function (DOI calibration function): $y = [a_0] x + [a_1]$ where $y$ is the depth, $x$ is the DOI variable mean value and $[a_0]$ and $[a_1]$ are free parameters.](image)

As expected the relation between the DOI variable and the depth is linear with R increasing with the depth. As the depth of interaction becomes closer to the SiPM, the light collected by the respective SiPM pixel increases (higher $E_{\text{max}}$) and due to the long path that the light photons need to travel until reach the glass plate, less light is shared with the neighbors (lower $\sum E$). On the other hand, if the depth of interaction is closer to the glass plate, due to long path that the light photons need to travel until reach the photodetector, less light is col-
lected by the SiPM (lower $E_{\text{max}}$) but due to the proximity with the light guide much is shared with neighbor crystals (higher $\sum E$). This justifies the behaviour of the DOI variable along the depth and confirms $R$ as reliable indicator of the depth of interaction. The depth assigned by the DOI calibration based on each $R$ value is defined as $\text{DOI}_{\text{calculated}}$. Since we have the real depth of irradiation from the matrix scanning, the $\text{step2}$ value defined in the acquisition script, we can verify if the assigned depth is close to the real depth by:

$$\Delta \text{DOI} = \text{DOI}_{\text{calculated}} - \text{step2} \quad (3)$$

The $\text{DOI}_{\text{calculated}}$ should be as close as possible to $\text{step2}$ and due to that $\Delta \text{DOI}$ should result in a distribution centered around 0 with a $\sigma$ value that represents the DOI resolution of each channel. An example is shown in Fig. 14.

FIG. 14. Example of a $\Delta \text{DOI}$ distribution with the $\sigma$ value accounting for the dispersion of $\text{DOI}_{\text{calculated}}$ for interactions in channel 928.

By plotting the 16 FWHM values from the 16 $\Delta \text{DOI}$ distributions, a distribution of the DOI resolutions as shown in Fig. 15 is obtained, with the mean value representing the DOI resolution for the matrix with 4 sides unpolished.

Due to the unexpected result of 7.651±0.538 mm FWHM for the DOI resolution shown in Fig. 15(a), an attempt to improve this result the DOI variable $R$ was calculated considering only the $\text{ch}_{\text{max}}$ direct neighbors for the sum of the energies, $\sum E$. The direct neighbors selection is shown in Fig. 16.

The improvement of $\approx$ 1 mm after direct neighbors selection supports the low quality of the energy calibration function, specially for low energy events. Many efforts related not only with the energy calibration but also with the DOI data treatment were made to achieve an improvement of the DOI resolution, however none of them was successful. Due to this, for this study the result of 6.523±0.135 mm FWHM shown in Fig. 16(b) is presented as the final one for the DOI resolution of the detector module with a LYSO matrix with 4 sides unpolished using the TOFPET2 ASIC.

FIG. 15. Distribution of DOI resolutions for the 16 pixels in a matrix with 4 sides unpolished with TOFPET2 ASIC - (a) distribution considering all the channels for $\sum E$ calculation; (b) distribution considering only the $\text{ch}_{\text{max}}$ direct neighbors when calculating $\sum E$.

FIG. 16. Representation of the direct neighbors selection (grey). The pixel with the star is the channel with maximum deposited energy, $\text{ch}_{\text{max}}$.

The direct neighbors selection was applied in all the future data treatment that uses the DOI variable ratio $R$.

B. Real PET scanner conditions

The CTR improvement of 64 ps result from a side irradiation of the LYSO matrix in the DOI tagging setup, in what can be considered as ideal conditions. With this side irradiation fundamental informations like the exact depth of irradiation, simulating the depth of interaction, were known a priori leading to a precise DOI calibration function and correction for timing depth dependence. In addition all the depths are irradiated in the same conditions which result in the same probability of
interaction for each depth. The previous depth information also allows an energy selection per channel and per depth excluding Compton events that otherwise would be included due to the shift of the photopeak along the depth as shown in Fig. 11.

In a real PET scanner ring the radiation detectors are placed next to each other with the scintillator matrices top surfaces pointing to the center. This means that the $\gamma$ will reach the scintillators through the top surface and travel into the photodetector direction until the interaction occurs. In this conditions any previous knowledge of depth is nonexistent and also the $\gamma$ attenuation along the crystal becomes evident, a condition that did not take place in the side irradiation.

To simulate the top irradiation, characteristic of real PET scanner, the experimental measurements were performed by placing both scintillators with the front surface pointing to each other as shown in Fig. 5.

With the side irradiation we were able to identify and distinguish the DOI variable distributions from each depth, resulting in the DOI calibration function that assigned a depth value to each R value. With the top irradiation, since the data extracted accounts for all the possible depths of interaction and also for the $\gamma$ attenuation along the crystal, the R plots for each channel are represented by a distribution where is not possible to make this distinction. An example is shown in Fig. 17.

![FIG. 17. Distribution of DOI variable for coincidence events between both scintillators from top irradiation.](image)

To overcome this difficulty imposed by the irradiation conditions, the depth identification was performed using the intrinsic radiation from the $^{176}$Lu decay present in the LYSO matrix.

1. **Depth identification using $^{176}$Lu decay**

The $^{176}$Lu is a radioactive element with a half-life $\approx 3.6 \times 10^{10}$ years. The main decay process is $^{176}$Lu$\rightarrow^{176}$Hf producing a $\beta$-particle emission with a maximum energy of 596 keV and three simultaneous $\gamma$-emissions of 88, 202 and 307 keV [11].

The use of the $^{176}$Lu decay is motivated by assuming that since the decay will occur in an isotropic way in the LYSO matrix, the ratio $E_{\text{max}}/\sum E$ plots will result in a distribution where its start and end points will correspond to the limits of the scintillator. To extract the data relative to the decay an acquisition with only the LYSO matrix (single events) was performed. Due to the similar patterns presented by the distributions from crystals in similar positions in the LYSO matrix, and more important with the same number of direct neighbors, the plots will be divided in three different groups according to the position of the respective crystal in the matrix: corner, side and middle.

![FIG. 19. Definition of the three different regions of the LYSO matrix according to ach crystal number of direct neighbors. Yellow (corner) - crystals with 3 direct neighbors; Orange (side) - crystals with five direct neighbors; Red (middle) - crystals with 8 direct neighbors.](image)

In the $^{176}$Lu decay either the three emitted $\gamma$ are absorbed in the crystal volume or some can escape. The small dimensions of the LYSO pixels size (3x3 mm) result in a high escape probability for the 202 keV and 307 keV $\gamma$ which is related with the patterns exhibit in the ratio plots in Fig. 20.

Due to their energies, the escape probability of the 307 keV $\gamma$ is higher than the probability of the 202 keV $\gamma$ to escape, this last probability being higher than no $\gamma$ escape from these small crystal pixels. Previous experimental measurements showed that, due to their low energy range, when a $\gamma$ escapes from the crystal where the decay occurred it can’t travel more than one crystal, which means that it will contribute to the ratio by interacting in an adjacent neighbor crystal.

Considering the ratio plot from the middle crystals (Fig. 20(a)) we notice that the peaks height reflects the probability of each of the three cases. The first peak on the left with higher amplitude corresponds to the case where...
FIG. 20. Distribution of the DOI variable from $^{176}$Lu decay. (a) middle crystal (red region in Fig. 19); (b) side crystal (orange region in Fig. 19); (c) corner crystal (yellow region in Fig. 19).

The 307 keV $\gamma$ escapes from the crystal. In this case the $E_{\text{max}}$ is smaller and the $\sum E$ is higher, resulting in a lower ratio value. The second peak corresponds to the case where the 202 keV $\gamma$ escapes and the third peak to the case where no $\gamma$ escapes. In this last case the $E_{\text{max}}$ is higher and the $\sum E$ is lower, which is the opposite situation of the first peak, leading to the highest ratio value. Considering the side and corner crystals (Fig. 20 (b) and (c)), we have the contribution of another condition: due to the shared walls with the outside, the escaped $\gamma$ can go to an adjacent neighbor or to outside the matrix. Due to this, the probability of the two first peaks for both crystals decreases. The difference between the first two peaks is related with the number of sides shared with the outside. Side crystals share three sides with direct neighbors and only one side with the outside, while crystals in the corner share two sides with the outside and another two with direct neighbors. This decreases even more the probability of a 307 keV escaped $\gamma$ to be detected in an adjacent neighbor and the difference between the two first peaks increases for corner crystals. One last aspect, present in the side and corner plots, is the increased amplitude of the last peak when compared with the plots from middle crystals. When the 202 or the 307 keV $\gamma$ escape to outside of the matrix and so don’t contribute neither to $E_{\text{max}}$ nor to $\sum E$, the ratio $R$ in each of these situations is closer to the ratio from the situation where none of the $\gamma$ escapes. This means that events that result from the escape of one of these two $\gamma$ that could contribute to the first or the second peaks, when the $\gamma$ escapes to the outside, will contribute to the last peak. These three peaks are more separated when the events with highest $E_{\text{max}}$ (88+202+307 keV) result from decays closer to the SiPM, which gives higher ratio, and the events with lower $E_{\text{max}}$ (88 + 202 keV) are coming from decays closer to the top of the matrix, which gives lower ratio. For other depths of interaction, which in this case coincide with depths of decay, these three cases overlap. Due to this, the first peak will be considered as the ratio that corresponds to a decay that occurred in a depth closer to the top of the crystal and the third peak closer to the SiPM. The position of the first peak will be assigned to the first depth while the last peak will be assigned to the last. To obtain the remaining ratio values for the intermediate depths, the range between the first and the last was divided in equally spaced bins. This method is supported by the linear relation between ratio and depth shown from the previous setup results. The DOI calibration function using the DOI variable from $^{176}$Lu ratio plots is shown in Fig. 21.

FIG. 21. $^{176}$Lu calibration function that correlates ratio $R$ and depth.

To confirm the validity of this values, the DOI resolution with the $^{176}$Lu calibration function for depth assignment was calculated. For this the side irradiation data is used since it’s the only data where each event has the real depth interaction in its information - step2. Again we obtain de $\Delta$DOI distribution for each channel and by plotting the 16 FWHM values extracted is obtained the distribution of the DOI resolutions shown in Fig. 22.

The DOI resolution of 7.565±0.271 mm FWHM using the $^{176}$Lu calibration function for depth assignment is a good result when compared with the 6.523±0.135 mm FWHM from the DOI tagging setup data. A degradation from this depth extraction method was already expected but the small difference of ≈ 1 mm allows us to validate it as a feasible method for depth assignment in a top irradiation.

2. Coincidence Time Resolution

With the depth assignment based on the ratio $R$ value provided by the $^{176}$Lu calibration function is possible to extract the CTR for a irradiation from the top of the crystal like in real PET scanner conditions. As referred before, due to the photopeak shift along the depth showed
in Fig. [11] is important to perform an energy selection not only for each channel but also for each depth, otherwise Compton events will be included for the time difference calculation degrading the CTR due to their delayed arrival time. With a top irradiation the previous knowledge of the photopeak position in each depth, as in side irradiation, is nonexistent. To overcome this situation the energy selection was applied in two stages: a first global energy selection to calculate the DOI variable \( R \) and after depth information extraction a new window more restrictive to select the events that will be considered to calculate the time difference \( \Delta t \). The global energy window results from a comparison between the photopeak position per channel, from the top irradiation, and the photopeak position in each depth from the side irradiation data. The range is defined in a way that all the depths are covered resulting in an asymmetric one:

\[
\mu - 5\sigma < E_{\text{max}} < \mu + 8\sigma
\]  

(4)

The DOI variable \( R \) is calculated in the same way as explained before, where for each \( \gamma \) interaction is extracted the maximum energy deposited, \( E_{\text{max}} \), as well as the respective channel that collected it, \( \text{ch}_{\text{max}} \). If the \( E_{\text{max}} \) is within the photopeak of the \( \text{ch}_{\text{max}} \), in this case defined by asymmetric energy range in [4], the energy collected in the direct neighbors is summed, \( \sum E \). With the \( E_{\text{max}} \) and the \( \sum E \) is calculated the DOI variable \( R \) that by the \( ^{176}\text{Lu} \) calibration function is assigned to a depth of interaction. With the informations of energy, channel and depth is possible to obtain an energy spectrum per channel and per depth as shown in Fig. [23].

From the spectra in Fig. [23] one can confirm that the global energy selection still includes a part of the Compton plateau, especially for the distributions from depths closer to the SiPM. This highlights the importance of an energy selection not only per channel but also per depth. By fitting each distribution is extracted the mean value and sigma of each depth photopeak. With these informations is possible to apply a second energy window more restrictive to select the coincidence events that will be considered for the time difference calculation.

As before from the \( \Delta t \) distribution per channel and per depth was extracted the function that corrects for the timing depth dependence and a \( \Delta t \) distribution only per channel with and without correction was obtained. By plotting the 16 FWHM values one obtains the CTR distributions, with and without correction for timing dependence, in the case of a top irradiation with an energy selection with depth information from the \( ^{176}\text{Lu} \) calibration function. Both distributions are shown in Fig. [24].

The detector module using a matrix with 4 sides unpolished when submitted to real PET scanner conditions showed a CTR improvement from 380.7 ps FWHM to 334 ps FWHM.

IV. FINAL REMARKS

In this work was developed a detector module for PET applications with DOI information for CTR improvement. With the information provided by the method of light sharing was possible to develop a detector module with a single-ended readout system that still allowed the extraction of a correction factor for the timing depth dependence, \( f(\text{DOI}) \). The single-ended readout is an added value of this detector module due to the reduced full cost of a PET scanner adopting this modality. Due to the observed shift of the photopeak along the depth, the energy window for photopeak events selection turned out as a major factor in this process of CTR improvement. The direct contribution of Compton events for the CTR degradation makes the energy selection with depth information a crucial factor regarding the improvement of the overall time performance in PET scanners using long crystals, as the case of whole body PET scanners. In a top irradiation the definition of an energy window per
depth is a difficult task to realize however the method described in this work with two energy ranges resulted in the best approximation to the result obtained from the DOI tagging setup. The detector module developed in this work show, from the DOI tagging setup results, that is possible to improve the CTR to under 300 ps FWHM with a DOI resolution of 6.54±0.526 mm FWHM. The depth assignment using the 176Lu calibration function resulted in 1 mm degradation showing a DOI resolution of 7.56±0.271 mm FWHM. The improvement of this result will allow us to approximate the 334 ps FWHM obtained for the real PET scanner conditions to the 298 ps FWHM from the ideal conditions in the side irradiation.

FIG. 24. CTR distributions for top irradiation with an energy selection with depth information from the 176Lu calibration function - (a) without correction for timing depth dependence; (b) - with correction for timing depth dependence.

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