Development and evaluation of a practical method to measure the Depth of Interaction function for a single side readout PET detector

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Abstract: In small animal and organ dedicated PET scanners, the knowledge of depth of interaction (DOI) of the gamma ray along the main axis of the scintillator is a fundamental information in order to avoid parallax error and to achieve high performances in terms of spatial resolution. Recently we developed a new method to obtain the DOI function for a single side readout PET module, recirculating the scintillation light in the matrix by means of a mirror placed on top of the module. In a complete PET scanner, periodical DOI calibrations have to be performed to prevent time dependent miscalibrations and performance degradations. The current DOI calibration relies on a coincidence system between the module and an external scintillator to provide a priori the DOI information and it is clearly not feasible in a real system without unpractical disassemblies of the scanner. In this paper we develop instead a fast and precise calibration method based on uniform irradiation of the scintillators. Three irradiation modalities are presented, in particular one where the source is placed on top of the module, one with the source placed on one side of the module and one that exploits the internal radioactivity of the scintillator. The three different procedures are evaluated and the calibration method is validated by comparing the information provided by the coincidence setup.

Keywords: Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Gamma detectors (scintillators, CZT, HPG, HgI etc)

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1 Introduction

Positron Emission Tomography (PET) modules are usually made of several scintillators that convert the energy of the incoming gamma into optical photons, and one or more photodetectors that convert the scintillation light into an electrical signal. One of the most suitable scintillators for PET applications is LYSO:Ce, given its characteristics of high ratio between the number of photons generated and the energy deposited (40000 ph/MeV \([2]\)), high density (7.4 g/cm\(^2\)) and fast scintillation profile. In small animal and organ dedicated PET scanners, the Depth of Interaction (DOI) of gamma rays along the main axis of the scintillator is a fundamental information to avoid parallax errors in the image reconstruction process and achieve high spatial resolution \([1]\). On the other hand, in Whole-Body PET scanners (WB-PET), the DOI information can be useful to correct for the time jitter of the optical photons propagation in the scintillator, therefore improving the time resolution of the system \([3]\). The DOI function can be achieved by using an external crystal placed in coincidence with the module providing a priori the information of the interaction point along the main axis of the scintillators. It is then easy to correlate the gamma impact position to the DOI estimator extracted from the module output. This method was presented and validated in a previous work \([4]\). There are many drawbacks for an application of this method in a realistic PET scanner and a new practical procedure to obtain such function has to be developed, by means of a calibration that will need to be feasible in a fully mounted system and relatively simple and fast, in order to be performed periodically during the scanner life time. Y. Shao, R. Yao, T. Ma presented an innovative method \([6]\) where the DOI calibration of a dual ended readout scintillator is obtained by an uniform irradiation from a radioactive source without the need of an additional reference crystal. In this study we present and validate the application of this method to a single side readout detector using the irradiation from the top of the module that is the most feasible in a realistic scanner.
2 Materials and method

In section 2.1 the concept of the PET module under study is briefly described. The proposed method to obtain the DOI function is then presented in section 2.2. Finally, the experimental setups used to test and validate this method, along with the data analysis procedure, are described in sections 2.3 and 2.4.

2.1 DOI encoding method

The PET module under study is based on a novel DOI encoding method that allows obtaining DOI information with a single side readout in a highly segmented scintillator array, without the need for one-to-one coupling between crystals and photodetectors [4]. The concept at the base of the PET module is represented schematically in figure 1. When a gamma ray interacts with a scintillator, the optical photons escape the crystal from the front (orange) and the back (green). A gap allows the light emitted from the front to be shared among the photodetector directly coupled to the crystal (red) and the neighbouring ones (blue). The light emitted from the back is recirculated into the crystal array by means of a reflector and can eventually reach the detectors. Identification of the crystal where the scintillation event took place is possible through an Anger-logic scheme. The DOI encoding is enabled by the recirculation into the array, by means of an optical mirror, of the light emitted by the side of the scintillators not coupled to the photodetectors.

![Figure 1. Schematic representation of the PET module proposed in [4]. (Figure from [4].)](image)

The coordinates \((x,y,z)\) of the impact point for an incident gamma ray are reconstructed on the basis of a set of observables \((u,v,w)\) defined as

\[
\begin{align*}
    u &= \frac{1}{p} \sum_{i=1}^{N} p_i X_i, \\
    v &= \frac{1}{p} \sum_{i=1}^{N} p_i Y_i, \\
    w &= \frac{p_{\text{max}}}{p}
\end{align*}
\]  

(2.1)

where \(X_i\) and \(Y_i\) are the positions of the center of the \(i\)-th photodetector, \(p_i\) is the charge collected by the \(i\)-th photodetector, \(N\) is the number of the photodetectors involved in the calculation, \(p_{\text{max}}\) is the maximum charge among the ones collected by the \(N\) photodetectors and \(P\) is the sum of the charges.
collected by the $N$ photodetectors. The photodetector receiving the most of scintillation light is typically the one facing the crystal where the scintillation undergoes, while the remaining part of the light is mostly collected by the 8 photodetectors surrounding it. For this reason, the $(u,v,w)$ variables can be efficiently calculated event by event by restricting to $N=9$ photodetectors. It was demonstrated in previous work that good crystal separation can be obtained using the information of the $u$ and $v$ variables. Finally, by means of an electronic tagging setup, it was shown that the $w$ variable is directly correlated to the DOI position of the incident gamma ray. This relation was found to be linear, within the limits of the precision of the experimental setup, and could be used in principle as the DOI function, since it allows the association of a $z$ position to each measured value of $w$. Nevertheless, this method presents several drawbacks, especially if one desires to apply it to a realistic system made of several thousands channels. A specific linear function needs to be determined for each crystal in the photodetector, but this operation is particularly time consuming, requiring typically several hours of acquisition per channel. Furthermore, the procedure is not possible in a fully assembled scanner, since the penetration of 511 keV gamma rays in LYSO is limited to 2–3 cm. Side irradiation of the scintillators would be impossible for the modules placed more than 3 cm from the side of a hypothetical photodetector plate. Unless unpractical periodical disassemblies of the scanner are foreseen, it would be impossible to recalibrate the DOI functions once the detector is installed, quickly leading to severe performance degradations.

2.2 Proposed DOI function determination method

The procedure to derive the DOI function that we propose in this study is based on a method previously developed for dual-side readout PET systems based on Avalanche Photo-Diodes (APDs) [6], briefly described here. In general, it is well known that the ratio $R = \frac{s_2}{s_1 + s_2}$ of the signal amplitudes $s_1$ and $s_2$ recorded by the two APDs connected to both ends of a single depolished LYSO crystal provides information on the DOI position along the $z$ axis of the incident gamma ray (see figure 2). In such a configuration, if there is no dispersion from the detector response the relation between $z$ and $R$ is a one to one relation that can be written as follows

$$\int_{0}^{z} P(z)dz = \int_{0}^{R} PDF(R)dR$$

(2.2)

where $P(z)$ is the interaction probability of a gamma ray as a function of the impact coordinate $z$ along the main crystal axis, and $PDF(R)$ is the probability density function for an interaction occurring at a position $z$ to produce a signal ratio equal to $R$. This $PDF(R)$ in turn can be derived by the normalization of the collected histogram of $R$, $H(R)$. If one scintillator is irradiated uniformly from one side, $P(z)$ is constant and a relation can be derived between $z$ and $R$

$$z = D \int_{0}^{R} PDF(R)dR$$

(2.3)

where $D$ is the length of the crystal scintillator. It is therefore sufficient to acquire a $H(R)$ histogram for each channel of the photodetector to obtain an appropriate DOI calibration function, without the need for an external tagging setup. Furthermore, the method can be extended to involve the use of the internal $^{176}Lu$ radioactivity of LYSO crystals (which is evenly distributed inside the crystals), avoiding the need for external irradiation from the side of the scintillators, which would be problematic in assembled detectors, as explained before [7].
Figure 2. Double side readout of a single crystal scintillator of length $D$. Upon interaction of a gamma ray, the signals collected by APD$_1$ and APD$_2$ are denoted as $s_1$ and $s_2$. The coordinate of the gamma impact point along the main crystal axis, $z$, is correlated to the ratio $R = s_2 / (s_1 + s_2)$.

The first aim of this study is to demonstrate that this method can be applied to our configuration simply by replacing the ratio $R$ with the variable $w$ defined in equation (2.1), since in our single-side readout setup this observable is meant to carry the same information provided in dual-side readout setups by $R$. This can be experimentally tested in our prototype module both for background irradiation from $^{176}$Lu and for lateral uniform irradiation (from now on denoted, for simplicity, as BG and LAT modalities). These modalities are schematically represented in figure 3 (a) and (b). Although LAT modality can be tested in an individual module, the BG modality would be the only feasible choice in an assembled detector. There are still reasons to desire the development of a further calibration modality. First of all, the light sharing mechanism at the base of our DOI encoding method relies on the capability to efficiently isolate scintillation events for which the energy deposition occurred in a single crystal. The background decay of $^{176}$Lu involves the emission of electrons with energy up to 401 keV, which mostly interact in the crystal where the decay occurred, and three gamma rays with 88 keV, 202 keV and 307 keV, which instead have a high chance of escaping the original crystal and depositing their energy in a neighbouring channel. This mechanism alters the distribution of the light in the crystals and therefore reduces the precision in the determination of the DOI function. Furthermore, the periodic calibration in a PET scanner is generally performed by irradiating the detector with 511 keV gammas coming from a $\beta^+$ planar source placed in the middle of the Field of View (FOV) (see figure 4). It would be preferable to extract the DOI functions directly from such a calibration run, without the need for a further acquisition and with the advantage of requiring shorter acquisition times with respect to $^{176}$Lu background, given the possibility of using high activity sources.

It is clear that the configurations shown in figure 4 do not provide uniform irradiation along the crystals main axis, so eq. (2.3) cannot be used. We therefore further extended the approach described above to also derive a procedure for non-uniform irradiation. If the direction of gamma rays irradiating a crystal is parallel to the main scintillator axis, the interaction probability $P(z)$ is given by an exponential relation

$$P(z) \sim e^{-\frac{D-z}{\lambda}}$$

(2.4)
Figure 3. Schematic representation of the three calibration configurations under study. For simplicity, only one crystal of the array is shown. (a) Background irradiation (BG): internal $^{176}$Lu radioactivity is used and no external source is involved. (b) Lateral irradiation (LAT): a gamma source irradiates uniformly the crystal from one side. (c) Top irradiation (TOP): a gamma source irradiates the crystal from the top.

Figure 4. Typical calibration setup for a generic ring detector (left) and planar detector (right), where a $\beta^+$ source is placed in the center of FOV. For each single crystal (red), a charge spectrum of all 511 keV gamma rays interactions can be constructed to derive the energy calibration, accepting single 511 keV events from all directions (dashed and continuous lines). In order to properly derive a DOI calibration function, instead, only 511 keV events in coincidence with a channel symmetrically opposite to the crystal (blue) are included into the $H(w)$ histogram.

where $\lambda$ is the attenuation length for 511 keV gammas in LYSO, for a crystal of length $D$ with the orientation of coordinate axis shown in figure 1. Given the definition of $w$ in eq. (2.1) and applying the boundary conditions, we get

$$P(z) = \frac{1}{\lambda (1 - e^{D/\lambda})} e^{-D/\lambda}$$

(2.5)
and therefore, by substituting in eq. (2.2)

$$z = D + \lambda \ln \left[ 1 - (1 - e^{-\frac{D}{\lambda}}) \int_0^w PDF(w) \, dw \right]$$

(2.6)

This equation holds only for gamma rays traveling in parallel to the main crystal axis. This can be obtained by selecting events where the two gammas are detected in opposite crystals (see figure 4). For a single module this can be obtained by irradiating the crystals with a source placed far enough from the top of the matrix (see figure 3 (c), TOP modality).

In this study we aim to demonstrate the feasibility of deriving the DOI function from eq. (2.6), and to compare its precision to the one obtained in BG and LAT modalities.

2.3 Experimental materials

2.3.1 Module structure

The prototype module is composed by a 64 LYSO:Ce crystals matrix organized in a 8 × 8 array and produced by Crystal Photonics Inc. (US). The dimension of each crystal is 1.53 × 1.53 × 15 mm$^3$. A 70 µm foil of Enhanced Specular Reflector (ESR) is placed in air contact between the crystals. The lateral surfaces of the scintillators are optically treated to be unpolished, increasing the probability of an optical photon to escape from the crystal during a lateral surface scattering (see figure 5). In a single side readout detector, this optical handling is fundamental to achieve the DOI information because it enhances the dependency of the light distribution on the scintillation event position along the main axis of the crystal. The photodetector is a 4 × 4 Hamamatsu TSV MPPC (S12642-0404PB-50) that consists in 16 MPPCs, each of them with an active area of 3 × 3 mm$^2$ and 3464 single avalanche photodiodes (SPADs). The photodetector is coupled to one side of the scintillator matrix using Rhodosil 47V optical grease to maximize the transmission of the light. On top of the matrix a glass light guide (1 mm thickness) is coupled by optical grease. A foil of ESR is placed on the top of the light guide to recirculate the light into the matrix as presented in 2.1.

Figure 5. The difference of the optical treatment between an unpolished crystal on the left and a polished one on the right.

2.3.2 Experimental setup

The module is plugged into a custom made electronic board. The bias voltage of the MPPCs is provided by a Keithley power supply and the output signal from the photodetectors is read out by a CAEN DT5740 digitizer. A different approach is adopted in the work of T. Niknejad et al. [8] where a Time-Over-Threshold readout is used to process the data and provide also the time information of
the scintillation events. In our setup, a $^{22}\text{Na}$ source (3 MBq of activity, 1 mm diameter) is placed 100 mm from the matrix to guarantee uniform irradiation of the module. The source can be placed on top of the matrix (position A in figure 6) or laterally (position B in figure 6) to reproduce the TOP and LAT irradiation of figure 3. The measure of the charge collected by each SiPM is recorded and stored in file for the offline analysis.

Figure 6. The two possible irradiations of the PET-like setup, with the source on top (A) and lateral (B). (Figure from [4].)

To obtain the reference for the DOI function, it is mandatory to know a priori the z position of the impact point of the scintillation events. A tagging crystal is used to determine the impact point of 511 keV $\gamma$ from the $^{22}\text{Na}$ source. The setup is schematically presented in figure 7. Being the two $\gamma$ of the $^{22}\text{Na}$ back to back, the detection of a 511 keV in the tagging crystal gives the detection of the 511 keV hitting the matrix. The tagging crystal can be moved performing a scan along the vertical direction of the matrix. The source and the tagging crystal are mounted on the same support to always ensure a correct alignment between the two components.

Figure 7. The tagging setup. (Figure from [4].)
2.4 Clustering algorithm

The data analysis relies on the set of coordinates \((u,v,w)\) that are directly linked to the \((x,y,z)\) impact point. After an acquisition, it is possible to plot a 3D histogram of \((u,v,w)\). The signal events cluster in 64 regions of high density along the \(w\) axis, corresponding to events localized in the 64 crystals as presented in figure 8. The diffuse cloud of events under them are background events.

![Figure 8](image_url)

**Figure 8.** The \((u,v,w)\) histogram of a measurement in the crystals separation configuration of the bench.

In the previous study [4], these density regions were separated by selecting intervals on \(u\) and \(v\) and some background events survive this selection. To avoid this issue a new separation algorithm is introduced based on a density clustering selection directly in the \((u,v,w)\) space. The algorithm studies the number of events in each voxel starting from the voxel \(V_0\) with the highest number of entries and moving then to the nearby voxels. If the number of entries is above a preset threshold the events are considered as part of the cluster and otherwise they are discarded. When all the voxels in proximity of \(V_0\) are studied, the ones that passed the selection identify a cluster of events. These events are then removed from the histogram and the algorithm runs on the remaining events starting from a new \(V_0\). The process is iterated until 64 region are found.

In figure 9, a \((u,v,w)\) dataset restricted to the volume corresponding to a single MPPC is shown and the results of the clustering algorithm are summarized. The four density regions that correspond to four crystals coupled to one MPPC are identified (on the right) starting from the raw data (on the left). It is clear that the background events originated from noise are not selected anymore as events of the crystals.

3 Results

In this section, the measurement results of the calibration method for LAT, BG and TOP irradiation modalities are shown and compared with the reference calibration obtained by the tagging setup described in subsection 2.3.2.
Figure 9. The \((u,v,w)\) histogram of one SiPM before the crystals separation algorithm (left) and after the separation (right).

3.1 DOI calibration using the tagging setup

In the tagging configuration, the DOI information is provided by the vertical position of the source and the tagging crystal, and its correlation with the \(w\) coordinate can be studied. The scan consists of 10 vertical position measurements along the crystal length with a step of 1.4 mm. After the clustering algorithm described in subsection 2.4, the \(w\) distribution for the different vertical positions of the tagging crystal is shown in figure 10. It can be observed that the peak position has different values at different \(z\) proving the correlation between the \(w\) coordinate and the DOI information.

![Figure 10](image)

Figure 10. The correlation between the DOI and the \(w\) coordinate.

The vertical position of the interaction can be plotted versus the peak position of the \(w\) distributions and a linear relation between the two variables established according to eq. (3.1). The uncertainty on the vertical position of the tagging crystal is estimated to be 0.3 mm.

\[
DOI = m \cdot w + q
\]  

(3.1)

The DOI resolution \(\sigma(DOI)\) of the PET module can be computed using eq. (3.2) where \(\sigma(w)\) is the sigma of the gaussian \(w\) distribution.

\[
\sigma(DOI) = m \cdot \sigma(w)
\]  

(3.2)
The DOI resolution of the module is $3.15 \pm 0.09$ mm (FWHM), but if we consider only the central crystals is $3.0 \pm 0.1$ mm. The previous result was $4.1 \pm 0.1$ mm (FWHM) and this performance improvement is due to the increase of the mechanical precision and to better analysis of the data using the clustering algorithm.

![Figure 11](image1.png)

**Figure 11.** The distribution of DOI resolution for all the 64 crystals (on the left) and for the 16 central ones (on the right).

The results obtained using the tagging setup are considered as a reference to validate the calibration methods described in subsection 2.2 and tested in subsection 3.2.

### 3.2 DOI calibration results

The DOI calibration method is based on the normalized histogram $H(w)$ of the $w$ distribution that is considered as a probability density function of the incoming gamma ray interaction along the crystal length. After an acquisition in the PET like setup, the data are analyzed by the clustering algorithm obtaining the spectra of each crystal. Before plotting the $H(w)$, an energy selection is performed on each crystal spectrum considering only the events with an energy deposition compatible with a photoelectric interaction in the LAT and TOP irradiations while no energy selection is applied to the BG irradiation due to the $\beta$ decay of the $^{137}$Lu. In figure 12, a typical $H(w)$ histogram of a central crystal is shown for a TOP irradiation.

The DOI information is extracted computing the $z$ according to the eq. (2.3) for the LAT and the BG irradiations and to the eq. (2.6) for the TOP one. The integral of a typical $w$ distribution and the resulting relation between $z$ and $w$ are reported in figure 13 for the TOP irradiation.

This procedure is repeated for all the possible irradiation modalities and compared with the results obtained by the tagging setup as presented in figure 14.

For each crystal, the difference $\Delta$ between the $z$ reconstructed by the calibration procedure and the $z$ obtained by the tagging setup is computed and plotted (figure 15) to establish the precision of the calibration procedure.

To quantify the precision of the method, the average and the RMS of the difference $\Delta$ are computed from these histograms and are summarized in the table 1.

For a quantitative comparison of the calibration accuracy with the different methods we focused on the 16 central crystals where it is possible to collect the shared light by the 8 surrounding crystals. Those central crystals are representative of the crystals in a full detector, where the majority of the channels are completely surrounded by other channels. The TOP calibration method is the only one
Figure 12. The $H(w)$ histogram of an irradiation with the source 100 mm above the PET module.

Figure 13. The calculation of $z$ for each $w$ value.

Table 1. The values of the average and the RMS of $\Delta$ for the different irradiation methods.

|                      | Average | RMS    |
|----------------------|---------|--------|
| All Crystals         |         |        |
| Top irradiation      | 0.18    | 0.8753 |
| Lateral irradiation  | -0.16   | 0.8173 |
| Internal radioactivity | 0.02 | 0.9945 |
| Central Crystals     |         |        |
| Top irradiation      | 0.04    | 0.3459 |
| Lateral irradiation  | -0.33   | 0.3176 |
| Internal radioactivity | -0.45 | 0.5747 |

that introduces an offset negligible in the reconstruction of the DOI information along the crystal length. The RMS is compatible with the uncertainty on the vertical position of the tagging crystal proving the accuracy of the calibration procedure. The TOP irradiation is the most suitable method
to obtain the DOI function thanks to the fact that a source can be easily placed in the center of the field of view of the scintillators. Furthermore it is the most feasible process for performing periodical calibration of PET scanners directly in situ providing also the energy response function of the system. The results are compatible with the results obtained for a dual ended scintillator readout by Y. Shao, R. Yao and T. Ma [6] where a good agreement between the reconstructed position and the position provided by an external crystal with a maximum discrepancy of 1.4 mm.

4 Conclusion

A DOI calibration method based on [6] was applied and verified on a single ended readout PET module in a frame of four crystals coupled to one photodetector. Three different irradiation modalities are successfully tested and compared: the irradiation from the internal radioactivity of the lutetium and from a $^{22}Na$ placed 100 mm laterally or above the module. In particular the most relevant result is the validation of the top irradiation procedure that it is feasible in a complete detector.
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