Performance Studies of a Depth Encoding Multicrystal Detector for PET

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to be submitted to IEEE Transactions on Nuclear Science

Abstract

We report the results of design studies for a multicrystal detector with the capacity to encode the Depth-Of-Interaction (DOI). These studies are based on a simulation that treats the interactions of γ -rays and tracks scintillation photons in state-of-the-art position encoding PET detectors. The simulation was used to study the impact of a simple modification to the standard surface treatment of the EXACT HR PLUS block that induces a significant sensitivity of the photopeak pulse height upon the DOI of 511 keV γ -rays. The depth resolution achieved with the altered block as well as the impact of the modification on its energy and position resolutions are presented. The results show a depth resolution of 6 to 7 mm for the inner crystals of the modified block. This is achieved at the cost of 16% less position addressing accuracy.

I. INTRODUCTION

The development of position encoding detectors with DOI sensitivity aims for a restoration of the spatial resolution uniformity in PET and, as by-products, increased sensitivity at lower fabrication costs through a reduction of the tomograph ring radius. PET detector designs capable of simultaneously good transverse and DOI resolutions through optimization of the crystals' surface treatment and read-out scheme have received much attention recently [1, 2, 3]. In particular, the TRIUMF group has devoted its efforts to the design of a depth encoding block detector in which DOI sensitivity is acquired by exploiting the gradient of the light collection efficiency in state-of-the-art position encoding multicrystal BGO detectors [4].

Further development of this approach seems worthwhile as it relies on a simple modification to detectors in commercial production, and offers the potential for rapid implementation in a full tomograph without significant increase in the fabrication costs. Figure 1 presents a schematic diagram of a modified version of the EXACT HR PLUS detector [5], manufactured by Siemens-CTI, with enhanced DOI sensitivity. The transaxial view at the top of the figure

Figure 1: Schematic diagram of the modified EXACT HR PLUS. (top) Transaxial view showing the modification to the reflector coating on the side walls of each crystal. (bottom) Top view, showing the PMT photocathodes and crystals A, B, C, and D that define the diagonal of one quadrant.

shows that the side walls' reflector coating of all crystals is replaced at the front face by an absorbing material over a segment, F, of the block length, L. The surface finish of the crystals' tip remains highly reflective as illustrated in the bottom part of the figure. The added absorbing component induces a loss in the crystal's efficiency to collect scintillation photons. The resulting increase of the photopeak pulse height, taking place as a function of depth, Z, from the front to the back face of the block, then allows the DOI of 511 keV γ -rays to be estimated.

The results presented here followed closely the actual development of three such depth sensitive EXACT HR PLUS prototypes. The technique to modify the blocks as well as the final experimental performances reached with these de-

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tectors on a tomograph ring gantry of 25 cm radius are detailed in [6]. Here, we present a Monte Carlo model of the new block design. The model was used to systematically study its performances, with a particular attention to crystals A, B, C and D located along the diagonal of a quadrant as illustrated in Figure 1. The impact of the modification on the energy response along with the achieved depth resolution is presented for these crystals. Finally we studied the effect of the modification on the block's transverse position response.

II. MODELING THE MODIFIED EXACT HR PLUS BLOCK

These performance studies are based on a simulation designed to treat the interactions of energetic photons in a scintillator, the geometry of a multicrystal position encoding PET detector, as well as the propagation and detection of individual scintillation photons. The simulation is based on DETECT [7] and in [8] was put to a test with a realistic model of the EXACT HR PLUS block.

The complete set of input parameters used in [8] to reproduce the measured performances of the original EXACT HR PLUS block was borrowed to model its DOI sensitive version. In particular, the standard ground option of DETECT was used to model the surface finish of the block. This option allows for a realistic model of the depth dependence of the photopeak pulse height in the original block, when using a reflection coefficient, RC, of 95%. In keeping with this description, the same option was used to model the reflective coating of the crystals' tip and unaltered component of the side walls in the DOI sensitive block. The ground finish reflection coefficient was allowed to be adjusted to model the crystals' absorbing component. To find a realistic value, a scintillation point source was simulated at the center of crystal B, which was chosen as a reference, and moved in steps of 1 mm along the depth axis of the crystal. The initial reflection coefficient of RC=95% was lowered until the simulation reproduced the actual depth dependence of the photopeak measured in that crystal on a first DOI sensitive HR PLUS block prototype. The crystals' side walls were made absorbing for a segment of F=3 mm in the simulated block. For the real block, F could be controlled only to an accuracy of ± 0.5 mm. Although the modification of the real block was made for F=2.5 mm, measurements were compared to the simulation at F=3 mm because of the insensitivity of our model to that parameter, as discussed below. The depth variation of the photopeak pulse height was measured as in [4] and [6] before and after modification, from the photopeak ADC channel as a function of the Z coordinate of a collimated fan beam of 511 keV γ -rays incident on a side face of the block. Selecting a reflection coefficient of RC=20% for the ground finish of the absorbing side wall components successfully reproduces the observed pulse height variation in the modified block, as will be

shown in the next section.

III. PERFORMANCES OF THE MODIFIED BLOCK

A. Pulse Height Response and DOI Sensitivity

Figure 2 presents simulated pulse height distributions for the on-diagonal crystals, A, B, C, D, in the original and modified HR PLUS blocks. The pulse height responses are presented in each case for a source of 511 keV γ -rays uniformly flooding the front face of the blocks, as well as for collimated fan beams incident on its side face at depths of Z=2, 12, 16 and 20 mm. The full histograms present the pulse height responses in the original HR PLUS block, while the hatched (empty) histograms present those for the modified block with absorbing side walls of F=3 mm (F=5 mm). The three numbers in parentheses are the photopeak FWHMs, in percent, for, respectively, the modified block with F=5 mm, that with F=3 mm, and the original block.

Figure 2: Simulated pulse height distributions for the on-diagonal crystals in the original and modified HR PLUS blocks. The pulse height distributions before (full histograms) and after modifications with F=3 mm (hatched histograms) and F=5 mm (empty histograms) are shown for a flood source and for fan beams at four different depths. The photopeak FWHMs, in percent, are given by the three numbers in parentheses for, respectively, the modified block with F=5 mm (first), that with F=3 mm (second), and the original block (third).

As can be seen on the figure, the original block is characterized by a photopeak pulse height that remains almost invariant with depth. As already noticed in [4], the response

to a frontal flood presents a clear peak that is broadened by the weak depth dependence of the collected pulse height. This broadening is significantly accentuated by the absorbing side walls of the modified blocks. A clear increase of the photopeak channel is induced as a function of the depth of the sideward fan beams. Formally, the pulse height response to the frontal flood of γ -rays can be described by:

$$\left(\frac{1}{N}\right) \frac{dN}{dP} = \frac{\left(\frac{1}{N}\right) \frac{dN}{dZ}}{dP/dZ} \quad (1)$$

where dN/dZ is the events' differential depth distribution and dP/dZ is the so-called DOI response, a monotonic function relating the photopeak pulse height, P , of events interacting in a given crystal to their depth-of-interaction. From the results in Figure 2, this function is close to a constant for the original block. For the modified one, it can be fitted by a polynomial of first or second order. Equation (1) also implies that knowledge of dN/dZ and dN/dP for a frontal flood of γ -rays allows calibration of the DOI response of the block without sideward fan beams. A first practical implementation of this approach is discussed in [6].

Figure 3 compares the measured and simulated DOI responses of the sixteen crystals in a quadrant of the original and modified blocks. The DOI responses were obtained on a crystal-by-crystal basis from the measured and simulated photopeak pulse height channel as a function of the Z coordinate of a collimated fan beam of 511 keV γ -rays incident on a side face of the block. For each crystal the top curve and data points give the DOI response of the original block, the middle ones give the response of the modified block with absorbing side walls over $F=3$ mm of the block length, while the bottom ones are for $F=5$ mm. The normalization of the simulated responses was fixed for all crystals at once by a single scaling factor that remains the same for all three data sets. The value of this factor was chosen to provide the best agreement with the measured responses of the unmodified crystal B.

The DOI sensitivities [3], S_{DOI} , of the simulated responses are given by the three numbers in parentheses for respectively the modified block with $F=5$ mm, that with $F=3$ mm and the original block. These were computed, as:

$$S_{DOI} = 100\% \left(\frac{P(20) - P(2)}{P(20)} \right), \quad (2)$$

and express the observed variation in the photopeak pulse heights, from $Z=2$ mm to $Z=20$ mm. The average DOI sensitivity of $11^{+7}_{-4}\%$ in the original block, is predicted to increase to $52^{+8}_{-6}\%$ with the addition of absorbing side walls of $F=3$ mm. With $F=5$ mm, the simulation predicts a small increase of the average DOI sensitivity to $60^{+7}_{-7}\%$.

The overall agreement between the measured and simulated DOI response curves proves to be good for the unmodified block and the $F=3$ mm modification. For these, the simulation predicts to a good accuracy the depth dependence of the photopeak pulse height on a crystal-by-

Figure 3: Measured (open circles) and simulated (full lines) DOI responses in a quadrant of the original and modified blocks. The top curve and data points give the response of the original block; the middle (bottom) ones are for the modified block with the $F=3$ mm ($F=5$ mm) modification. For the simulated data, the DOI sensitivities, S_{DOI} , are given in parentheses for the block with $F=5$ mm (first), that with $F=3$ mm (second) and the original block (third).

crystal basis. This confirms that our choice of surface finish models based on crystal B extends well to the other crystals of the block. The simulation also successfully predicts the apparent saturation of the photopeak pulse height for deeply interacting events that was initially noticed by Cherry *et al.* in [5]. Remaining discrepancies between the measured and simulated absolute pulse height values of the unmodified block and $F=3$ mm modification are attributed to the modeling of the relative crystal-to-PMTs geometrical couplings and were discussed in [8].

A significant discrepancy stands out between the measured and simulated DOI responses for the modified block with $F=5$ mm. Though the simulation successfully predicts that the slopes of the DOI responses stay the same for the $F=3$ mm and $F=5$ mm modifications, it does not account for the observed drop in the absolute values of the photopeak pulse heights. This indicates the failure of our effective model to account for all details of the modifications to the surface finish of this last version of the block.

B. Depth Resolution

Using its Monte Carlo history, the depth residual of each event was calculated as the difference between the Z coordinate estimated from its pulse height and crystal DOI response, and the depth of its energy weighted centroid.

Figure 4 presents simulated depth residual distributions for the crystals along the diagonal of a quadrant of the HR PLUS block. The distributions before and after modification with $F=3$ mm are first shown for a flood source of 511 keV γ -rays incident on the front face of the blocks. In addition, for the modified block, the residuals are also shown for sideward fan beams at four different depths. Where statistically meaningful, the FWHMs of gaussian fits to the residual distributions of the modified block are given on the figure.

Figure 4: Simulated depth residual distributions for the crystals along the diagonal of a quadrant of the HR PLUS block. The distributions before (full histograms) and after modification with $F=3$ mm (hatched histograms) are first shown for a flood source. For the modified block, the residuals are shown for sideward fan beams at four different depths. The FWHMs of gaussian fits to the residual distributions of the modified block are also given.

The residual distributions for the frontal flood source demonstrate the overall improvement in depth resolution with the addition of absorbing crystals' side walls. While the unmodified block has poor depth resolution, the inner crystals of the modified one present residual distributions of 6 to 7 mm FWHMs. The corner crystal displays a FWHM of only 13 mm due to its poorer pulse height resolution. The depth dependence of the modified block's resolution is also clear from the variation of the residual widths observed with the four fan beam data sets. As a percentage of the fan beam depth coordinates, the resolu-

tion steadily improves from shallow to deep interactions as can be expected from the variation of the photopeak pulse height resolution.

C. Impact on the Position Response

Figure 5 compares the simulated 2D position responses of the HR PLUS block before and after modification of the side wall reflectors over a segment of $F=3$ mm. The normalized distributions were obtained for floods of respectively 30 000 and 15 000 γ -rays of 511 keV incident on the front face of the blocks. Estimates, X_γ and Y_γ , of individual event coordinates were computed from the relative PMT signals as described in [8]. In the (X_γ, Y_γ) plane, the center and corner of the block lie at $(0,0)$ and $(1,1)$ respectively. The maximum of the vertical scale truncates the peak of the distributions at the corner of the block and was chosen to emphasize the central region.

Figure 5: Simulated 2D position flood responses of the HR PLUS block before (top) and after (bottom) modification of $F=3$ mm to obtain DOI sensitivity.

The figure highlights the impact of the absorbing side walls on the position response of the block. The modified block is characterized by a stronger pin cushion distortion that pulls the position response distribution towards the edge and corner of the block. This is possibly caused by the absolute loss in scintillation photons available to the three PMTs not directly coupled to the quadrant. While still showing resolved peaks, the position response of the inner crystals presents poorer peak-to-valley ratios.

Table 1 compares the probabilities to correctly assign events incident on crystals along the diagonal of each block as predicted by the simulation. Simple rectangular regions-of-interest (ROIs) were used to delimit the contribution of

each crystal in the (X_γ, Y_γ) signal plane. Three boundaries, along X_γ and Y_γ respectively, were found by requiring that each row and column included four local maxima of the block's 2D position flood response. The coordinates, $(X_\gamma, Y_\gamma)_{max}$, of the upper right corner of the ROIs are also given in the table for each block.

Crystal	unmodified		modified	
	$(X_\gamma, Y_\gamma)_{max}$	Prob.	$(X_\gamma, Y_\gamma)_{max}$	Prob.
A	(1.00,1.00)	52%	(1.00,1.00)	46%
B	(0.88,0.91)	45%	(0.94,0.94)	44%
C	(0.70,0.70)	58%	(0.75,0.80)	54%
D	(0.38,0.38)	71%	(0.38,0.45)	55%

Table 1: Probabilities to correctly assign events incident on diagonal crystals and the region-of-interest boundaries defining these crystals for the unmodified block and modified one with $F=3$ mm.

The position encoding accuracies of crystals A, B, and C remain within 6% of those found in the unmodified block. The center crystal, D, presents the most significant loss, with 16% less encoding accuracy. This is due to the increased pin cushion distortion of the modified block, which stretches its position response towards $X_\gamma=1$ or $Y_\gamma=1$. While this increases the miscoding of events incident at the center into the outer crystals, it also tends to suppress the probability to miscode events incident on the edge and corner ones, since these are already at the edge of the signal space in the unmodified block.

IV. DISCUSSION AND CONCLUSIONS

In this work, we presented a Monte Carlo model of a DOI sensitive version of the EXACT HR PLUS. The impact of absorbing crystal side wall reflectors was accounted for by the addition of one free parameter to our previous description of the original block [8]. The model reproduced well the measured depth sensitivity of the photopeak pulse height for the crystals making a quadrant of a second block prototype before and after the same modification. The model however could not predict the additional drop in the absolute values of the photopeak pulse heights observed when the block was further modified over a segment of $F=5$ mm. This discrepancy remains unexplained and indicates the failure of our effective model to account accurately for all details of the surface finish of this last version of the block.

With side walls made absorbing over a segment of $F=3$ mm, an averaged depth resolution of 6 to 7 mm is predicted for the inner crystals of the block. The absolute loss in photostatistics available to encode the edge and corner crystals translates into a depth resolution significantly poorer than at the center. The most significant miscoding increase was found to take place at the center, with 16% less position encoding accuracy in the modified block

compared to the unmodified one. That a depth resolution better than 10 mm is possible with this approach without sacrificing too much of the original transverse position resolution is well supported by the performance measurements reported in [6].

V. ACKNOWLEDGEMENTS

We are grateful to R. Nutt, M. Andreaco and C. W. Williams of Siemens-CTI for providing us EXACT HR PLUS blocks and for their collaboration throughout this study. At TRIUMF, we also want to thank Arlene Prunkl for her help in proofreading our manuscripts. Christian Moisan and Glenn Tsang acknowledge the Natural Sciences and Engineering Research Council of Canada for its support through postdoctoral and postgraduate fellowships respectively.

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