Monolithic LaBr3:Ce crystals on silicon photomultiplier arrays for time-of-flight positron emission tomography

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Monolithic LaBr₃:Ce crystals on silicon photomultiplier arrays for time-of-flight positron emission tomography

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Abstract

Positron emission tomography detectors based on monolithic scintillation crystals exhibit good spatial and energy resolution, intrinsically provide depth-of-interaction information, have high γ-photon capture efficiency, and may reduce the manufacturing costs compared to pixelated crystal arrays. Here, we present the characterization of a detector consisting of a 18.0 mm × 16.2 mm × 10.0 mm monolithic LaBr₃:5%Ce scintillator directly coupled to a 4 × 4 array of silicon photomultipliers. An energy resolution of 6.4% full-width-at-half-maximum (FWHM) was obtained. The point-spread-function (PSF) was determined for different regions of the detector. The full-width-at-half-maximum (FWHM) of the PSF was measured to be < 1.5 mm at the center of the detector and < 1.7 mm averaged over the entire crystal. Both values are not corrected for the ~0.6 mm FWHM test beam diameter. Furthermore, the influence of edge effects was investigated. We found that near the edges of the detector the spatial resolution degrades to 2.2 mm (FWHM), and a bias in the position estimates, up to 1.5 mm, was observed. Moreover, the coincidence resolving time for two identical detectors in coincidence was measured to be as small as ~198 ps FWHM.

(Some figures may appear in colour only in the online journal)

1. Introduction

The use of monolithic scintillators on multi-channel light sensors is a promising detector concept for application in time-of-flight (TOF) positron emission tomography (PET). Monolithic scintillator detectors exhibit a number of favorable properties such as the intrinsically available depth-of-interaction (DIO) information, good spatial resolution,
excellent energy resolution, high $\gamma$-photon capture efficiency, and relatively simple detector assembly (Bruyndonckx et al. 2004, 2006, 2007, Maas et al. 2006, van der Laan et al. 2007, van Dam et al. 2011a, 2011b). This detector concept is all the more interesting as recent progress in solid-state photosensor technology has made arrays of so-called silicon photomultipliers (SiPMs) commercially available. SiPMs (also referred to as multi-pixel photon counters (MPPCs) or solid state photomultipliers (SSPMs)) offer high gain, fast response, insensitivity to magnetic fields, compactness, ruggedness, and potential cost effectiveness.

Recently, applying one of the first available arrays of SiPMs (SensL SPMarray 3035G16) to a 13.2 mm $\times$ 13.2 mm $\times$ 10.0 mm monolithic LYSO:Ce$^{3+}$ scintillator yielded very promising results (Schaart et al. 2009). A spatial resolution as good as 1.58 mm full-width-at-half-maximum (FWHM) and an energy resolution of 14.2% at 511 keV were measured. Yet, the (single detector) timing resolution of this detector was moderate with 960 ps FWHM. In principle, however, SiPM-based scintillation detectors are capable of much better timing performance as e.g. shown by Kim et al. (2009) and Wang (2010). One reason for the suboptimal timing resolution in our earlier measurement was the performance of the preamplifiers. In order to overcome this issue a new amplifier concept was developed (Huizenga et al. 2012). Using these improved readout electronics we could recently demonstrate for individual SiPMs (Hamamatsu MPPC-S10362–33-50C) optically coupled to 3 mm $\times$ 3 mm $\times$ 5 mm LaBr$_3$:5%Ce scintillators that SiPMs can even outperform the timing performance of conventional photomultiplier tubes (PMTs) (Schaart et al. 2010, Seifert et al. 2012).

In this work, an improved monolithic scintillator detector is characterized. In this detector a 16-channel version of our improved preamplifier is utilized to read out the signals of a 4 $\times$ 4 SiPM array which is directly optically coupled to a matching, monolithic, LaBr$_3$:5%Ce scintillator. This scintillator material was chosen for its higher light yield (de Haas and Dorenbos 2008), better energy resolution (Nassalski et al. 2007) and better timing performance (Seifert et al. 2012) compared to LYSO:Ce.

2. Methods

2.1. Detector

The detector is based on a bare 18.0 mm $\times$ 16.2 mm $\times$ 10.0 mm monolithic LaBr$_3$:5%Ce scintillator (Saint-Gobain) with one 18.0 mm $\times$ 16.2 mm surface optically polished and the remaining five surfaces mechanically depolished. The polished crystal surface matches the dimensions of the SiPM array and is optically coupled to it using LS-3252 encapsulation gel from Nusil. All other faces of the crystal are covered with a highly reflective PTFE-based material (Spectralon). The SiPM array (Hamamatsu MPPC-S11064–050P) consists of 4 $\times$ 4 SiPM pixels (see figure 1) mounted at a pitch of 4.50 mm in one direction (hereafter referred to as the $x$-direction) and 4.05 mm in the other direction (the $y$-direction). Each pixel has an active area of 3 mm $\times$ 3 mm, made up of 3600 Geiger-mode avalanche photodiodes (microcells).

Because of the high degree of hygroscopicity of the LaBr$_3$:5%Ce crystal, the detector is contained in a moisture-tight enclosure. This detector enclosure is directly connected to a second casing which provides electronic shielding for the preamplifiers. The temperature inside the shielding box is regulated actively. This is done by a feedback loop where the temperature is measured as close to the SiPM as possible while regulating the cooling power of a Peltier element which is used to cool the air that is constantly flushed through the shielding-box. In this way the measured temperature inside the shielding-box was kept at 15.00 ± 0.03 °C during the measurements. Additionally, the temperature of the moisture-tight enclosure was
Monolithic LaBr₃:Ce crystals on silicon photomultiplier arrays for time-of-flight PET

2.2. Preamplifier

The preamplifier for the 4 × 4 SiPM array is based on a preamplifier concept that was developed to specifically suit the requirements of SiPMs. In this concept the amplifier input stage features a common-base transimpedance amplifier which presents a very low input impedance to the SiPM at high frequencies. A single-channel version of this preamplifier has been shown to enable excellent timing performance when used in combination with individual SiPMs (MPPC-S10362-33-50C) and small scintillation crystals (Schaart et al 2010, Seifert et al 2012).

The details of the single channel amplifier are described elsewhere (Huizenga et al 2012). In short, the main feature of this amplifier is a transistor in common-base configuration at the amplifier input of each channel. By applying a constant voltage to the transistor base this transistor configuration is acting as voltage source, i.e. the voltage at the transistor emitter is kept constant while a low impedance is presented to the SiPMs. The signal current is copied at the collector of the transistor which in turn presents a high impedance to subsequent circuitry, thus essentially isolating the large SiPM capacitance from subsequent electronics.

The concept of the single-channel design enables relatively easy adaption toward a multichannel amplifier. In this work, the design shown in figure 2 was implemented to read out the 16-channel SiPM array. Each detector element has its own input transistor (T₁–T₁₆), similar to the single channel version. The individual energy signals are obtained by inserting a filter network (comprised by \( R_s \) and \( C_s \)) in between each SiPM and the input of the corresponding transistor.

In order to obtain a combined timing signal from all detector elements the signal currents are summed by connecting all collectors to the input of a secondary common-base amplifier (T₀) which keeps this node (Isum) at a constant voltage. In order to minimize transit time
Figure 2. Simplified schematic layout of the 16 channel amplifier.

... differences between the channels the trace length of each collector to the summing node must be kept equal. The transit time on the printed circuit board is more than 50 ps cm\(^{-1}\). It can therefore contribute significantly to timing errors. The sum of the signal currents is copied to the collector of this transistor. In analogy to the input stage of each channel, this second common-base amplifier isolates the parasitic capacitances of the 16 collectors and the inherent parasitic layout capacitances of the board traces from the subsequent resistor (100 \(\Omega\)), which is used to convert the summed current signal to a voltage. Keeping the capacitance at this point low is of utmost importance for the bandwidth of the amplifier because the resistor and the capacitances form a low-pass filter for the signal.

A practical feature of this design is the ability to fine-tune the individual SiPM detector bias voltages. The total bias voltage across the detector is the sum of the –HV voltage and the emitter voltage of the input transistor. This emitter voltage can be controlled via the base voltage for each channel separately (Vdc1, ..., Vdc16). In this way the SiPM array can be operated using a single bias supply only.

2.3. Measurements

All measurements were performed at two bias voltages corresponding to \(V_{ob} = 1.2\) V and \(V_{ob} = 2.0\) V above the average breakdown voltage of the SiPMs in the array. The lower \(V_{ob}\) corresponds to the recommended bias voltage given by the manufacturer, while \(V_{ob} = 2.0\) V appeared to be optimal in terms of the timing resolution. Spatial resolution measurements were performed using the setup described by Maas et al (2009). The detector is irradiated with a beam of 511 keV annihilation photons in the so-called front-side readout (FSR) geometry, i.e. the photosensor is coupled to the surface of the scintillation crystal facing the beam, which we define as the front surface (see figure 3). The beam is defined by placing the detector close to
Monolithic LaBr₃:Ce crystals on silicon photomultiplier arrays for time-of-flight PET

Figure 3. Illustration of the measurement geometry showing a monolithic scintillator detector irradiated in front-side readout (FSR) geometry at a given position \( v = (x, y) \) by a perpendicularly incident beam of \( \gamma \)-photons. This beam is defined by electronic collimation accepting only coincidence events between the detector-under-test and a reference detector with a Pb-collimator.

A 0.5 mm diameter \(^{22}\text{Na}\) source and operating it in coincidence with a collimated LaBr₃:5\%Ce detector (Saint-Gobain 25S25) placed on the opposite side of the source. The collimators’ bore diameter is 5 mm, the distance between source and collimator is 815 mm, and the distance between the source and the closest surface of the LaBr₃:5\%Ce crystal is 27.3 mm.

A geometric estimate of the beam diameter thus results in \( \sim 0.69 \) mm at the crystal surface closest to the source diverging up to \( \sim 0.77 \) mm at the crystal surface furthest away. A more detailed analysis of the beam size by means of a Monte Carlo simulation that takes into account the finite positron range and acollinearity results in a beam-profile with a FWHM of 0.57 mm and 0.64 mm at planes corresponding to the crystal surfaces closest and furthest away from the \(^{22}\text{Na}\) source, respectively (Maas et al 2010).

The detector is mounted on a translation stage that allows moving the detector in the plane perpendicular to the annihilation photon beam (i.e. the \( x \)- and \( y \)-plane). Reference events were recorded at an equidistant, 71 \times 65 grid of reference beam positions \((x_i, y_j)\), covering the entire front surface of the crystal at a pitch of 0.25 mm (as indicated by the dots in figure 1). At each grid position 300 events were acquired.

Pulse height spectra were derived by correcting the digitized pulse heights of all detector channels for offsets and gain differences and then adding the 16 corrected pulse heights of each event. The spectra were normalized such that the center of the photopeak corresponded to 511 keV. No corrections for nonlinearity of the SiPMs signal were applied, assuming that the influence of saturation is negligible as will be justified in section 3.1.

The energy resolution was determined as the FWHM of a Gaussian fit to the 511 keV photopeak including a constant offset. In order to exclude the broadening due the x-ray escape peak, only data above 495 keV were considered for the fit. Under absence of so-called transfer noise and a negligible noise contribution of readout electronics the energy resolution of a scintillation detector is commonly expressed in terms of the so-called intrinsic energy resolution \( R_{\text{int}} \) of the scintillation material and the statistical variation of the number of detected photons \( N \) under the assumption of Poisson statistics (Dorenbos et al 1995, Moszynski et al 1998):

\[
\frac{\Delta E_{\text{FWHM}}}{E} = \sqrt{\left( R_{\text{int}}^2 + 2.35^2 \frac{\text{ENF}}{N} \right)},
\]

where ENF is often referred to as the excess noise factor. It represents the broadening of the signal variance due to the dispersion associated with the multiplication process(es) in the
photosensor. Without this dispersion the statistical contribution to the signal variance follows Poisson statistics, i.e. $ENF = 1$.

The detector timing resolution was determined by irradiating an area of $\sim 4$ mm diameter with 511 keV annihilation photons from a $^{22}$Na point source and measuring the coincidence resolving time (CRT) against a reference detector. The irradiated area was located in the center of the detector if not mentioned otherwise. The reference detector consists of a $3 \, \text{mm} \times 3 \, \text{mm} \times 5 \, \text{mm}$ LaBr$_3$:5%Ce crystal mounted on a $3 \, \text{mm} \times 3 \, \text{mm}$ SiPM (MPPC-S10362–33-50C). The single-detector timing resolution of this reference detector was previously measured to be 65 ps FWHM (Seifert et al. 2012). The fast summed signal of the monolithic LaBr$_3$:5%Ce detector and the timing signal of the reference detector were sampled by two synchronized 10-bit sampling ADCs (Acqiris DC282, sampling rate 8 GS s$^{-1}$). Simultaneously, the signals of the energy channels were shaped (CAEN 568B; 100 ns shaping time) and the peak values were digitized (CEAN V785) and stored together with the timing traces for off-line analysis.

Only photopeak events, i.e. events within the full-width-at-tenth-maximum, FWTM, of the 511 keV peak, were selected for further processing of the timing data. This selection corresponds to an energy window of 481–541 keV for the measurement with $V_{ob} = 1.2$ V, and of 475–547 keV for the data recorded at $V_{ob} = 2.0$ V, respectively. For all valid events, a cubic spline interpolation was performed on the sampled traces and time stamps were determined as the point where the interpolated trace crosses a certain threshold value. This threshold value was optimized separately for each measurement. A more detailed description of the method is given elsewhere (Schaart et al. 2010, Seifert et al. 2012).

2.4. Position estimation

The complete set of 1384 500 measured events served both as reference data for the position estimation and as test data for the determination of the spatial resolution, using the leave-one-out method described by Maas et al (2009). The position of interaction of a given test event was determined by an improved form of the so called $k$-nearest neighbor ($k$-NN) method described by van Dam et al. (2011a). First all light patterns were normalized such that the sum of all 16 SiPM signals equaled unity. The unknown annihilation photon interaction position $\mathbf{v} = (x, y)$ of the unclassified event was subsequently estimated by calculating the Euclidean distances, i.e. the square root of the sum-of-squared-differences, of the measured light distribution to those of all events in the reference set. A subset of the reference data consisting of the $k$ (here $k = 400$) closest matches (nearest neighbors) was selected and a histogram of their $(x, y)$ irradiation coordinates was created. This 2D irradiation position histogram is smoothed with a moving average filter of $5 \times 5$ bins. Thus, each new bin value is based on the average of 25 bin values of the original histogram. Near the edges of the histogram the number of bins for averaging was decreased at the side of the edge. The coordinate corresponding to the maximum value of the smoothed histogram was assigned to the unclassified event. A 2D-error histogram was created from the differences between all estimated coordinates and their respective ‘true’ irradiation points. By proper normalization one may obtain the so-called point-spread function (PSF) for the detector. The PSF was interpolated with a 2D cubic spline and the FWHM and the FWTM of the interpolated PSF were determined as measures for the detector spatial resolution along the $x$-direction and $y$-direction, respectively.

The above procedure was repeated using only the errors corresponding to irradiation positions from specific regions of interest. One region, hereafter referred to as center region, is demarcated by a $9.25 \, \text{mm} \times 8.25 \, \text{mm}$ rectangle around the 4 pixels in the center of the sensor. Furthermore, four edge regions were defined which include all irradiation points recorded...
within 2 mm of either edge of the sensor. These regions will be denoted as upper, lower, left, and right edge region according to their position relative to the center region. Lastly, all remaining data points are summarized in the intermediate region. All regions are depicted in figure 1.

In order to evaluate a possible bias in the position estimation a bias vector \( \mathbf{b}(v) \) was calculated at each reference beam position \( v = (x_i, y_j) \). The individual vector elements of \( \mathbf{b}(v) \) are hereby defined as the mean difference between the reference beam position \( v \) and the corresponding estimates on the \( x \)- and \( y \)-coordinates \( \hat{x}(v) \) and \( \hat{y}(v) \):

\[
\mathbf{b}(v) = \left[ \frac{\sum_{m=1}^{M} (\hat{x}_m(v) - x_i)}{M}, \frac{\sum_{m=1}^{M} (\hat{y}_m(v) - y_j)}{M} \right]
\]

where \( \hat{x}_m(v) \) and \( \hat{y}_m(v) \) are the estimated \( x \)- and \( y \)-coordinates of the \( m \)th data point recorded at \( v \). \( M \) is the number of reference events recorded per position (namely \( M = 300 \)).

One possible issue with the calculation of \( \mathbf{b}(v) \) is the contribution of random events. As random events are not correlated to the beam position they cause a background which is distributed within the bounds of the crystal dimensions. It is easy to see that if (2) is evaluated for a uniform distribution the resulting bias vector increases toward the edges of this distribution. This means that including random events in the bias estimation leads to an overestimation of the bias vector toward the detector edges. In order to reduce this effect only those terms were taken into account in the corresponding sums in (2) for which \( \hat{x}_m(v) - x_i \) and \( \hat{y}_m(v) - y_j \) are smaller than 4 mm, which corresponds to approximately the FWTM of the PSF, see section 3.2.

3. Results and discussion

3.1. Energy spectra.

Figure 4 shows the pulse height spectrum containing all data measured over the entire surface of the detector for \( V_{ob} = 1.2 \) V (squares) and \( V_{ob} = 2.0 \) V (circles). Both spectra were normalized to the integral value of the photopeak region between 410 and 560 keV. For illustration the fitted function used to estimate the energy resolution for the measurement at \( V_{ob} = 1.2 \) V is depicted by the lines in figure 4. The FHWM of the fitted function equals 6.4% in the case of \( V_{ob} = 1.2 \) V and 7.8% in the case of \( V_{ob} = 2.0 \) V. This observed difference can be attributed to the increasing probabilities for crosstalk and afterpulses to occur as \( V_{ob} \) is increased (Du and Retière 2008), which increases the observed excess noise of the SiPMs.

We estimate the photon detection efficiency (PDE) of the detector to be 7% at \( V_{ob} = 1.2 \) V and 9% at \( V_{ob} = 2.0 \) V, by multiplying the fill factor (49%) of the array and the measured PDE of the 3 mm \( \times \) 3 mm \( \times \) 5 mm LaBr\textsubscript{3}:Ce crystal coupled to a single 3 mm \( \times \) 3 mm MPPC-S10362-33-050C (Seifert et al 2012), which is identical to a single pixel in the MPPC-S11064-050P array. This means that on average \( \sim 2250 \) and \( \sim 3100 \) microcells are fired, respectively, in response to a 511 keV \( \gamma \)-photon. Using these values in (1) one can estimate the ENF for the MPPC array. This results in ENF = 1.2 at \( V_{ob} = 1.2 \) V and ENF = 2.7 at \( V_{ob} = 2.0 \) V. This increase in the observed excess noise is in agreement with the values given by Szczeńiak et al (2010) for the upper limit of the excess noise for the MPPC-S10362-33-050C.

The influence of optical SiPM saturation is considered to be negligible. The total number of fired cells might be up to \( \sim 50\% \) larger than the number of cells that are triggered by scintillation photons (2250–3100) due to crosstalk and afterpulsing. Yet, the number of microcells in the whole of the array equals \( 16 \times 3600 = 57600 \), which is an order of magnitude larger, still. This assessment may be confirmed by comparing the two pulse height spectra presented in
figure 4, which reveal no significant change in the relative positions of the 511 keV photo-peak and Compton edge.

3.2. Position estimation

3.2.1. Spatial resolution. The point spread function obtained in the center region, the intermediate region, the left edge region, and the lower edge region (as defined in figure 1 and section 2.4) are depicted in figure 5. The plots for the right edge region and the upper edge region are omitted as they are essentially mirror images of the left edge region and the lower edge region, respectively. In addition, the spatial resolutions in terms of the FWHM and the FWTM of the PSF in the x- and y-direction that were determined for the measurements at the two different $V_{ob}$ are summarized in table 1 for all defined regions. It is noteworthy that the spatial resolution that was obtained at $V_{ob} = 2.0$ V does not seem to be worse compared to the values obtained at $V_{ob} = 1.2$. One might expect a degradation of the spatial resolution due to the large increase in the excess noise at the higher bias voltage (van der Laan et al. 2007). Yet, in the present detector this degradation is partially compensated for by the increase in the photon detection efficiency and the corresponding increase in the number of detected photons.

The spatial resolution in the center region of the detector ($\sim$1.4 mm FWHM) is excellent for application in clinical PET. It is can be noted that the resolution in the y-direction appears to be slightly better than the resolution in the x-direction. This probably is a result of the difference in the pixel pitch for the two directions (see figure 1), which may be explained best by considering the underlying mechanisms of the position estimation routine.

As described in section 2.1, the estimation of a given interaction position is based on the resulting light distribution on the photosensor. The probability for a given event at $v = (x, y)$ to be misclassified by a certain distance $\Delta v$ depends on the similarity between the measured light distribution and the light distributions recorded at $v + \Delta v$. In other words, the spatial
resolution, i.e. the ability to distinguish two neighboring interaction positions, depends on
the change in the measured light distribution with a certain change in the interaction position
(van der Laan et al 2007). It should be noted that this limitation of the spatial resolution by the

Table 1. Spatial resolution values for the entire detector and the different regions of interest
(see text and figure 1).

<table>
<thead>
<tr>
<th>$V_{dd}$</th>
<th>Region</th>
<th>x-direction FWHM (mm)</th>
<th>x-direction FWTM (mm)</th>
<th>y-direction FWHM (mm)</th>
<th>y-direction FWTM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 V</td>
<td>Entire detector</td>
<td>1.64</td>
<td>4.03</td>
<td>1.54</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>1.43</td>
<td>3.30</td>
<td>1.36</td>
<td>3.08</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>1.76</td>
<td>4.12</td>
<td>1.66</td>
<td>4.52</td>
</tr>
<tr>
<td></td>
<td>Upper edge</td>
<td>1.64</td>
<td>3.94</td>
<td>2.12</td>
<td>4.64</td>
</tr>
<tr>
<td></td>
<td>Lower edge</td>
<td>1.60</td>
<td>3.95</td>
<td>2.16</td>
<td>4.94</td>
</tr>
<tr>
<td></td>
<td>Left edge</td>
<td>2.15</td>
<td>4.95</td>
<td>1.43</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>Right edge</td>
<td>2.02</td>
<td>4.43</td>
<td>1.48</td>
<td>3.79</td>
</tr>
<tr>
<td>2.0 V</td>
<td>Entire detector</td>
<td>1.63</td>
<td>4.11</td>
<td>1.59</td>
<td>3.92</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>1.44</td>
<td>3.32</td>
<td>1.39</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>1.72</td>
<td>4.54</td>
<td>1.66</td>
<td>4.55</td>
</tr>
<tr>
<td></td>
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<td>3.90</td>
<td>2.30</td>
<td>4.91</td>
</tr>
<tr>
<td></td>
<td>Lower edge</td>
<td>1.60</td>
<td>3.82</td>
<td>2.19</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td>Left edge</td>
<td>2.11</td>
<td>4.86</td>
<td>1.43</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>Right edge</td>
<td>1.96</td>
<td>4.80</td>
<td>1.57</td>
<td>3.79</td>
</tr>
</tbody>
</table>
gradient in the light distribution with respect to the interaction position is a general principle and independent on the exact means of the position estimation.

Now, let us consider a scintillation event at $v = (x, y)$ somewhere in the center of the detector. The intensity of direct scintillation light (i.e. light which was not reflected or scattered prior to its detection) decreases monotonically with increasing distance from $v$. In consequence, the intensity measured by the two sensor pixels that are direct neighbors to the pixel closest to $v$ observes less direct light than the two neighbors in the $y$-direction, due to the $\sim 30\%$ larger inactive area between neighboring pixels in the $x$-direction. As a result, the absolute change of the light distribution with a certain change of $v$ in $x$-direction is smaller than if the same change is applied in the $y$-direction.

The reduction of the change in the measured light distribution with a given change in $v$ also leads to the degradation of the spatial resolution in the intermediate and edge regions of the detector that can be observed in figure 5 and table 1. The light distributions become more and more similar for neighboring interaction positions toward the edges of the detector due to the reflection of scintillation light at the sides of the crystal. Therefore the resolution worsens significantly (up to 2.2 mm FWHM) in the direction perpendicular to the closest edge. It is interesting to note that the resolution parallel to the edges does not change significantly compared to the values determined for the entire detector even for interactions close to the edge.

The degradation in the spatial resolution discussed in the previous paragraph is mitigated by a second edge-effect, which is that only coordinates within the bounds of the detector can be assigned. This truncation of the PSF at the edges of the detector is visible in the corresponding graphs in figure 5 in the form of a distinct asymmetry of the average PSFs in the edge regions with respect to the axis parallel to the closest edge.

3.2.2. Positioning bias. The calculated bias vector $b(v)$ as a function of the reference beam position $v$ is illustrated in figure 6. In order to keep this figure legible the average of $b(v)$ over intervals of $3 \times 3$ irradiation positions (i.e. $0.75 \text{ mm} \times 0.75 \text{ mm}$) is displayed. Furthermore the length of $b(v)$—calculated as the Euclidian norm of $b(v)$—is show in the same figure. The detector center exhibits a bias of negligible magnitude ($<0.1 \text{ mm}$). In the intermediate
region the bias vector \( \mathbf{b}(v) \) has a magnitude in the order of \( \sim 0.5 \) mm and is pointed away from the detector center. The edge regions exhibit the strongest bias (up to 1.5 mm), yet in contrast to the intermediate region \( \mathbf{b}(v) \) it is directed toward the center of the detector. This behavior is a consequence of the two competing edge effects that were discussed in the previous section.

The increasing similarity between light distributions of neighboring interaction positions with decreasing distance to the crystal edge means that for a given interaction at \( v \) with a corresponding light distribution it is more likely to find matching light distributions at coordinates closer toward the detector edge than to find matching light distributions at coordinates closer to the detector center. The position estimation relies on the selection of a number of best matching light distributions (see section 2.4.) which is a probabilistic process. As a result, the position estimation for events within a certain range of a crystal edge (in our case \( \sim 4 \) mm) is biased toward the crystal edge as observed in the intermediate region.

The same reasoning can be applied when considering the influence of the PSF cut-off at the detector edges. This truncation of the sample space for the selection of best matching light distributions reduces the number of matching light distributions with coordinates closer toward the edge than the true interaction position \( v \). Additionally, the maximum distance for a misclassification is bound on one side by the distance between \( v \) and the edge of the detector. The combination of the biased sample space and the asymmetric probability distribution of misclassifications results in the bias toward the detector center that is evident for events close to the detector edge.

It is interesting to note the different ranges for the two competing edge effects. The effect of increasing light distribution similarity has a range of \( \sim 4 \) mm. As argued in the text above, this effect is closely related to the layout of the photosensor and it is therefore not surprising that its range is similar to the pixel pitch. The influence of the truncation of possible coordinates, on the other hand, is directly linked to the misclassification of events. Its range is therefore determined by the average range of coordinates from which matching distributions are drawn in the positioning routine, which roughly corresponds to the spatial resolution in our measurement (i.e. \( \sim 2 \) mm in the edge regions).

This distinction has consequences for the formation of strategies aimed at minimizing the influence of edge effects on the accuracy and the bias of the \( \gamma \)-interaction position estimation in monolithic scintillation detectors. The influence of light distribution similarity might e.g. be minimized by intelligent photosensor design with smaller pixels toward the edges of the crystal. It is expected that such a design would not only reduce the bias in the intermediate region but also lead to an improvement of the spatial resolution. This, in return, would also reduce the bias due to the coordinate-cut-off. Beyond this, however, we see no further obvious design solution to reduce the contribution of the coordinate-cut-off.

In principle one could correct for the remaining bias in the position reconstruction by reversing the vectors shown in figure 6 and using this data as a transformation map. A different approach would be to re-bin data obtained for uniform irradiation of the detector in such a way that the number of counts per bin is equal for all bins and to apply a transformation to the bin edges in order to obtain a uniform grid. Alternatively, a more crude solution could be to choose the bin size large enough so that the bias introduced by the coordinate-cut-off is contained within one bin, thus avoiding the need for additional bias-correction entirely.

### 3.3. Timing resolution

In figure 7 the coincidence spectra that were obtained at the different \( V_{ob} \) are compared. The spectra are plotted together with their corresponding Gaussian fits (lines). The FWHM of those
fits is used as a measure of the timing resolution. Quadratically subtracting the timing resolution of the reference detector (65 ps FWHM) and multiplying with $\sqrt{2}$ yields the predicted CRT between two identical detectors operated at the same voltage-over-breakdown: CRT\text{FWHM} = 239 ps FWHM and CRT\text{FWHM} = 198 ps FWHM for $V_{ob} = 1.2$ V and $V_{ob} = 2.0$ V, respectively. Thus a significant improvement is observed at the larger $V_{ob}$.

This is the reversed trend as the one that was observed for the energy resolution. The reason for this lies in the fundamental difference between the observed excess noise for SiPM-based scintillation detectors and for detectors based on proportional photosensors such as photomultiplier tubes (PMTs) and avalanche photodiodes (APDs). The ENF is commonly defined in terms of the relative deterioration of the observed energy resolution of a scintillation detector (see equation (1)). This deterioration is associated with the multiplication noise for individual photoelectrons/electron–hole pairs in the case of PMTs and APDs. In contrast, the ENF of SiPMs, which are based on a large number of Geiger-mode single-photon counters, is largely dominated by crosstalk and afterpulsing.

The latter two effects occur with a certain time delay after the firing of the original microcell by a scintillation photon. As the time stamps for scintillation events are created at very early parts of the scintillation pulse, it can be argued that the influence of afterpulses on the CRT is negligible and that the contribution of crosstalk is small (Seifert et al. 2012). The fact that these two major contributions to the ENF of SiPM-based scintillation detectors have only little influence on the timing resolution means that ENFs determined from pulse-height spectra cannot be applied in the same way to timing performance estimates as for detectors based on PMTs or APDs.

In order to investigate a possible dependence of the timing resolution on the interaction position, timing spectra were measured at a number of different detector positions such that the centers of the irradiated areas were located at various distances $(\Delta x, \Delta y)$ from the detector center: $(\Delta x = 0 \text{ mm}, \Delta y = 0 \text{ mm})$; $(\Delta x = 4 \text{ mm}, \Delta y = 0 \text{ mm})$; $(\Delta x = 4 \text{ mm}, \Delta y = 4 \text{ mm})$; and $(\Delta x = 8 \text{ mm}, \Delta y = 0 \text{ mm})$. These measurements were performed at an intermediate bias voltage $V_{ob} = 1.6$ V. The FWHM determined for the recorded timing spectra are summarized in table 2. The changes of the FWHM with respect to the center of the detector are within...
Table 2. Width (FWHM) of the timing spectra measured irradiating different areas of the detector.

<table>
<thead>
<tr>
<th>Distance to detector center</th>
<th>FWHM (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δx (mm) Δy (mm)</td>
<td></td>
</tr>
<tr>
<td>0 0</td>
<td>174</td>
</tr>
<tr>
<td>4 0</td>
<td>168</td>
</tr>
<tr>
<td>4 4</td>
<td>164</td>
</tr>
<tr>
<td>8 0</td>
<td>167</td>
</tr>
</tbody>
</table>

4%–6% and do not exhibit a clear trend. It thus would appear that the timing resolution is uniform throughout the detector.

4. Conclusions

Our experiments show that monolithic LaBr$_3$:5%Ce-based PET detectors equipped with currently available SiPM arrays and dedicated readout electronics may offer a combination of very good spatial and energy resolution as well as excellent timing performance. No appreciable effect of SiPM saturation was observed in the energy spectra because of the large number of available microcells in the detector array (57 600). This can be an added advantage of monolithic scintillation crystals compared to e.g. one-to-one coupling of small scintillation crystals where an increase of the linear range of the detector often has to be balanced with the resulting decrease of the SiPM fill-factor.

As expected, increasing the applied bias voltage above the nominal value increases the observed excess noise and, thus, worsens the energy resolution of the detector from 6.4% FWHM to 7.8% FWHM. In contrast, the measured spatial resolution of about ∼1.6 mm FWHM was affected only marginally by the increase in $V_{ob}$ despite the increase of the ENF. This is attributed to the increase in the PDE of the SiPMs, which largely compensates for the degrading effect of the larger ENF.

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Considering that timing resolution of state of the art TOF PET systems is in the order of 375 ps–600 ps (Daube-Witherspoon et al 2010, Surti et al 2007, Lois et al 2010) the CRT that was measured for our detector is certainly encouraging. Moreover, the timing resolution significantly improved at the higher $V_{ob}$ (from CRT = 239 ps FWHM to CRT = 198 ps FWHM). This illustrates that the concept of the excess noise factor must be applied with caution to SiPMs, because the energy resolution and the timing performance are affected very differently by afterpulsing and crosstalk. As an energy resolution of 7.8% FWHM is still respectable for a PET detector it might thus be favorable to operate the detector at comparatively large $V_{ob}$ for optimum overall performance in a TOF PET system. Furthermore, improvements on the image quality due to a better energy resolution or a better spatial resolution are limited by statistical noise and, in the case of spatial resolution, the physical limits of the positron range and acollinearity of the annihilation photons. In contrast, there is no such limitation on the benefits of the timing resolution of a TOF PET system (e.g. Moses 2007, Conti 2011).

Nonetheless, the detector presented in this work is a prototype and a number of practical issues need to be addressed before the presented detector concept can be taken to a full system level. For example the front-side readout of scintillators might be challenging from a system engineering point of view. One particular issue in this respect might be the possible need for temperature control of the SiPMs to avoid gain fluctuations. An elegant solution to this problem has been demonstrated by Yamamoto et al (2011) in the form of temperature-dependent $V_{ob}$-control of the SiPMs. Other crucial issues are the detector calibration and the...
processing of the data. Some interesting concepts have been introduced in order to address these challenges such as e.g. the application of neural networks for the position estimation by Bruyndonckx et al (2007), or the suggestion of a much faster line-source calibration by Van Dam et al (2011a). Nevertheless, these works are first steps and considerable effort will be required to refine and combine these concepts and test them in practice. Furthermore, the application of monolithic scintillators might require novel image reconstruction algorithms in order to bring out the full potential of these detectors.

Still, the results presented in this work indicate that it may well be worth the effort to tackle these remaining obstacles. The combination of an energy resolution <10%, a spatial resolution <2 mm and a timing resolution <200 ps highlights the unique potential of monolithic scintillators for application in TOF PET. In addition, γ-radiation detectors utilizing monolithic scintillators will hugely benefit from recent developments in the field of pixelated solid state photosensors. For example, the dead space in between the individual pixels is practically eliminated in the next generation of 4 × 4 SiPM arrays from Hamamatsu (MPPC S11828–3344M), thus improving the overall photon detection efficiency by almost 50%.3 A further example is the emergence of the so-called digital SiPM (Degenhardt et al 2009) which facilitates nearly noise-free measurements of the light intensities on the individual pixels as well as accurate time stamping for individual pixels.

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References


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