Abstract—State-of-the-art scintillation detectors for time-of-flight positron emission tomography (TOF-PET) typically employ scintillation crystals with a high aspect ratio (e.g. \(4 \times 4 \times 22 \, \text{mm}^3\)) read out on one of the small crystal surfaces. This single-sided readout (SSR) geometry may be unfavorable in terms of the coincidence resolving time (CRT) that can be achieved because of its effect on the light collection efficiency; the spread in the scintillation photon propagation times; and depth-of-interaction (DOI) related, variable detection delays. In this work it is investigated to which extent these effects can be mitigated by applying a fast photosensor on each of the small crystal surfaces. Such double-sided readout (DSR) has been introduced previously to counter the issue of DOI-related parallax errors. For the present purpose, we used Hamamatsu MPPC-S10362-33-050 C silicon photomultipliers (SiPMs) optically coupled to LSO:Ce,Ca scintillators. For polished \(3 \times 3 \times 20 \, \text{mm}^3\) crystals with SSR, CRT values of \(184 \pm 6 \, \text{ps} \, \text{FWHM}\) and \(215 \pm 6 \, \text{ps} \, \text{FWHM}\) were determined for irradiation head-on and from the side, respectively. In this case, DSR improved the CRT measured under side irradiation to \(174 \pm 6 \, \text{ps} \, \text{FWHM}\). A much more substantial improvement was observed for equally sized crystals having etched side surfaces. For these crystals the CRT changed from \(358 \pm 5 \, \text{ps} \, \text{FWHM}\) (head-on irradiation) and \(343 \pm 6 \, \text{FWHM}\) (side irradiation) with SSR to \(180 \pm 5 \, \text{ps} \, \text{FWHM}\) with DSR (side irradiation). These values are compared with the time resolution of detectors employing LSO:Ce,Ca crystals with a size of \(3 \times 3 \times 5 \, \text{mm}^3\) (CRT = \(121 \pm 2 \, \text{ps} \, \text{FWHM}\)) and \(3 \times 3 \times 10 \, \text{mm}^3\) (CRT = \(162 \pm 9 \, \text{ps} \, \text{FWHM}\) and CRT = \(183 \pm 3 \, \text{ps}\) for polished and etched crystals, respectively).

Index Terms—LSO, scintillation detectors, time resolution, time-of-flight PET.

I. INTRODUCTION

It is well established that improvements in the coincidence resolving time (CRT) of TOF-PET scanners directly relate to better signal-to-noise ratio and image quality (e.g. [1]–[8]). It therefore is desirable to further improve the time resolution of TOF-PET detectors. Recently, it has been shown that the time resolution that can be achieved with a given scintillation detector is ultimately limited by the statistical properties of the signals generated by the individual scintillation photons [9]. This lower limit on the time resolution depends on three major factors: the number of scintillation photons detected; the expected time profile of the scintillation light emission; and the overall signal transit time distribution (TTD). In other words, the desired improvement of the time resolution necessitates advances in these key performance areas.

The scintillation emission time-profile is entirely determined by the scintillator, while the number of scintillation photons detected is limited by the scintillator light yield as well as the spectral overlap between the emission spectrum and the photodetection efficiency (PDE) curve of the photosensor. In consequence, significant improvement of the CRT largely hinges on the development of faster and brighter scintillators and/or improved photosensors.

The overall TTD and, to some extent, the number of detected scintillation photons are influenced by the transport of optical photons. The significance of these effects strongly depend on the distribution of the possible paths that the scintillation photons may travel before reaching the photosensor. An obvious way to keep this distribution narrow is to keep the crystal dimensions small. This strategy can be very useful when establishing bench marks and to better understand the fundamental factors affecting time resolution [9]–[11].

Scintillation crystals with a length < 10 mm (as used in the abovementioned references) are usually considered to be of limited practical use for clinical TOF-PET scanners that require high detection efficiency for 511 keV \(\gamma\)-photons. The crystal length in clinical (TOF-) PET detectors typically is in the order of 20 mm or more.

Furthermore, the localization of the detected \(\gamma\)-photons is commonly achieved by crystal identification schemes. This means that the spatial resolution is limited by the transversal cross section of the crystals. To achieve high spatial resolution, PET systems with crystal diameters well below 1 mm have been realized (e.g. [12], [13]). However, such small crystal dimensions may compromise other system parameters (such as the energy resolution and the timing performance), come at the cost of a reduction of the packing fraction, and drastically increased system complexity. Therefore, commercial TOF PET scanners typically utilize scintillators with cross sections of about \(4 \times 4 \, \text{mm}^2\).

In PET systems, crystals are commonly read out on the small crystal surface facing away from the scanner axis, which leads to both a relatively high mean value of, and a relatively large spread in, the number of reflections undergone by scintillation photons prior to detection. This gives rise to light losses and a broadening of the photon TTD, both of which have a deteriorating effect on the detector time resolution. In addition to these...
effects, the difference in the velocities of gamma and optical photons in the scintillation material institutes that the time difference between the emission of a 511 keV annihilation photon and the registration of the event by the photosensor depends on the depth-of-interaction (DOI) of the $\gamma$-photons within the crystal. This introduces a third cause of time blurring that can be in the order of a few hundred ps [14].

An interesting approach to mitigate these effects has been published by Moses, et al. [15], who proposed a scanner geometry that allows coupling the photosensors to one of the larger side surfaces of the crystals. It was demonstrated that this geometry can improve the timing performance by more than 50%. In combination with further optimization (e.g. regarding the choice of the scintillator, the crystal surface treatment, the photosensor type, and reflective material), a time resolution of 220 ps could be achieved with $4 \times 4 \times 22$ mm$^3$ LSO:Ce crystals. Still, the propagation time of the $\gamma$-photon within the crystal remains unknown in this geometry, adding some ~ 60 ps to the timing uncertainty. Furthermore, the readout of the scintillation crystals at the side surfaces prohibits a dense stacking of scintillation crystals.

In this work we propose to improve the time resolution by utilizing double-sided readout (DSR) of the scintillation crystals, i.e. to collect the photon signal on the two small faces of the scintillator. DSR facilitates the determination of the DOI [12], [16]–[20], which makes it possible to correct for the contribution of DOI-dependent effects to the timing uncertainty. Furthermore, this geometry roughly halves the average propagation distance of the scintillation photons compared to single-sided readout (SSR) of the same crystal.

II. METHODS

A. Detector Assembly

The scintillation crystals used in this work were supplied by Agile Engineering Inc. All crystals were cut from the same boule of LSO:Ce co-doped with 0.2 at% Ca in the melt [21]. The material was grown at the Scintillation Materials Research Center at the University of Tennessee. The crystals were cut into rectangular cuboids of $3 \times 3 \times z$ mm, where $z$ equaled 5 mm, 10 mm, or 20 mm. Those crystal surfaces that were attached to photosensors were polished, while the remaining surfaces were either polished or chemically etched, as indicated in Table I. The cutting and surface preparation was performed by the manufacturer and the crystals were used as delivered.

Hamamatsu MPPC-S10362-33-050 C silicon photomultipliers (SiPMs) were attached to either one (SSR) or both (DSR) of the $3 \times 3 \times 3$ mm crystal faces, using an optical coupling medium (Meltmount 1.582 from Cargille Laboratories, Inc.). Subsequently, the crystals were wrapped with Teflon tape.

In what follows, the assembled detectors will be denoted with a letter indicating the surface finish of the sides not read out by photosensors (E for etched and P for polished) followed by an acronym for the readout geometry (i.e. SSR or DSR), and the crystals’ $z$ dimension in mm. For example, PDSR20 stands for a detector composed of a polished $3 \times 3 \times 20$ mm LSO:Ce,Ca crystal with SiPMs coupled to both $3 \times 3$ mm faces (see Table I for a complete list of assembled detectors).

B. Time Resolution Measurements

All measurements were performed at an ambient temperature of $21^\circ\text{C} \pm 1^\circ\text{C}$ without further temperature stabilization. For each crystal size and readout geometry tested, the voltage over breakdown ($V_{\text{br}}$) of the SiPMs was optimized for timing performance in steps of 0.1 V. In all cases the optimum $V_{\text{br}}$ for timing appeared to be $2.1 \text{ V} \pm 0.1 \text{ V}$. In this work we give all time resolutions as the mean value obtained in this voltage range. Error bars denote the sample standard variation within these measurements.

The SiPM signals were amplified with preamplifiers made in house [22]. The timing signals available from these amplifiers were digitized using two synchronized Acqiris DC282 digitizers at 4 GS/s. The energy information was obtained from a separate, slower preamplifier channel connected to a shaping amplifier (CAEN N568B; customized to provide 100 ns shaping time) and a peak-sensing ADC (CAEN V785). The digitized timing traces and the corresponding energy value of each event were stored together for further processing.

In the data processing we closely followed procedures that have proven to perform well with data obtained from small scintillation crystals [10], [23]. As described in detail in these works, a refined energy selection is imposed, in which only data within the photopeak are accepted; a baseline correction is applied; and the digitized timing trace is interpolated with a cubic spline. However, whereas in our previous works a leading edge trigger (LED) was applied to determine timestamps for the digitized traces, we now normalize the signals to the amplitude of the energy signal recorded by the corresponding sensor before determining the time-of-threshold-crossing. This was done to avoid the effect of so-called amplitude walk on the determined time stamps.

The value of the threshold was optimized independently for each measurement by applying threshold levels in the range of $1.5 \text{–} 31.3$ mV at 511 keV (corresponding to $0.6 \text{–} 12.8$ single cell amplitudes). In case of DSR the same threshold level was

<table>
<thead>
<tr>
<th>Detector ID</th>
<th>Crystal $z$ dimension (mm)</th>
<th>Crystal readout</th>
<th>Surface finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSR5</td>
<td>5</td>
<td>SSR</td>
<td>etched, etched, polished</td>
</tr>
<tr>
<td>ESSR10</td>
<td>10</td>
<td>SSR</td>
<td>etched, etched, polished</td>
</tr>
<tr>
<td>PSSR10</td>
<td>10</td>
<td>SSR</td>
<td>polished, polished, polished</td>
</tr>
<tr>
<td>ESSR20</td>
<td>20</td>
<td>SSR</td>
<td>etched, etched, polished</td>
</tr>
<tr>
<td>EDSR20</td>
<td>20</td>
<td>DSR</td>
<td>polished, etched, polished</td>
</tr>
<tr>
<td>PSSR20</td>
<td>20</td>
<td>SSR</td>
<td>polished, polished, polished</td>
</tr>
<tr>
<td>PDSR20</td>
<td>20</td>
<td>DSR</td>
<td>polished, polished, polished</td>
</tr>
</tbody>
</table>
applied to both SiPMs of the detector. Subsequently the time
difference histograms were determined for the time stamps
obtained at each combination of threshold levels on the two
detectors. The threshold setting yielding the spectrum with the
smallest width was chosen as the optimum. In what follows,
time resolution values are always quoted for the optimized
threshold setting.

For the detectors with DSR the timing information of the
two photosensors need to be combined to create a single time-
stamp for each γ-event in the detector. As will be shown in
Section IV-B, a simple averaging of the times at which the
two corresponding timing signals cross equal relative thresh-
olds performs remarkably well. Unless mentioned otherwise,
this method is applied to create timestamps for detectors with
DSR.

The time resolution of the different assembled detectors was
determined by means of coincidence measurements of 511 keV
annihilation photons from a 0.5 mm $^{22}\text{Na}$ point source. In this
work we will use the term measured time resolution to indicate
the (uncorrected) full-width-at-half-maximum (FWHM) of the
distribution of timestamp differences (i.e. the time difference
spectrum) of the two detectors measured in coincidence. The
FWHM is extracted by fitting a Gaussian function to the cor-
responding time difference spectrum. The CRT is subsequently
determined as the FWHM of the time difference spectrum that
is expected for two identical detectors. In most cases this means
that the measured time resolution was first corrected for the con-
tribution of the reference detector by quadratic subtraction and
then multiplied by $\sqrt{2}$.

For all measurements presented in this work an ESSR5 de-
tector served as a reference. In order to establish the time res-
olution of this detector, a coincidence measurement using two
such detectors was performed. The single-detector time reso-
lation was then estimated assuming identical detectors, i.e., by
dividing the obtained CRT by $\sqrt{2}$.

The detectors that include either 10 mm or 20 mm long crys-
tals were placed in different irradiation geometries as illustrated
in Fig. 1. All detectors with DSR were irradiated from the side
as this provides a simple way to switch between approximately
homogenous irradiation of the scintillation crystal (Fig. 1(b)) and
irradiation with an electronically collimated beam (Fig. 1(c)),
namely by placing the point source at different positions along
the axis between the detectors. The collimated side irradiation
was used to directly verify the DOI determination (see Sec-
tion II-C) for the 20 mm long crystals. All CRT values for the
detectors with DSR were obtained for homogenous side irra-
diation. Here, the distance $d_{ss}$ between the reference detector
and the source (as defined in Fig. 1) was 1.6 cm in all cases,
while the distance $d_{uu}$ between the detector-under-test and the
source equaled 8 cm and 10 cm for the crystals with $z = 10 \text{ mm}$
and $z = 20 \text{ mm}$, respectively.

In order to provide a direct comparison, the detectors with
SSR were also irradiated homogeneously from the side using
the same values of $d_{ss}$ and $d_{uu}$ as for the detectors with DSR.
The time resolution for these detectors was also determined
under head-on irradiation (Fig. 1(a), i.e. with the front surface
facing the $^{22}\text{Na}$ source, resembling the irradiation geometry in
a TOF-PET scanner.

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**Fig. 1.** Irradiation geometries for the tested scintillation detectors. (a) head-on
irradiation (b) homogenous side irradiation (c) collimated side irradiation.

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### C. Depth of Interaction

In this work, we use the term depth-of-interaction to denote the
γ-interaction position along the longest crystal axis, regard-
less of the actual irradiation direction. Accordingly, the front
surface and back surface are defined as the 3 mm × 3 mm sur-
faces at DOI = 0 mm and DOI = z, respectively. The attached
SiPMs will correspondingly be referred to as front sensor and
back sensor. As the scintillation crystal is irradiated from the
side, however, the choice of which surface/sensor is chosen as
the front or back is arbitrary.

DSR of the crystals allows utilizing the contrast $c$ between the
two photosensors as a measure of the DOI [19]:

$$
c = \frac{I_{\text{back}} - I_{\text{front}}}{I_{\text{back}} + I_{\text{front}}}$$

(1)

where $I_{\text{front}}$ and $I_{\text{back}}$ are the light intensities recorded by the
two photosensors. In order to determine the relation between
the DOI and $c$ (or any other DOI-dependent parameter), exten-
sive calibration measurements are commonly performed. How-
ever, this relation can also be extracted from the distribution of $c$
within a large set of reference events if the true DOI distribu-
tion for these events is known and if the relation between the
DOI and $c$ is monotone [24].

In order to establish the DOI calibration for a given detector,
a set of 100000 reference events was recorded. The source was
positioned at a distance of 10 cm from the detector and no co-
incidence requirement was imposed. It is thus assumed that the
distribution of events within the crystal is homogenous. Conse-
quently, a DOI-histogram of the reference data set should be uni-
form. This means that the DOI calibration can be estimated by
ordering the events according to their $c$-value and subsequently
grouping them in bins such that a uniformly filled histogram
is obtained. The contrast values demarcating the histogram bin
edges are stored as a DOI calibration look up table. In this work,
the number of histogram bins was chosen such that the width of
a single DOI bin equals 0.5 mm.
Fig. 2. Energy spectra recorded for the detectors with single-sided readout employing LSO:Ce,Ca crystals with etched surfaces (a) and polished surfaces (b), for different crystal heights and irradiation geometries. All detectors utilize the same MPPC and preamplifier. The spectra were recorded with a $^{22}$Na source in coincidence with the 5 mm reference detector (see also Fig. 1).

In order to verify this procedure, the detectors were irradiated with an electronically collimated beam of 511 keV annihilation photons at various positions, as illustrated in Fig. 1(c) (with $d_{\text{d-s}} = 2$ cm and $d_{\text{r-e}} = 10$ cm). The coincidence requirement on the two detectors results in a restriction of the volume of the crystal-under-test containing accepted events. A first order estimate diameter $d_{\text{beam}}$ of this electronically collimated annihilation photon beam can be made on the basis of the geometry of the setup, neglecting the effects of the positron range, and the divergence of the beam within the crystals:

$$d_{\text{beam}} = d_{\text{d-s}} \left( d_{\text{ref}} + d_{\text{source}} \right) + d_{\text{source}}$$

where $d_{\text{source}}$ is the diameter of the $^{22}$Na source (i.e. $d_{\text{source}} = 0.5$ mm), and $d_{\text{ref}}$ is the diameter of the scintillation crystal in the reference detector (i.e. $d_{\text{ref}} = 3$ mm). This simple geometric estimate yields a beam diameter of $d_{\text{beam}} \approx 1.1$ mm.

At first the detector was positioned such that the scintillation crystal is irradiated approximately in the center. The detector was then moved parallel to the longest crystal axis with $+0.1$ mm precision to 8 different positions covering a DOI range of 17.5 mm.

III. RESULTS

A. Energy Spectra

Fig. 2 depicts the energy spectra that were recorded for the detectors with SSR as a function of the crystal $z$-dimension and the irradiation geometry. The spectra are corrected for the effects of cross talk, afterpulsing, and saturation using the method described in [25].

All detectors represented in this figure were assembled utilizing the same MPPC, preamplifier, and sampling ADC channel. This allows for a qualitative comparison of the measured light yields (i.e. the photopeak positions) to within the uncertainty due to gain fluctuations (resulting from e.g. temperature or bias voltage drifts). This uncertainty is estimated to be $\pm 7\%$ ($2\sigma$), based on the energy spectra measured for the reference detector.
Fig. 4. Timing spectra measured with single-sided SiPM readout employing LSO:Ce,Ca crystals with etched (a) and polished (b) side and front surfaces under “head-on” irradiation. The timing spectra obtained with double-sided readout of the different detectors is depicted in (c). The spectra were obtained in coincidence with a reference detector utilizing a 3 mm x 3 mm x 5 mm LSO:Ce,Ca crystal. The dashed lines indicate the corresponding Gaussian fits.

Fig. 3 shows the energy spectra measured for the detectors with DSR. The individual spectra recorded for the front- and backside MPPC are shown, as well as the spectra obtained after summing the signals of both MPPCs.

### B. Timing Measurements

Fig. 4 depicts the timing spectra measured for the detectors with SSR under head-on irradiation. The figure also indicates the Gaussian functions that were fitted to the data (dashed lines). Fig. 4 depicts the corresponding data for the detectors with DSR under side irradiation. The FWHM values of all fitted Gaussian functions are summarized in Table II.

The CRT of the detectors utilizing the 3 mm x 3 mm x 5 mm crystals is found to be 121 ps FWHM. Based on this value we estimate the single-detector time resolution of our reference detector to be 85 ps FWHM. The expected CRT for two (presumably) identical 10 mm or 20 mm detectors can be estimated by correcting the time resolution measured with these detectors.

<table>
<thead>
<tr>
<th>Detector ID</th>
<th>Head-on irradiation</th>
<th>Side irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (ps)</td>
<td>CRT (ps)</td>
</tr>
<tr>
<td>ESSR5</td>
<td>121 ± 2</td>
<td>121 ± 2</td>
</tr>
<tr>
<td>ESSR10</td>
<td>155 ± 2</td>
<td>183 ± 3</td>
</tr>
<tr>
<td>ESSR20</td>
<td>267 ± 3</td>
<td>358 ± 5</td>
</tr>
<tr>
<td>PSSR10</td>
<td>143 ± 5</td>
<td>162 ± 9</td>
</tr>
<tr>
<td>PSSR20</td>
<td>156 ± 3</td>
<td>184 ± 6</td>
</tr>
<tr>
<td>EDSR20</td>
<td>-</td>
<td>153 ± 3</td>
</tr>
<tr>
<td>PDSR20</td>
<td>-</td>
<td>150 ± 3</td>
</tr>
</tbody>
</table>

Table II: Measured time resolution and the corresponding CRTs for pairs of identical detectors. CRTs are calculated from the FWHM of the measured time difference spectra by quadratic subtraction of the reference detector resolution and subsequent multiplication by sqrt(2).

Fig. 5. Distributions of DOI estimates for the EDSR20 detector (a) and the PDSR20 detector (b) under collimated side irradiation at different irradiation positions. The irradiation positions are indicated in the top half of the figure. The positions are given relative to the position denoted as DOI_C, which was aligned to the centroid of the corresponding DOI distribution.
TABLE III
MEDIAN AND WIDTH OF THE DOI-ESTIMATE DISTRIBUTIONS DEPICTED IN FIG. 5. THE WIDTH IS DETERMINED AS THE DOI RANGE AROUND THE MEDIAN THAT INCLUDES 76% OF ALL EVENTS MEASURED AT A GIVEN POSITION.

<table>
<thead>
<tr>
<th>DOI Position (mm)</th>
<th>EDSR20 Median DOI</th>
<th>Width DOI Distribution</th>
<th>PDSR20 Median DOI</th>
<th>Width DOI Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>2.2</td>
<td>0.3</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>2.4</td>
<td>2.0</td>
<td>4.1</td>
<td></td>
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<td>4.0</td>
<td>2.0</td>
<td>4.1</td>
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<td>8.9</td>
<td>1.7</td>
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<td>6.2</td>
<td></td>
</tr>
<tr>
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<td>1.7</td>
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<td>5.6</td>
<td></td>
</tr>
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<td>4.9</td>
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<td>17.4</td>
<td>2.2</td>
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</tr>
<tr>
<td>18.4</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

for the reference detector value. These estimates are listed in Table II along with the measured time resolution.

C. DOI Resolution

Fig. 5 shows the distribution of the DOI estimates that were derived from the data measured with the EDSR20 detector, at different detector positions. As mentioned in Section II-C, all detector positions were defined relative to a detector position DOI, corresponding to the irradiation of the approximate center of the detector. The detector positions relative to DOI, are therefore indicated as small vertical lines in Fig. 5, aligned such that the DOI indicator coincides with the centroid of the corresponding DOI distribution. It can be observed that the centroids of the various DOI estimates correctly follow the movement of the detector.

The DOI estimates are furthermore characterized by determining the median and the width of the corresponding distributions. Herby we define the width of the distribution as the DOI range around the median that includes 76% of all events recorded at a given beam position. For a Gaussian distribution this corresponds to the FWHM. The results of this procedure are summarized in Table III. It should be noted that these values still contain the contribution of the test beam diameter.

Lastly, DOI dependency of the timestamps that are created for the front sensor and the back sensor, respectively, is determined. To this end, the data obtained from homogenous side irradiation is sorted into 0.5 mm DOI bins. The corresponding histograms are depicted in Fig. 6. Subsequently, the average trigger times for each of the two photosensors are determined for each bin. The results of this procedure are depicted in Fig. 7(a) for the EDSR20 detector and in Fig. 7(b) for the PDSR20 detector. In addition, the mean value of the two timestamps for each bin are shown in both figures.

IV. DISCUSSION

A. Energy Spectra

The energy spectra shown in Fig. 2 illustrate that the photon collection efficiency of the detectors decreases as the z-dimension of the crystals is increased. This is not surprising, given that the increasing aspect ratio of the crystals entails an increase of the average number of reflections undergone per scintillation photon before detection, while each reflection is associated with a certain probability that the photon is lost.

A comparison of the energy spectra measured for crystals of equal z-dimension but different surface treatment might suggest that the average number of detected photons is slightly larger for the etched crystals. This holds for both single-sided and double-sided readout. Still, this cannot be said with certainty as the differences are within the observed gain fluctuations (see Section III-A).

Furthermore, Fig. 2 and Fig. 3 exemplify a fundamental difference between the light transport within the crystals with polished (i.e. predominantly specular reflecting) and etched (i.e. predominantly diffuse/Lambertian reflecting) surfaces. In a crystal with specular reflecting surfaces, the number of reflections required for a given photon before it can reach the photosensor changes linearly with its emission position along the z-dimension of the crystal (i.e. with the DOI). Interestingly,
this change is negative for photons that are emitted into a solid angle towards the photosensor and positive for photons emitted into opposite directions. Thus, in first order approximation, the average number of reflections of all scintillation photons does not change with the DOI. Consequently, the width of the photopeak changes little with the length of polished crystals.

Moreover, it is clear that for crystals with specular reflecting surfaces the $z$-component of the photon propagation vector can only change by reflection at the front or back surface. This entails that the number of photons received by the two SiPMs in the PDSR20 is only weakly DOI dependent. Other mechanisms that may lead to a DOI dependent contrast—such as path-length dependent losses, imperfections in the polishing, and an amount diffuse reflection introduced by the Teflon wrapping—appear to be of secondary importance. This can be observed in the narrow distribution of the corresponding photopeaks in Fig. 3(b) as well as in the much worse DOI resolution (see Fig. 5, see also Section IV-B).

A substantial diffuse contribution to the reflection breaks the symmetry of the photon propagation. In this case, the probability for a given photon to first reach either the front or back surface is a strong function of the DOI. This is illustrated by the spectra recorded for the individual SiPMs of the EDSR20 detector in Fig. 3(a). The onset of the spectra recorded for the individual SiPMs of the EDSR20 detector is $\approx 3000$ photons for both photosensors. These onsets are associated with the intensity seen by the corresponding sensors for scintillation events in their immediate proximity. Conversely, events occurring at the opposite end of the crystal can be associated with the cut-off of the photo peak that is clearly visible at $\approx 1000$ photons for both photosensors, superimposed on the Compton continuum. It thus appears that the ratio between the intensity seen by the two sensors is approximately 3:1 for scintillation events occurring close to either of the small surfaces.

In the EDSR20 detector the probability that a photon is reflected back into the crystal after reaching either of the 3 mm x 3 mm surfaces is small as both of these surfaces are optimized for light extraction to the SiPMs. This is not the case in the ESSR20 detector, where the front surface is also a diffuse reflector and photons impinging on this surface may still reach the photosensor. Allowing for only one front side reflection and assuming similar light yield and surface conditions as for the ESSR20 detector, one would expect the onset of the photo peak at $\approx 3250$ photons: 3000 “direct” photons from the event close to the photosensor and 250 “front-side reflected” photons (1/4th of the $\approx 1000$ photons reflected from the front side). A similar consideration for events close to the front surface yields $\sim 1750$ photons (1000 “direct” photons and 750 “front-side reflected” photons). These values are only slightly smaller than the onset and cut-off that can be observed in the corresponding spectra in Fig. 2(a): $\sim 3500$ photons and $\sim 2100$ photons, respectively. This seems to indicate that it becomes increasingly unlikely to detect photons that are reflected multiple times at the front side.

Lastly, it may be interesting to highlight the distinct difference in the shapes of the energy spectra measured with the ESSR20 detector under side and head-on irradiation, which are depicted in Fig. 2(a). The corresponding photopeaks reflect the approximately homogenous DOI distribution in case of the side irradiation and the exponential DOI distribution in case of head-on irradiation, where the majority of $\gamma$- photons interact relatively far away from the sensor.

B. DOI Estimation

As discussed in the previous section, the contrast between the two SiPMs of the detectors with double-sided readout changes much more strongly in case of the etched crystals compared to the crystals with polished sides. Consequently, the DOI resolution is much better for the EDSR20 detector than for the PDSR20 detector: 1.7 mm compared to 6.0 mm in the crystal center and 2.2 mm compared to 4.5 mm close to the front or back surface (see Table III and Fig. 5).

In Fig. 6 it can be seen, that the distribution of DOI estimates is homogenous in the range of 5–15 mm. In the case of the EDSR20 detector the frequency with which events are estimated to have a low DOI value (i.e. to have taken place close to the front side SiPM) is reduced even further, while large DOI values are assigned uncharacteristically often. As pointed out earlier in this work the contrast changes only weakly with the DOI in the polished crystals. The corresponding DOI estimate therefore is very susceptible to e. possible drift of the gain of the SiPMs. E.g. $\sim 5\%$ drift of the SiPM gain over the course of the $\sim 2$ days in between the calibration measurement and the timing measurement is sufficient to cause the observed bias of the DOI estimates.

C. Timing Measurements

The CRT of the detectors utilizing the 3 mm x 3 mm x 5 mm crystals (121 ps FWHM) is practically identical to the CRT of 120 ps FWHM that was measured for the same crystals mounted to a single pixel of a so-called digital silicon photomultiplier (dSiPM) array [26]. Furthermore, this value constitutes an improvement of 12%–17% with respect to the CRT obtained with detectors utilizing the same type of SiPM as used in this work, in combination with LYSO:Ce crystals of the same dimensions (CRT $\approx 138$ ps FWHM [10], and CRT $\approx 147$ ps FWHM [11]). This improvement is consistent with what one might expect given that, in comparison with LYSO:Ce, Ca-codoped LSO:Ce has a 25% faster decay time (i.e. $\tau_d \approx 33$ ns) and similar light yield [10], [27], [28].

As one might expect, the time resolution of the detectors with SSR degrades considerably as the $z$-dimension of the crystal is increased. One factor contributing to the observed degradation is the decrease of the (average) photon collection efficiency as the crystal aspect ratio is increased, as discussed in the previous section. However, the observed degradation of the timing performance cannot be explained by the reduction of the number of detected scintillation photons alone. This is illustrated by a comparison of the CRTs of detectors employing etched crystals with those that use polished crystals of the same size. In all cases, the measured CRTs are significantly worse for the etched crystal (see Table II) compared to the polished ones.
In general one can identify two additional mechanisms that may lead to a broadening of the measured timing spectra as the crystal aspect ratio is increased:

1. longer crystal dimensions entail an increased spread of the scintillation photon propagation times, also referred to as “optical TTS,” for any given DOI, and
2. the average delay between the annihilation event and the event registration time is a function of the DOI and therefore the DOI uncertainty is folded into the time resolution.

At this point, we would like to highlight that the consequence of an increased optical TTS (1) as well as the above mentioned reduction of the number of detected scintillation photons result in a true loss of information on the γ-interaction time contained in a recorded scintillation pulse [9]. This loss of information and the corresponding increase of the uncertainty in any estimate of the γ-interaction time are irreversible. Conversely, average effects summarized under 2) may in principle be corrected for; either explicitly (for which the DOI needs to be known accurately) or implicitly by clever choice of the crystal readout architecture.

For a given DOI, the average delay between γ-emission and event registration can be separated in two independent components; namely the delay between the emission of an annihilation photon and its interaction within the crystal, and the average delay between the γ-photon absorption and the event registration. The delay between the γ-emission and absorption within the crystal is simply given by the distance between the emission and absorption position multiplied by the velocity of the γ-photon, which for all practical purposes can be assumed to be equal to the speed of light in vacuum.

The second delay component, i.e. the average delay between the γ-interaction and the registration time, is much more difficult to predict. It is important to note that the “event registration time” is defined as the timestamp assigned to the event. This definition explicitly includes contributions that originate from sources that may only be indirectly linked to the photon transport, such as time stamp offsets due to pulse shape variations or amplitude walk. This means that the systematic difference between the average registration times for two different DOIs is not necessarily determined only by the difference in the average optical transit times corresponding to the two DOI positions.

The optical transport related delay component is illustrated in Fig. 7 for the EDSR20 detector (a) and the PDSR20 detector (b). It is clear that the change in the average registration time with the DOI strongly depends on the light transport in the crystal and thus on the surface finish. The comparison of the two graphs depicted in Fig. 7 indicates that the light transport is considerably slower within crystals with predominantly diffuse reflection compared to polished crystals. E.g., in the EDSR20 detector an interaction at a DOI of 0 mm takes ~ 326 ps longer to be registered at the back sensor than an interaction at a DOI of 20 mm, while the same events in the PDSR20 detector are registered on average ~ 150 ps apart.

Similar behavior has been reported by Moses and Derenzo [14] and by Yeom, et al. [11] for detectors with SSR, which they attribute to the random propagation of scintillation photons in crystals with diffusely reflecting surfaces. Moses and Derenzo furthermore suggest that the DOI dependence of the scintillation photon propagation time may to a large degree be responsible for the overall time resolution of the detector [14]. The comparison of the magnitude of the propagation time delay and the time resolution measured with the corresponding detectors with SSR (257 ps FWHM for the ESSR20 detector and 175 ps FWHM for the PSSR20 detector) indeed seems to confirm this hypothesis. However, it should be noted that the dependence in DSR crystals shown in Fig. 7 may be different in crystals with SSR where photons reflected at the front surface of the crystal may contribute to the timestamp generation at the back sensor.

Moreover, it can be seen in the graphs in Fig. 7 that for both photosensors the registration time varies nearly linearly with the DOI over a large range of DOI values, while the sign of the constant of variation is opposite for the two sensors. In consequence, the mean registration time of the two sensors remains nearly constant. This explains why a simple averaging of the two timestamps yields a significant improvement of the time resolution for the etched 20 mm long crystals when switching from SSR to DSR (153 ps FWHM compared to 257 ps FWHM). The relative improvement on the time resolution measured for the polished crystals is much smaller (150 ps FWHM compared to 175 ps FWHM).

Lastly, it is interesting to note the DOI dependencies of the γ-photon flight time within the crystal and the scintillation photon transport delay partially compensate each other in the commonly employed measurement geometry of SSR with the sensor at the backside [14], [29]. For this reason one would expect a reduction of the time spread induced by DOI-dependent delays when a crystal is irradiated head-on, compared to irradiation from the side. In addition, head-on irradiation results in a narrower DOI distribution compared to homogeneous irradiation from the side due to the exponential absorption profile. This further reduces the spread in DOI-dependent delays. In this respect, the ESSR10 and PSSR20 detectors behave as expected.

However, the reversed trend is observed for the ESSR20 detector. We explain this with the fact that under head-on irradiation the largest absorption probability occurs at shallow DOIs, i.e., at positions far away from the sensor. For these interaction positions, however, a significantly reduced number of scintillation photons reach the sensor (see Fig. 2(a) and Section III-A) and the increase of the optical transit time spread can be expected to be larger, both worsening the overall time resolution. It thus appears that these effects negate the reduction of the contribution of DOI-dependent delays.

V. Conclusions

The results presented in this work show that it can be beneficial for the timing performance of long PET crystals to record the scintillation signal at both the front and back surfaces. In particular, it appears that the effects of photon transport can be mitigated by employing double-sided readout. Consequently, the improvement of the CRT is largest for detectors in which the transport of optical photons is least efficient, such as in crystals with diffusely reflecting surfaces. Whereas a large difference is observed between the CRTs for polished and etched surfaces in the case of a 20 mm long scintillator with single-sided readout (184 ± 6 ps FWHM compared to 358 ± 5 ps FWHM, respectively), the same two crystals with SSR perform quite similarly, with measured CRTs of 174 ± 6 ps FWHM and 180 ± 5 ps
FWHM, respectively. In this context, one can expect the relative benefit of double-sided readout to be the larger if the combined reflective properties of the crystal-reflector interface are worse. This is pointed out as the Teflon wrapping of scintillation crystals is commonly seen as a best case scenario that might be difficult to approach using thin reflective foils.

Furthermore, we would like to highlight the fact that the time resolution achieved with DSR appears to be largely independent of the surface finish of the crystals used in this work. This means that the etched crystals can be expected to have superior timing performance in a scanner geometry with front-side irradiation, as their excellent DOI resolution allows to accurately correct for the flight time of the $\gamma$-photon within the crystal. In this respect, it should be kept in mind that exchanging the Teflon wrapping for a commonly used specular reflector may completely remove any DOI capability for polished crystals. As to how far the DOI resolution and possibly the timing performance of rough crystals may be affected, warrants future research.

REFERENCES


