Characterization studies of silicon photomultipliers and crystals matrices for a novel time of flight PET detector

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ABSTRACT: This paper describes the characterization of crystal matrices and silicon photomultiplier arrays for a novel Positron Emission Tomography (PET) detector, namely the external plate of the EndoTOFPET-US system. The EndoTOFPET-US collaboration aims to integrate Time-Of-Flight PET with ultrasound endoscopy in a novel multimodal device, capable to support the development of new biomarkers for prostate and pancreatic tumors. The detector consists in two parts: a PET head mounted on an ultrasound probe and an external PET plate. The challenging goal of 1 mm spatial resolution for the PET image requires a detector with small crystal size, and therefore high channel density: 4096 LYSO crystals individually readout by Silicon Photomultipliers (SiPM) make up the external plate. The quality and properties of these components must be assessed before the assembly. The dark count rate, gain, breakdown voltage and correlated noise of the SiPMs are measured, while the LYSO crystals are evaluated in terms of light yield and energy resolution. In order to effectively reduce the noise in the PET image, high time resolution for the gamma detection is mandatory. The Coincidence Time Resolution (CTR) of all the SiPMs assembled with crystals is measured, and results show a value close to the demanding goal of 200 ps FWHM. The light output is evaluated for every channel for a preliminary detector calibration, showing an average of about 1800 pixels fired on the SiPM for a 511 keV interaction. Finally, the average energy resolution at 511 keV is about 13 %, enough for effective Compton rejection.

KEYWORDS: Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Timing detectors; Multi-modality systems; Intra-operative probes

ArXiv ePrint: 1501.04233

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1 Introduction

Positron Emission Tomography (PET) is a non invasive, diagnostic imaging technique for measuring the metabolic activity of cells in the human body. Nowadays it is widely used for cancer diagnosis [1].

Among the tumors, pancreatic carcinoma is one of the most aggressive and resistant to current therapies [2], and most often is detected only on an advanced state of development. On the other hand, prostate cancer is the most common cancer among males [3].

Both pancreas and prostate are surrounded by organs with high uptake: the liver and the heart are close to the pancreas while the bladder is near the prostate. In these cases the current full-body multimodal PET scanners have strong limitations, due to the noise from the neighboring organs and the lack of specific biomarkers [4, 5]. EndoTOFPET-US [6] aims to overcome these limits, allowing to investigate the performances of newly developed specific biomarkers of tumoral processes for pancreas and prostate. Both organs are usually examined with ultrasound probes through natural cavities, therefore the diagnostic capability can be enhanced by fusing the morphological image from ultrasound with a PET metabolic image. The endoscopic approach and the use of the TOF information with an unprecedented CTR of 200 ps (3 cm along the line of response) allow to define a specific Region Of Interest (ROI) and significantly suppress the background from the neighboring organs.
Figure 1. The EndoTOFPET-US detector with a magnification of the pancreatic endoscope (top circle) and the external plate (bottom circle).

The EndoTOFPET-US detector consists of a PET head extension mounted on a commercial US endoscope placed close to the ROI and an external PET plate facing the patient’s abdomen, in coincidence with the PET head (figure 1).

Compared to standard PET scanners, the unusual detector design requires a tracking system with a precision better than 1 mm. For the prostate case this is achieved with an optical tracking, while an electromagnetic system is currently under test for the pancreatic probe. This novel design required also a custom developed image reconstruction software, based on the maximum-likelihood expectation-maximization (ML-EM) algorithm. The reconstruction accounts for the TOF and tracking information and has to cope with the limited detector rotation around the ROI. The main application of the EndoTOFPET-US will be image-guided surgery, therefore the PET image will be provided in order of minutes thanks to the computation on several Graphical Processing Units (GPUS).

The external plate is a square of 23 x 23 cm², and it is made of 256 detector unit modules. Each module consists in a 4x4 LYSO:Ce crystal matrix glued to a discrete array of 4x4 analog SiPMs from Hamamatsu. LYSO:Ce crystals have high light yield and fast decay time, therefore appropriate for TOF PET. SiPMs are novel photon detectors also suitable for TOF PET applications [7], thanks to their compactness, high gain, insensitivity to magnetic fields, low operating voltage and excellent timing properties.

The following sections describe the experimental setups and the results of the characterization of the SiPMs, crystals and the combined system (SiPM + crystal). All the setups have been designed for a fast and reliable measurement of a large quantity of components, rather than a detailed study of single devices.
2 Photodetector characterization

The SiPMs chosen for the external plate are matrices of 4x4 discrete MPPCs (Multi Pixel Photon Counter) from Hamamatsu photonics (S12643-050CN). Each SiPM in the matrix is a square of 3.0 x 3.0 mm$^2$ with 3464 active pixels (50 x 50 µm$^2$ each). The distance between two adjacent SiPMs in the matrix (center to center) is 3.6 mm. These SiPMs exploit the Through Silicon Via (TSV) technology, leading to less dead space and a reduced connection length as compared to conventional wire-bonded SiPM. The connection through the silicon is placed right in the center of the active area of each SiPM. The following sections describe the experimental setup, the analysis method and the results of the characterization of 256 SiPM matrices.

2.1 Experimental setup

The layout of the experimental laboratory setup is shown in figure 2. In a light tight box, the SiPM matrix is mounted on a motherboard incorporating linear amplifiers (Infineon BGA614) and high voltage filters. The signal for each of the 16 SiPMs of the matrix is obtained using low intensity blue light (Advanced laser diode system, 451 nm). The amplified SiPM output is readout by a VME-based charge-to-digital converter (CAEN QDC965A) with a resolution of 25 fC per QDC bin. The heat generated by the active components on the SiPM motherboard is dissipated by a fan. The temperature is monitored by a sensor (Dallas DS18B20) but not actively controlled.

2.2 Gain and breakdown voltage

The integrated charge spectrum given by the light pulses is shown in figure 3. The number of photons of the illuminating light pulses follows Poisson distribution and the mean is adjusted to be around one, so that it ensures a good visibility to single pixel firing peak. The integration gate in the QDC is synchronized with the laser pulses and it is set to 100 ns, enough to cover the full length of the SiPM signal. The charge spectrum is obtained acquiring 200k event samples. The first peak in the spectrum corresponds to the pedestal (zero pixel fired, only electronic noise) while the following peaks correspond to an increasing number of pixels fired. The period of the peaks, i.e. the gain $G$ of
the SiPM, can be obtained by calculating the autocorrelation of the spectrum. If the spectrum \( H(q) \) is periodic with period \( q = G \), the correlation of \( H(q) \) with \( H(q + m) \) will have maximum at \( m = 0, m = G, m = 2G \), etc. The autocorrelation of the spectrum, defined as \( R(H(q)) \), can be obtained by:

\[
R(H(q)) = \mathcal{F}^{-1}[\mathcal{F}(H(q)) \cdot \mathcal{F}^*(H(q))],
\]

(2.1)

where \( \mathcal{F} \) is the Fast Fourier Transform of the data, \( \mathcal{F}^* \) is the complex conjugate and \( \mathcal{F}^{-1} \) is the inverse Fast Fourier Transform of the data. Therefore the first local maximum where \( q > 0 \) in \( R(H(q)) \) corresponds to the distance between the peaks (i.e the gain \( G \)) in the original charge spectrum. This approach shows results consistent with other methods for gain extraction [8]. This method is preferred because it does not require any guess on the spectrum parameters, and therefore it is convenient for an automated data analysis.

The gain is finally converted from QDC units into number of electrons by multiplying by the QDC resolution (25 fC per QDC bin) and dividing by the amplification factor of the readout board (19 dB, \( \sim 8.9 \)). The error on the gain is about 1\%, obtained as one bin in the Fourier space plus an additional uncertainty of 0.5\%, evaluated by repeating the measurement multiple times under the same conditions.

The charge spectrum of figure 3 is repeated for 30 voltage steps. Figure 4 shows the gain dependence on the voltage bias applied. As expected, the gain is linearly proportional to the bias voltage applied, according to

\[
G = \frac{C_{\text{pixel}} \cdot \Delta U}{e^{-}} = \frac{C_{\text{pixel}}(U_{\text{bias}} - U_{\text{bd}})}{e^{-}},
\]

(2.2)

where \( C_{\text{pixel}} \) is the pixel capacitance, \( e^{-} \) is the electron charge, \( \Delta U \) is the excess bias voltage, \( U_{\text{bias}} \) is the applied bias voltage and \( U_{\text{bd}} \) is the breakdown voltage. Hence \( U_{\text{bd}} \) is obtained by applying a linear fit and extrapolating to zero gain, with an uncertainty of the order of a few tens of mV.

Figure 5 shows the distribution of the gain slope \((G \text{ at } 1 \text{ V excess bias})\) for all the SiPMs. The mean value is \( 0.48 \cdot 10^{6} \text{ V}^{-1} \) with a spread of 3\% among the SiPMs tested.
Entries 4096
Mean 0.4826
RMS 0.01492

Figure 5. Distribution of the gain slope (gain per volt) for all the SiPMs.

Entries 4096
Mean 64.29
RMS 0.4334

Figure 6. Distribution of the extracted breakdown voltage for all the SiPMs.

Entries 256
Mean 0.1401
RMS 0.05765

Figure 7. Distribution of the maximum $\Delta U_{bd}$, i.e. the difference between maximum and minimum $U_{bd}$ in one matrix. The deviation is below the 0.5 V requirement specified to the SiPM producer.

Figure 8. Difference between $U_{op}$ given by the SiPM producer and $U_{op}$ calculated from the measurement.

It is known that the $U_{bd}$ depends on the temperature [9], and some fluctuations have occurred during the whole set of measurements. Moreover, local differences in temperature have been observed within the SiPM matrix, due to the inhomogeneous dissipation of the heat generated by the amplifiers. Therefore an offline temperature correction (see section 2.5) has been applied in order to compare the results. Figure 6 shows the distribution of the breakdown voltages at 25 °C for all the SiPMs.

Although the $U_{bd}$ spread for all the SiPM is about 2 V, this must not exceed 0.5 V in each single SiPM matrix, because this is the maximum voltage bias tuning range of the ASIC developed for the SiPM readout [10, 11]. As shown in figure 7, all the SiPM matrices respect this requirement.

Finally, the results obtained have been compared to the operating voltages ($U_{op}$) provided by the SiPM producer. The $U_{op}$ is defined as: $G(U_{op}) = 1.25 \cdot 10^6$. The differences between the $U_{op}$ calculated using equation (2.2) with data from the measurements and $U_{op}$ provided by Hamamatsu are shown in figure 8. The agreement is good, despite a shift of 6% and a spread of 10%.
2.3 Dark count rate

Even in absence of light, an avalanche breakdown can be triggered by a photoelectron generated from thermal excitation or by tunneling effect. This phenomenon, usually called Dark Count Rate (DCR), is Poisson distributed and it is measured by randomly integrating the charge with a time window $\Delta t$ of 100 ns (same time window as for the gain measurement). A typical noise spectrum is visible in figure 9.

The probability of having two dark events in the time $\Delta t$ is very low, therefore the events corresponding to more than 1 pixel fired are mainly due to correlated noise, which will be described in the next section.

The events in the pedestal peak, i.e. the events with charge less than 0.5 pixel threshold, are not affected by correlated noise, hence they are used to calculate the uncorrelated DCR, defined as $DCR_{0.5\text{pix}}$. In a time range $\Delta t$, the expected number of uncorrelated dark count events $n$ is given by $n = DCR_{0.5\text{pix}} \cdot \Delta t$. The number of events in the pedestal distribution is given by the Poisson probability density function for zero dark count events in the time $\Delta t$:

$$P_0(\Delta t) = e^{-DCR_{0.5\text{pix}} \cdot \Delta t},$$

(2.3)

The $DCR_{0.5\text{pix}}$ is therefore calculated using:

$$DCR_{0.5\text{pix}} = -\frac{\ln(N_0/N_{\text{total}})}{\Delta t},$$

(2.4)

where $N_0$ is the number of events in the pedestal peak and $N_{\text{total}}$ is the total number of events recorded. The error on the calculated value depends on the statistics of the sample and on the quality of the spectrum.

For each SiPM the $DCR_{0.5\text{pix}}$ is evaluated for 30 voltage levels, in a range of 3 V starting about 1 V above the breakdown voltage. 500k event samples are collected for each voltage point.

Also the DCR has a dependence on the temperature, therefore a correction (see section 2.5) has been applied in order to compensate for temperature variations.

The distribution of $DCR_{0.5\text{pix}}$, corrected to 25 $^\circ$C and at 2.5 V excess bias, is shown in figure 10 for all the SiPMs.

The DCR has a negative impact on the time resolution. The best time resolution is achieved when the timing threshold on the readout ASIC is set as low as possible, up to the noise level. Therefore a $DCR_{0.5\text{pix}}$ acceptance limit of 3 MHz for each SiPM has been agreed with the SiPM producer. Almost all the SiPMs are within the limit, however 5 matrices have been sent back to the producer because they included at least one SiPM with excessive $DCR_{0.5\text{pix}}$.

2.4 Correlated noise

Correlated noise includes after-pulse and inter-pixel optical crosstalk [12].

After-pulses are generated if an electron produced during an avalanche is trapped and released at a later time, with a delay ranging from nanoseconds up to several microseconds. Depending on the trapping time constant and the pixel recovery time, trapped electrons can generate an avalanche of equivalent or smaller charge with respect to the primary dark pulses.

Inter-pixel crosstalk is due to optical photons generated during a pixel breakdown. These photons have a certain probability to reach the neighboring pixels, triggering new avalanches.
Figure 9. DCR charge spectrum. The events below the 0.5 pix threshold (pedestal peak) are used to calculate $DCR_{0.5pix}$.

Figure 10. Distribution of the $DCR_{0.5pix}$ at 2.5 V excess bias and at 25 °C for all the SiPMs. The red line indicates the threshold of acceptable DCR. Entries marked in red correspond to the rejected SiPMs.

Figure 11. Correlated noise probability $P_{cn}$ at 2.5 V excess bias.

The precise measurement of each of the two effects is beyond the scope of this study. However, it’s possible to estimate the combined effect of crosstalk and after-pulse with order of nanoseconds with the same set of data used for $DCR_{0.5pix}$ evaluation. We define the correlated noise triggering probability $P_{cn}$ as:

$$P_{cn} = \frac{DCR_{1.5pix}}{DCR_{0.5pix}},$$

where $DCR_{1.5pix}$ is calculated similarly to $DCR_{0.5pix}$, but setting the threshold to 1.5 pixel fired.

Figure 11 shows the correlated noise probability at 2.5 V excess bias for all the SiPMs. The average results obtained, about 30%, is compatible with measurements on similar devices and does not represent an issue for the detector operation.

2.5 Temperature dependence

As mentioned in previous sections, SiPM properties depend on temperature. Therefore, DCR, gain, breakdown voltage and correlated noise have been measured at different temperatures for a single SiPM in an array.
Using a climate chamber (Espec LU-123), several voltage scans have been performed in a temperature range between 6 °C and 30 °C. Figure 12 shows the linear temperature dependence of the breakdown voltage; the uncertainty on the temperature is included but it is smaller than the marker size. The coefficient obtained from the linear fit is 70.1 mV/°C, and is used for the temperature corrections applied in section 2.2 and 4.1.

The dependence of the \( DCR_{0.5\text{pix}} \) as a function of the temperature should scale with the density of the thermal carriers [13] according to equation:

\[
n(T) = C_{\text{pixel}} T^{3/2} e^{-E_a/k_B T},
\]

where \( C_{\text{pixel}} \) is the pixel capacitance, \( T \) is the temperature of the SiPM in Kelvin, \( E_a \) is the activation energy and \( k_B \) is the Boltzmann constant.

Figure 13 shows the \( DCR_{0.5\text{pix}} \) as a function of temperature at 2.5 V excess bias. An activation energy \( E_a=0.6 \text{ eV} \) is obtained by fitting the data with equation (2.6). This value is compatible to previous studies [14], and it has been used for the temperature corrections applied in section 2.3.

The change in the gain is found to be less than 1%/10°C, which is negligible for the temperature variations occurred during the gain characterization of all the SiPMs. Also the correlated noise shows a mild dependence on the temperature, but it is not relevant for the detector performances.

### 3 Crystals characterization

The crystals for the external plate are grouped in 256 matrices of 4x4 LYSO:Ce scintillators, produced by Crystal Photonics Inc. The volume of each crystal is 3.5x3.5x15 mm³ and within the matrix they are separated by a reflector foil (ESR Vikuiti by 3M). The length of the crystals allows the requested detector sensitivity, although shorter crystals give better time resolution.

In order to ensure the system uniformity, measurements of light output and energy resolution have been performed on both faces of each matrix using the MiniACCOS setup [15], which allows a fast, automatic and highly reproducible data acquisition process. In this setup, each matrix is
placed on a custom made teflon plate, for a total of 25 matrices per plate. A PMT is placed on the bottom side of the crystals, with an air gap of 5 mm between the crystal surface and the PMT window. The crystals are excited by a $^{137}$Cs $\gamma$-source placed over the crystals. Both the PMT and the $\gamma$-source are fixed, while the the crystal plate is moved in the x-y plane by a stepping motor for an automated scan.

Systematic measurements were performed to evaluate uncertainties arising from the bench, yielding a total relative error of 4.7% for the light output and 12.8% for the energy resolution.

Figure 14 shows the distribution of light yield obtained with MiniACCOS setup for all the 256 matrices. The distribution spread is 6.4%, which subtracting the uncertainty of the setup gives a 4.3% as light output dispersion. Figure 15 shows the distribution of the energy resolution for all the modules, with a mean value of 13.4%. The spread is comparable to the bench uncertainty, therefore the variations in energy resolution are just due to the setup.

In the final detector configuration, each crystal is optically coupled to the SiPM with glue and the top side is covered by a reflector foil. The reason is the improvement of the time resolution with the light yield, therefore the collection of the scintillation light must be maximized. The scintillator timing model reported in [16] allows to estimate the light yield necessary for a given CTR, depending on the crystal rise time and decay time. Assuming a typical decay time of 40 ns and rise time of about 100 ps for LYSO crystal, about 2000 scintillating photons must be detected for a CTR of 200 ps FWHM. The corresponding crystal light yield is obtained by the following formula:

$$LY = -\ln \left(1 - \frac{N_{\text{det}}}{N_{\text{tot}}} \right) \frac{N_{\text{tot}}}{PDE},$$

(3.1)

which relates the number of detected photon on the SiPM ($N_{\text{det}}$) to the incoming scintillating light from the crystal ($LY$), taking into account the saturation effect of the SiPM. $PDE$ is the SiPM Photon Detection Efficiency and $N_{\text{tot}}$ is the total number of pixels in the SiPM. Therefore, setting $N_{\text{tot}}$ to 3464 and PDE to a typical value of 30%, the minimum crystal light yield necessary to achieve 200 ps FWHM is about 20000-25000 Ph/MeV.

In order to assess the quality of the crystal matrices, the light yield obtained with MiniACCOS setup must be rescaled to the final detector configuration. In order to obtain this, light output for a subset of 13 matrices was measured on a standard XP2020Q PMT, using Rhodosil 47V grease as optical coupling and teflon as back wrapping. The scaling factor between this measurement condition and MiniACCOS was found to be 13.15, with a correlation coefficient of 0.89 between the two data sets, as shown in figure 16.

The average light yield for all the crystal matrices can therefore be derived as $32500 \pm 2700$ Ph/MeV, including in the evaluation of the uncertainty also the systematics arising from the calibration process. Therefore all the the 256 matrices are suitable for the requested detector time resolution.

## 4 Detector module characterization

A dedicated bench has been developed to glue the crystal matrices on the SiPM arrays, allowing to assemble 5 modules per day. Figure 17 shows the setup: the crystal matrices are placed on a movable support and a camera allows the visual alignment with the SiPM matrices located under
Entries 256
Mean 2504
RMS 159.9

Figure 14. Light yield distributions for all the 256 crystal matrices.

Entries 256
Mean 13.44
RMS 1.324

Figure 15. Energy resolution distributions for all the 256 crystal matrices.

Figure 16. Light yield correlation between MiniACCOS setup and the values from the PMT. The red line is the linear fit of the data with its 95% confidence interval band (green).

Every module is then measured regarding light output, energy resolution and CTR, which are described in the next sections.

4.1 Detector light output

The detector light output for the 511 keV photon (defined here as $LO_{511}$) is of primary importance for the detector time resolution. As shown in section 3, the number of detected photoelectrons must be maximized in order to achieve the best time resolution. Moreover, all the channels should have the same response for the 511 keV photon, allowing an easier detector calibration.

A $^{22}$Na source with an activity of about 1 MBq is used as a $\beta^+$ emitter, and it is placed right in front of the crystal modules. The setup is similar to the one described in section 2.1 but the SiPM signal is not amplified and the resolution of the QDC is set to 200 fC. The charge integration gate
Figure 17. The bench for the module assembly. The binocular with the camera is placed over the 5 supports for the crystal matrices, the SiPM matrices (not visible) are located below.

is set to 450 ns and it is triggered by the SiPM signal itself, using a discriminator (CAEN model 96) and a gate generator (LeCroy model 222). A channel switcher (Keithley 7002 switch system) provides automatic scan through the 16 channels in each matrix. The temperature is recorded before each channel measurement. Each SiPM is operated at $U_{op}$ as defined in section 2.2, eventually corrected for temperature variations according to the coefficient of 70.1 mV/°C (see section 2.5).

Figure 18 shows a typical $^{22}$Na spectrum for a single channel. The peak corresponding to the 511 keV photon in the charge spectrum is fitted by a Gaussian function. Hence the light output $LO_{511}$, expressed in number of pixels fired on the SiPM, is obtained by the following relation:

$$LO_{511} = \frac{(Q - P) \cdot r_{qdc}}{G \cdot e^{-}}$$  \hspace{1cm} (4.1)

where $Q$ is the mean value of the Gaussian fit, $r_{qdc}$ is 200 fC per bin, $P$ is the pedestal position, and $G$ is 1.25x10$^6$.

The uncertainty on $LO_{511}$, of the order of about 30 pixels, is given by statistical error and temperature uncertainty of 0.5 °C. According to the results reported in section 2.5, this temperature fluctuation corresponds to a variation of 35 mV in the SiPM excess bias. A scan of $LO_{511}$ versus excess bias has been performed in order to estimate the corresponding uncertainty in pixels fired. No additional error for the $U_{op}$ is available.

The light output distribution for all the channels is shown in figure 19. According to the calculation reported in section 3, the average value of about 1800 pixels should allow to reach the CTR of 200 ps FWHM. Finally, a preliminary detector calibration will be based on these measurements.
4.2 Inter channel cross-talk

The cross-talk between the module channels is measured on a sample module. Similarly to the setup described in section 4.1, the $^{22}$Na source is placed in front of the module and only one channel is chosen as trigger. Any other channel in the module is acquired simultaneously to the trigger, using a common integration gate of 450 ns in the QDC. The channel switcher provides the automatic scan through the 15 channels, each operated at its own $U_{opt}$.

Figure 20 shows the $^{22}$Na spectrum in the trigger channel (black) together with the cross-talk induced in the neighboring channel (red), where the $^{22}$Na spectrum is still recognizable.

In every channel, only the events corresponding to the photopeak in the trigger are selected. Therefore, dividing the mean charge of these events by the photopeak position in the trigger, the cross-talk for the 511 keV photon is obtained for all the remaining 15 channels in the module. The measurement is repeated by selecting different trigger channels in the module. Figure 21 shows the average cross-talk obtained from 4 different measurements: every time one of the central channels in the module is used as a trigger. The cross-talk does not exceed 20%, and can be suppressed by setting a threshold at 100 keV.

4.3 Energy calibration

As already introduced in the previous sections, the SiPM is a non-linear device due to the limited number of pixels, therefore a non-linear correction is necessary in order to estimate the energy resolution for the 511 keV gamma.

Using the setup described in section 4.1, the detector light output is measured for different gamma energies: 356 keV from $^{133}$Ba, 511 and 1277 keV from $^{22}$Na, and 662 keV from $^{137}$Cs.

The measurement is performed on a sample of 4 modules (64 channels): for each sample channel the light output data are fitted with the function describing the SiPM saturation (figure 22):

$$N_{pix} = N_{max} \left( 1 - e^{-\frac{E}{E_{max}}} \right),$$

(4.2)
where \( N_{\text{pix}} \) is the average number of pixels fired on the photodetector, \( \epsilon \) is the number of pixel fired on the SiPM per unit of energy deposited in the crystal and \( E \) is the energy of the detected gamma photon. \( N_{\text{max}} \) is related to the maximum number of pixels in the SiPM. This number is actually higher than the nominal value (3464 pixels) because the pixel recovery time is about 20 ns, which is half of the decay constant of the crystal (40 ns).

However these parameters are not unique for all the channels. It is expected that the parameter \( \epsilon \) varies among the channels according to \( LO_{511} \), which takes into account the variations in the SiPM properties (photo detection efficiency, correlated noise), crystal light yield and the optical coupling.

The dependence of \( N_{\text{max}} \) and \( \epsilon \) to \( LO_{511} \) for the 64 channels is shown in figure 23 and 24 respectively. Although the linear dependence of \( \epsilon \) was expected, also \( N_{\text{max}} \) shows a dependence on \( LO_{511} \), maybe due to variations in the pixel recovery time or crystal decay time. In both cases a linear fit is applied and the relations obtained are used to calculate the specific \( N_{\text{max}} \) and \( \epsilon \) for any other channel depending on the channel \( LO_{511} \).

Figure 25 shows the energy obtained using the inverse of equation (4.2) and setting the specific \( N_{\text{max}}, \epsilon, \) and \( N_{\text{pix}} = LO_{511} \) for every channel. Similarly, the corresponding energy of the 1277 keV peak of the \(^{22}\text{Na} \) spectrum is estimated for every channel (figure 26). In both cases the predicted energy is in good agreement with the measurements, the precision worsens only if the channel \( LO_{511} \) is significantly lower than the average.

Finally, the derivative \( \frac{dN_{\text{pix}}}{dE} \) of equation (4.2) is evaluated at \( E = 511 \) keV for every channel. The energy resolution can then be obtained as:

\[
\frac{\Delta E}{E} = \frac{1}{E} \frac{dE}{dN_{\text{pix}}} \Delta N_{\text{pix}} = \frac{\Delta N_{\text{pix}}}{E} \frac{1}{\frac{dN_{\text{pix}}}{dE}},
\]

where for each channel \( \Delta N_{\text{pix}} \) is obtained from the measured \( N_{\text{pix}} \) distribution in response to 511 keV photons.

Figure 27 shows the energy resolution distribution for all the detector channels. Only one channel is out of the detector requirement: at least 20% is necessary to effectively discriminate the 511 keV gammas from the Compton events.
Figure 22. Single channel light output for different gamma energies, the data are fitted with equation (4.2).

Figure 23. Distribution of the parameter $N_{\text{max}}$ of equation (4.2) depending on $LO_{511}$ for 64 channels. The red line is the linear fit.

Figure 24. Distribution of the parameter $\epsilon$ of equation (4.2) depending on $LO_{511}$ for 64 channels. The red line is the linear fit.

Figure 25. Energy distribution calculated using the inverse of equation (4.2) with the specific $N_{\text{max}}$, $\epsilon$, and $N_{\text{pix}} = LO_{511}$ for every channel. The tail on the right correspond to the channels with very low $LO_{511}$.

Figure 26. Energy distribution calculated using the inverse of equation (4.2) with the specific $N_{\text{max}}$, $\epsilon$, and $N_{\text{pix}} = LO_{1277}$ for every channel. $LO_{1277}$ is obtained from the 1277 keV peak (see figure 18), in the same way as $LO_{511}$.
4.4 Coincidence time resolution

The coincidence time resolution of all the channels is measured using the setup shown in figure 28. The two modules are facing each other at 10 cm distance, while a $^{22}$Na point like source is placed between them on the line connecting the module centers. One module has been selected as the reference for the measurement of the other 255 modules.

The output signal of the SiPM is amplified and discriminated by NINO ASIC [17] and sent to a high precision TDC (HPTDC- 25ps LSB) [18]. NINO uses the Time-over-Threshold (ToT) technique: the input SiPM signal triggers a square pulse whose length is proportional to the input charge. The leading edge of the square pulse gives the time information.

The data analysis is performed with a total number of $4 \times 10^6$ triggers. As shown in figure 29, the ToT spectra are obtained for any two channels in coincidence, then a gaussian fit is applied to the peaks corresponding to the 511 keV gamma events. Hence the time difference for the gamma events of the two channels are histogrammed and shown in figure 30. A Gaussian fit is applied and the FWHM is taken as the CTR of the channel measured ($227.3 \pm 3.2$ ps in this case).

As reported in [19] and [20], the timing performance of the SiPM depends on the PDE and therefore also on the excess bias applied. Figure 31 shows the CTR as a function of bias voltage for two channels in coincidence with the reference module. Due to the increase of the SiPM Photon Detection Efficiency (PDE) with the increase of excess bias, it is expected that also the CTR improves accordingly. However, also the DCR increases with the excess bias, and at a given point it becomes predominant. It is important to notice that the CTR does not vary significantly around the best value for about 1 V. This is important for the detector operation, because small variations in the excess bias of the SiPM do not deteriorate the CTR.

In order to compare the CTR of all the 256 modules, an excess bias of 2.5 V is used for any channel, the temperature is fixed at 19 °C and the NINO ASIC threshold is kept fixed at 55 mV, which is equivalent to the threshold of 0.5 photoelectron. The CTR distribution for all the channels, measured with respect to the reference module, is presented in figure 32 and shows an average of $239 \pm 10$ ps FWHM.
Figure 28. The setup used for the timing measurements. The two detector modules are placed facing each other, 10 cm apart. A $^{22}$Na source is placed between the two modules.

Figure 29. Typical Time over Threshold spectra for two channels in coincidence.

Figure 30. The CTR is the FWHM of a Gaussian fit of the time difference between each channel pair.

Figure 31. CTR as function of bias voltage for one pair of channels with respect to the reference module. Temperature fixed at 19 °C.

Figure 32. The CTR distribution of all channels pairs, at 19 °C and at 2.5 V excess bias.
5 Conclusions

In the frame of the EndoTOFPET-US project, all the detector modules for the external plate have been characterized. The gain, breakdown voltage, DCR and correlated noise have been measured for all the received SiPMs, only 2% of them have been rejected due to excess DCR.

The LYSO:Ce crystal matrices show a very good light yield and a promising average CTR of $239 \pm 10$ ps FWHM has been obtained, which can be further improved in ideal conditions, such as lower temperature or optimal excess bias for each channel. The average energy resolution (at 511 keV) for all the modules is about 13%, and it complies with the minimum requirement of 20%. The light output for every channel is available for a preliminary detector calibration, and an average of about 1800 pixels fired for a 511 keV gamma interaction has been obtained.

The detector modules are now ready for integration with the dedicated ASICs and the final mechanical assembly.

Acknowledgments

The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under Grant Agreement no. 256984, and is supported by a Marie Curie Early Initial Training Network Fellowship of the European Community’s Seventh Framework Programme under contract number (PITN-GA-2011-289355-PicoSEC-MCNet).

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