CONTRIBUTION TO THE WLS STUDIES

FOR THE AXIAL PET

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E.Chesi, A.Rudge, J.Seguinot and P.Weilhammer

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Abstract

Measurements were performed with 2 LYSO bars and 6 WLS strips mounted with the same topological configuration used for the AX-PET demonstrator. The main purposes of the measurements were threefold: (1) to investigate the influence of operational parameters (threshold, gain), (2) to study the effect of the surface property of a screen behind the WLS strips on the photoelectric yield and cluster multiplicity of the WLS strips, and (3) to measure the dependence of the WLS strip response on the gamma energy.
1. The test set-up

The tests were performed with 2 LYSO bars (3x3x100 mm$^3$) and 6 WLS strips (3x.9x40 mm$^3$) mounted with the same topologicical configuration used for the demonstrator.

The hexagonal SMD 3.2 x 1.2 mm$^2$ GAPDs glued to the WLS strips are, in contrast with the modules of the demonstrator, connected to the FE electronic by mean of pogo pins (Intercontinental Devices) with a spring force of about 5 gr.

All the GAPDs have been characterized and their gain measured within ±2%.

The Na$^{22}$ source (480 kBq) of the test set up is positioned at 2 cm of the LYSO bars and collimated by mean of a 3 mm hole diameter in a 8 mm thick lead plate. The beam spot is centered at half the length of the bar.

The detection of the collinear opposite 511 keV gammas is assured by a 12 mm diameter cylindrical LYSO crystal and 18 mm length located at 25 cm from the source on the axis of the set-up. The crystal, wrapped with Teflon, is coupled with optical grease to a PMT Photonis XP3102 operated at 900 V.

The GAPDs which detect gamma interactions in the LYSO bars were operated at a fixed gain of 4.8.10$^5$ while the gain for those coupled to the WLS strips was varied from 6.3 to 10.10$^5$ (setting of the demonstrator) for the tests discussed below.

The trigger logic of the fast NIM electronic is comparable to that used in previous tests or for the demonstrator with a low threshold set at 30 mV and the high level adjusted between 70 and 350 mV as a function of the energy of the gammas selected. With these experimental conditions the coincidence rate was limited to few hertz.

The on-line program was modified (E:C) in order to select events with only one hit LYSO crystal and a cluster of adjacent hit WLS strips unambiguously identified.

The screen installed behind the WLS strips could easily be removed in order to change the properties of its optical surface to be absorptive (photographic black paper), reflective (aluminized Mylar) or diffusive (white paper). Optical screens could also, easily, be inserted between the strips.

The measurements were performed between 25°C and 25.5°C.
As illustration, the fig.1 below shows, after selection, the response of a LYSO indicating that an energy resolution of 10% (FWHM) was obtained.

The fig.2a displays the distributions, for 511 keV gamma interactions, of the total charge detected by the WLS strips, \( \Sigma_{i=1,m} Q_i \), as a function of the cluster multiplicity \( m \) for a GAPD’s gain of 8.5 \( \times \) 10^5 when diffusive optical surfaces are used for the screen underneath the strips and with separators inserted between the strips. An increase of the charge detected with the cluster multiplicity is clearly observable.
In fig 2b, instead, an absorptive surface (photographic black paper) is used without separators, and the gain of the GAPDs set at $6.3 \times 10^5$. The distributions display the same dependence with the cluster multiplicity but with a significant lower mean multiplicity.
2. Choice of the optical surface of the screen

The results discussed in par. 2 to 4 were obtained by selecting only photoelectric interactions of 511 keV gammas (high trigger level = 350 mV) in a single LYSO bar, as previously stated.

The fig. 3 displays the dependence of the mean value of the charge distribution detected \( <Q> = \langle \sum_{i=1}^{m} Q_i \rangle \) by the WLS strips as a function of the cluster multiplicity m, for the different optical surfaces of the screen underneath the strips at a GAPD’s gain of 6.3 \( \times \) 10^5.

![Fig. 3 - Variation of the mean charge detected \( <Q> = \langle \sum_{i=1}^{m} Q_i \rangle \) with the cluster multiplicity for different optical surfaces of the screen underneath the WLS strips](image)

The linearity of the responses confirms preceding observations but, as previously stated, such variation is surprising, especially its importance. A flat response was expected with the cluster multiplicity which, obviously, depends on the depth of the interaction in the crystal bar. It appears that the light intensity transmitted from the lyso to the WLS strips is strongly dependent on the location of the gamma interaction point. An observation which is not reproduced by the simulations (Geant 4 code).
The goal of the tests described below was to obtain more detailed experimental information’s to understand such a response and, possibly, a guide line to optimize the design of the axial PET concept.

The slope $\Delta<Q>/\Delta m$ obtained for a reflective (aluminized mylar) and a diffusive (white paper) optical surfaces of the screen, is $\sim 40.5$ ADC counts (or 19.6 pe’s) but decreases to about 33 ADC count (16 pe’s) for an absorptive surface (black paper) or by using separators between WLS strips additionally with a diffusive screen.

The difference between the mean values $<Q_i>$ measured with an absorptive and a reflective surface proves that a large fraction of the scintillation light escaping the LYSO bar is not absorbed in .9 mm thick WLS strips and is detected after reflection on the aluminum coating increasing significantly the cluster multiplicity (fig.4).

An overall characterization of the results above is obtained by estimating the mean number of detected photoelectrons,

$$<n_{pe}> = \frac{\sum_{i=1,6} n_{pe}(i) \cdot N_i}{\sum_{i=1,6} N_i}$$

where $i$ is the WLS strip address.
The results are summarized in the table below,

<table>
<thead>
<tr>
<th>Screen Optical Surface</th>
<th>(&lt;m&gt;)</th>
<th>(&lt;Q&gt;) (ADC counts)</th>
<th>Pe’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorptive</td>
<td>1.83</td>
<td>71.4</td>
<td>34.6</td>
</tr>
<tr>
<td>reflective</td>
<td>2.51</td>
<td>136</td>
<td>65.8</td>
</tr>
<tr>
<td>diffusive</td>
<td>2.11</td>
<td>110.2</td>
<td>53.2</td>
</tr>
<tr>
<td>diffusive with separators between strips</td>
<td>1.72</td>
<td>94.8</td>
<td>45.8</td>
</tr>
</tbody>
</table>

(Calibration factor of the detection chain (GAPD-FE-VA) : .484 pe /ADC count for G (GAPD)= 6.3 \(10^5\)).

In order to minimize the cluster multiplicity an absorptive optical surface (black paper) should be preferred to a diffusive surface with separators between strips because of the simplicity of the construction, despite the loss of detected photoelectrons. However, these results show that a gain of 6.3 \(10^5\) is acceptable for 511 keV gammas but is too small for an efficient detection of low gamma energies from Compton interactions (\(E \geq 50\) keV) when the detection threshold is adjusted to about 5 pe’s (see discussion next paragraph) to reject the dark noise. In that respect, in order to increase the sensitivity, the WLS strips should be thicker or (and) a reflective coating used.

The fig.5 shows the influence of the separators on the profile image of the hit WLS strips. One can observe a slight shift between the barycentre of the distributions indicating a small asymmetry of the light detected without separators.
3. Choice of the gain of the GAPDs

The tests discussed in par. 3 and 4 were essentially obtained with diffusive optical surfaces and separators between WLS strips.

As previously shown a linear response of the mean charge detected $<Q>$ for $1 \leq m \leq 4$ is still measured independently of the gain of the GAPDs (Fig. 6).
Fig. 6 - Mean charge detected ($<Q> = \sum_{i=1}^{m} Q_i$) as a function of the cluster multiplicity for $G = 6.3, 7.4, 8.5$ and $10.10^5$ and $U_{th}(VA) = 30 \text{ mV}$

In Fig. 7, the variation of the mean number of detected photoelectrons with the gain of the GAPDs is in good agreement with the known dependence of the photoelectron detection efficiency (PDE) (see the characterization of the MPPCs discussed in a preceding PET meeting – 10/29/2008) and normalization to the result obtained at $G = 10^5$. 

Calibration of the detection chain (GAPD-FE electronic-VATA):

- $G(\text{APD}) = 6.3 \times 10^5$: $s = .484 \text{ pe/ADC count}$
- $G(\text{APD}) = 7.4 \times 10^5$: $s = .412 \text{ pe/ADC count}$
- $G(\text{APD}) = 8.5 \times 10^5$: $s = .359 \text{ pe/ADC count}$
- $G(\text{APD}) = 1.10^6$: $s = .304 \text{ pe/ADC count}$
This result shows that a gain of $10^6$ is needed to detect gamma energies down to 50 keV when the threshold of the VATA-GP5 readout chip is set to about 5 pe’s, despite the large increase of the cluster multiplicity for 511 keV gammas (Fig. 8).
As a consequence of the results above it results that $<n_{pe}>$ is strongly correlated with the cluster multiplicity (Fig. 9).
Fig.9 - Variation of the mean number of detected photoelectrons $\langle n_{pe} \rangle = \Sigma_{i=1,6} \langle n_{pe}(i) \rangle .N_i / \Sigma N_i$ vs the cluster multiplicity $m$ for $G(GAPD) = 6.3, 7.4, 8.5, 9.25, 10.10^5$.

It is interesting to notice that the number of detected photoelectrons for $m = 1$ and the slope $\Delta n_{pe} / \Delta m$ reach a plateau for a gain higher than $8.5.10^5$ (Fig. 10) for 511 keV gammas.
Fig. 10 - Variation with $G$ (GAPD) of $\Delta n_{pe}/\Delta m$ and $n_{pe}(m=1)$

$m$ being the cluster multiplicity

Diffusive optical surfaces with separators between strips
4. Incidence of the threshold of the VATA-GP5 readout chip:

The mean charge detected for different detection threshold of the VATA at fixed gain ($7.4 \times 10^5$), hence at constant PDE, still exhibits a linear dependence with the cluster multiplicity (fig.11).

**Fig. 11** Mean charge detected ($\langle Q \rangle = \langle \sum_{i=1}^{m} Q_i \rangle$) as a function of the cluster multiplicity $m$ for $U_{th}(V_A) = 20, 30, 40$ mV and $G(GAPD) = 7.4 \times 10^5$

Calibration detection chain : $0.412$ pe / ADC count
However, the mean number of detected photoelectrons is less dependent with the threshold as shown fig. 12 indicating that the detection efficiency is not significantly affected, at least for 511 keV gammas.

\[
\langle n_{pe} \rangle = \frac{\sum_{i=1,5} n_i N_i}{\sum_{i=1,5} N_i}
\]

5. Response of the WLS strip array with the gamma energy
A strict linear dependence of the mean charge detected with the cluster multiplicity \( m \) is obtained in Fig.13 for different gamma energies and a GAPD’s gain of \( 1 \times 10^6 \). Gammas of 330, 234 and 121 keV mean energy were selected from Compton interactions by decreasing the high level of the trigger logic down to 70 mV.

Fig.13 - Variation of the mean charge detected \( \langle Q \rangle = \Sigma_{i=1}^{m} Q_i \) with the cluster multiplicity \( m \) at 511, 330 and 234 keV for \( G = 10 \times 10^5 \) and \( U_{th}(VA) = 30 \) mV.

As expected, the slope \( \Delta n_{pe} / \Delta m \) and \( n_{pe}(m=1) \) are proportional to the gamma energy (Fig.14) and not significantly dependent on the gain (Fig. 15) above \( 8 \times 10^5 \).
Fig. 14 - Variations of the slope \( \frac{\Delta n_{pe}}{\Delta m} \) and \( n_{pe} \) (m=1) with the gamma energy for \( G(\text{GAPD}) = 10.10^5 \) and \( U_m = 30 \text{ mV} \)
However, the mean number of detected photoelectrons,

$$<n_{pe}> = \sum_{i=1,6} <n_i> \cdot N_i / \sum_{i=1,6} N_i,$$

exhibits (fig. 16) a deficit at decreasing energies with respect to a proportional variation, and by assuming full detection efficiency at 511 keV.
The variation of $<n_{\text{pe}}>$ is again clearly correlated with the cluster multiplicity (fig.17).
Fig. 17 Variation of the mean number of detected photoelectrons

\[ \langle n_{\text{pe}} \rangle = \frac{\sum_{i=1}^{6} n(i) \cdot N(i)}{\sum_{i=1}^{6} N(i)} \]

with the mean cluster multiplicity for \( G(\text{GAPD}) = 8.5 \) and \( 10.10^5 \)

However, the measurement of the detection inefficiency with energy at \( G=8.5 \cdot 10^5 \) and \( 10^6 \) in Fig. 18 is far to be satisfactory and suggest a lower limit of about 100 keV for the detection of Compton interactions. These results which are obtained at half the length of the LYSO bars clearly suggest improving the light intensity and its collection efficiency in the WLS strips by increasing their thickness and by using a reflective screen.
The limitation in energy is also still illustrated in Fig. 19 which shows the variation of the cluster multiplicity with the gamma energy.
Fig. 19  Variation of the mean cluster multiplicity \( \langle m \rangle = \frac{\sum_{i=1}^{6} m_i N_i}{\sum_{i=1}^{6} N_i} \)
with the gamma energy for \( G(\text{GAPD}) = 8.5 \text{ and } 10.10^5 \).
6. Photoelectrons yield dispersion

The Fig.20 shows a summary of the performances obtained with diffusive optical surfaces (white paper) for the screen and the separators between strips as a function of the cluster multiplicity. In Fig.20a the r.m.s value of the distributions is compared with the statistical fluctuation expected from the mean number of detected photoelectrons. The comparison clearly proves that the resolution is dominated by the light dispersion on the light transmitted to the WLS strips and not by the statistic. This observation is well illustrated in Fig.20b which shows that the dispersion is almost independent of the photoelectron statistic.
The same observation in Fig.21 is valid for an absorptive optical surface of the screen but without separators for a GAPD’s gain of $6.3 \times 10^5$ instead of $1.10^6$ above. The dispersion, however, is as expected from the results discussed in par. 2 and 3, a factor about 2 lower.

The Fig.22 displays the response as a function of the gamma energies at the maximum gain of $1.10^6$ for diffusive optical surfaces.
The variation of the resolution $D_{npe}/n_{pe}$ justify the detection inefficiency discussed in the preceding paragraph.

7. Some observations about the tests performed in June 2009 with the module of 2 layers of 8 lyso crystals and 26 WLS strips per layer,

The tests were performed in the same experimental conditions than those discussed above. Their interest in this report is to allow the observation of the background detected by the WLS strips beside the beam profile. The counting rate of the module during these tests was 18 kHz, of which 4 kHz for the intrinsic radioactivity, and the DAQ rate defined by the geometry limited to 3.7 Hz.
What is remarkable to observe is that the mean value of the charge distribution of each of the strips is compatible with the values discussed in the preceding paragraphs independently of their address in the layers. This is illustrated in the Fig.23 below.

The probability to detect a charge on a WLS strip is displayed in Fig.24 which shows the beam profile with a logarithmic scale in order to see the background distributions. The tails of the profiles are flat and range between 0.7 to 0.9% according to the layer.

The corresponding charge distribution of the profile in layer #1 (mean charge detected of Fig.23 weighted by its detection probability of Fig.24) is shown in Fig.25 below. The mean cluster multiplicity in the profile is 2.6.

The detection probability of the tails cannot be interpreted as accidentals because of the low counting rate of the module with a Data Lock (DL) width of 60 ns. Moreover the distributions of the charges detected are incompatible with the detection of accidentals. It appears that the background is due to the light escaping from the lyso bars by diffusion at the multiple bounces during its propagation along the crystal contributing to the light absorption length.
Module 2 x 8 lyso crystals – run 2009/06/26 at 27 deg. cent.

$Q(i, j) \quad i = 1, 26 \quad j = 1, 2$
Fig. 20  Variation of the mean number of detected photoelectrons with the cluster multiplicity for 511 keV gammas with G(GAPD) = 6.3, 7.4, 8.5, 9.25 and 10.10\(^5\) and for gammas of 121, 234, 331, 511 keV when G(GAPD) = 8.5 and 10.10\(^5\)
6. Summary and comments

- The linear variation of the total detected charge $Q$ by the WLS strips with the multiplicity $m$ is a true physical response.

- This observation is not only surprising but also not reproduced by M.C simulations (Geant 4). There is presently no coherent description of the experimental observations.

- The slope $\Delta Q/\Delta m$ depend on the properties of the optical surface of the screen underneath the WLS strips and of the gain of the GAPDs, the last because of the variation of the Photon Detection Efficiency (PDE). The sensitivity to the threshold of the VATA readout chip is, as expected, much less significant.

- The mean value of the total number of detected photoelectrons varies with the GAPD’s gain in good agreement with the dependence of the PDE.

- One observes a deficit of the mean number of detected photoelectrons at decreasing energies with respect to the expected value due to a loss of detection efficiency. This limits to about 100 keV the threshold for Compton reconstruction. Nevertheless, because of the large dispersion on the light collection in the WLS strips a small fraction of 50 keV events can be detected.

- It is interesting to notice that there is a strong correlation between the number of detected photoelectrons and the cluster multiplicity independently of the gain; the gamma energy and the threshold of the GP5 readout chip (see Fig. 26).

- The tests suggest increasing the thickness of the strips and to use a reflective coating for the screen between the layers in order to improve the detection efficiency at low gamma energies but for the detection of the photo peak of 511 keV gammas an absorptive surface should be preferred.

- The axial reconstruction error is not affected by the response of the WLS strips array because of the symmetry of the hit WLS strips distribution.