Blue Enhanced Large Area Avalanche Photodiodes in Scintillation Detection with LSO, YAP and LuAP Crystals

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Abstract

Scintillation detectors consisting of LSO, LuAP and YAP crystals fitted to bevelled-edge large area avalanche photodiodes of 10 mm in diameter characterised by a high quantum efficiency up to 68% at 350 nm wavelength were studied. Among the properties measured were the number of electron-hole pairs, energy resolution and noise contribution of the LAAPDs at shaping time constants down to 20 ns at different gains. A high electron-hole pair numbers of 11000±550 e-h/MeV and 19500±980 e-h/MeV for the YAP and LSO crystals were measured, respectively. The energy resolution for ^{137}Cs γ-rays of 5.9% in FWHM for the YAP crystal, much better than that of 9.9% for the LSO crystal were measured at 0.5 μs shaping time constant and the APD gain of 40. The same study done with a fast shaping of 20 ns and the APD gain of 160 showed the energy resolution of 6.7%.

I. INTRODUCTION

Further study into the properties of avalanche photodiodes (APD) is driven by a growing interest in the application of APDs in a positron emission tomography (PET) [1] and in future experiments at LHC in CERN [2]. In the previous work [3] we have studied the ultimate time resolution obtainable with an LSO crystal fitted to the bevelled-edge large area APDs. The performances was excellent reflected in a high number of electron-hole pairs namely 19600±900 e-h/MeV, a good energy resolution for 662 keV γ-peak from a ^{137}Cs source of 11% and an excellent time resolution of 570 ps for ^{60}Co γ-rays and the energy threshold set at 1 MeV.

Recently developed by Advanced Photonix, Inc. blue enhanced LAAPDs with quantum efficiency up to 68% at 350 nm suggest to test them with YAP [4] and LuAP [5,6] crystals. Although LuAP is still in the early phase of its development [5,6], both these scintillators with peak emission at 365 nm are important for future applications in PET, both human and animal.

The aim of this work was to study the properties of the scintillation detectors consisting of YAP, LSO and LuAP crystals fitted to the new large area avalanche photodiodes. In the first part of the study a number of electron-hole pairs produced by the tested scintillators coupled to several LAAPDs was measured. The known light output of the crystals [7] allows for the estimate of effective quantum efficiency of the APDs at about 365 nm (YAP and LuAP) and 420 nm (LSO) wavelengths.

In the second part of the work the energy resolution study was carried out versus gain of APD and a shaping time constant in the amplifier down to 20 ns. Measurements of the noise level in the APD system and the number of electron-hole pairs allow to discuss various contributions to the observed energy resolution.

II. EXPERIMENTAL DETAILS

All tests were carried out on three bevelled-edge large area APDs 10 mm in diameter produced by Advanced Photonix, Inc. [9]. The main characteristics of the diodes under tests are listed in Table 1. Note the high gain of 150 and the low dark current below 200 nA with the bias voltage of 2400 V. The rise time of the diodes measured for the step function of about 8 ns is quoted by the manufacturer. The quantum efficiency characteristics of the LAAPDs are presented in Fig. 1. Note that the UV enhanced LAAPD has the quantum efficiency of 68% at 350 nm wavelength.

Table 1
The main parameters of the tested APDs

Model	394-70-73-500		
Serial No.	TOX2-1-10	92-10-1	92-10-2
Diameter	10 mm		
Window	none		
Q.E. at 350 nm	59 %	68%	
Gain at 2400 V	150	120	120
Dark current	185 nA	123 nA	120 nA
Capacitance	50 pF		
Rise time	12.4 ns	7.8 ns	8.5 ns

All the LAAPD studies were carried out with the 4x4.5x14.5 mm^3 LSO crystal, see refs [3,10], the 5x5x5 mm^3 YAP crystal, see ref. [8] and 5x6x1 mm^3 LuAP crystal. Crystals coated with Teflon tape were used in the measurements. The LSO crystal was fitted with its 4x4.5 mm^2 face to the LAAPD. A large degradation of the light output in this case is expected. The main characteristics of the studied crystals are collected in Table 2, together with their performances, as measured with an XP2020Q photomultiplier. Note that the LuAP crystal is still in an early phase of development [5,6].

Table 2
The main properties of LSO, YAP and LuAP crystals

Parameters	LSO:Ce	YAP:Ce	LuAP:Ce
Ce content	0.22%	0.56 mol%	0.11 mol%
Light output[a] [ph/MeV]	27300 ±1400	18000 ±900	11300 ±450
τ [ns]	47.2	25	16
ρ [g/cm^3]	7.4	5.37	8.4
λ_p [nm]	420	365	365
Refractive index	1.82	1.95	1.97
Energy res. for ^{137}Cs[b]	10%	5.7%	9.3%
Time res. for ^{60}Co[c]	160 ps	158 ps	160 ps
Background	^{176}Lu	none	^{176}Lu

[a] the absolute light output, see Ref. [7], [b] measured with an XP2020Q photomultiplier, [c] measured with an XP2020Q photomultiplier, E≥1MeV.

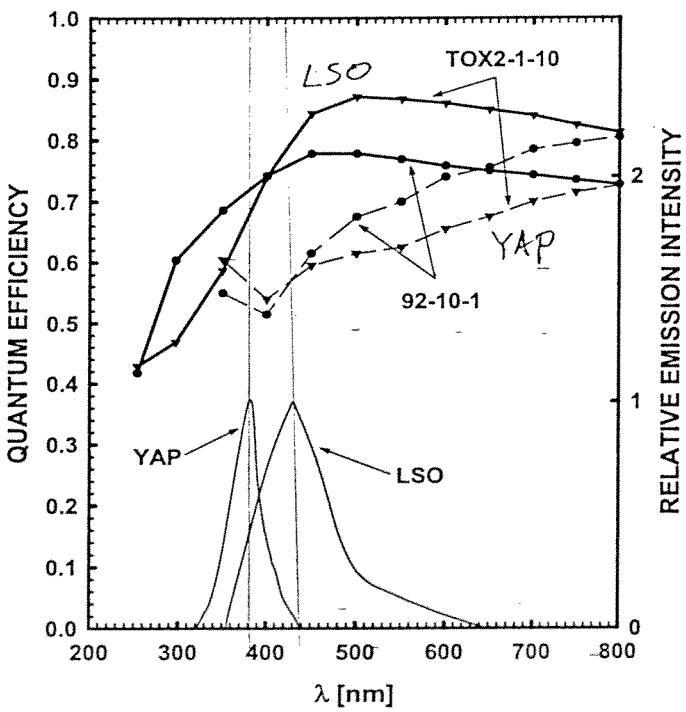

Figure 1: Quantum efficiency characteristics of LAAPDs together with the emission spectra of LSO and YAP crystals. The dashed lines present the calculated characteristics for the interface of YAP crystal with the LAAPDs.

In the measurements, the LAAPD signal was sent to an ORTEC 142AH preamplifier and then to a TC244 spectroscopy amplifier. It allowed for the measurements of energy spectra with a shaping time constant down to 0.25 μs. The measurements with a shaping time constant below 100 ns were carried out with an ORTEC 579 timing filter amplifier. Its output signal was sent to a fast integrating stretcher working as a gated integrator.

III. RESULTS

A. Number of Electron-Hole Pairs

The number of electron-hole pairs was measured by comparing the 662 keV full energy peak position from a ^{137}Cs source detected in the scintillators, with that of 16.6 keV X-rays from a ^{93}Mo source detected directly by the LAAPD. Since the energy required to produce e-h pair in silicon is 3.6 keV, the number of e-h pairs can be determined, see [3,7]. Table 3 summarizes the results of the measurements with different LAAPDs. Note a high number of e-h pairs for the LSO and YAP crystals confirming the high quantum efficiency of LAAPDs in the blue part of the spectral response, see fig. 1.

In the second row of Table 3 the light outputs of the tested crystals, as measured with the calibrated XP2020Q photomultiplier, following ref. [7], are given. Note that the number of photons from the LSO crystal fitted perpendicularly (by 4x4.5 mm^2 face) is 27% lower than that quoted in the Table 1, measured for the same sample in the horizontal position. Note also the lower light output of the YAP crystal tested in this work then that given in Table 1, see also Ref. [8]. The best sample of YAP was to large to work with the 10 mm diameter APD. In contrast, the light output of the LuAP sample used in the present experiments was by 15% larger than the sample studied in refs [6] and [7].

Table 3
Number of e-h pairs [e-h/MeV] measured for the LSO, YAP and LuAP scintillators and estimated quantum efficiency of LAAPDs

Crystal	LSO	YAP	LuAP
Light output [ph/MeV][a]	20000±1000	13500±700	12900±650
TOX2-1-10	19500±980	10700±550	7000±500
Q.E. [%]	97.5	79.3	54.3
92-10-1	19300±960	11200±560	7200±600
92-10-2	18600±930	10800±550	7100±500
Q.E. [%]	95±7	81.5±6	55.4±5
Corr. Q.E. [%][b]	71±7	59±6	

[a] number of photons collected by the XP2020Q photomultiplier from the tested samples, measured following ref. [7], [b] Mean Q. E. corrected for the reflectivity of silicon.

The known light output of the crystals allows to estimate an integral quantum efficiency for tested LAAPDs, see Table 3. It is interesting to note the same measured integral QE's for both types of LAAPDs, in spite of the fact, that the quantum efficiency of the TOX2-1-10 LAAPD is significantly lower, as measured by the manufacturer. To understand the problem the

quantum efficiency of both types of LAAPD was calculated assuming an interface of YAP crystal with the LAAPDs. The curves presented in fig. 1 show comparable quantum efficiency for both types of LAAPDs, lower than measured in air and much lower than those estimated experimentally for the scintillation light. The high quantum efficiencies of 95±7% for the LSO crystal and 80±6% for the YAP are, in fact, enhanced by the collection of reflected light from the LAAPD due to a Teflon reflector at the crystals. The quantum efficiency corrected for the reflectivity of silicon corresponding to the peak emission of the LSO and YAP crystals are given in the last row of Table 3. The reflectivity of 1.35 and 1.37 accounted for the LSO and YAP, respectively, follow those measured by Holl et al [11] for the Hamamatsu photodiodes. These quantities, however, may indicate only the effect. In fact we do not know precise values of the LAAPD reflectivity in these conditions.

The reason for the low number of electron-hole pairs measured for the LuAP crystal, as compared to the YAP, is not clear. The emission spectra and refractive indexes of both the crystals are the same [5]. Thus, we should expect the same quantum efficiency, which is not confirmed in Table 3. Perhaps, this effect can be accounted for a large parasitic absorption of the light observed for samples of even 1 mm thickness [12]. Thus, we can expect that reflected light from the LAAPD is absorbed in the LuAP and, in fact, we are observing only primary light from the crystal. This conclusion seems to be supported by the comparable quantum efficiency found for the LuAP to that estimated for the YAP after correction for the reflectivity of silicon. It confirms that LuAP development is still in early phase.

It is worthy to add that the same crystals tested with Hamamatsu photodiodes showed inferior performance. For the LSO crystal fitted horizontally to the S2744-03 photodiode the 18300±360 e-h/MeV was measured [7,10] corresponding to the quantum efficiency of about 53%, less by 25% than that observed with the Advanced Photonix LAAPD, see Table 3. Tests of YAP and LuAP crystals with Hamamatsu photodiodes were unsatisfactory. Because of low quantum efficiency it was not possible even to distinguish full energy peaks from the Compton spectra and a measurement of electron-hole pair number was not possible [7].

B. Energy Resolution Study

The energy resolution study of the tested scintillation detectors was carried out in two regions of shaping time constants. In the microsecond range down to 0.25 μs the TC244 spectroscopy amplifier was used. In the range below 100 ns the Ortec 579 timing filter amplifier with a single RC differentiation and integration was applied. Then the output pulse was sent to a fast integrating stretcher working with the gate of 300 ns width.

Figs. 2 and 3 present the energy spectra of γ-rays from ^{137}Cs, ^{22}Na and ^{57}Co sources measured with YAP and LSO crystals fitted to the TOX2-1-10 LAAPD, respectively. The spectra were

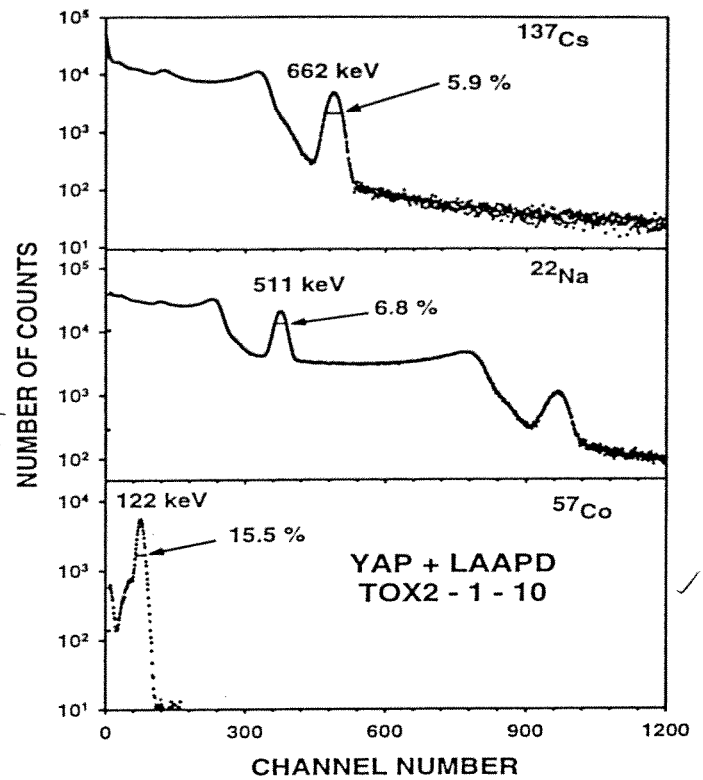

Figure 2: Energy spectra of γ-rays from ^{137}Cs, ^{22}Na and ^{57}Co sources measured with the YAP crystal at 0.5 μs shaping and APD gain of 40.

measured with a 0.5 μs shaping time constant and LAAPD gain of 40. Note the high energy resolution of 5.9% measured with the YAP crystal for 662 keV γ-rays from a ^{137}Cs source. It is the best one measured with the avalanche photodiodes and better than that observed with the XP2020Q photomultiplier (7.5%). It confirms a very good properties of the LAAPD and a low intrinsic energy resolution of the YAP crystal [8]. An energy resolution of the 122 keV peak from a ^{57}Co source equal to 15.5% corresponds to the FWHM=730 eV in the Si units or 86 rms electrons. No doubt this reflects also a low noise contribution of the APD and preamplifier.

Similar spectra measured with the LSO crystal, see Fig. 3, show much inferior energy resolution. For the 662 keV γ-rays from a ^{137}Cs source it is equal to 9.9%, in spite of the fact, that it was measured for the signal created by almost a factor two larger number of electron-hole pairs than that of the YAP, see Table 3. The energy resolution of 122 keV peak is equal to 20.2%, much larger than that measured with the YAP crystal. Thus, the energy resolution measured with the LSO crystal coupled to the APD is limited by the intrinsic energy resolution of LSO.

The energy resolution of 14.5% measured for the 662 keV peak from a ^{137}Cs source with the LuAP crystal shows its poor properties reflected also above in a low number of e-h pairs, see Table 3. No doubt, however, that LuAP crystals of better quality will work excellently with APD in the near future.

Fig. 4 shows the results of the energy resolution study with fast shaping. The energy spectra of γ-rays from ^{137}Cs and ^{57}Co sources were measured by the YAP and LSO crystals with 20 ns

shaping in the timing filter amplifier and integration by the fast integrating stretcher. The bias voltage corresponding to the gain of 160 was applied to the TOX2-1-10 LAAPD.

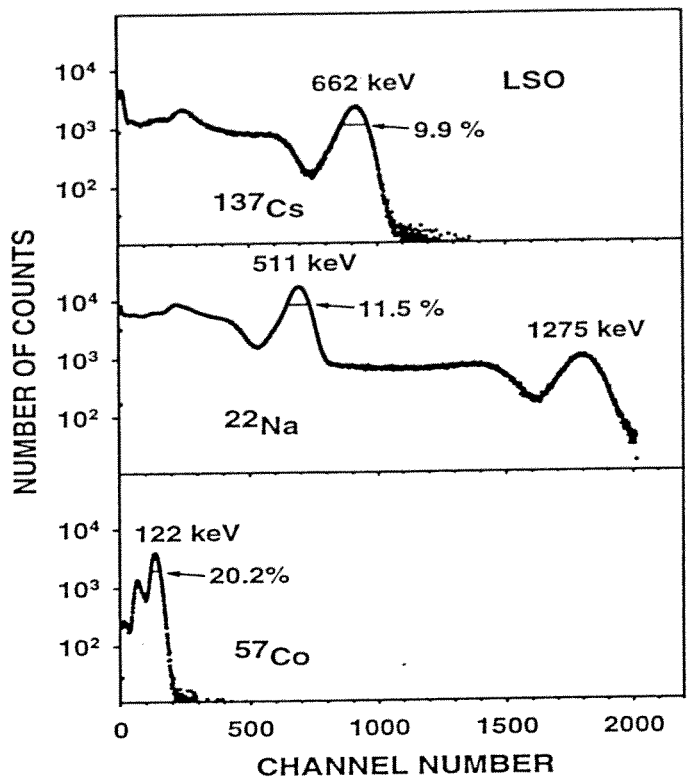

Figure 3: Energy spectra of γ-rays from ^{137}Cs, ^{22}Na and ^{57}Co sources measured with the LSO crystal at 0.5 μs shaping and APD gain of 40.

Note a very good energy resolution of 6.4% for 662 keV γ-peak from a ^{137}Cs source measured with the YAP crystal. It is worse only by 10%, as compared to that measured with the spectroscopy amplifier, while the timing filter amplifier is not predicted to be used in a precision spectrometry. In the low energy part of spectrum the 122 keV peak from a ^{57}Co is seen. Its energy resolution of 15.2% is comparable to that presented in fig. 2. It reflects that under these conditions (a high gain of APD and a short shaping time constant), the noise contribution is the same. Note a small pedestal in the spectrum inserted by the charge integrating stretcher.

The same spectrum measured with the LSO crystal shows energy resolution fully comparable to that measured with the spectroscopy amplifier. No doubt that the combination of a fast shaping amplifier working with a time constant of 20 ns and charge integrating stretcher presents the best arrangement for high count rate measurements in APD scintillation detection. Moreover, it shows also that YAP and LSO crystals coupled to the APD represent the best detectors for recording energy spectra at high count rates.

C. Noise Contribution and Energy Resolution in the LAAPD Scintillation Detection

The impressive energy resolution obtained for the YAP crystal fitted to the LAAPD allows for an evaluation of noise contribution in the APD-scintillator configuration and other factors determining energy resolution in the LAAPD spectrometry system.

The noise contribution of APD-charge sensitive preamplifier system was measured by the standard method used in the semiconductor detector spectroscopy. Noise performance is specified as the spread of the energy line generated in the pulse height spectrum by a test pulser injecting charge into the preamplifier. The charge of the test pulse was calibrated in relation to the number of electron-hole pairs produces in the LAAPD by the scintillation light. In all the measurements the pulse from the generator was calibrated against the 122 keV peak from ^{57}Co detected in the YAP crystal corresponding to the 1340 e-h pairs. To increase the accuracy all the measurements were carried out at least three times and a mean values are plotted in figs 5 and 6.

Fig. 5 presents the dependency of the noise in the LAAPD system, expressed in rms electrons, on the shaping time constants plotted for the different gains of LAAPD between 10 and 160. In the microsecond range (0.25 - 2.0 μs) the experimental points correspond to that measured with the spectroscopy amplifier. In the nanosecond range (20 - 100 ns) the measurements were taken using the timing filter amplifier and integrating stretcher. Since in the timing filter amplifier a single RC-CR shaping was used, its noise contribution is somewhat larger (by a factor of 1.16) than that of a gaussian shaping in the spectroscopy amplifier.

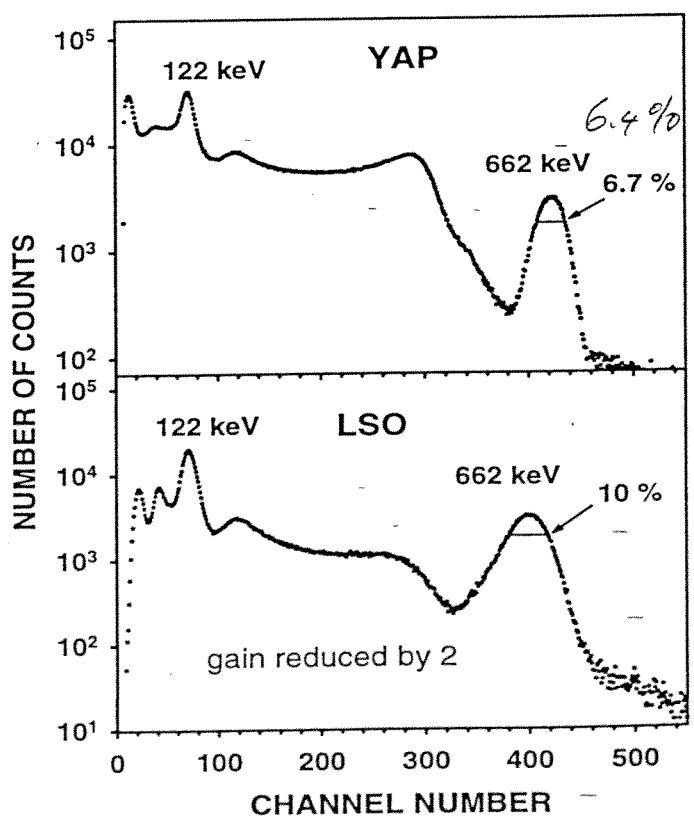

Figure 4: Energy spectra of γ-rays from ^{137}Cs and ^{57}Co sources measured with YAP and LSO crystals at 20 ns shaping and 160 gain of LAAPD.

The data shown in Fig. 5 indicates that in the measurements with the spectroscopy amplifier (microsecond shaping) an APD gain about 50 is sufficient to reach the optimal noise contribution. For the fast shaping, below 100 ns, a higher gain of about 150 is required.

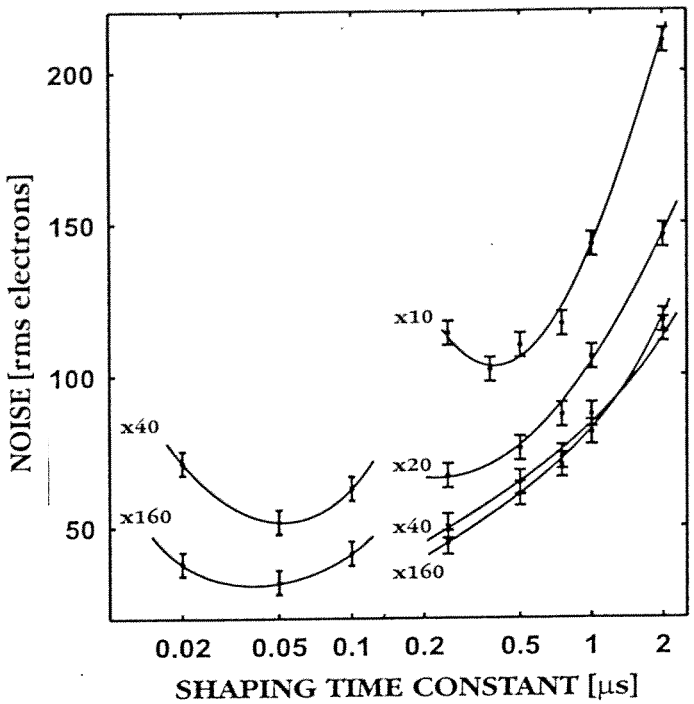

Figure 5: The noise of the LAAPD system versus shaping time constant. In the microsecond range the TC244 spectroscopy amplifier was used. In the nanosecond range the Ortec 579 timing filter amplifier and integrating stretcher were applied.

This effect is better presented in Fig. 6 showing the noise contribution of the APD versus its gain. No doubt that for a fast shaping of 50 ns a high gain of 160 is of importance. The character of the curves is understandable considering the APD work. As the gain increases, the resolution improves at first because of the attenuation of the effect of a preamplifier noise and unamplified APD noise component. At high gain the curves have a tendency to turn up, because of dark excess noise and fluctuations in avalanche gain both of which increase with the excess noise factor, F, at high gains. It is worthy to add that this character of the curves presented in fig. 6 is predicted in Ref. [13], calculated based on the McIntyre model of APD gain and noise [14,15].

The relative variance in the pulse height distribution, ΔE^2, of the full energy peak measured with the scintillator coupled to the APD can be express as:

$$\Delta E^2 = \Delta_{noise}^2 + \Delta N^2 + \Delta_{sc}^2 \qquad (1)$$

where: Δ_{noise}^2 - variance in the noise,
ΔN^2 - statistical variance in the signal,
Δ_{sc}^2 - variance in the intrinsic resolution of the crystal.

The statistical accuracy of the signal in the APD is affected by the excess noise factor, F, reflecting the statistical fluctuation of the APD gain. The relative variance is given by:

$$\Delta N^2 = F/N \qquad (2)$$

where: N - number of primary electron- hole pairs

In good bevelled-edge APDs an excess noise factor of 2 to 2.5 is observed [13] depending on the APD gain, as follows:

$$F = k_{eff}M + (2 - 1/M)(1 - k_{eff}) \qquad (3)$$

where: k_{eff} - a weighted average ratio of the electron and hole ionisation rates (about 0.002 [13]),
M - the APD gain.

Fig. 7 presents the dependency of the energy resolution measured with the YAP and LSO crystals on the γ-rays energy. In the double logarithmic plot the straight lines for both the crystals are observed with a slope of about 0.5. For the YAP crystal the contribution of the statistical accuracy and the noise were calculated and plotted in fig. 7. It allows for the estimation of the intrinsic energy resolution of the YAP. The obtained intrinsic energy resolution shown in Fig. 7 is close to that measured with an XP2020Q photomultiplier for the YAP crystal [8].

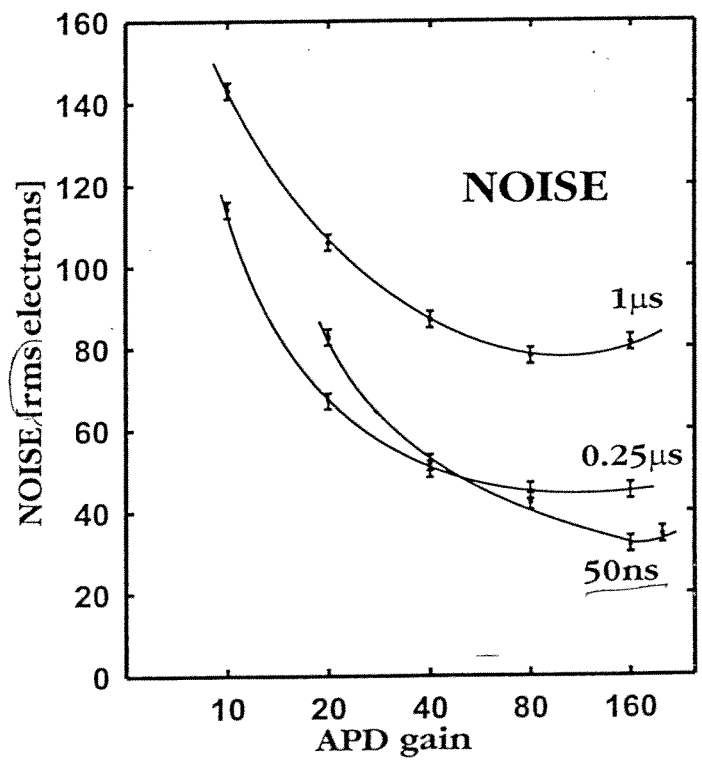

Figure 6: The noise of the LAAPD versus its gain measured for the different shaping time constants.

It is important to note that for the energies below 100 keV the energy resolution is controlled by the noise of APD-preamplifier system. For higher energies the energy resolution is dominated by statistical fluctuation in the number of primary e-h pairs and APD gain (excess noise), and the intrinsic resolution of the crystal. In this respect APDs with its roughly three times higher quantum efficiency when compared to photomultipliers allow for a better statistical accuracy.

In the case of the LSO crystal the energy resolution seems to be described mainly by the intrinsic energy resolution of the crystal and is weakly affected by the APD. The measured energy resolution is much worse, while the number of e-h pairs is almost a factor 2 larger than that of YAP, see Table 3.

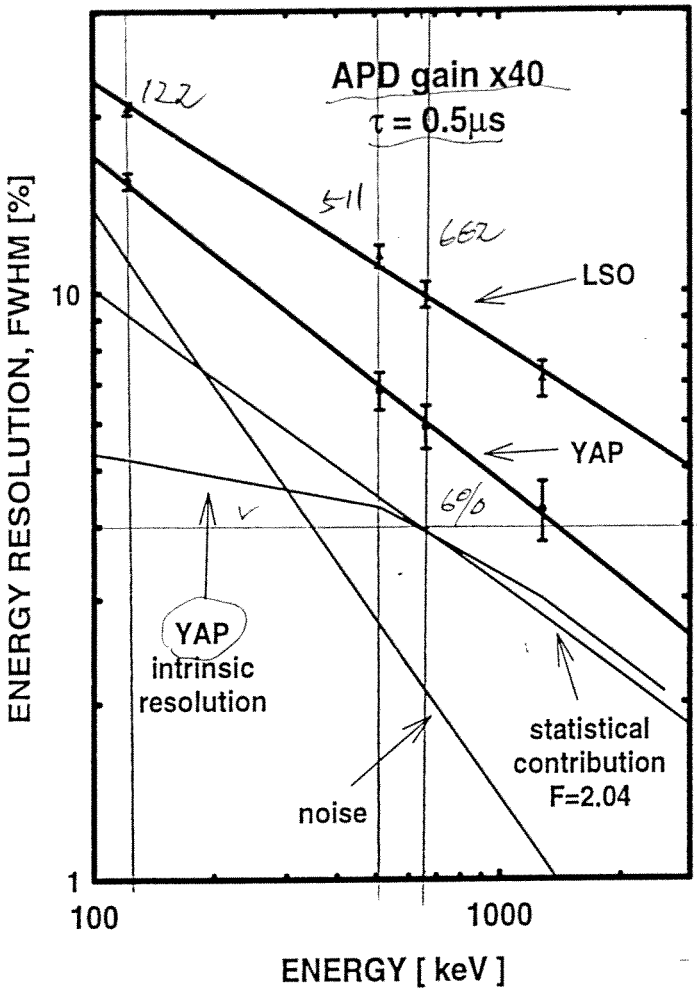

Figure 7: Energy resolution versus γ-rays energy measured with the YAP and LSO crystals. The thin continuous lines reflect a noise contribution, a statistical spread of the signal and a contribution of the intrinsic resolution of the YAP crystal.

Although the presented data on the energy resolution and the noise contribution of the APD were based on the measurements carried out mainly with the LAAPD ser. no. TOX2-1-10, similar results were obtained for the remaining LAAPDs studied in the course of this work.

IV. Conclusions

The presented study has confirmed the high quantum efficiency of the new large area avalanche photodiodes developed recently by Advanced Photonix, Inc.. It is reflected in a high number of electron-hole pairs measured for the LSO and YAP crystals, with the peak emission at 420 nm and 365 nm, respectively. The experimentally estimated quantum efficiency seems to justify that quoted by the manufacturer in this range of wavelengths.

The energy resolution study done for the YAP, LSO and LuAP crystals showed excellent performances of YAP crystal working with large area APDs. The energy resolution of 5.9% was measured for the 662 keV γ-rays from a ^{137}Cs source at 0.5 μs shaping time constant, better than that measured with the tested YAP crystal coupled to the XP2020Q photomultiplier. A high energy resolution of 6.7% was observed also with 20 ns shaping in the timing filter amplifier working at the output with a charge integrating stretcher. A similar study done with LSO and LuAP crystals showed a comparable energy resolution measured with the APD to that observed with photomultipliers.

The study of the noise contribution of the APD system confirmed that for microsecond shaping times an APD gain below 50 is sufficient, while for a fast shaping in the nanosecond range a gain above 100 is required.

The proposed arrangement consisting of a fast shaping amplifier and a gated integrating stretcher seems to be best for high counting rate studies with the APD. In this respect the studied YAP, LSO and LuAP crystals coupled to the LAAPD are particularly recommended. By extension, these γ-ray detection methods are very promising for use in Positron Emission Tomography.

V. Acknowledgements

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VI. References

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Cs I $N_{ph} = 60.000$ ph/MeV.
$\tau = 600 - 800$ ns
$\lambda = 640$ nm

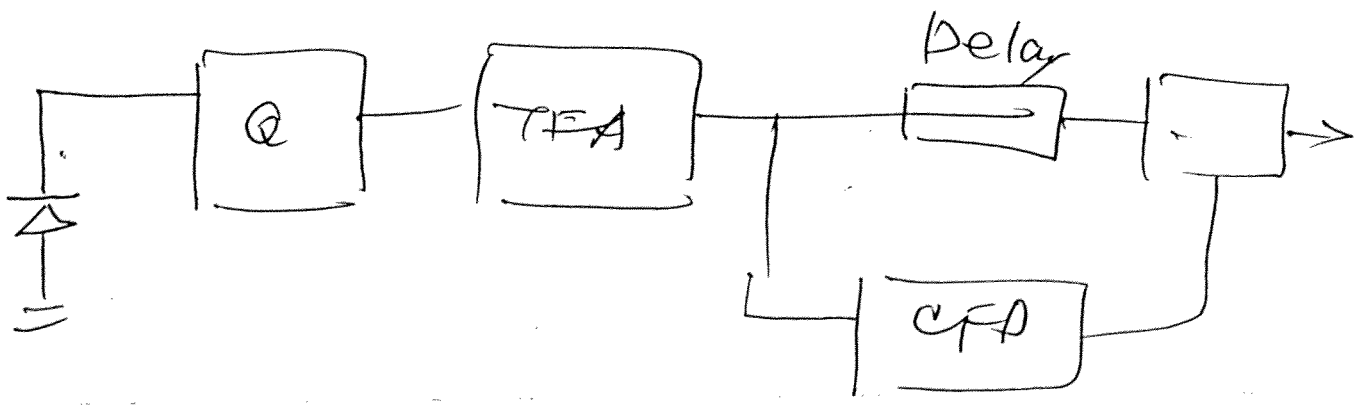
NaI(Tl) $N_{ph} = 40.000$
$\tau = 230$ ns
$\lambda = 420$ nm

BGO: $N_{ph} = 8500$ ph/MeV
$\tau = 300$ ns
$\lambda = 480$ nm

LSO: Ce $N_{ph} = 26000$
$\tau = 46$ ns
$\lambda = 420$ nm

YAP: Ce $N_{ph} = 18.000$
$\tau = 30$ ns
$\lambda = 365$ nm

LuAP: Ce $N_{ph} = 11.000$ ph/MeV
$\tau = 17$ ns
$\lambda = 365$ nm



- CMS experiment at CERN
  ~30 mln US$ for APDs.

Nuclear Medicine:

- PET (human)
  APD + LSO (LuAp)
  Dynamic Studies
  Animal PET:
  APD + YAP (LSO, LuAp)

- Gamma Camera
- mammography
- Microprobes for detection of residual radioactivity.