Mixed Analog-Digital Processing for Energy, Time and Pulse Shape Analysis with CLYC Scintillator Signals

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Outline

• Analog vs digital processing with CLYC scintillators
• The new CLYC Multi-Band Shaper (MBS)
• Energy, time and PSD with CLYC digitized waveforms
• Conclusions
Signal processing with analog electronics

Hamamatsu R6233-100 PMT → Mesytec MPR-1 Preamplifier → Shaping Amplifier → MCA → Energy 4.8% FWHM @662 keV

→ CFD → TDC → Time < 2ns FWHM @1.3 MeV

→ *LaBrPro → PSD γ/n

1” x 1” CLYC-6 (by R.M.D.)

With separate processing chains, intrinsic detector performance can be easily reached (but it’s complicated and preamplifiers don’t like to share the input signal)

*IEEE NSS C.R. [10.1109/NSSMIC.2010.5873761](https://doi.org/10.1109/NSSMIC.2010.5873761) or N2AP-43, A 16 Channels NIM Module for Pure LaBr₃ and LaBr₃-Nal Phoswich Detectors
Digital processing: CLYC

Intrinsic detector performance can be easily reached for time and PSD, but not for energy.
Analog vs. digital energy estimation

- **Hamamatsu R6233-100 PMT**
- **Mesytec MPR-1 Preamplifier**
- **Shaping Amplifier**
- **MCA**
  - ≈ 4.8% FWHM @ 662 keV

- **500 MHz 12/14 bit FADC**
- **Energy filter**
  - > 5.2% FWHM @ 662 keV

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The equivalent analog filter

Shaping time: 3 µs

8 µs

Energy resolution % (FWHM @ 662 KeV) as a function of the integration time

2 MeV energy range

10% worse than expected

The digital filter, even better for photon counting, so why worse energy resolution?
Analog vs digital energy estimation

Hamamatsu R6233-100 PMT

Mesytec MPR-1 Preamplifier

Shaping Amplifier

MCA

≈ 4.8% FWHM @ 662 keV

Energy filter

> 5.2% FWHM @ 662 keV

Front-end & ADC quantization noise

500 MHz 12/14 bit FADC

8 µs

2 MeV energy range

10% worse than expected

Integration Time [us]

Energy Resolution FWHM @662 keV [%]

10% worse than expected

Even better for photon counting, so why?
ADCs used in the tests

**Lecroy HRO66Zi**
(12 bit, 600 MHz BW, 2 GS/s)
Variable front-end dynamic range from 16 mV to 8 V
Ethernet connection to PC

**CAEN V1730**
(16 channels, 14 bit, 500MS/s)
Two choices of front-end dynamic range: 0.5 V or 2 V
Optical fiber connection to PC
FPGA available on board for on-line waveform processing (not used)

Electronic noise spectral density is complex (but reproducible)
CLYC properties

- Light yield: 20k ph. / MeV -> energy resolution = 4.7% @ 662 keV -> good energy resolution
- Decay time: 1000 ns -> 20k ph./1000 ns = 20 ph./ns -> no deterministic pulses as with LaBr₃
- Energy must be estimated with long filters but S/N ratio of tails is poor... (where to stop?)
- Optimal filter for photon counting is not optimal for electronic noise reduction
- DPLMS* (digital penalized least mean squares method) algorithm can calculate optimal filters also for scintillators

*10.1109/NSSMIC.2007.4436375

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CLYC Multi-Band Shaper (M.B.S.)

- Linear amplifier
- Low noise (≈ 1.5 nV/√Hz)
- 80 MHz bandwidth
- Bipolar input / output (± 3V output range)
- OUT1(s)/IN(s) = 6
- OUT2(s)/IN(s) = g0(1+s\tau_1)/(1+s\tau_2)
- Low Freq. gain > High Freq. gain

“Fast signal” front is preserved

“Slow signal” is integrated (e.g. 1 µs decay time)
Multi-Band Shaper IN/OUT

Hamamatsu R6233-100 PMT → CLYC MBS → 500 MHz 12/14 bit FADC → Digital algorithms → Energy Time PSD

Peak to area ratio is reduced by a factor of 6 because tails are integrated

Signal front is preserved: timing and pulse shape discrimination are guaranteed

20 ns (10%-90%) (PMT response)

20 ns (10%-50%) (PMT response)
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Digital Filters for Energy Estimation

Valuable characteristics:

- **Photo-electron counting** ("signal integration", ideally neglecting "after pulse" contributions)
- **Pulse pile-up minimization**, when the product of rate \( R \ [s^{-1}] \) and pulse width \( T \ [s] \) is \( \gg 0.1 \)
  in case of \( \text{LaBr}_3 \) this means \( R > 0.1/100 \text{ ns} \approx 1 \text{ MHz} \), but in case of CLYC \( R > 0.1/3\mu\text{s} \approx 30 \text{ kHz} \)
- **Analog signal offset removal** (zero-area filters)
- "**Low cost hardware**" implementation
  can be: off-line CPU time, FPGA occupation and power consumption, re-configurability, ...
- **Electronic noise minimization**
  usually it not required with fast/high resolution scintillators (e.g. \( \text{LaBr}_3 \))
  or slow/low resolution scintillators (e.g. BGO)

It is important for CLYC, in case **low energy** pulses are measured with
a **high dynamic range** (DR) set-up

\[- \Delta E_{id} \propto \sqrt{E} \] (ideal value)

- Equivalent Noise Charge (ENC) \( \propto \text{DR} \)

\[- \Delta E = \sqrt{(\Delta E_{id}^2 + \text{ENC}^2)} \] (realistic value)
Digital Filters for Energy Estimation

BLUE: zero area “rectangular” filter
RED: zero area “optimized” filter

Example: 1”x1” CLYC-6 waveforms (8 µs long) acquired by CAEN V1730 (500 MHz, 14 bits) of $^{137}$Cs, $^{60}$Co and Am-Be at 5 kHz rate 4 MeV FADC range with the M.S.B. front-end electronics

Is it worth using “optimized” (e.g. by DPLMS) vs “standard” filters for energy reconstruction?

For $E=662$ keV, $\Delta E_{id} = 31$ KeV FWHM (4.7 %)
$\Delta E = \sqrt{(31^2 + 2^2)} = 31.06 \text{ vs } \sqrt{(31^2 + 4^2)} = 31.25$
Negligible improvement with optimized filters, but more complicated implementation

However, at $20$ MeV FADC range and ENC 5x higher
$\Delta E = \sqrt{(31^2 + 10^2)} = 32.5$ KeV FWHM (4.9 %) vs.
$\Delta E = \sqrt{(31^2 + 20^2)} = 37$ KeV FWHM (5.5 %)
Using “standard” zero area “rectangular” filter

31 KeV - 4.7% FWHM

662 KeV

thermal neutrons (≈3 MeV)

4 MeV energy range
Digital Filters for Time Estimation

- **Hamamatsu R6233-100 PMT**
- **1”x 1” CLYC-6**
- **Coincident events from $^{60}$Co source**
- **2.5”x 3” BaF$_2$**
- **Hamamatsu R6231-100 mod PMT**
- **CLYC MSB Out 2**
- **500 MHz 12 bit FADC**
- **Digital CFD**
  - $T_{CLYC}$
  - $T = T_{CLYC} - T_{BAF}$
  - $T_{BAF}$

“Standard” digital set-up for coincidence time measurement
1”x 1” CLYC-6 Time Resolution

\[ \Delta T = T_{\text{CLYC}} - T_{\text{BAF}} - T_{\text{OFFSET}} \]

\[ \text{Var}(\Delta T) = \text{Var}(T_{\text{CLYC}}) + \text{Var}(T_{\text{BAF}}) \]

\[ \sqrt{\text{Var}(T_{\text{BAF}})} \approx 0.8 \text{ ns FWHM (constant)} \]

\[ \sqrt{\text{Var}(T_{\text{CLYC}})} = \sqrt{\text{Var}(\Delta T)} - \text{Var}(T_{\text{BAF}}) \]
As in the case of energy estimation, the improvement obtainable using customized filters as opposed to the standard ones (thus related to the algorithms only) is not worth the additional effort required, unless in case of high input dynamic range (> 5 MeV).

With standard filtering (integration):

\[ Q_{\text{long}} = \text{sum(signal)} \]
\[ Q_{\text{short}} = \text{sum(signal)} \]

\[ \text{PSD} = \frac{Q_{\text{short}}}{Q_{\text{long}}} \]
n-\(\gamma\) P.S.D. (2’’ x 2’’ CLYC-7)

\[
\text{PSD} = \frac{Q_{\text{short}}}{Q_{\text{long}}}
\]

ENERGY

0 4.4 [MeV]

PSD

0 100

0 100 150 200 250 300

10 20 30 40 50 60 70 80 90 100

50 100 150 200 250 300
n-γ P.S.D. (2”x 2” CLYC-7)
n-\(\gamma\) P.S.D. (2”x 2” CLYC-7)

Figure Of Merit = \(\frac{\text{DISTANCE}}{\text{FWHM #1} + \text{FWHM #2}}\)  
(as a function of Energy)
n-\(\gamma\) P.S.D. (2"x 2" CLYC-7)

- **511 keV**
- **1.4 MeV**
- **4.4 MeV**

- Gammas (red)
- Neutrons (light blue)
- Gammas and Neutrons (blue)

- S.E.P.
- F.E.P.
Conclusions

• The difference between analog and digital processing with CLYC signals was reviewed
• The new CLYC Multi-Band Shaper (MBS) was introduced
• The results of digital filters for energy, time and PSD with CLYC signals + Multi-Band Shaper were illustrated
• With the MBS F.E. electronics it is possible to preserve the intrinsic CLYC performances in terms of energy, time and PSD by applying proper digital filters to a single digitized waveform (500 MHz, 14 bits) up to 20 MeV input dynamic range.

THANK YOU FOR YOUR ATTENTION