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Introduction

In recent years CAEN has developed a complete family of digitizers that consists of several models differing in sampling frequency, resolution, form factor and other features. Besides the use of the digitizers as waveform recorders (oscilloscope mode), CAEN offers the possibility to upload special versions of the FPGA firmware that implement algorithms for the Digital Pulse Processing (DPP); when the digitizer runs in DPP mode, it becomes a new instrument that represents a complete digital replacement of most traditional modules such as Multi Channel Analyzers, QDCs, TDCs, Discriminators and many others.

In this application note, we describe the capability of the series x724 (14 bit, 100MSps) to perform Pulse Height Analysis in Radiation Spectroscopy. The development of this FPGA firmware was based upon digital trapezoidal filters applied to the digitized signals output by a Charge Sensitive Preamplifier.

Traditional Analog Approach

The traditional electronics for Radiation Spectroscopy rely upon three fundamental devices: the Charge Sensitive Preamplifier, the Shaping Amplifier and the Peak Sensing ADC.

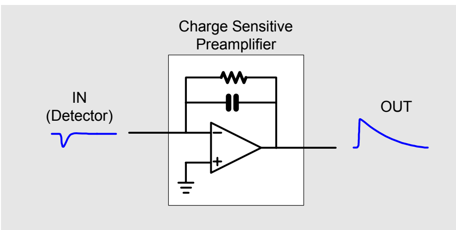

Fig. 1: Charge Sensitive Preamplifier converts the area of the input pulse (charge) to the amplitude of the output.

Usually [1] [2], the result of a particle interaction within the detector's sensitive volume is the excitation of the absorber medium, e.g. scintillators, or the release of an observable burst of charge proportional to the energy lost by the particle in the interaction, e.g. semiconductors. In some cases, the value of this charge is sufficient to be managed by the front end electronics, but in many applications, typically where a semiconductor detector is required, a preamplification stage is mandatory. In order to minimize the noise, it is wise to amplify the signal as closest to the detector as possible, and sometimes to insert the very first stage of the preamplifier in the detector's architecture, as happens in HPGe detectors.

The Charge Sensitive Preamplifier (Fig. 1) integrates the signal coming from the detector, thus converting the collected charge into a voltage step. Ideally, it is just a simple capacitor; however, in order to avoid saturation, the integrating capacitor is put in parallel with a discharging resistor, so that the preamplifier output will have pulses with a fast rise time and a long exponential tail with decay time τ. The charge information (proportional to the energy released by the particle in the detector) is here represented by the pulse height.

The charge – amplitude proportionality is set by the capacitor value $V_{out} = \frac{Q}{C}$ and the decay time of the output signal is $\tau = RC$.

In order to have a good charge-amplitude conversion and to minimize the noise, the decay time τ is much larger than the width of the detector signal, typically 50-100 µs, and for this reason pile-up of different particle detections can arise (see Fig. 2).

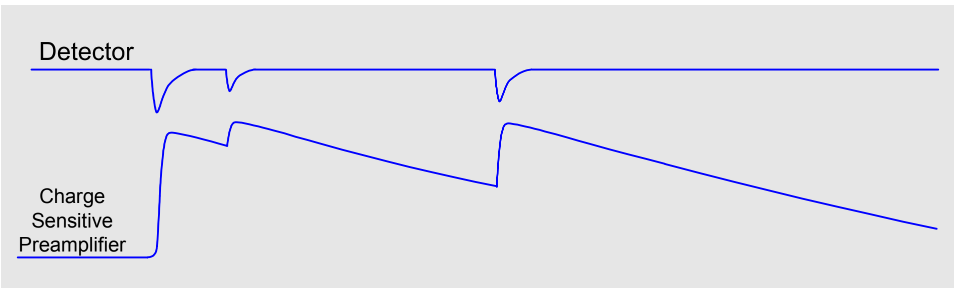

Fig. 2: Pile-up of detector signals due to the large decay time of the Preamplifier output.

Another issue with the output signal of the Charge Sensitive Preamplifier is that the peak is too sharp for the Peak Sensing ADC to be detected with the required precision.

In order to avoid these problems in a traditional analog acquisition chain a Shaping Amplifier is requested. This amplifier (see Fig. 3) receives the signal from the Preamplifier output and provides a quasi-Gaussian output whose width can be changed selecting different shaping time. The height is still proportional to the energy released by the detected particle.

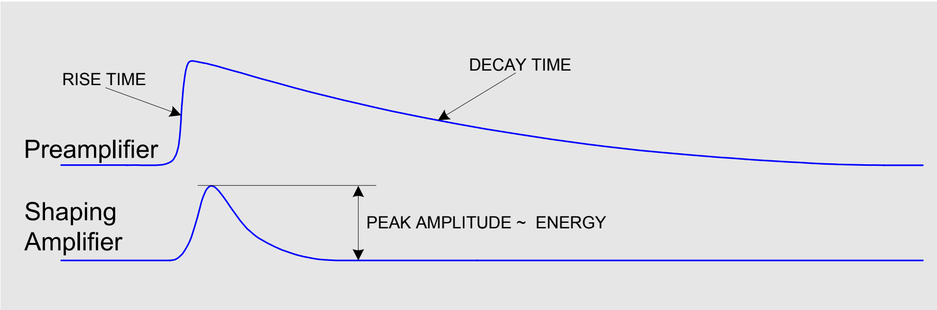

Fig. 3: Shaping Amplifier converts the long - tailed Preamplifier output in a quasi Gaussian signal preserving the proportionality between energy and peak amplitude.

In this way it's possible to reduce the pile-up and feed the Peak Sensing ADC with a smooth signal.

Finally, the Peak Sensing ADC is capable to evaluate and digitize the height of the pulses output by the Shaping Amplifier, filling a histogram with these values, i.e. an energy spectrum.

CAEN Digital Approach

CAEN Digital Pulse Height Analyzer is a self-consistent system composed by a digitizer (also know as Flash ADC) of the **724** series (**100 MS/s, 14 bit**) loaded with DPP-PHA firmware and managed by the DPP-PHA Control Software.

In this system the digitizer replaces both the Shaping Amplifier and the Peak Sensing ADC; in fact, the digitizer samples the pulses output by the Charge Sensitive Preamplifier and converts them into a continuous data stream. The pulse shaping is done in digital by means of a trapezoidal filter running online on the digitizer FPGA.

The trapezoidal filter [3], also known as moving window deconvolution, can be shortly described as a filter able to transform the typical long-tailed exponential signal generated by a Charge Sensitive Preamplifier into a trapezoid whose height is proportional to the amplitude of the input pulse that is to the energy released by the particle in the detector (Fig. 4). It is important to highlight that this trapezoid filter plays more or less the same role of the Shaping Amplifier in a traditional analog acquisition system; for instance, both have a "shaping time" constant: setting the parameters of the trapezoidal filter is like operating on the potentiometers of the Shaping Amplifier.

The control of the Analyzer is managed by DPP-PHA Control Software, that allows the user to set the parameters for the acquisition, configure the hardware and perform the data readout, the histogram collection and the spectrum or waveform plotting and saving. The histograms saved in the output files can be easily managed by third part software tools for spectroscopy analysis.

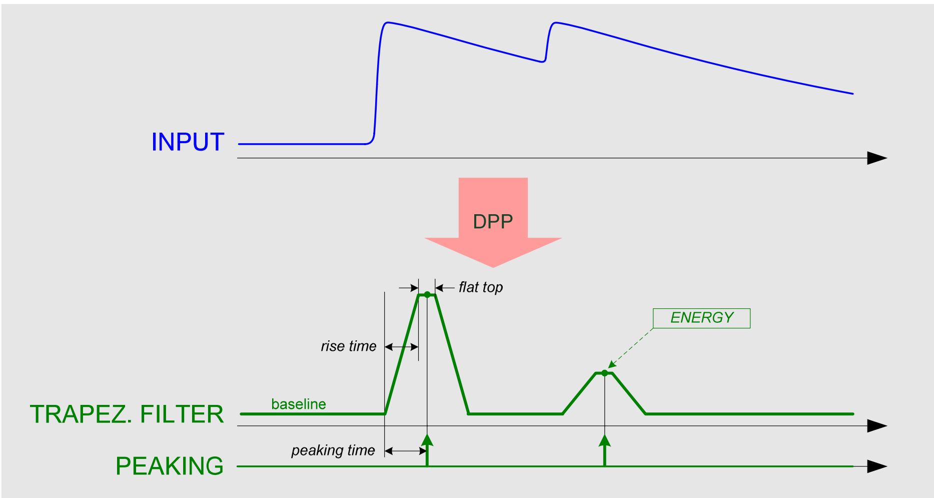

Fig. 4: Trapezoidal filter with the relevant parameters.

Once the DPP-PHA has performed the trapezoidal filtering, the energy of the detected particle can be calculated as the height of the trapezoid in respect to its baseline; this value can be finally saved to the digitizer memory. The original raw data coming from the ADC, i.e. the samples, can be discarded in order to minimize the data throughput from the board to the computer, even though it might be useful, in some cases, to save also a piece of the waveform for further analysis or for monitoring the signals. It is worth noticing that the DPP-PHA firmware is also able to calculate and save the time stamp of the input pulses.

Measurements

All detector and gamma source based tests were performed at the Institute for Nuclear Science and Technology (CEA, Saclay) in collaboration with Mr. Georges Meyer and Mr. Bernard Rousse. The data analysis was performed using ROOT and Visu Gamma®.

Set-up description

The measurements shown in this Application Note were performed using an HPGe detector, mod. Ortec GEM-10175P, whose preamplified output fed a CAEN DT5724 with DPP-PHA firmware. This board is the 4 channel, Desktop version of 724 digitizer series; a dynamic range of 500 mVpp was used.

^{137}Cs and ^{60}Co sources were placed close to the detector according to the different measures; different counting rates were reached modifying the distance between source and detector.

Trapezoid Rise Time & Input Counting Rate

The first set of measures was performed in order to test the system capabilities, mainly Energy Resolution and Peak Shift, as a function of the Input Counting Rate and Trapezoid Rise Time. This parameter is the time needed by the trapezoid to reach its maximum, i.e. flat top, from the baseline. It plays the same role as the shaping time of a analog Shaping Amplifier: for a quick comparison, a value of Trapezoid Rise Time of 1 µs is equivalent in performances to 0.45 µs of analog Shaping Time.

As in the analog case, this value should be greater that the collection time of the detector, but it can be increased without rising the parallel noise being the result of a digital computation; in HPGe detectors the value of this parameter is usually in the range of 1- 20 µs.

In order to analyze how the system's performances change as a function of Input Counting Rate and Trapezoid Rise Time, the ^{137}Cs energy spectrum was acquired setting the Rise Time to 1 µs, 5 µs and 9 µs for each rate value. The rate was raised up to 100 kcps.

In Fig. 5 the energy spectrum collected with Rise Time = 9 µs and ICR = 1.1 kcps is shown; a resolution of 1.60 keV was obtained for the 661.7 keV photopeak.

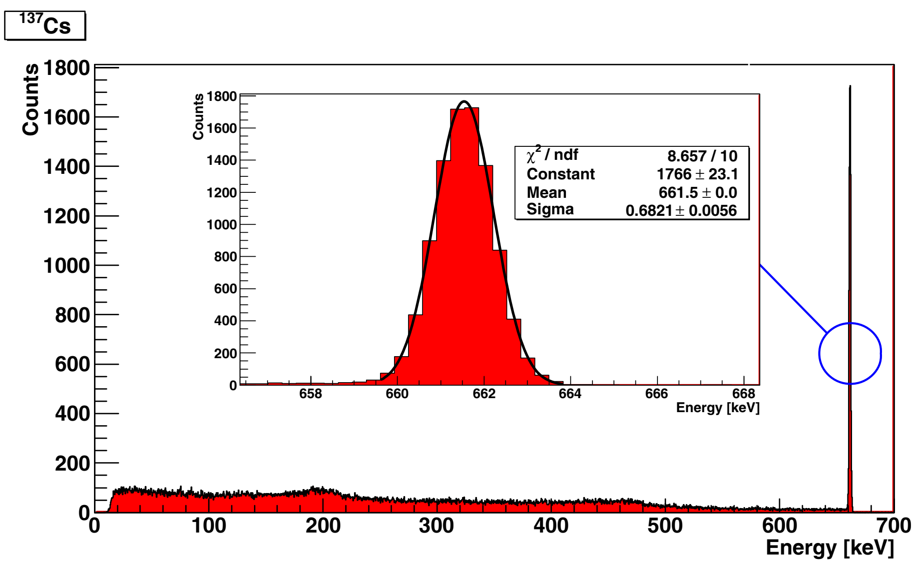

Fig. 5: ^{137}Cs spectrum obtained with Trapezoid Rise Time = 9 µs, ICR 1.1 kcps and Zoom of the 661.7 keV photopeak.

In Fig. 6 the energy resolution of the 661.7 keV photopeak as a function of the ICR is shown for each value of Rise Time.

As expected, the higher the value of Rise Time the better the resolution. Nevertheless, rising the ICR, it is more and more probable the pulse pile-up, so it is preferable to have shorter shaped signals not to loose resolution significantly and also to reduce the pile-up rejection.

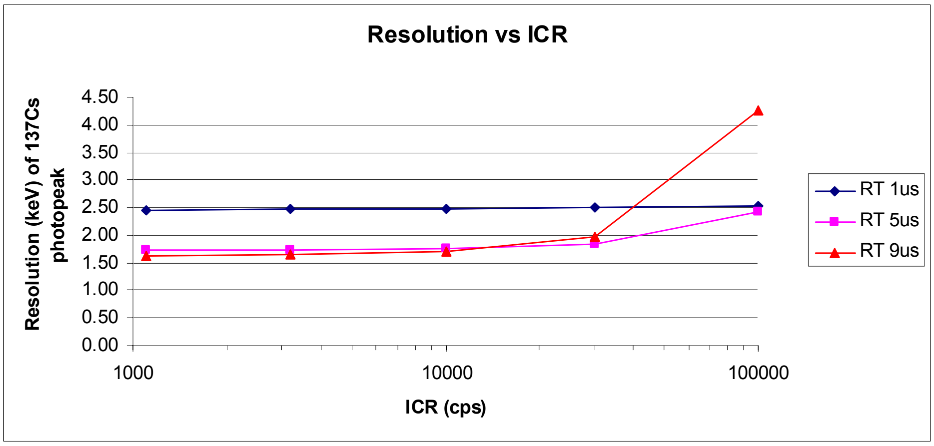

Fig. 6: Resolution of the 661.7 keV ^{137}Cs photopeak as a function of the Input Counting Rate (ICR) for different values of Trapezoid Rise Time (RT).

In **Fig. 7** it is shown the Peak shift as a function of the ICR for each value of Rise Time; even at 9 µs of Rise Time there is no notable shift of the photopeak up to 30 kcps.

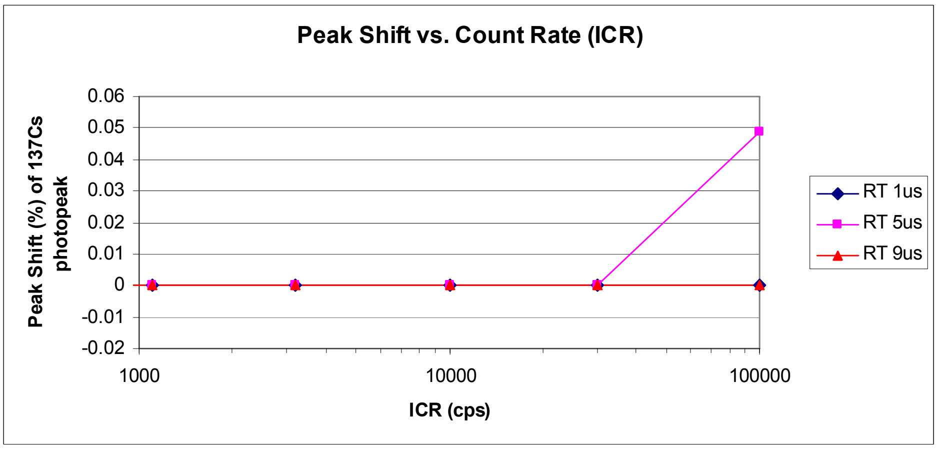

Fig. 7: Peak position of the 661.7 keV ^{137}Cs photopeak as a function of the Input Counting Rate (ICR) for different values of Trapezoid Rise Time (RT).

Baseline Restorer

In order to correctly evaluate the trapezoid height it is important to carefully estimate its baseline. The baseline, in fact, can fluctuate for a number of reasons as microphone noise, grounding, power supply, etc. The Digital Pulse Height Analyzer can evaluate the baseline level by means of a moving average window whose length can be selected by software. The main effect of a not well-compensated baseline fluctuation is clearly noticeable in the peaks collected in an energy spectrum; the base of the peak is larger than what would be expected by a pure Gaussian peak, as shown in Fig. 8.

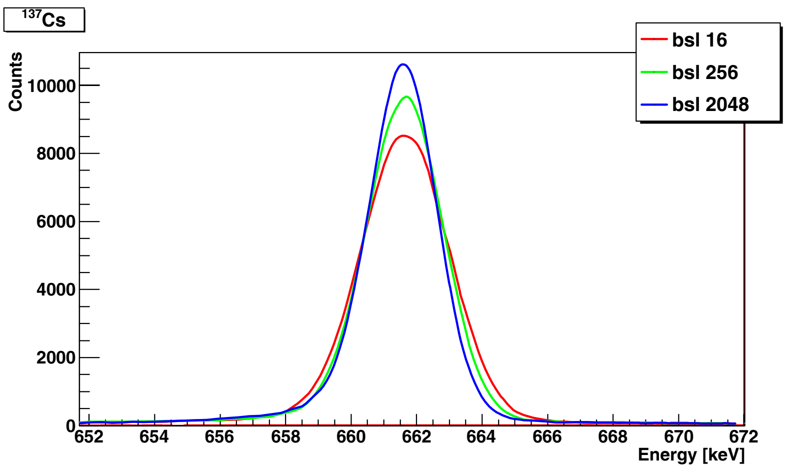

Fig. 8: ^{137}Cs photopeak collected changing the Baseline parameter. If the baseline fluctuations are not carefully compensated, the base of the peak is larger than the expected. The histograms were drawn with a smoothed line in order to highlight their shape.

Advanced Settings: Peaking Holdoff

To avoid the loss of energy resolution when the Input Counting Rate increases, DPP-PHA allows the user to introduce a Peaking Holdoff. This parameter inhibits the height analysis of pulses closer than a programmable time value.

In principle, two trapezoids can be considered valid, i.e. it is possible to correctly calculate their heights, even if the second pulse overlaps the falling edge of the first one. Anyway, because of the overlap, the height of the second trapezoid is evaluated in respect to the baseline value calculated before the first one. This means that the baseline could have been changed in the meanwhile and therefore a loss of energy resolution can be introduced. Peaking Holdoff can be used in order to store the heights of only well-separated pulses, ensuring a precise baseline calculation for each trapezoid.

Of course, the drawback of this technique is to increase the pulse rejection: this parameter sets the minimum separation of the trapezoids before they are considered piled-up. In order to evaluate the effectiveness of the Peaking Holdoff, several spectra of the ^{137}Cs source were acquired, changing the holdoff width. The results are shown in Fig. 9, Fig. 10 and Fig. 11.

It can be noticed that the area of the histograms, i.e. total counts, decreases for higher values of Peaking Holdoff because of the pulse rejection.

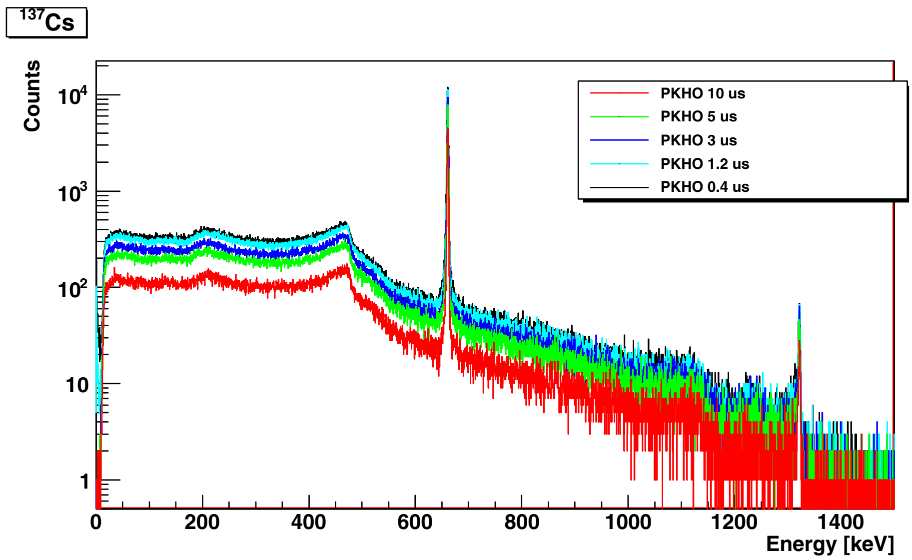

Fig. 9: ^{137}Cs spectra acquired with different Peaking Holdoff values. The measurements were performed with Rise Time set to 1 µs. The ICR was about 110 kcps.

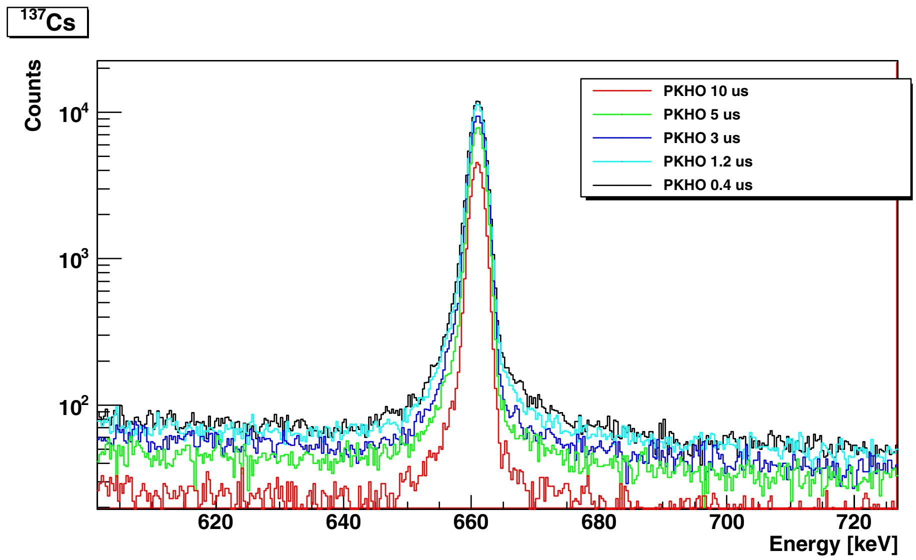

Fig. 10: Zoom of the 661.7 keV photopeak of Fig. 9. The effect of the Peaking Holdoff is to let a precise evaluation of the trapezoids' baseline.

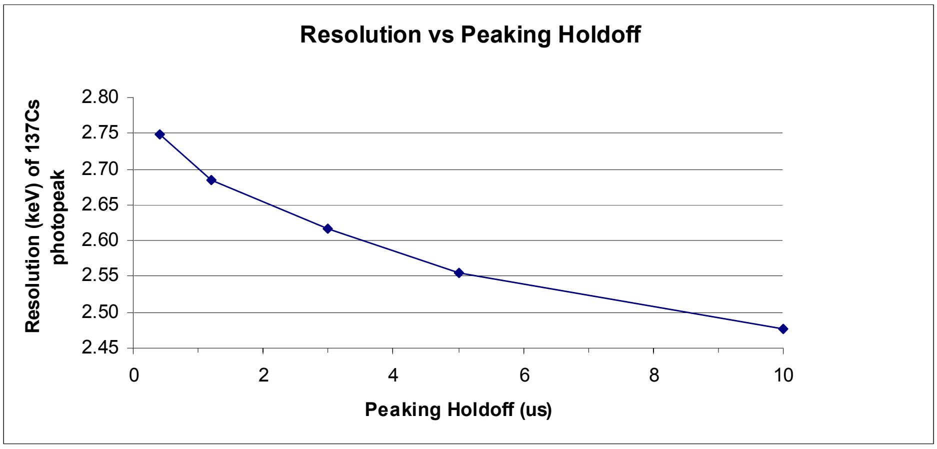

Fig. 11: Resolution of the 661.7 keV ^{137}Cs photopeak as a function of the Peaking Holdoff.

Dead Time & Pile-up Rejection

Unlike the analogue Peak Sensing ADCs, CAEN Pulse Height Analyzer is not affected by conversion time, being based on Flash ADCs. This means that the ADCs housed by the board digitize continuously the analogue inputs making the samples always available to the DPP-PHA algorithm running on the FPGA.

Anyway, the system could be unable to correctly evaluate the height of some pulses for three reasons:

- dead time due to saturation of the input stage (ADC over range)
- dead time due to full memories in the digitizer
- piled-up events

Concerning the first two points, both the situations are related to a very high ICR, of the order of several Mcps. In fact, being CAEN Pulse Height Analyzer a conversion time-less system, the only sources of dead time, i.e. inability of the system to manage the analogue inputs and to analyze the detector's pulses, are the saturation of the input dynamic range, due to an high event pile-up, and the inability of the readout link to sustain the data throughput from the memories that contain the energy values to the computer. If the ICR is not so high, the system is never dead to the detector's pulses, but conversely it is always capable to analyze the digitized signals: the system is not affected by dead time, as traditionally defined.

However, even at lower rates, the probability to have piled-up events is high enough to cause the rejection of a significant number of events. In fact, pulses really close to each other produce an overlap of the related trapezoids. In this situation, the system is unable to disentangle the heights of the piled-up pulses so, in order to not lose energy resolution and create false peaks in the spectra, it rejects these events as shown in Fig. 12.

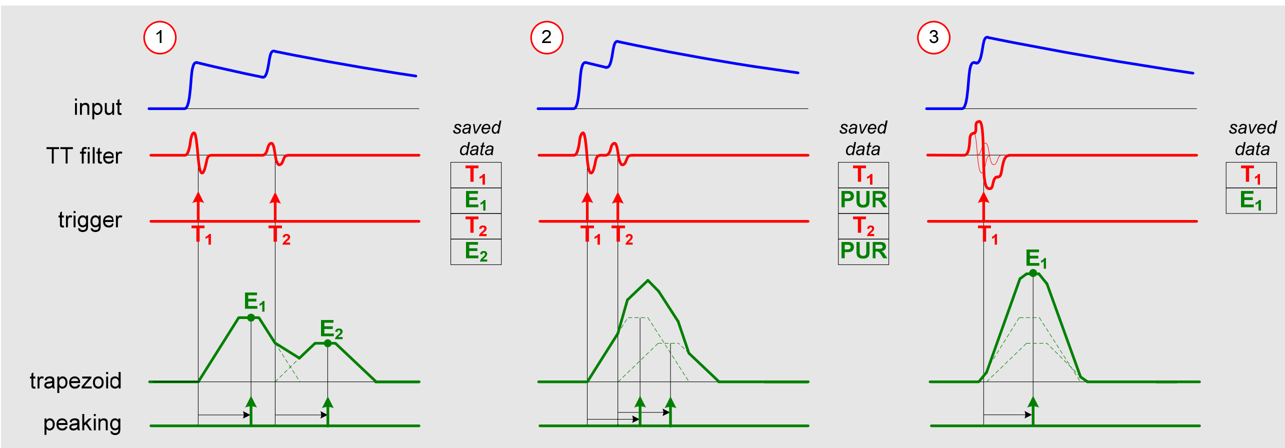

Fig. 12: The effect of trapezoids overlapping in three main cases: 1) The second trapezoid starts on the falling edge of the first one. 2) The second trapezoid starts on the rising edge (ΔT < peaking time) of the first one. 3) The second trapezoid starts on the rising edge of the first one (ΔT < input rise time).

In this case, in addition to an effective capability to recognize and reject the piled-up events, it is necessary to know how many pulses have been rejected in order to precisely estimate the Input Counting Rate that is related to the activity of the radiation source and therefore correct the energy spectra.

CAEN Pulse Height Analyzer is able both to recognize with high efficiency the piled-up pulses and to count how may of them have been rejected; this capability is ensured by the digital implementation of a fast Trigger and Timing Filter.

The aim of the Trigger and Timing Filter (TTF) is to identify the input pulses, generate a trigger on them and calculate the time stamp by means of a kind of Constant Fraction Discriminator. To make an analogy with an analog system, the TTF is like a RC-CR^2 filter: the integrative component is a smoothing filter based on a moving window averaging filter that reduces the high frequency noise and prevent the trigger logic to generate false triggers on spikes or fast fluctuation of the signals.

On the other hand, the purpose of the derivative component is to subtract the baseline, so that the trigger threshold is not affected by the low frequency fluctuation and, more important, by the pile-up. As a result of the double derivation (CR^2), the output signal of the TTF is bipolar and the zero crossing is independent of the pulse amplitude. This is the same principle of the CFD. The trigger logic uses the threshold to get armed, then waits for the zero crossing to generate the trigger signal and produce a time stamp.

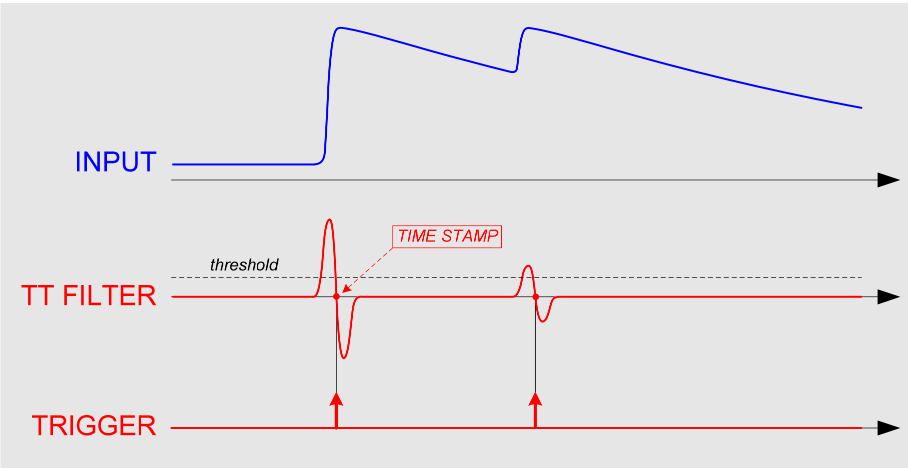

Fig. 13: The Trigger and Timing Filter is used by the channels to autotrigger on the input pulses.

In Fig. 14, the Output Counting Rate, that is the rate of the pulses whose height was evaluated by the system (i.e. not piled-up pulses), versus the Input Counting Rate is shown. As expected, the longer is the Rise Time the sooner the maximum OCR is reached; anyway, an ICR up to 10 kcps can be analyzed with no significant event rejection even with 9 µs of Trapezoid Rise Time.

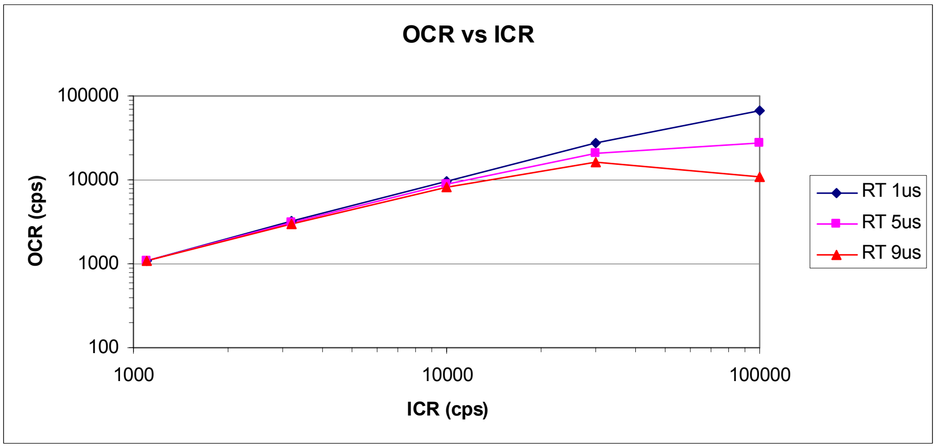

Fig. 14: Output Counting Rate vs Input Counting Rate for different values of Trapezoid Rise Time.

Rise Time Discriminator

When the Input Counting Rate is very high, the probability to observe two pulses output by the preamplifier piled-up on their rising edge is not negligible. In this situation, the usual pile-up rejection methods are ineffective, since the pile-up occurs before the first pulse reaches its maximum: the two pulses are not rejected, producing false peaks in the spectrum, as shown in Fig. 12.

Anyway, if the two pulses are not exactly simultaneous, there is the possibility to reject the undesired events by analysing the rise time of the piled-up signal: CAEN DPP-PHA can reject the pulses whose rise time exceed a settable value.

In Fig. 15 two measures obtained with an ICR of 110 kcps are shown. In the first measure the Rise Time Discriminator was disabled, leading to the creation of a pile-up peak whose energy is twice the 661.7 keV energy of ^{137}Cs gamma ray. In the second measure, the RTD wad enabled; as a result, the pile-up events are strongly suppressed.

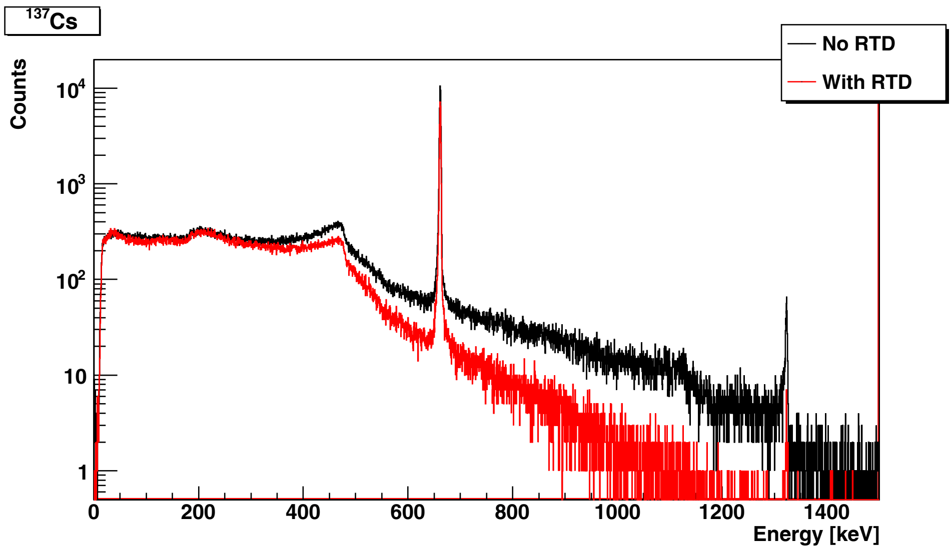

Fig. 15: ^{137}Cs spectra with ICR 110 kcps. The black spectrum was collected without Rise Time Discriminator, the red one was obtained using RTD. The measurements was performed with Trapezoid Rise Time set to 1 µs.

The value of RTD must be carefully set in order not to reject good pulses. In fact, especially in large detectors, it may happen that not piled-up signals show a rise time longer respect to the usual ones, depending on the interaction point within the detector.

Unsteady Sources & Live Spectrum Correction

Thanks to the high efficiency in the input pulse counting, CAEN digital Pulse Height Analyzer is able to manage a live correction of the energy spectrum in respect to the piled-up events. This is very important whenever an unsteady radiation sourced is used, e.g. short living isotopes or activity transients.

In these situations, it is not possible to compensate the lost counts simply extending the acquisition time, because in this way the correction is applied only to the source still active in the additional time. What it is done in many traditional systems is to correct the spectrum only at the end of the acquisition run, redistributing the lost counts in respect to the collected histogram; this may lead to correction errors, since this method does not take into account the ICR variations during the data acquisition.

As a proof of CAEN Pulse Height Analyzer capabilities to live correct the energy spectra, a measurement was performed acquiring a mid counting (10 kcps) ^{60}Co source for 3 minutes. During this acquisition, an high counting (100 kcps) ^{137}Cs source was added for just 10 seconds. In this situation, the addition of the ^{137}Cs source produced a sudden transient in the ICR, increasing therefore the piled-up events. Because of the higher activity of the ^{137}Cs source, it is more probable that the piled-up pulses involved ^{137}Cs photons than ^{60}Co ones, so the correction should be more focused on the former source than the latter. If a traditional correction is applied, the simple redistribution of the lost counts at the end of the acquisition would compensate the lost counts in respect to the final spectrum shape that is, of course, related not only to the activity but also to the collection time.

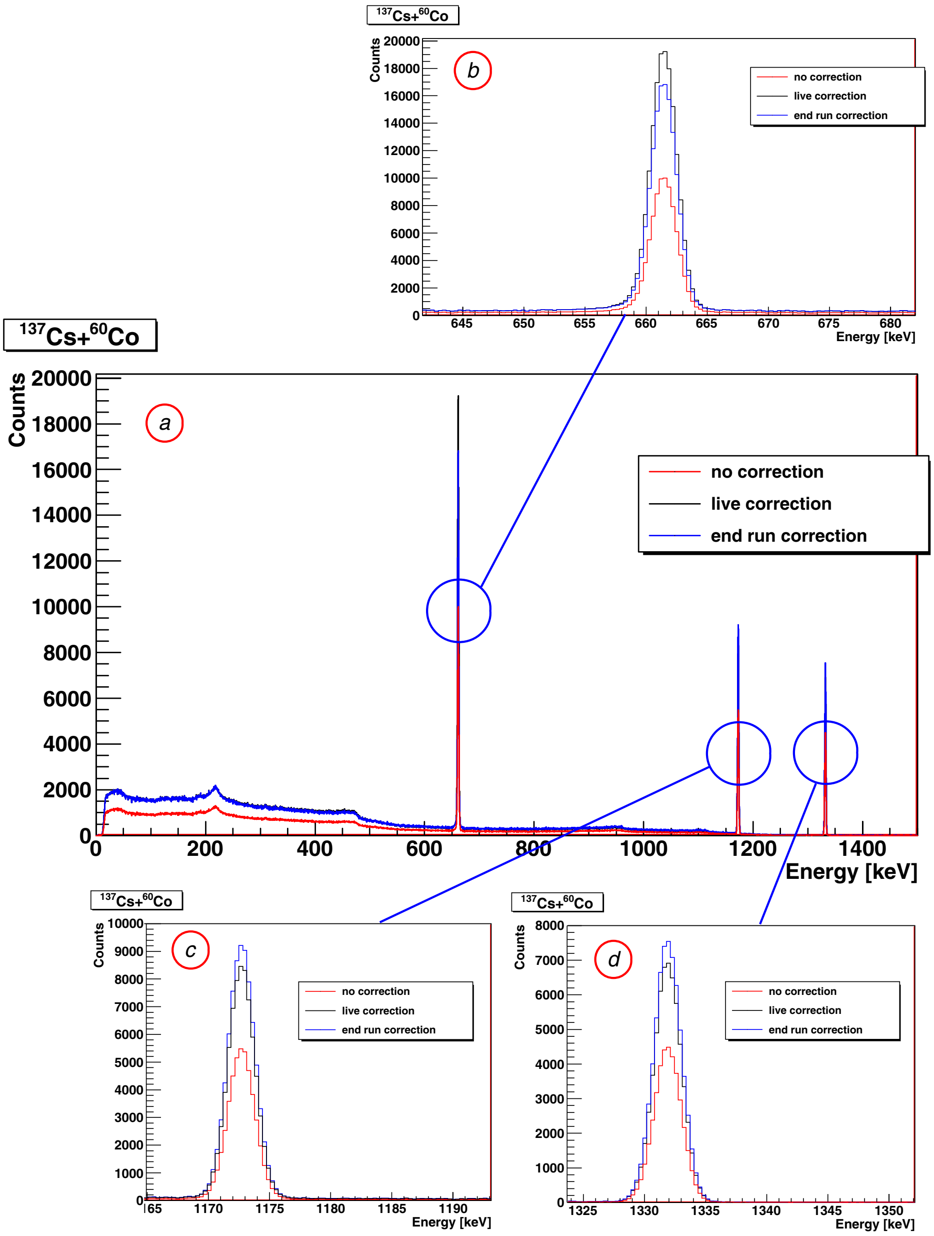

Fig. 16 (a): Energy spectrum acquiring a mid counting (10 kcps ICR) ^{60}Co source for 3 minutes and adding an high counting (100 kcps) ^{137}Cs source for 10 seconds. The red histogram is the uncorrected spectrum, the blue one is the spectrum corrected at the end of the run and the black one is the live corrected spectrum. The measurement was performed with Trapezoid Rise Time set to 1 µs and RTD enabled.

(b): Zoom of the ^{137}Cs photopeak. (c) (d): Zoom of the ^{60}Co photopeaks. As can be noticed, the traditional correction performed at the end of the run does not take in account the Input Counting Rate variation during the measurement, redistributing the lost counts in respect to the integrals of the ^{137}Cs and ^{60}Co spectra. This leads to an undercompensation of the ^{137}Cs photopeak and an overcompensation of the ^{60}Co ones.

References

[1] G. Knoll, Radiation Detection and Measurement John Wiley & Sons, 4th Edition.

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[3] V. Jordanov, G. Knoll, Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy Nuclear Instruments and Methods in Physics Research A 345(2): 337-345.

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