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A digital approach for real time high-rate high-resolution radiation measurements

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ABSTRACT

Modern spectrometers are currently developed by using digital pulse processing (DPP) systems, showing several advantages over traditional analog electronics. The aim of this work is to present digital strategies, in a time domain, for the development of real time high-rate high-resolution spectrometers. We propose a digital method, based on the single delay line (SDL) shaping technique, able to perform multi-parameter analysis with high performance even at high photon counting rates. A robust pulse shape and height analysis (PSHA), applied on single isolated time windows of the detector output waveforms, is presented.

The potentialities of the proposed strategy are highlighted through both theoretical and experimental approaches. To strengthen our approach, the implementation of the method on a real-time system together with some experimental results are presented. X-ray spectra measurements with a semiconductor detector are performed both at low and high photon counting rates (up to 1.1 Mcps).

1. Introduction

Nowadays, spectroscopic systems with high-rate and high-resolution capabilities are considered desirable in many physics applications. Generally, “High-rate and high-resolution capabilities” mainly concern the abilities of a system to perform accurate and precise measurement of (i) the input counting rate (ICR) and (ii) the energy spectra even at extreme ICR conditions. At high ICRs, low dead time losses, low variations of energy calibration and a trade-off between energy resolution and throughput must be ensured. Pile-up (tail and peak pile-up) and baseline shifts (mainly due to thermal drifts, poor pole-zero cancellation [1] and AC couplings) are the major drawbacks at high ICR environments and therefore high performance spectrometers must be equipped with both robust pile-up rejectors (PURs) [1] and baseline restorers (BLRs) [1].

A modern spectroscopic system should also perform multi-parameter analysis, i.e. provide, besides ICR and energy spectrum, additional experimental parameters for each event, among which: (i) the event arrival time (e.g. for coincidence/anticoincidence measurements), (ii) the pulse shape (e.g. for detector performance enhancements, photon tracking or particle identification) and (iii) the time width of the detected pulses (for dead time corrections). Moreover, a fine time evolution of the energy spectrum and counting rates should be provided to analyze variable or transient radiation. Multi-parameter analysis performed at very high fluence rates ($>10^6$ photons mm^{-2} s^{-1}) can be very helpful in the development of advanced energy resolved photon counting detectors, recently proposed in diagnostic medicine (computed tomography and mammography), industrial imaging and security screening [2–5].

Currently, the most common high performance spectrometers are developed by using digital pulse processing (DPP) systems [6–19], where the detector output signals (i.e. the output signals from charge sensitive preamplifiers) are directly fed into fast digitizers and then processed by using digital algorithms. DPP systems are typically realized by using two different processing approaches: (i) a personal computer (PC) controls a simple digitizer, receives and records ADC data in files and performs off-line processing [14,17–23]; (ii) a PC controls a field programmable gate array (FPGA), equipped with local memory and digitizer; FPGA, wherein pulse processing algorithms are implemented (DPP firmware), receives and processes on-line ADC data, stores results in local memory, gets packets and sends them, when ready, to PC [6–13,15,16,24–26].

Data results are used for quick look processing (for on-line system running control) and are stored in PC files for much deeper off-line analysis [24,25].

As widely recognized, the digital approach gives many benefits against the analog one, among which: (i) possibility to implement

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custom filters and procedures, which are challenging to realize in the analog approach, (ii) stability and reproducibility (insensitivity to pick-up noise as soon as the signals are digitized) and (iii) the possibility to perform multi-parameter analysis for detector performance enhancements and new applications.

Many efforts on the implementation of optimal filtering (trapezoidal, triangular, pseudo-Gaussian, cusp) [27–30] and correction techniques (ballistic deficit, pole-zero cancellation, PUR, baseline recovery) [13,31–34] have been made. However, further improvements are required in the development of high-rate high-resolution spectrometers. To our knowledge, the major limitation of many current DPP systems is represented by their trend to exactly replicate the classical analog pulse processing procedures, showing the same difficulties of the analog systems to mitigate high rate drawbacks. Moreover, due to the potentialities of the DPP approach, more radiation features than ICR and energy spectrum should be provided to the users (e.g. event arrival time, pulse shape, pulse width) to realize non-standard, general purpose radiation detection systems.

In this work we present a DPP method for real time high-rate high-resolution radiation measurements. We propose a method able to perform multi-parameter analysis (event arrival time, pulse shape, pulse height, pulse time width, etc.) even at high ICRs. The pulse detection and the pulse shape and height analysis (PSHA) is carried out by using the classical single delay line (SDL) shaping technique. The PSHA is performed in a robust approach, applied on single isolated time windows of detector output waveforms. First we outline, in a time domain, the typical features of the SDL shaping and its appealing capabilities in pulse detection and in PSHA. Following, the typical high-rate distortions in PSHA, together with possible solutions, will be discussed.

Moreover, to strengthen our approach, the implementation of the method on a real-time system together with some experimental results obtained with a semiconductor detector will be presented.

The aim of this work is to present helpful digital strategies for the development of real time high-rate high-resolution spectrometers. Obviously, these strategies are also suitable for off-line acquisition.

2. Single delay line (SDL) shaping overview

In this section, we outline the main features of the classical SDL shaping (also known as delay line clipping) [1,35–37] applied to the typical output waveform from resistive feedback charge sensitive preamplifiers (CSPs), coupled to semiconductor detectors.[1] SDL shaping is obtained by subtracting from the original pulse its delayed and attenuated fraction. SDL shaping gives short rectangular output pulses with fast rise and fall times. In fact, the falling edge of the pulse is a delayed mirror image of the leading edge. These features make SDL shaping very appealing for timing and PSHA at both low and high counting rates. This classical shaping technique has not been widely used in analog pulse processing, because long-stable delays and stable attenuations are challenging to realize in analog approach. Of course, these difficulties are not present in a digital domain [36,37]. To better explain the properties of SDL shaping, we model a typical single isolated CSP output pulse, with arrival time at $t=0$, as following:

$$V_{CSP}(t) = V_0 \times (1 - e^{-(t/\tau_L)}) \times e^{-(t/\tau_F)}, \quad t \geq 0, \qquad (1)$$

where V_0 is an amplitude constant, τ_L is the time constant of the leading edge and τ_F is the time constant of the falling edge ($\tau_F \gg \tau_L$).

SDL shaping is obtained through the following relation:

$$V_{SDL}(t) = V_{CSP}(t) - V_{CSP}(t - T_d) \times e^{-(T_d/\tau_F^*)}, \qquad (2)$$

where T_d is the delay time and τ_F^* characterizes the attenuated fraction. This attenuation, by using the correct τ_F^* value (i.e. $\tau_F^* = \tau_F$), is able to avoid undesirable undershoots (or overshoots) in the shaped pulses, therefore, working as the classical "*pole-zero cancellation technique*" [1]. Fig. 1 shows both CSP output pulses and the SDL shaped pulses with different T_d values; T_p is the peaking time of the CSP output pulse, i.e. the time it takes to reach its full amplitude.

The key features of SDL shaping are reported below:

(i) the time width of each SDL shaped pulse is well defined, in all cases equal to $T_p + T_d$;
(ii) there is a zero baseline before ($t < 0$) and after ($t > T_p + T_d$) the leading edge of the SDL shaped pulse (using $\tau_F^* = \tau_F$);
(iii) by using $T_d > T_p$, the leading edge (pulse height and peaking time) of each CSP output pulse is preserved;
(iv) by using $T_d < T_p$, the maximum amplitude of the SDL shaped pulse is equal to the CSP value at $t = T_d$.

After this general overview on SDL shaping, we will show in the following sections its appealing capabilities for the development of a digital method working at both low and high ICRs.

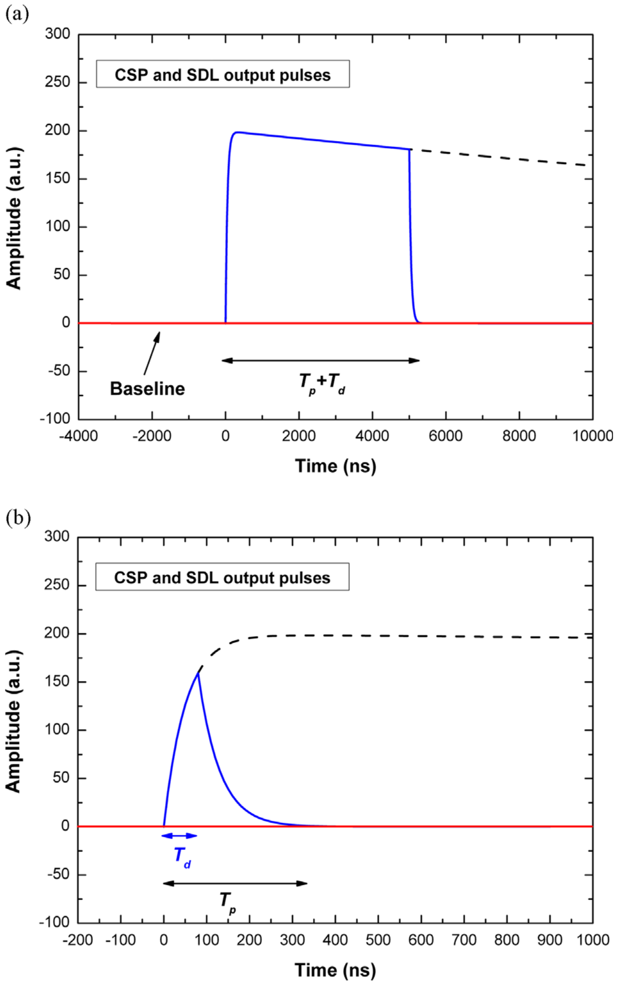

Fig. 1. (color online) (a) Single isolated CSP output pulse (dashed line) with arrival time at $t=0$ and the SDL shaped pulse (solid line) with a delay time $T_d > T_p$ (peaking time of CSP pulses). Both the leading edge and the baseline of the CSP pulse are preserved. (b) By using a $T_d < T_p$, the maximum amplitude of the SDL shaped pulse is equal to the CSP value at $t = T_d$.

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[1] Of course, the SDL shaping can be easily applied to reset preamplifier output waveforms, which after high pass filtering (needed to ADC input range interfacing) not require pole-zero cancellation [1].