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Digital pulse processing and optimization of the front-end electronics for nuclear instrumentation

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HIGHLIGHTS

- Digital pulse processing based on a recursive implementation of a Gaussian filter.
- Optimization of the front-end electronics for the coupling to the ADC.
- Improvement of detection threshold of a high-efficiency well-type NaI(Tl) detector.
- Digital processing applied to a Si drift detector with reset-type preamplifier.

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ABSTRACT

This article describes an algorithm developed for the digital processing of signals provided by a high-efficiency well-type NaI(Tl) detector used to apply the $4\pi\gamma$ technique. In order to achieve a low-energy threshold, a new front-end electronics has been specifically designed to optimize the coupling to an analog-to-digital converter (14 bit, 125 MHz) connected to a digital development kit produced by Altera®. The digital pulse processing is based on an IIR (Infinite Impulse Response) approximation of the Gaussian filter (and its derivatives) that can be applied to the real-time processing of digitized signals. Based on measurements obtained with the photon emissions generated by an ^{241}Am source, the energy threshold is estimated to be equal to ~2 keV corresponding to the physical threshold of the NaI (Tl) detector. An algorithm developed for a Silicon Drift Detector used for low-energy x-ray spectrometry is also described. In that case, the digital pulse processing is specifically designed for signals provided by a reset-type preamplifier (^{55}Fe source).

1. Introduction

National Metrology Institutes involved in radionuclide metrology are particularly concerned by the problem of ensuring the maintenance or the renewal of their nuclear instrumentation (Keightley and Park, 2007). Classical instrumentation dedicated to radionuclide metrology is composed of several modules designed to implement specific functionalities (counting, dead-time processing, pulse-height analysis, etc.). The current trend is to translate the pulse processing usually implemented in that modular instrumentation into algorithms programmed on specialized units such as FPGA circuits (Field Programmable Gate Array) in order to be directly applied on digitized signals. At LNE-LNHB (Laboratoire National Henri Becquerel), the capabilities of digital technology were first investigated to perform the counting processing and the dead-time management as implemented in home-made modules specifically designed for radionuclide metrology (Bouchard, 2000). Following the experience acquired with those specialized modules, the algorithm developed for digital processing is based on extendable dead times associated with the live-time technique. The feasibility of this development was first validated with a digital instrumentation connected to a high-efficiency NaI(Tl) well-type detector used for the $4\pi\gamma$ method (Censier et al., 2010). In that case, the pulse processing was designed for an off-line processing performed on time-stamped events collected in real-time by the FPGA circuit. A second digital system was also developed to apply several primary standardization techniques used at LNE-LNHB: TDCR (Triple to Double Coincidence Ratio), $4\pi\gamma$, $4\pi\beta-\gamma$ coincidence, etc. In that case, the digital board (development kit manufactured by Altera® equipped with a Stratix III FPGA) was selected for its capability to perform an on-line processing of pulses delivered by usual detectors in metrology laboratories. Contrary to off-line processing, the dead-time management and the counting are carried out in real-time in the FPGA circuit (Bobin et al., 2010, 2012). In these studies, the pulse-height analysis was performed on signals provided by shaping amplifiers.

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Digital nuclear instrumentation offers the possibility to reduce the analog part of the electronic chain. In that configuration, the digitization stage is performed as close as possible to the detector in order to register all the useful information for subsequent pulse processing. As a result, nuclear functionalities originally performed by the shaping amplifier in a spectroscopy chain can be directly programmed in digital systems. This paper describes the development of algorithms for counting and pulse-height analysis based on the recursive implementation of the Gaussian filter (and its derivatives) originally proposed by Young and van Vliet (1995) for computer vision (image filtering, edge detection, etc.). The algorithms were specifically developed for the processing of signals generated by photons detected in a high-efficiency well-type NaI (Tl) detector and a Silicon Drift Detector (SDD). In both cases, the front-end electronics especially designed to optimize the coupling between the analog part and the digitization stage (14 bit, 125 MHz, installed in the Stratix III development kit) is described. The problem of dead-time management as usually applied at LNE-LNHB in the case of primary activity measurements is also addressed. Based on long-term experience, extendable dead times associated with the live-time technique are generated as close as possible to the real behaviour of detectors (after-pulses, saturated signals, etc.). This article reports the preliminary results obtained with the digital pulse processing developed in MATLAB®. These algorithms are applied to digitized pulse trains according to an off-line processing in a development phase in order to be programmed in the future in the Stratix III FPGA circuit for on-line processing for routine measurements.

2. Digital processing of pulses delivered by a high-efficiency well-type NaI(Tl) detector

2.1. Description of the detection system and the associated electronic chain

At LNE-LNHB, the 4πγ counting technique is based on a high-efficiency NaI(Tl) well-type detection set-up (⌀ 152 mm, h 127 mm). For the present study, a new front-end electronics was specifically designed to optimize the link between the detector and the ADC in order to obtain a low-detection threshold for the application of the zero-energy extrapolation as needed by the 4πγ technique (Pommé, 2007). This interface was also designed to handle the high dynamic range of signals provided by the NaI(Tl) detection set-up and to limit the influence of saturated pulses generated for instance by high-energy gamma photons or cosmic rays. For that purpose, the first stage of the front-end electronics is composed of a high-voltage, wideband operational amplifier (THS4631, Gain = 1) designed to accept pulses of high amplitudes (~20 V). The goal is to limit the effect of saturated signals that generally leads to undershoots resulting from an abrupt decrease of the input impedance when a collector-base junction is forward biased. The decay time (ranging between 5 μs and 10 μs) is defined by the RC value at the interface input. The second stage of the interface limits the signal voltage delivered by the first one. It is composed of a wide-bandwidth-voltage feedback clamp amplifier (AD8036, Gain = 1) in order to limit both positive and negative polarities. This stage is used to set the maximum voltage delivered to the last interface stage. Designed as a Rauch-type filter, the last stage (THS4631, Gain = 10) sets the final gain and it implements an anti-aliasing low-pass filter (Bessel type, 2.2 MHz). This output stage has a ± 10 V dynamic range (50 Ω). The power supply is equal to ± 24 V.

The digital platform used was previously described for the implementation of primary techniques according to an on-line processing (Bobin et al., 2010, 2012). For the present study, the development kit produced by Altera® (Stratix III FPGA) was used for the sampling and the recording of digitized pulse trains delivered by the front-end electronics. A mezzanine card equipped with two analog-to-digital converters (AD9254, 14 bit, 125 MHz) is connected to the main board through HSMC connectors. The inputs were modified to allow a DC coupling needed to process accurately the dead times generated by lengthy saturated signals. Initially comprised between 0 V and 2 V, the dynamic range has also been increased to accept signals delivered by usual shaping amplifiers for the first investigations of the digital system (Bobin et al., 2012). The digitized pulse trains are first recorded in a 1 Gbyte DDR2 SDRAM installed on the development kit in order to be transferred subsequently on the hard drive of a PC. This operation is carried out using an interface programmed in the FPGA circuit and based on an Ethernet link (1 Gbit/s, UDP protocol). An acquisition consists of several pulse trains of about 2 s (268 435 456 samples).

2.2. Description of the digital pulse processing

The digital pulse processing described hereafter is based on a recursive implementation of the Gaussian filter and its derivatives proposed by Young and Van Vliet (1995). Developed for image filtering and edge detection, the IIR (Infinite Impulse Response) expression given by the authors can be programmed in a FPGA circuit for real-time processing of digitized pulses delivered by nuclear detectors (pulse-height analysis, dead-time management). In the algorithms described in the present article, the Gaussian filter is applied as a low-pass filter for pulse-height analysis corresponding to the “slow channel” in a classical instrumentation. The leading-edge detection is computed in the “fast channel” using the 1st derivative of the Gaussian filter for its sensitivity to the fast component of the digitized pulses. As depicted in Fig. 1, this differential operator generates fast signals that are used to trigger the dead-time management, the counting and the pulse-height analysis in the “slow channel”. The Laplacian filter (2nd derivative of the Gaussian filter) can be applied for pile-up identification by finding zero-crossings (see Fig. 2). The detection of local maxima of the 1st derivative can be also used as a Constant Fraction Discriminator to reduce the jitter-effect on the signal triggering.

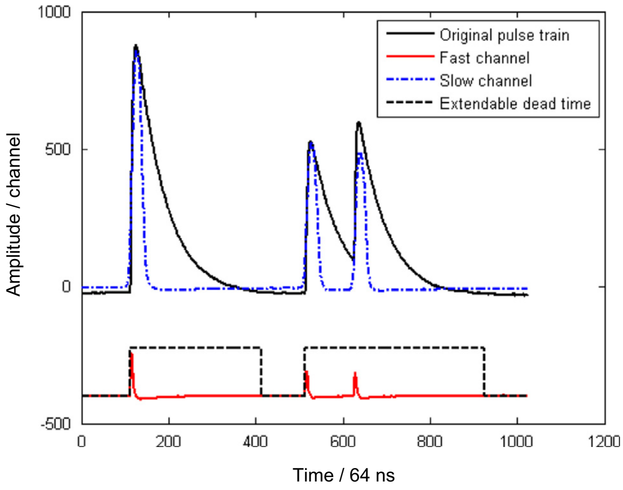

Fig. 1. Digital pulse processing applied to signals delivered by a high-efficiency well-type NaI(Tl) detector. The “fast channel” is used to trigger the extendable dead-time management (minimum duration equal to 300 samples) and the pulse-height analysis in the “slow channel”.

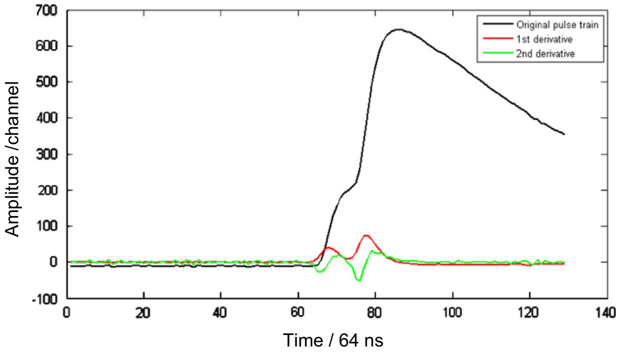

Fig. 2. These plots describe a procedure for pile-up identification based on zero-crossing detection using the 2nd derivative of the Gaussian filter. The time-jitter between the pulses is equal to ~600 ns corresponding to the rise time.

As shown in the following expressions (1) and (2), the recursive implementation of the Gaussian filter is computed from the concatenation of causal and anti-causal third-order filters.

- Expression of the causal part of the Gaussian filter depending on present and past inputs (the vector in refers to the original pulse train)

$$w[n] = B \times \mathrm{in}[n] + (b_1 \times w[n-1] + b_2 \times w[n-2] + b_3 \times w[n-3])/b_0 \qquad (1)$$

- Expression of the anti-causal-filter component depending on present and future inputs (the vector out refers to the filtered pulse train)

$$\mathrm{out}[n] = B \times w[n] + (b_1 \times \mathrm{out}[n-1] + b_2 \times \mathrm{out}[n-2] + b_3 \times \mathrm{out}[n-3])/b_0 \qquad (2)$$

with the normalisation constant $B = 1-(b_1+b_2+b_3/b_0)$ which is obtained using the constraint that the transfer function of the filter should be equal to 1.0 for the frequency $\omega = \Omega = 0$ (Young and Van Vliet, 1995). The coefficients b_0, b_1, b_2 and b_3 are calculated for a given standard deviation σ corresponding to the cut-off frequency of the low-pass filter.

The 1st derivative of the Gaussian filter is also based on the concatenation of causal and anti-causal filters in such a way that the phase terms cancel each other.

- Causal part of the 1st derivative of the Gaussian filter

$$\begin{aligned} w[n] = {} & B/2 \times (\mathrm{in}[n+1] - \mathrm{in}[n-1]) \\ & + (b_1 \times w[n-1] + b_2 \times w[n-2] + b_3 \times w[n-3])/b_0 \end{aligned} \qquad (3)$$

- Anti-causal part given by expression (2) remains unchanged.

As described in the following sections, the original data stream is oversampled using a frequency equal to 125 MHz. The above expressions are implemented after a downsampling phase which is applied by averaging samples in order to improve the Signal/Noise ratio. The number of samples is chosen with regards to the rise time of the digitized signals which depends on the detector used. The aim is to keep all the information needed for the leading-edge detection given by the 1st Gaussian derivative. The associated standard deviation used to implement expressions (2) and (3) is defined to optimize the Signal/Noise ratio in the “fast channel”. As mentioned by Young and Van Vliet (1995), the low-pass nature of the Gaussian filter attenuates the high-frequency component of signals amplified by the derivative process. The purpose is to obtain a low-detection threshold applied to fast signals. For the pulse-height analysis in the “slow” channel, a larger standard deviation is chosen for the computation of expressions (1) and (2). Its value depends on the delay imposed to generate differentiated signals and on the cut-off frequency of the Gaussian filter to smooth these pulses from which the amplitude is measured.

The pulse processing algorithm described hereafter has been developed for the implementation of the pulse-height analysis, the counting and the dead-time management of pulse trains acquired with the high-efficiency NaI(Tl) well-type detector. The digitized pulse trains are given by photon interactions provided by a ^{241}Am source ($\sim 2 \times 10^4\ \mathrm{s}^{-1}$).

- A smoothing filter (8-sample averaging) is first implemented on the digitized pulse trains in order to obtain a new original signal. After the downsampling process, the leading edge of x-ray pulses is defined by about 10 samples (~600 ns rise time).
- The “fast channel” is computed using the 1st derivative of the Gaussian filter ($\sigma = 0.5$) for the leading-edge detection. As already mentioned, this standard deviation is set to define the cut-off frequency of the low-pass filter associated with the 1st Gaussian derivatives. An example of the processing of the extendable dead time using the signals generated in the “fast channel” is given in Fig. 1 (minimum duration set to 300 samples corresponding to ~19 μs). The dead-time triggering is also used to start the pulse-height analysis of the associated signal in the “slow channel”. The live-time technique is carried out by sampling the time intervals between the dead-time periods (sampling period equal to 64 ns after the downsampling phase).
- Considering the “slow channel”, a differentiation is first computed by subtracting from the original pulse train the attenuated and delayed (24 samples, ~1.5 μs) original signal. The pole-zero compensation is set by the value of the attenuation. The mean value of the offset on the original pulse train is continuously estimated prior the dead-time triggering. The differentiated signal is smoothed using the Gaussian filter with an optimized standard deviation for pulse-height analysis ($\sigma = 4.0$). The amplitude is given by the first maximum value corrected for the baseline level of the differentiated signal measured prior the dead-time triggering.
- An example of pile-up identification is displayed in Fig. 2. The zero-crossing detection is performed on the signals obtained with the 2nd Gaussian derivative. It can be observed from Fig. 2 that the pile-up generated by two signals separated by a duration equal to the rise time (~600 ns) can be well detected.

The algorithm described above has been developed taking into account the shapes of signals delivered by the new front-end electronics. Contrary to usual shaping amplifiers, no significant distortion of pulse shapes has been observed following the occurrence of high-amplitude or saturated signals. Because no lengthy undershoot is observed, the dead-time management can be simplified in the digital pulse processing. Extendable dead times are only triggered by the “fast channel”. In a classical electronic chain equipped with the MTR2 module (Bouchard, 2000), dead times are prolonged by the discrimination period generated by undershoots or saturated signals.

The histogram given in Fig. 3 represents the emission provided mainly by XL-photons (ranged between 11 keV and 22 keV) and γ-rays of about 59.6 keV. The total duration of the acquisition is equal to about 20 s. As the objective of the preliminary tests was not the improvement of the throughput, the minimum dead time was set to 200 samples (~13 μs). From the ^{241}Am-photon histogram in Fig. 3, a low-energy threshold of about 2 keV has been estimated (compared to ~6 keV in a classical electronic chain) corresponding to approximately the detection physical threshold of the high-efficiency NaI(Tl) well-type detector. By avoiding the noise generated by a shaping amplifier, this result can be interpreted as a beneficial effect of the front-end electronics especially

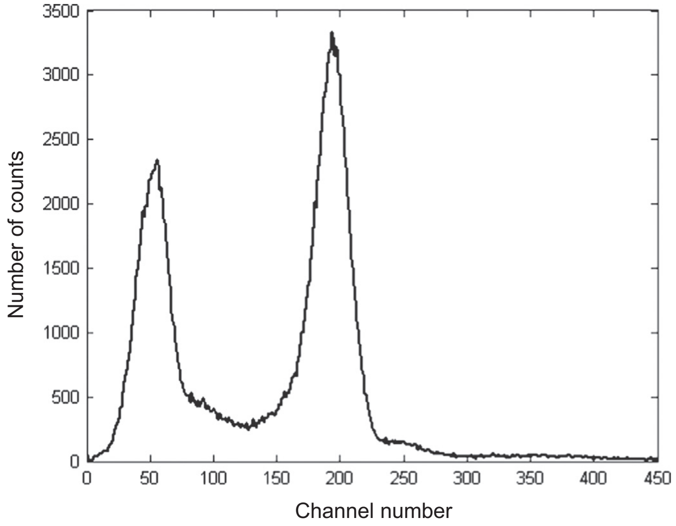

Fig. 3. The energy spectrum has been obtained with the digital pulse processing developed for signals provided by a high-efficiency well-type NaI(Tl) detector. The peaks correspond to the photon emission of a ^{241}Am source (XL-photons ranged between 11 keV and 22 keV, γ-ray photons of about 59.6 keV). The threshold is estimated to be equal to 2 keV (~6 keV in a classical electronic chain equipped with a "traditional" shaping amplifier).

designed to optimize the transmission of signals provided by a NaI (Tl) detector.

3. Digital processing of pulses delivered by a reset-type preamplifier

3.1. SDD detection set-up and the associated electronic chain

The detection set-up used is composed of a Silicon Drift Detector (SDD) produced by PNdetector (Type SD3-10-128pnW) connected to a reset-type preamplifier. The active volume is equal to 5.0 mm^2 × 450 μm. Measurements were carried out at a temperature equal to approximately—20 °C using the Peltier unit attached to the detector. The energy resolution given by the manufacturer is equal to 127 eV FWHM for the Mn-*K* energy peak.

The front-end electronics has already been described in the case of preliminary measurements obtained with a HPGe detector (Bobin et al., 2012). Its design is close to the front-end previously described for the NaI(Tl) detector. For the present study, the home-made interface establishes the link between the reset-type preamplifier and the ADC input. The first stage consists of a wide-bandwitdth buffer (AD811, Gain = 1) that offers the possibility to compensate for the baseline shift of the preamplifier. The second component is a wide-bandwidth-voltage feedback clamp amplifier (AD8036) with a clamp voltage set to ± 2 V. The third stage is a high-voltage and wideband operational amplifier (THS4631, Gain = 5), which is implemented as a Rauch-type filter (Gaussian shape, number of poles = 3). The purpose of this filter is to eliminate the high-frequency noise as well as to make an anti-aliasing filter (cut-off value ~2.5 MHz) large enough to transmit the signal without deformation of the leading-edge. This last stage has also the possibility to drive a 50 Ω load. The maximum voltage delivered by this electronic interface is equal to 10 V.

3.2. Description of the digital pulse processing

The acquisition of digitized samples (sampling frequency equal to 125 MHz) has been carried out with a ^{55}Fe source (low-energy x-ray photons: Mn-*K*α ~5.9 keV and Mn-*K*β ~6.5 keV). The raw data provided by the reset-type preamplifier is characterized by successive ramp signals of durations mainly comprised between 10 ms and 30 ms. The reset pulse is clearly identified by a typical swing signal (duration ~1 μs) which has to be accurately detected for the dead-time treatment. The following algorithm has been developed for the implementation of the pulse-height analysis, the counting and the dead-time processing.

- At first, a new original signal is obtained using a smoothing filter (4-sample averaging directly applied to the digitized pulse trains). The leading edge of x-ray pulses is defined by about 5 samples (corresponding to a rise time of about 160 ns) after the downsampling process.
- The "fast channel" is implemented using the 1st derivative of the Gaussian filter ($\sigma = 1$) applied to the smoothed signal. As described in the case of the NaI(Tl) detector, it is used to trigger the dead time as well as the pulse-height analysis. Subsequent pulses occurring during a dead-time period are only considered to extend the dead time.
- The treatment of the particular case of reset-type pulses is depicted in Fig. 4. The dead time is triggered by negative components delivered by the "fast channel"; the extendable dead time is systematically prolonged by both positive and negative components of fast signals. In that particular case, there is no counting and no pulse-height analysis. It can be observed in Fig. 4 that the reset-type pulses can be also identified by the signals of negative amplitude generated in the "slow channel".
- Triggered by pulses generated in the "fast channel", the pulse-height analysis and the counting are carried out in the "slow channel". A differentiation is implemented by subtracting from the original signal the same delayed signal (64 samples corresponding to ~2 μs). No pole-zero compensation is needed when using a reset-type preamplifier. The Gaussian filter is implemented for the smoothing of differentiated signals ($\sigma = 16$); the amplitude used for histogramming is given by the maximum value. The minimum dead-time period (128 samples corresponding to ~4 μs) is defined by the discrimination period.

The energy spectrum given by the digital pulse processing developed for the SDD connected to a reset-type preamplifier is displayed in Fig. 5 (counting rate ~200 s^{-1}). The FWHM energy resolution estimated on the Mn-*K*α peak is consistent with the

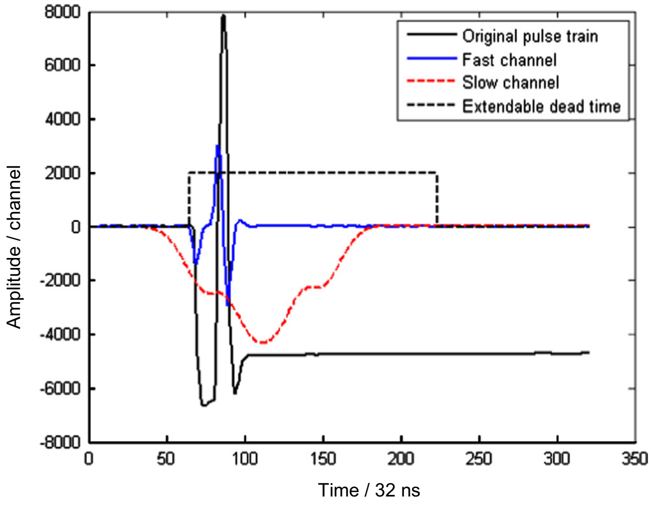

Fig. 4. These plots describe a procedure to detect reset-type signals that have to be taken into account in the dead-time processing. These spurious pulses are identified by the negative signals generated in the "fast channel" and also by the negative amplitudes in the "slow channel".

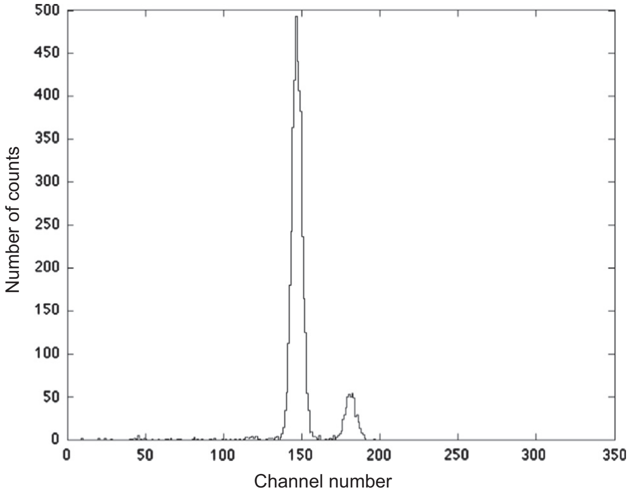

Fig. 5. ^{55}Fe energy spectrum obtained with a Silicon Drift Detector coupled to a reset-type preamplifier (Mn-*K*α ~5.9 keV and Mn-*K*β ~6.5 keV). The FWHM energy resolution on the Mn-*K*α peak (127 eV) is consistent with the value given by the manufacturer.

value given by the manufacturer. Because no entrance window was placed in front of the detector, the events observed at lower energies are attributed to electrons directly detected.

4. Discussion

The preliminary results obtained in the present work demonstrate that digital processing developed for image filtering can be adapted to digitized signals provided by nuclear detectors. This development has been associated with new front-end electronics specifically designed for the detectors used. The algorithms are based on a recursive implementation of the Gaussian filter proposed by Young and Van Vliet (1995). Translated from the standard use of a classical instrumentation, the digital pulse processing has been constructed in order to treat the digitized samples by two specialized channels ("fast" and "slow"). Computed with the 1st derivative of the Gaussian filter, the "fast channel" is used to detect the leading-edge of signals in order to trigger the dead-time management and the pulse-height analysis. The "slow channel" is implemented using the Gaussian filter (low-pass filter) for the amplitude determination. The algorithms were developed to match with the signals provided by two types of nuclear detectors: a high-efficiency NaI(Tl) well-type detector used for the 4πγ technique and a Silicon Drift Detector coupled to a reset-type preamplifier dedicated to x-ray spectrometry.

In the case of the 4πγ instrumentation, a specialized front-end electronics was designed in order to limit the distortion of high-amplitude signals usually encountered in a classical electronic chain. The objective was to reduce the influence of those signals in the dead-time processing. The first results have also shown that a low-energy threshold of about 2 keV can be obtained (~6 keV in classical electronic chain). This feature is particularly interesting for the zero-energy extrapolation needed for the 4πγ technique. It has to be mentioned that similar results were obtained at LNE-LNHB with the same well-type NaI(Tl) detector used by the Transfer Instrument of the International Reference System (Michotte et al., 2012) developed at BIPM for the comparison of short-lived radionuclide standardization (^{99m}Tc).

The implementation of recursive Gaussian filter in the FPGA circuit for an on-line processing is underway. Preliminary tests of the digital pulse processing were carried out with the Stratix III operating at a frequency equal to 62.5 MHz (due to the fact that the FPGA speed depends on the complexity of the code). As a smoothing filter based on an averaging of the digitized samples (125 MHz) is applied, this frequency does not represent a limitation for future developments.

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