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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 $4\pi\gamma$ 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 $4\pi\gamma$ 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.

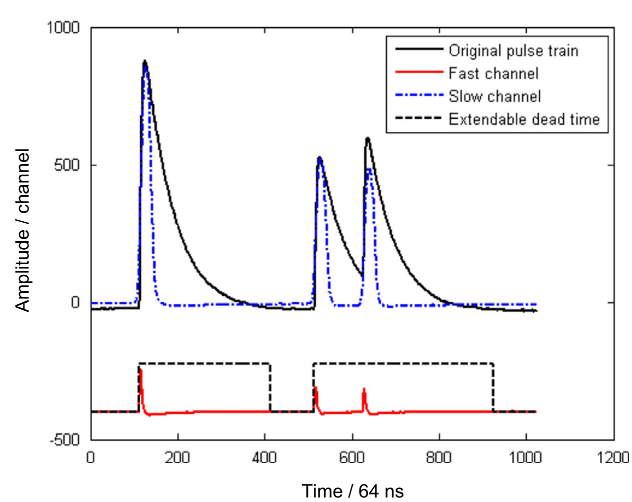

Fig. 1. Digital pulse processing applied to signals delivered by a high-efficiency well-type NaI(Tl) detector. The "fast channel" is used to trigger the extendable dead-time management (minimum duration equal to 300 samples) and the pulse-height analysis in the "slow channel".