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Overview of a FPGA-based nuclear instrumentation dedicated to primary activity measurements

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ABSTRACT

In National Metrology Institutes like LNE-LNHB, renewal and improvement of the instrumentation is an important task. Nowadays, the current trend is to adopt digital boards, which present numerous advantages over the standard electronics. The feasibility of an on-line fulfillment of nuclear-instrumentation functionalities using a commercial FPGA-based (Field-Programmable Gate Array) board has been validated in the case of TDCR primary measurements (Triple to Double Coincidence Ratio method based on liquid scintillation). The new applications presented in this paper have been included to allow either an on-line processing of the information or a raw-data acquisition for an off-line treatment. Developed as a complementary tool for TDCR counting, a time-to-digital converter specifically designed for this technique has been added. In addition, the description is given of a spectrometry channel based on the connection between conventional shaping amplifiers and the analog-to-digital converter (ADC) input available on the same digital board. First results are presented in the case of α- and γ-counting related to, respectively, the defined solid angle and well-type NaI(Tl) primary activity techniques. The combination of two different channels (liquid scintillation and γ-spectrometry) implementing the live-time anticoincidence processing is also described for the application of the $4\pi\beta$–γ coincidence method. The need for an optimized coupling between the analog chain and the ADC stage is emphasized. The straight processing of the signals delivered by the preamplifier connected to a HPGe detector is also presented along with the first development of digital filtering.

1. Introduction

Classical instrumentation dedicated to activity measurements is usually composed of numerous electronic modules having specific functionalities (counting, pulse shaping, pulse-height analysis for histogramming, dead-time processing, etc.). In several National Metrology Institutes (NMI) involved in radionuclide metrology, new nuclear setups are developed using programmable digital systems (Keightley and Park, 2007). At LNE-LNHB, this technology is investigated using FPGA-based (Field-Programmable Gate Array) boards (Censier et al., 2010; Bobin et al., 2010). A commercial digital system has been selected to enable the connection to standard detectors used by primary activity measurements such as: $4\pi\beta$–γ coincidence counting, TDCR (Triple to Double Coincidence Ratio) method, well-type NaI(Tl) technique and α-counting using Defined Solid Angle (DSA) measurements. In addition, an important specification was the ability to fulfill an on-line processing of the live-time technique using extendable dead-times as already carried out in the MTR2 module (Bouchard, 2000). The feasibility of this on-line implementation has been validated in the case of TDCR measurements based on liquid scintillation (LS) (Bobin et al., 2010).

This paper presents an overview of the new functionalities programmed in the digital board to allow on the one hand, on-line processing of information for routine measurements; and on the other hand, the acquisition of raw data for off-line developments. In the first part of this paper, alternatives to the standard processing of TDCR counting are presented. Based on extendable dead-times generated with single pulses, the counting delivered by the MAC3 module (Bouchard and Cassette, 2000) is compared to a processing triggered by coincidences between photomultipliers (PMT). Especially designed for TDCR measurements, a time-to-digital converter has also been implemented to enable the storage of two histograms filled with the time intervals necessary to obtain double and triple coincidences between PMTs.

In a second part, the development and the applications using a spectrometry channel are emphasized:

- As a first step, the validation of the on-line amplitude analysis of pulses delivered by conventional shaping amplifiers is presented. The spectrometry functionality is described as well as the modification of the front-end electronics designed to adapt the signals delivered by shaping amplifiers to the

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analog-to-digital converter (ADC). Comparisons with classical instrumentations are presented in the case of the 4π–γ method using a well-type NaI(Tl) detector and an α-counting system based on the DSA method with a PIPS detector. By a combination of both the LS and γ-spectrometry channels, the 4πβ–γ coincidence method is presented in the case of the live-time anticoincidence technique (Baerg et al., 1976; Bobin et al., 2007).

- And as a second step, sampling routines have been added to the digital board to store raw-data acquired from preamplifier signals for the development of digital filters according to an off-line implementation. Preliminary results are presented in the case of γ-spectrometry using a HPGe detector. The objective is to optimize the digital filters to be programmed afterwards in the FPGA device for on-line processing. The electronic interface specifically designed for a direct coupling between the preamplifier and the digital system is also described.

2. Description of the digital board

The digital platform has already been described in the case of TDCR measurements (Bobin et al., 2010). Produced by Altera®, the Stratix®III FPGA development kit has also been selected to enable 4πβ–γ coincidence measurements according to the live-time anticoincidence technique (Baerg et al., 1976; Bobin et al., 2007). An important specification was the possibility to implement nuclear-instrumentation functionalities according to an on-line processing: live-time technique, extendable dead-times, amplitude and timing histogramming, etc. Based on an Ethernet link (1 Gbits/s) using the UDP protocol (User Datagram Protocol), the exchange of information with a PC is done through a FPGA-programmed application. Two HSMC (High Speed Mezzanine Card) connectors are also available allowing two additional daughter-cards to be used. For spectrometry applications, one HSMC connector is tied to a dual 14-bits analog-to-digital converter (ADC) card (produced by Terasic and able to run at a maximum speed of 150 MSPS). As described in Section 4.1, the front-end electronics of this ADC (AD9254) has been modified to adapt its input possibilities to the signals delivered by usual shaping amplifiers (DC bandwidth, input voltage range). The digital board is also equipped with a 1 Gbytes DDR2 SDRAM memory allowing the storage of digitized signals such as those delivered by a HPGe-detector preamplifier.

3. Alternatives to the counting processing implemented in the MAC3 module

3.1. Extendable dead-times triggered on coincidences

Up to now, TDCR measurements have been implemented at LNHB using the MAC3 module (Bouchard and Cassette, 2000). In order to achieve a good protection against the excess of counting due to after-pulses, the acquisition is done using extendable dead-times combined to the live-time technique. The feasibility of a similar on-line processing in a FPGA system has been validated in a previous study (Bobin et al., 2010). The application of the TDCR method requires that the counting threshold has to be set before the single photoelectron. In the MAC3 module, the common dead-time between PMTs is triggered and prolonged by single pulses delivered by PMTs. The live-time duration is thereby sensitive to the signals generated by thermal photoelectrons. This effect can be reduced with dead-times only triggered by coincidences between PMTs. This processing has been implemented maintaining the prolongation of the dead-time period by single PMT pulses in order to take into account scintillation after-pulses.

The detection system described in previous studies remains unchanged (Bobin et al., 2010). Delivered by a setup composed of three XP2020Q PMTs, the pulses are first amplified by a fast amplifier module (Phillips scientific model 777) in order to feed afterwards a Constant Fraction Discriminator (CFD) module (Canberra Quad CFD 454). Used to set the threshold before the single photoelectron signal, this CFD module delivers logical pulses, which are directly treated by the FPGA through three connections available on the second HSMC connector. Several free connection pins of this HSMC connector are programmed for a real-time monitoring of the counting processing (dead-time, double and triple coincidences, etc.).

The comparison between the two dead-time triggering modes has been carried out using a ^{60}Co source in Ultima Gold. Using both modes, triple and double coincidences have been measured during the same time and corrected for background. The following counting settings have been applied in both cases: 6 cycles of 300 s measurement time, coincidence resolving time = 80 ns and minimum dead-time = 50 μs. In the case of the MAC3-type dead-time triggering, the following coincidence rates have been obtained: $(2950.7 \pm 1.5)\,s^{-1}$ for double coincidences and $(2867.3 \pm 1.5)\,s^{-1}$ for triple coincidences. Concerning the dead-time triggered by coincidences, the results are: $(2951.3 \pm 1.5)\,s^{-1}$ for double coincidences and $(2866.0 \pm 1.5)\,s^{-1}$ for triple coincidences. The results given by these two modes are in agreement within the counting uncertainty (the differences are lower than 0.05%). As expected, a significant difference is observed between respective live-time measurements: 214 s for the MAC3-type triggering and 248.7 s for the coincidence mode.

As described in Section 4.4, the triggering mode on coincidences is implemented for the anticoincidence processing when the counting in the β-channel is based on liquid scintillation.

3.2. Development of a time-to-digital converter specifically designed for TDCR measurements

In a previous study carried out for the validation of TDCR measurements, a significant influence on coincidence counting was observed when increasing the resolving time. Furthermore, it has been shown that this behavior cannot be disregarded when calculating the activity in the case of the standardization of ^{3}H (Mo et al., 2010; Bobin et al., 2010). It has been suggested that this fact is the consequence of a higher sensitivity of the coincidence counting to the fluorescence lifetime due to the low number of scintillation photons emitted when measuring low-energy emitters (such as ^{3}H).

In the MAC3 and the FPGA-based modules, triple and double coincidences are counted using a resolving time that has one drawback: the information related to the time-arrival fluctuations between PMTs is not recorded. Digital systems can overcome this problem with the complete storage of PMT timestamps for off-line counting processing (Steele et al., 2009). Based on the usual time-to-digital converter (TDC) functionalities, an interesting alternative is to store time-interval durations following the dead-time triggering according to two time histograms corresponding, respectively, to double and triple coincidences.

As already described for TDCR measurements with the FPGA board (Bobin et al., 2010), the common extendable dead-time is implemented using the CFD logical pulses. The dead-time triggered by a CFD pulse in a first PMT is used to start the TDC application. The subsequent CFD pulses that come from the two other PMT channels are used to stop the time-measurement process. The duration between a “start” and a detection in a second PMT is recorded in the double-coincidence histogram;