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Time resolution studies using digital constant fraction discrimination

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Abstract

Digital Pulse Processing (DPP) modules are being increasingly considered to replace modular analog electronics in medium-scale nuclear physics experiments (100–1000s of channels). One major area remains, however, where it has not been convincingly demonstrated that DPP modules are competitive with their analog predecessors—time-of-arrival measurement. While analog discriminators and time-to-amplitude converters can readily achieve coincidence time resolutions in the 300–500 ps range with suitably fast scintillators and Photomultiplier Tubes (PMTs), this capability has not been widely demonstrated with DPPs. Some concern has been expressed, in fact, that such time resolutions are attainable with the 10 ns sampling times that are presently commonly available.

In this work, we present time-coincidence measurements taken using a commercially available DPP (the Pixie-4 from XIA LLC) directly coupled to pairs of fast PMTs mated with either LSO or $LaBr_3$ scintillator crystals and excited by ^{22}Na γ-ray emissions. Our results, 886 ps for LSO and 576 ps for $LaBr_3$, while not matching the best literature results using analog electronics, are already well below 1 ns and fully adequate for a wide variety of experiments. These results are shown not to be limited by the DPPs themselves, which achieved 57 ps time resolution using a pulser, but are degraded in part both by the somewhat limited number of photoelectrons we collected and by a sub-optimum choice of PMT. Analysis further suggests that increasing the sampling speed would further improve performance. We therefore conclude that DPP time-of-arrival resolution is already adequate to supplant analog processing in many applications and that further improvements could be achieved with only modest efforts.

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1. Introduction

Intermediate scale nuclear experiments requiring 100–1000's of electronic signal processing channels are not well served at present either by conventional modular (e.g. NIM) electronics or by ASICs. The former are bulky, expensive and difficult to set up, calibrate and re-configure by hand on a large scale, while the latter have long expensive development cycles, cannot be reconfigured to adapt to changing needs, and typically sacrifice some performance to meet compactness and low-power requirements. Digital Pulse Processing (DPP) modules with relatively high densities at a reasonable cost per channel have become available that implement many of the classical analog processing functions (i.e. pulse discrimination, energy filtering, pile-up inspection, and coincidence and multiplicity triggering) at least as well as modular analog electronics. Further, these DPP modules are more readily scalable to larger experiments than simple trace digitizers because their on-board processing can substantially reduce the amount of bandwidth needed to export event data over data buses.

Thus, since DPP technology appears to be otherwise scalable to these intermediate experiments, we decided to benchmark its Time-of-Flight (TOF) capability to determine whether that too could match or surpass the analog state of the art. We therefore undertook to develop a Constant Fraction Discriminator (CFD) that could be readily implemented in a Field Programmable Gate Array (FPGA) and tested it with both a digital pulser and in coincidence timing measurements using fast scintillators

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and PMTs. Obtaining results that are competitive but not state of the art, we also investigated the factors limiting our results in order to set the stage for future improvements.

2. Material and methods

2.1. DGF-Pixie Hardware

For a DPP module we used the DGF Pixie-4 and Pixie-16, members of XIA LLC's DGF-Pixie family. These multi-channel coincidence spectrometers with a Compact PCI interface share clock and trigger signals over a PXI backplane and are intended for small to medium nuclear physics setups [1]. The 4-channel Pixie-4 (3U format) is flexible enough for small prototype systems, and the 16-channel Pixie-16 (6U format) handles larger channel count applications. After DC coupled amplification and Nyquist filtering, the modules directly digitize their input signals and implement pulse detection, energy filtering, pile-up inspection and discrimination operations all digitally, primarily in an FPGA, with a Digital Signal Processor (DSP) available for more complex operations. They have onboard memory for storing spectra and captured traces and can export data over the PXI bus at up to 100 MB/s.

2.2. CFD development

$$\int \mathrm{CFTrace}[k] = \sum_{i=1}^{L} \{\mathrm{F} * \mathrm{Trace}[k-i] - \mathrm{Trace}[k-i-D]\}. \quad (1)$$

Our first task was to develop an algorithm that would be "FPGA friendly" so that, if successful, it could easily be implemented. We therefore investigated processes of the form shown in Eq. (1), which digitally approximates the classic analog CFD by subtracting a pulse's signal trace delayed by D from a fraction F of the original trace and then computing the resultant signal's first zero crossing to digitally estimate the pulse's time-of-arrival. The running averaging of length L is for noise reduction. This class of CFD is readily implemented in modern FPGAs using FIFOs (for D), shift registers (for F), and accumulators (for L). Linear interpolation can either be done in the FPGA through successive approximations or carried out in the DSP [1]. In this work, we computed zero crossing times by simple linear interpolation between the first CFTrace points above and below zero. To optimize the filter, we captured signals in several timing situations described below, processed them offline using Eq. (1), and adjusted D, F and L to obtain the best timing resolution.

Fig. 1 shows a typical LSO scintillator trace, together with CFTrace computed using values $L = D = 1$ and $F = 0.5$. As shown, these pulses have sufficiently fast risetimes that the zero crossing point lies well up on the pulse's rising edge and thus may show a certain amount of jitter, depending upon the arrival time of the pulse relative to the digital clock's edge transitions. The maximum of the shown pulse integral is proportional to the number of photoelectrons collected, a point that we will discuss later.

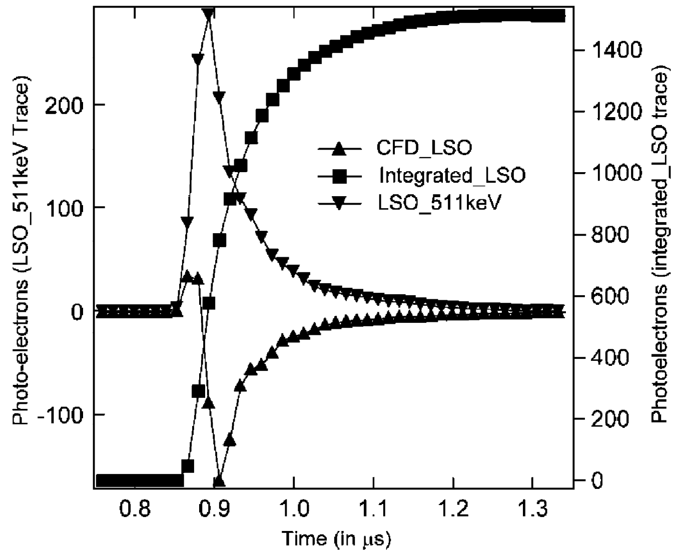

Fig. 1. PMT output pulse and computed CFTrace ($L = D = 1$, $F = 0.5$) from a 511 keV event in LSO. The integral of the PMT pulse is also shown.

2.3. TOF setups

We generated TOF signals in two ways. The first was using an in-house pulser that makes up to 16-buffered copies of arbitrary waveforms generated digitally in an FPGA and fed to a fast 14-bit Digital–to-Analog Converter (DAC). With the pulser set to produce pulses having 50 ns risetimes and 2.5 μs exponential decay times, its outputs were connected to pairs of DGF-Pixie inputs using RG-58 cables of calibrated lengths (equal or unequal) to create pulses having precisely separated arrival times.

The second signal source was from a pair of fast Photonis XP2020 2" PMTs, both coupled either to $2 \times 2 \times 3\,\mathrm{mm}^3$ LSO crystals (unwrapped) or to 1 in. diameter by 1 in. high $LaBr_3$ crystals (Teflon wrapped and canned), and facing oppositely a 1 μCi ^{22}Na source. The PMTs were biased at −1700 and −1350 V for LSO and $LaBr_3$ respectively for photocurrent non-linearity below 1%. Typical count rates were 100 cps for LSO and 4,000 cps for $LaBr_3$. Fig. 2 shows energy resolutions obtained from the LSO (12%), $LaBr_3$ (3.9%) and the pulser (0.04%). We note degraded energy resolution from the tiny unwrapped LSO crystals.

2.4. Trace capture

The Pixie-4 and Pixie-16 were configured to capture data only for detected coincidence events. Thus, when either channel's fast trigger filter detected a pulse it issued a fast wired-OR trigger and started its FIFO collecting a digitized signal trace. When the pulse was validated after pile-up