Sub-Nanosecond Time Resolution in Time-of-Flight Style Measurements with White Rabbit Time Synchronization

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Abstract— **As radiation detector arrays in nuclear physics applications become larger and physically more separated, the time synchronization and trigger distribution between many channels of detector readout electronics becomes more challenging. Among applications requiring the highest precision are time-of-flight measurements which try to determine the time difference in two or more related particle interactions in two or more separate detectors to sub-nanosecond precision, ideally in the tens of picoseconds. Clocks and triggers are traditionally distributed through dedicated cabling, but newer methods such as the IEEE 1588 Precision Time Protocol and its high accuracy profile (White Rabbit) allow clock synchronization through the exchange of timing messages over Ethernet.**

We report here the use of White Rabbit, implemented in the Pixie-Net XL detector readout electronics, to synchronize multiple modules that read out separate detectors. The timing performance is characterized both coincident gamma rays from ^{22}Na and a split pulser signal. Time resolutions are about 300 ps full width half maximum for ^{22}Na and about 90 ps for the pulser, compared to ~15 ps for 2 channels on the same module using the pulser.

I. Introduction

In[1] large nuclear physics applications, which can include hundreds or thousands of separate detector channels, it is usually required to synchronize the clocks of multiple digital detector readout electronics modules to ensure that data from different channels can be matched by their time stamps and that time differences can be computed to high precision, for example in time of flight measurements or coincidence windows. Such clocks and triggers are traditionally distributed through dedicated cabling, which can become quite complex. The timing requirements depend on the application, and can range from hundreds of nanoseconds for coincidence background measurements to ideally tens of picoseconds for time-of-flight measurements. More recently, high precision time synchronization through data networks has been developed, such as the IEEE 1588 precision time protocol (PTP) [1] and its high accuracy profile, White Rabbit (WR) [2]. Since detector readout electronics are usually already connected to a data network for readout to storage, these methods can be used as an alternative to dedicated cabling. The challenge for the use of such techniques in detector readout electronics is to integrate the synchronization with the data capture from analog to digital converters (ADC) and the processing of digitized detector signals in a field programmable gate array (FPGA). We reported previously [3] how this has been implemented for a new electronics module, the Pixie-Net XL. In this paper, we show results of measurements to characterize its timing performance.

II. Experimental Setup

A. Pixie-Net XL Electronics

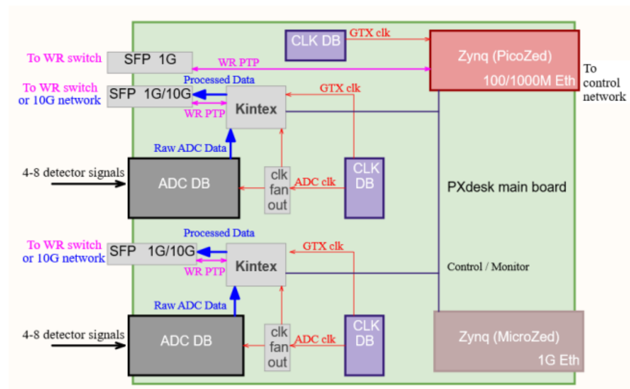

Fig. 1. Block diagram of the Pixie-Net XL. Note the high speed data flow is directly from ADC to FPGA to SFP (Ethernet) and can reach up to 10 Gbit/s.

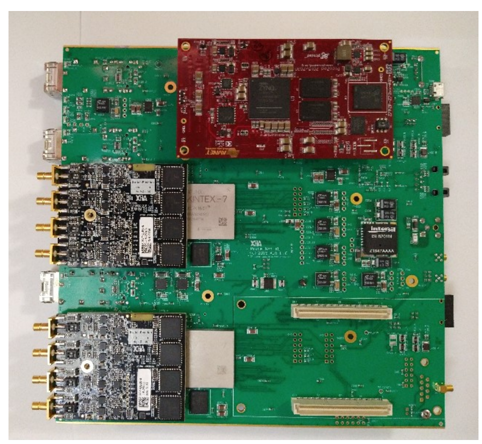

Fig. 2. Picture of the Pixie-Net XL electronics boards

As shown in Fig.1 and Fig.2, the Pixie-Net XL electronics hardware design [3] centers on two Kintex 7 FPGAs. Each FPGA is connected to a high density connector for ADC daughter cards that implement multiple channels of analog

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signal conditioning and digitization. Four daughter cards have been used in this work so far:

- DB01 with a 125 MSPS, 14bit quad ADC for 4 channels with single ended coaxial input signals,
- DB04 with four 250 MSPS, 14bit dual ADCs for 8 channels,
- DB06 with four 250 MSPS, 16bit ADCs for 4 channels,
- DB06 with four 500 MSPS, 14bit ADCs for 4 channels.

Each FPGA is further connected to an SFP card cage for 1G Ethernet with WR or 10G Ethernet without WR and to a variety of general purpose I/O connections and to other peripherals. A clock daughtercard for each FPGA implements the voltage controlled oscillators used by the WR IP core. Both FPGAs are also connected to a slower control and setup bus from a Zynq processor module (Avnet MicroZed or PicoZed) that is used to configure the FPGA, set parameters, and read out data in diagnostic mode. The PicoZed can also implement the WR IP core which allows the unit to operate with WR synchronization and 10G Ethernet output from the Kintex FPGAs. The fully assembled Pixie-Net XL is shown in Fig. 3.

Fig. 3. Picture of the fully assembled Pixie-Net XL

B. Signal Sources and Analysis

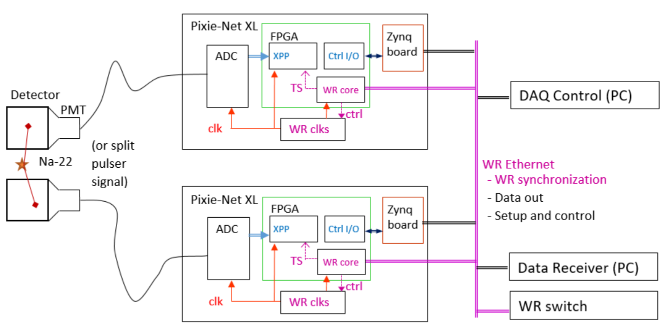

Fig. 4. Setup of time-of-flight measurements. The White Rabbit switch is acting as a data router and clock master. Detectors can be replaced with a pulser signal split between both ADCs.

Simplified time-of-flight measurements are set up with a ^{22}Na source emitting coincident radiation placed between two $LaBr_3$ detectors. The detector signals are digitized in the Pixie-Net XL's ADCs. Pulses are detected in the FPGA trigger logic (roughly 300 counts/s), timestamped with the WR time and a "local time" that is reset at the start of the data acquisition and increments synchronous with the WR clock, and recorded as event-by-event list mode data. Data acquisition control, WR synchronization, and list mode data storage use the same 1G Ethernet network managed by a WR switch. In non-WR comparison measurements, a 10G network was used for list mode data. In pulser reference measurements, a CAEN DT5810B replaced the $LaBr_3$ detectors (1000 counts/s). The list mode data is used to compute the difference of the time of arrival in the two channels, using time stamps and captured waveforms (linear interpolation of two samples closest to a constant fraction (CFD) threshold). The threshold level was optimized for each measurement. The time difference is histogrammed for typically 5,000 pulse pairs and the full width at half maximum of a Gaussian fit of the resulting distribution is what we call the time resolution. In $LaBr_3$ measurements, only those pulse pairs were histogrammed that deposit 511 keV in each detector, which improves the time resolution by a few hundred picoseconds at the expense of ~80% of the acquired pulses. Three sets of measurements were performed:

(1) Every ADC daughtercard with the same (reference) pulser output signal, using a) 2 channels in the same daughtercard, b) 2 separate units synchronized via WR in the Kintex and c) 2 separate units synchronized via WR in the PicoZed. (The input signal shape and amplitude unavoidably vary slightly due to the different gain, bandwidth and cabling of the daughtercards.)

(2) DB04 daughtercard with pulser sample and amplitude optimized, subsets a) and b)

(3) DB04 daughtercard with $LaBr_3$, subsets a) and b)

III. Characterization Measurements

A. Time Resolution

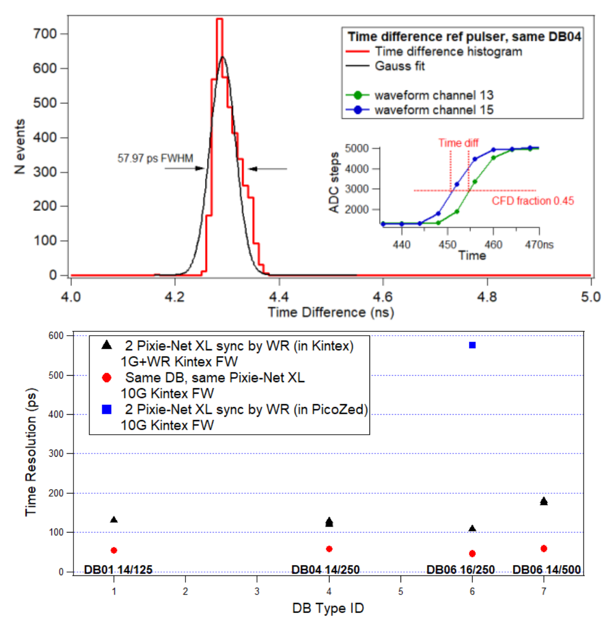

Fig. 5. Time resolutions in measurements set 1b (top) and all of 1 (bottom).

Fig.5 (top) shows a typical pulse shape and time difference histogram for DB04, measurement set (1a). Fig.5 (bottom) shows complete set (1) results. Time resolutions in the same daughterboard (1a) are typically 50-60 ps FWHM; 100-200 ps for WR Kintex synchronization (1b); and ~550 ps for WR PicoZed synchronization (1c). Fig.6 shows time resolutions for all types of measurements with DB04, plus DB06 PicoZed pulser tests and a Pixie-4e reference test for $LaBr_3$. Optimized pulser resolutions are ~15 ps for the same daughterboard and ~90 ps for WR Kintex synchronization, independent of data rate or length of the data acquisition. Tests with $LaBr_3$ produce resolutions of ~300ps, with the WR measurements actually being the lowest (222 ps).This, however, is more of an indication of the delicate nature of these timing measurements than the superiority of WR over using the same clocks.

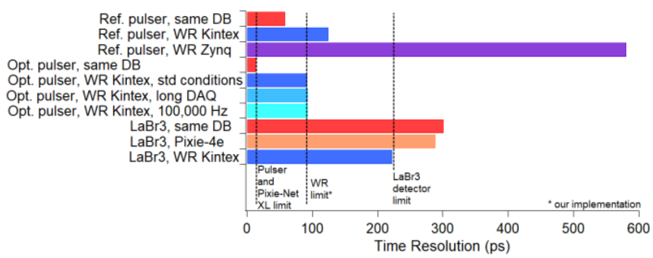

Fig. 6. Time resolutions for DB04 in modes 1 (Ref pulser), 2 (Opt. pulser), and 3 ($LaBr_3$). Same-daughterboard shown in red, WR synchronization (Kintex) in blue. For comparison, PicoZed WR synchronization is shown in purple and Pixie-4e reference tests in orange.

B. Energy Resolution

Since the Pixie-Net XL is designed as a detector readout module, we also measured its energy resolution with a high purity Germanium detector. At combined ~1400 counts/s (input rate), from multiple sources, we measured full width at half maximum (FWHM) energy resolutions of ~0.14% at 1.3 MeV and just below 0.1% for 2.6 MeV (Fig. 7).

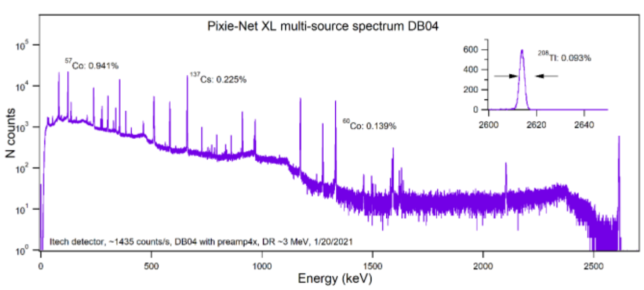

Fig. 7. Pixie-Net XL multi-source spectrum with HPGe detector (DB04).

C. Data Output Rates

Processing throughput in list mode, i.e. recording energy, timestamps, and waveforms for every event, is characterized events with 1us waveforms, ignoring the digitization rate and data format. For measurements with the 1G firmware, we used the WR IP core as the Ethernet data interface, and received data in a Windows 7 PC with a standard 1G Ethernet port (RG-45), using an SFP to RG-45 for the Pixie-Net XL SFP output and a generic 1G Ethernet switch. For measurements with the 10G firmware, we used the 10G IP core as the Ethernet data interface, and received data in a Linux PC with a 10G network card with SFP ports. Data was directed through a 10G switch [4]. In both cases, throughput was measured by the programs tcpdump, bmon, and/or wireshark, as well as file size on disk.

Fig.8 shows list mode data throughput limits for several current and historic pulse processor modules made by XIA. We can see that the throughput for our implementation of the 1G Ethernet interface is roughly equivalent to the PCIe interface of the Pixie-4e and that the throughput for the 10G Ethernet is significantly higher. We note that when waveforms are transferred in 10G mode, the bottleneck is the PC writing the data to disk (all events arrive at the PC but they can not be saved quickly enough).

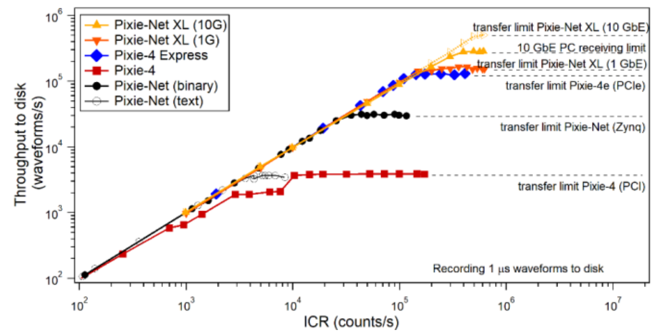

Fig. 8. Throughput as a function of input count rate for several of XIA's pulse processing units

IV. Summary

In summary, we measured time-of-flight style time resolutions with detector readout electronics synchronized by White Rabbit and compared to traditional "shared clock" performance. Resolutions are about 300 ps FWHM with $LaBr_3$ independent of the method of synchronization, indicating that WR is sufficient and equivalent to sharing clocks for many timing experiments. With a pulser, WR synchronization reached about 90 ps, compared to ~15 ps for shared clock, indicating the performance limit of our WR implementation. The electronics achieves good energy resolution and is capable of streaming out ~200,000 events/s or 70 MB/s through the WR 1G interface (~500,000 events/s or 360 MB/s with the 10G interface) for each of the two ports.

[1] IEEE 1588-2019 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems. IEEE Standards Association [Online]. Available: https://standards.ieee.org/ieee/1588/6825

[2] M. Lipiński, T. Włostowski, J. Serrano and P. Alvarez, "White Rabbit: a PTP application for robust sub-nanosecond synchronization," 2011 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication, Munich, pp. 25-30, 2011. doi: 10.1109/ISPCS.2011.6070148

[3] W. Hennig, S. Hoover, "White Rabbit Time Synchronization for Radiation Detector Readout Electronics". IEEE Trans. Nucl. Sci. Volume: 68, Issue: 8, August 2021, p 2059. doi: 10.1109/TNS.2021.3085242

[4] Mikrotik CRS309-1G-8S-+IN or CRS306-1G-4S+IN. [Online] Available https://mikrotik.com