White Rabbit Time Synchronization for Radiation Detector Readout Electronics

W. Hennig, S. Hoover • XIA LLC, 31057 Genstar Rd, Hayward, CA 94544, USA • whennig@xia.com

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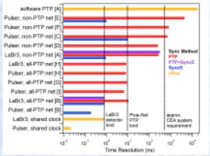
Background

Radiation detector systems in nuclear physics applications are often large arrays of individual detectors and can be physically separated in different rooms or buildings. In such systems, the time synchronization of the data collected from different detectors is essential to reconstruct multi-detector events such as scattering and coincidences. Traditionally, this is accomplished by distributing clocks and triggers via dedicated connections, but newer methods such as the IEEE 1588 Precision Time Protocol (PTP) and White Rabbit (WR) allow clock synchronization through the exchange of timing messages over Ethernet. Consequently, we report here the use of White Rabbit in a new detector readout electronics module, the Pixie-Net XL.

Previous work [1] studied the use of PTP and Synchronous Ethernet (SyncE) for synchronization of detector data from multiple Pixie-Net modules, an earlier and smaller version of the digitizing and pulse processing electronics described here. The time resolution for coincident events reached ~10ns FWHM with PTP synchronization and 200-800ps FWHM with SyncE synchronization, compared to 20-50ps FWHM with a dedicated clock connection. Thus we concluded that PTP and SyncE are good alternatives for a number of applications (e.g. coincidence background suppression), but not sufficient for the most demanding applications (e.g. time of flight measurements requiring <100ps timing). Preliminary tests with a commercial WR demo kit obtained better time resolution than SyncE (~150ps FWHM) and thus in the current stage of the project we integrated the WR firmware and hardware into the new electronics.



[A] Dell PowerConnect 2216 non-PTP
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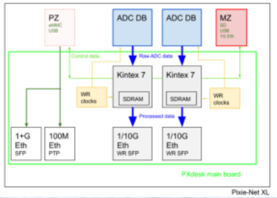
[G] Moxa EDS-405A-PTP, PTP
[H] Oregano syn1588, PTP
[I] Artel Quarra 2800, PTP

Figure 1. Summary of FWHM time resolution for various signal sources and PTP/SyncE network configurations with Pixie-Net electronics (pictured left)

Pixie-Net XL Hardware design

The electronics hardware design centers on two Kintex 7 FPGAs on the "PXdesk" main board. Each FPGA is connected with high speed LVDS lines, gigabit transceiver lines, and slower CMOS control lines to a high density connector for ADC daughter cards that implement multiple channels detector signal digitization. Moving the ADC circuitry to a daughter card allows customization of the inputs for different applications. Each FPGA is further connected to a dedicated 4Gb SDRAM memory for buffering of output data, an SFP card cage for 1G Ethernet for the WR connection (capable of 10G with upgrades), and a variety of general purpose I/O connections and other peripherals. Both FPGAs are further connected to a daughterboard implementing the DAC controlled oscillators from WR reference designs [2], which also clock the ADCs (with buffers).



- **ADC DB:** ADC daughtercards for detector readout (flexibility in ADC channels, rate, precision, or non-ADC functions)
- **MZ:** Zynq controller board (MicroZed [3]) reused from Pixie-Net (optionally PicoZed, PZ)
- High speed data flow from ADC to FPGA to WR Ethernet output
- WR, PTP, SyncE can be used as source for ADC and FPGA clocking

- Targets:
  - <100ps timing resolution
  - 10G Ethernet
  - processing ~1M pulses/s

Prototypes built so far

PXdesk main board with ADC daughtercards and Zynq controller

Fully assembled box

4-channel, 75-125 MHz, 14bit ADC daughtercard

8-channel, 250 MHz, 12bit ADC daughtercard Differential inputs via HDMI cable

4-channel, 16bit, 250 MHz or 14bit, 500 MHz ADC daughtercard

Figure 2. Pixie-Net XL block diagram and pictures

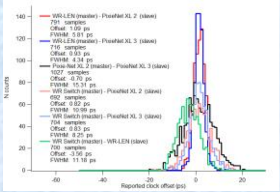
About XIA LLC

XIA LLC invents, develops and markets advanced digital data acquisition and processing systems for x-ray, gamma-ray, and other radiation detector applications in university research, national laboratories and industry. Having pioneered digital detector readout electronics for over 20 years, our most recent new products integrate PTP and/or White Rabbit

Timing Characterization Measurements

SW/FW reports

- The WR "SoftPLL" core reports performance values, e.g. the clock offset of WR slave to WR master.
- Measured for a variety of commercial WR modules and the Pixie-Net XL
- Histogramm offsets, apply Gauss fit



- Timing resolutions 4.3-15.3 ps FWHM
- No significant difference between commercial WR modules and Pixie-Net XL

But is a SW report a good measure for actual performance ??

Clock jitter tests

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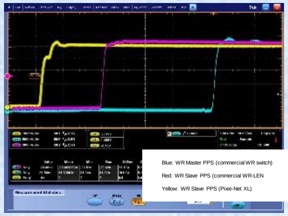
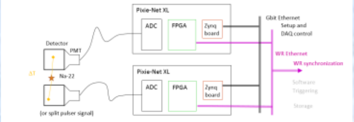
- Oscilloscope reports std.dev. of delay from edge to edge (= "jitter")

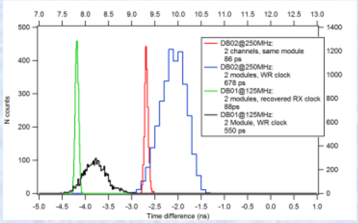


- Pixie-Net XL jitter is ~100ps, but commercial WR module reaches 10-15ps
- Further probing shows tuned WR clock on Pixie-Net XL is unusually jittery, and clock fanout for ADCs adds even more jitter (~300ps)
- But fortunately the Recovered RX Ethernet clock is low jitter (17ps) and can be routed from FPGA to ADC as a workaround

Time of Flight (Pulser)

- Two detector signals (or split pulser) connected to two Pixie-Net XL synchronized via WR
- Capture waveforms and timestamps, compute sub-sample time of arrival by interpolation on rising edge [6]
- Histogram the difference of time of arrival ΔT in both modules, apply Gauss fit
- This is the measure of performance closest to "real world" applications
- Below 100ps resolution, performance depends strongly on pulse shape, interpolation method, etc





Cosmic coincidences

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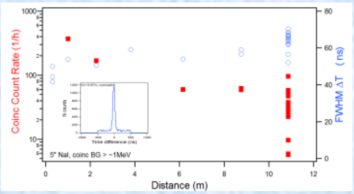

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References and Acknowledgments

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[2] https://ohwr.org/project/white-rabbit
[3] http://zedboard.org/product/microzed
[4] https://www.xia.com/dgf_products.html
[5] http://xillybus.com/xillybus-lite
[6] equivalent to A. Fallu-Labruyere et al, NIM A 579 (2007), p247.
[7] M. Lipinski, et al, 2011 IEEE Intl. Symposium on Precision Clock Synchronization for Measurement, Control and Communication

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2) Controller I/O with Zynq board to write processing parameters and read out data in slow debug mode, using [5].
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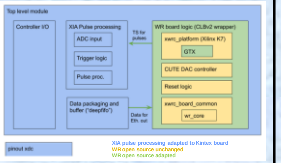

Figure 3. Pixie-Net XL firmware block diagram

Software Triggering

To further reduce cabling complexity, we are developing "software triggering", where decisions to record data are made through the exchange of data packets over the network by software instead of hardwired connections. Each Pixie-Net XL in a multi-module system will send out minimal data packages (metadata) which are used by a central Decision Maker (DM) to make accept/reject decisions, which are then communicated back to all Pixie-Net XL modules. The Pixie-Net XL then independently move their full data to long term storage or discard.

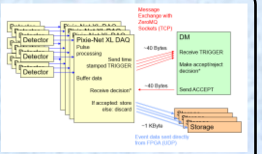

Figure 4. Concept of software triggering, for example to apply coincidence decision during the data acquisition without the need of hardwire logic.

Detector Readout Performance

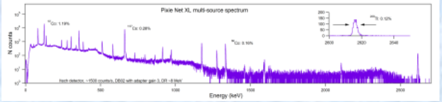

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Figure 5. Multi-source HPGe spectrum with DB02 (12bit, 250 MSPS).

Summary

We implemented the White Rabbit time synchronization in a new detector readout electronics module, the **Pixie-Net XL**. Time resolutions in preliminary measurements are 5-15ps per software output, ~100ps per clock jitter measurements and ~500ps per digitized coincident pulser signal; overall well below 1ns. The method has been proven suitable for distances of more than 10m. A software triggering scheme has been demonstrated and performance with radiation detectors is being characterized

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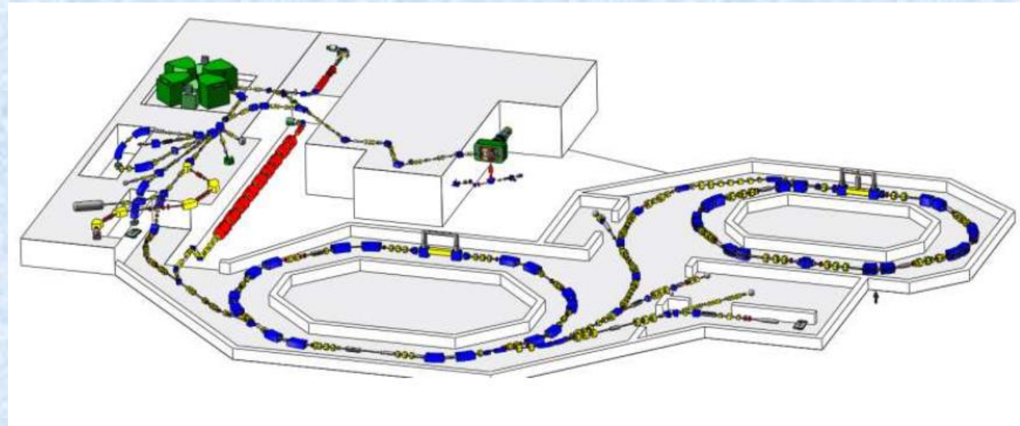
Motivation

Large nuclear physics experiments often use physically separated radiation detectors

Electronics to read out detectors must be synchronized to 100ns-100ps, ideally <10ps

Traditionally use clock/trigger cables for synchronization ☹



XIA has been developing digital data acquisition electronics for radiation detector applications for over 20 years

Modern technologies allow time synchronization through data network

New DAQ electronics with White Rabbit / PTP synchronization

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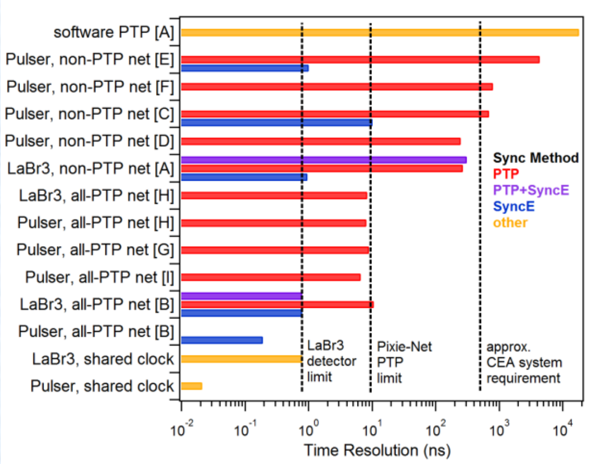

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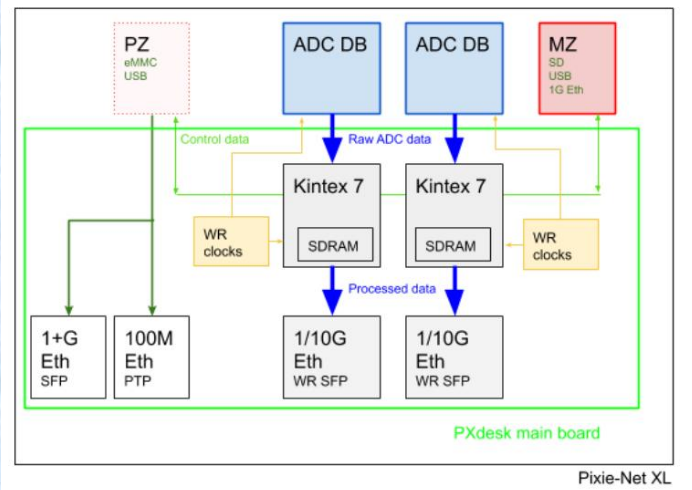

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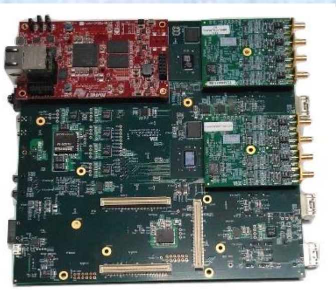

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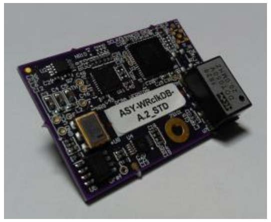

White Rabbit Clock Daughterboard

Figure 2. Pixie-Net XL block diagram and pictures

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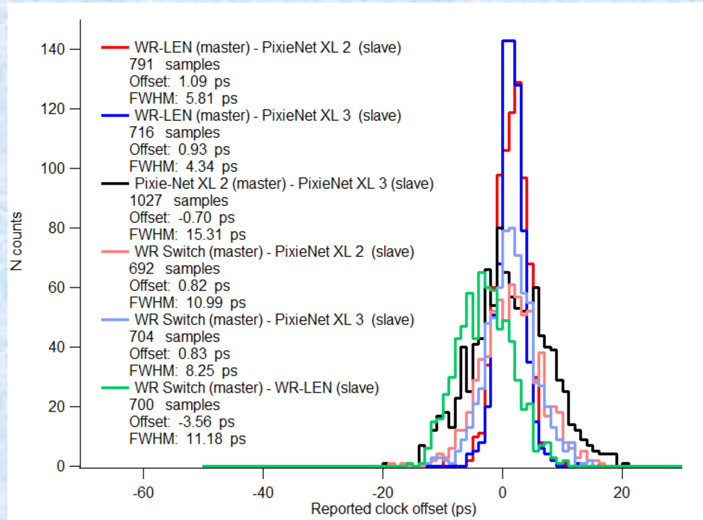

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Blue: WR Master PPS (commercial WR switch)

Red: WR Slave PPS (commercial WR-LEN

Yellow: WR Slave PPS (Pixie-Net XL)

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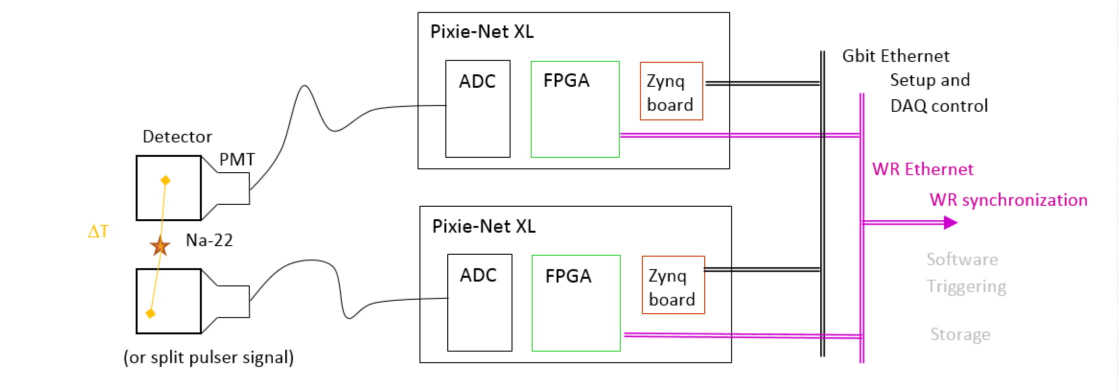

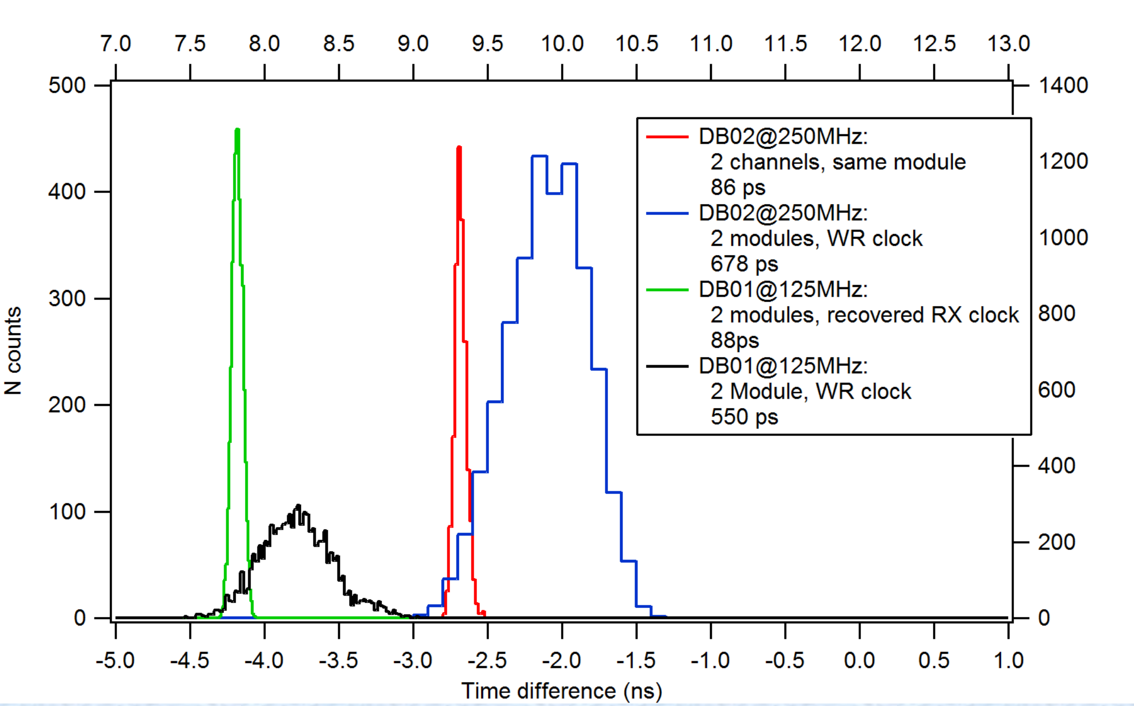

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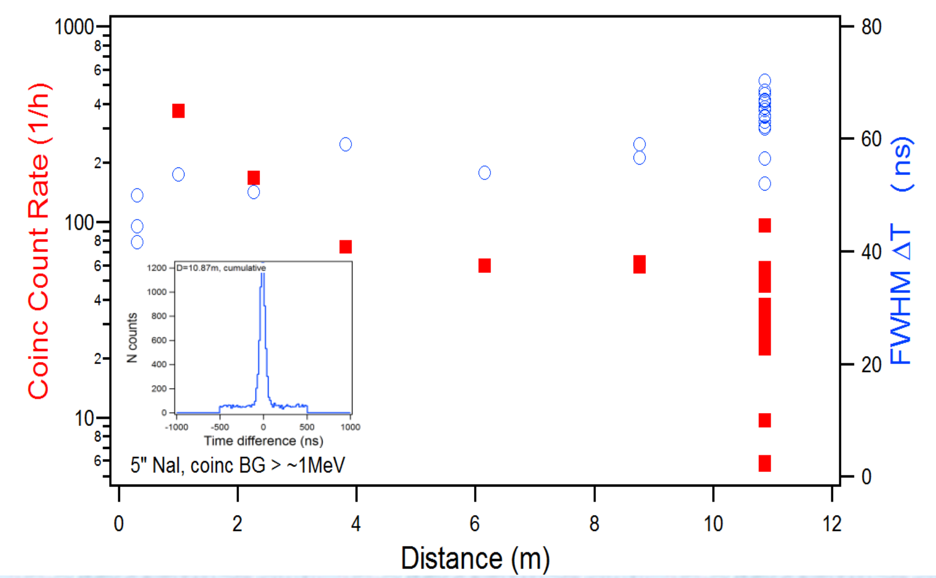

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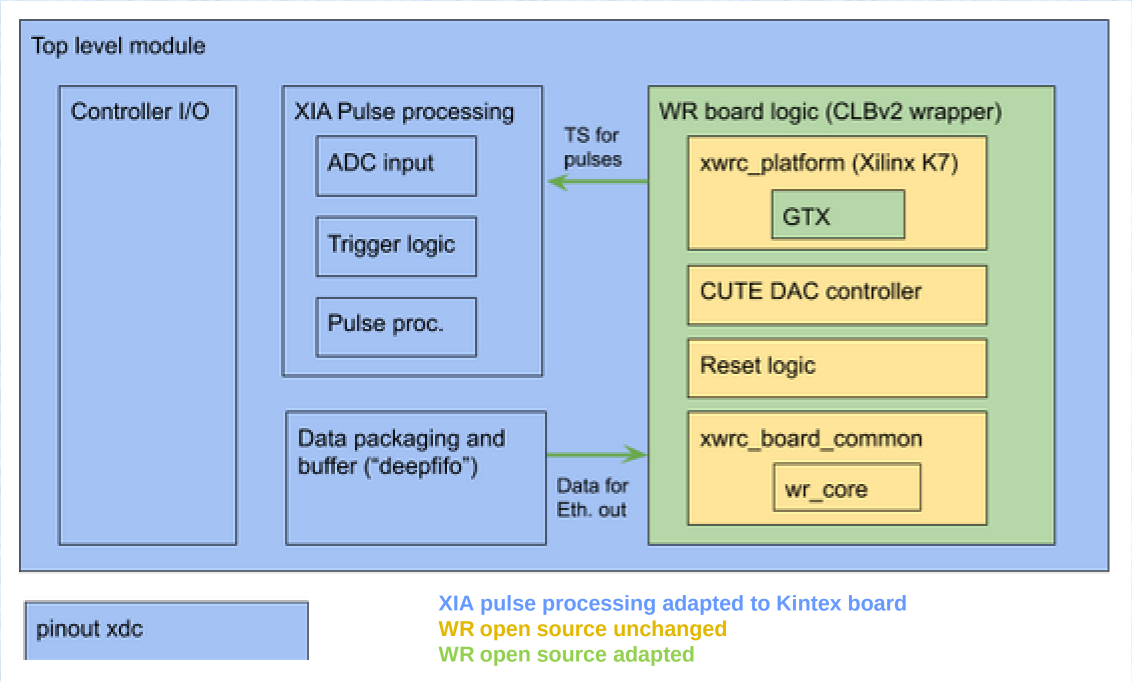

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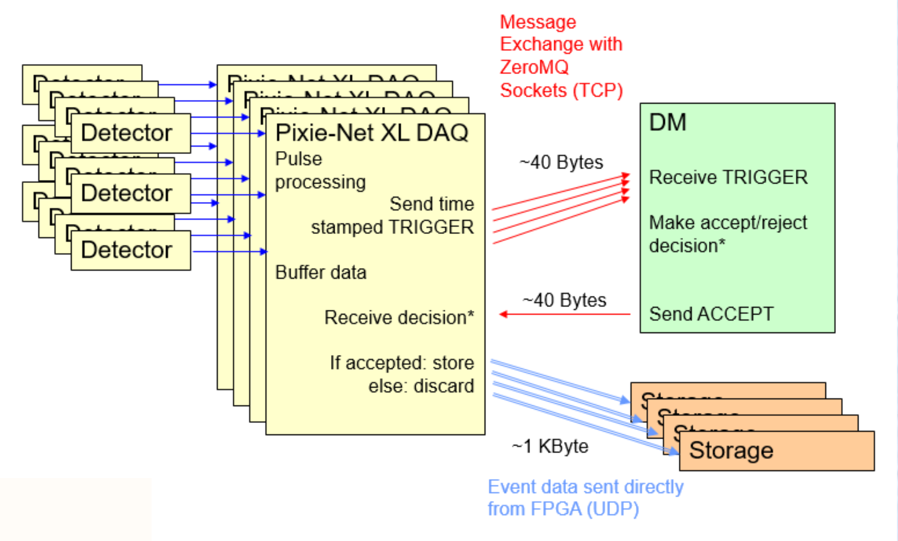

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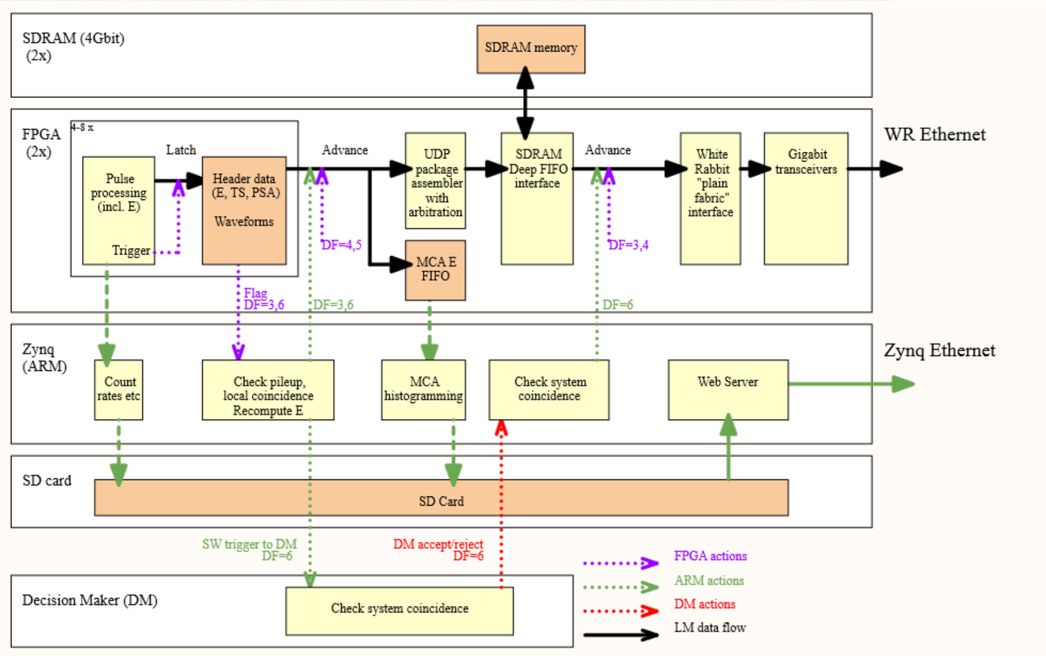

Figure 4b. Data flow in FPGA

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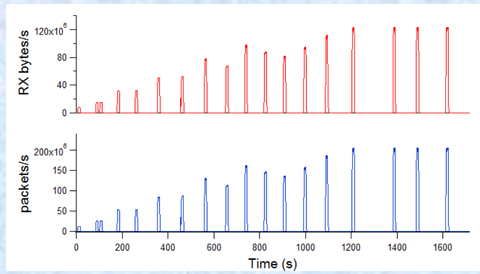
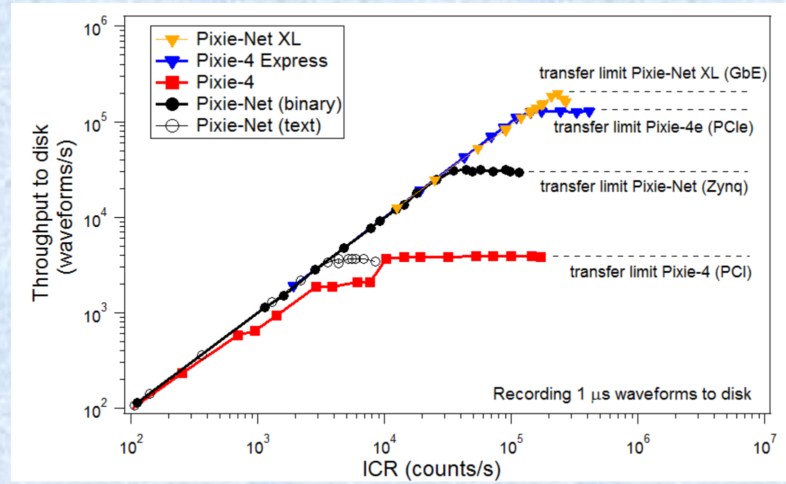
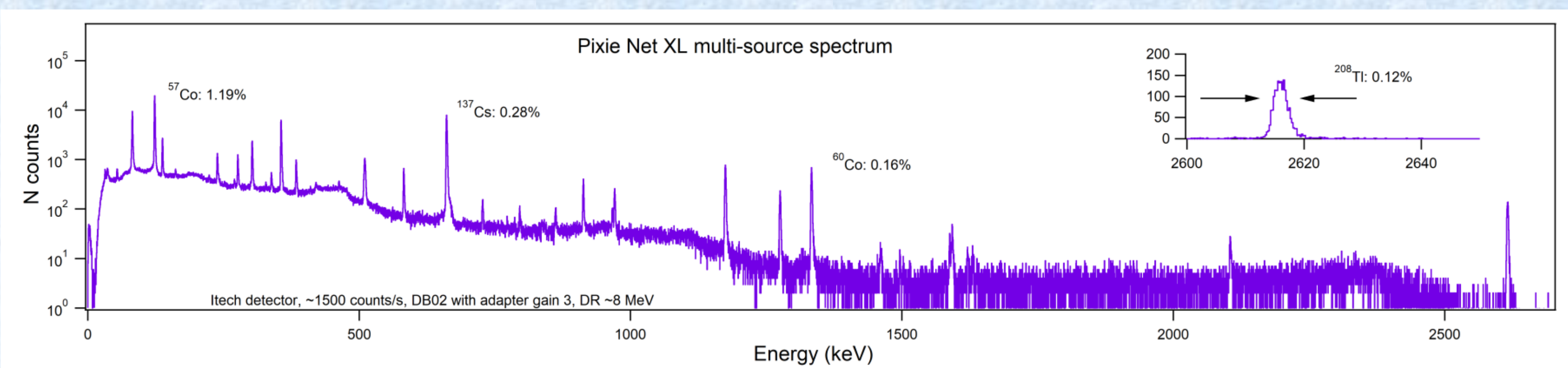


Preliminary tests of the list mode data output throughput, in comparison to previous Pixie DAQ modules are summarized in the plot to the right. Using the "bmon" utility on the receiving PC, we measured RX rates from the Pixie Net-XL of ~122 MB/s or ~200,000 packets/s (above), with each packet containing a list mode record with header and 1us waveform.





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Key results:

- White Rabbit IP core integrated into detector readout pulse processing logic
- HW design with multiple ADC daughtercard options
- Software triggering scheme
- Sub-nanosecond timing resolution in time-of-flight type measurements
- 1Gbps Ethernet data output with White Rabbit synchronization, demonstrated 10Gbps data capability of hardware

Outlook

To bring this project to completion, we plan to

- Revise and finalize the clock circuitry for minimal jitter
- Explore the Dolosse data management scheme in the data readout
- Fully characterize timing and detector performance

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About XIA LLC

XIA LLC invents, develops and markets advanced digital data acquisition and processing systems for x-ray, gamma-ray, and other radiation detector applications in university research, national laboratories and industry.

Having pioneered digital detector readout electronics for over 20 years, our most recent new products integrate PTP and/or White Rabbit

Contact:
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References and Acknowledgments

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