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 www.xia.com

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.

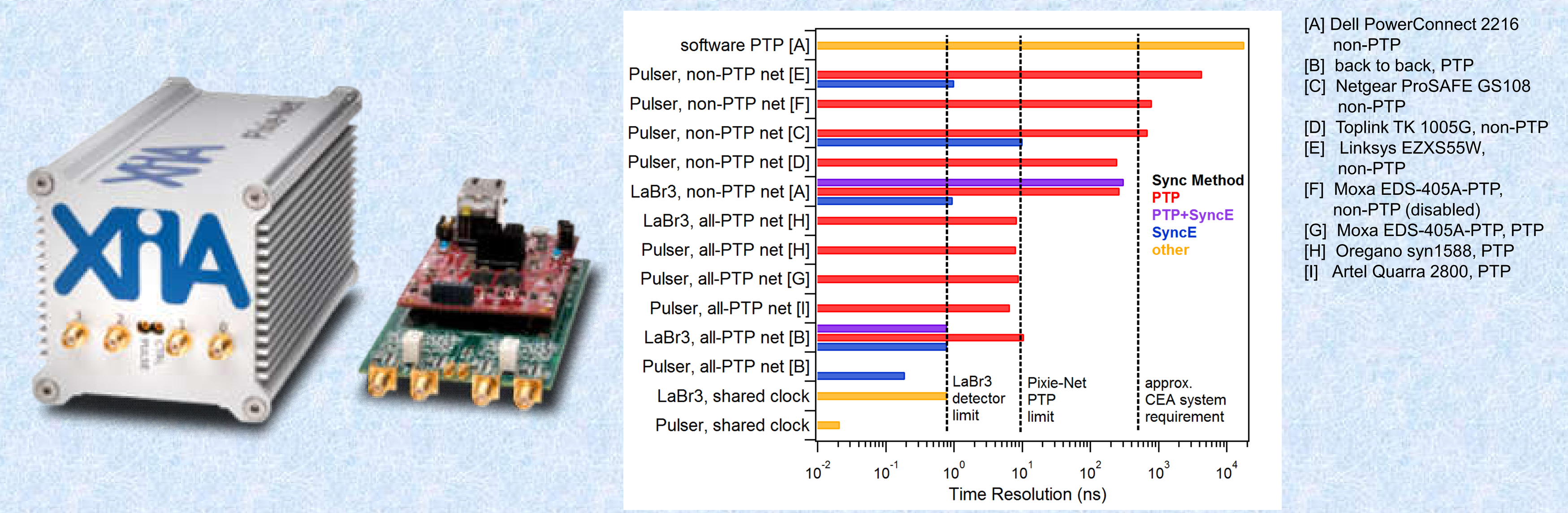
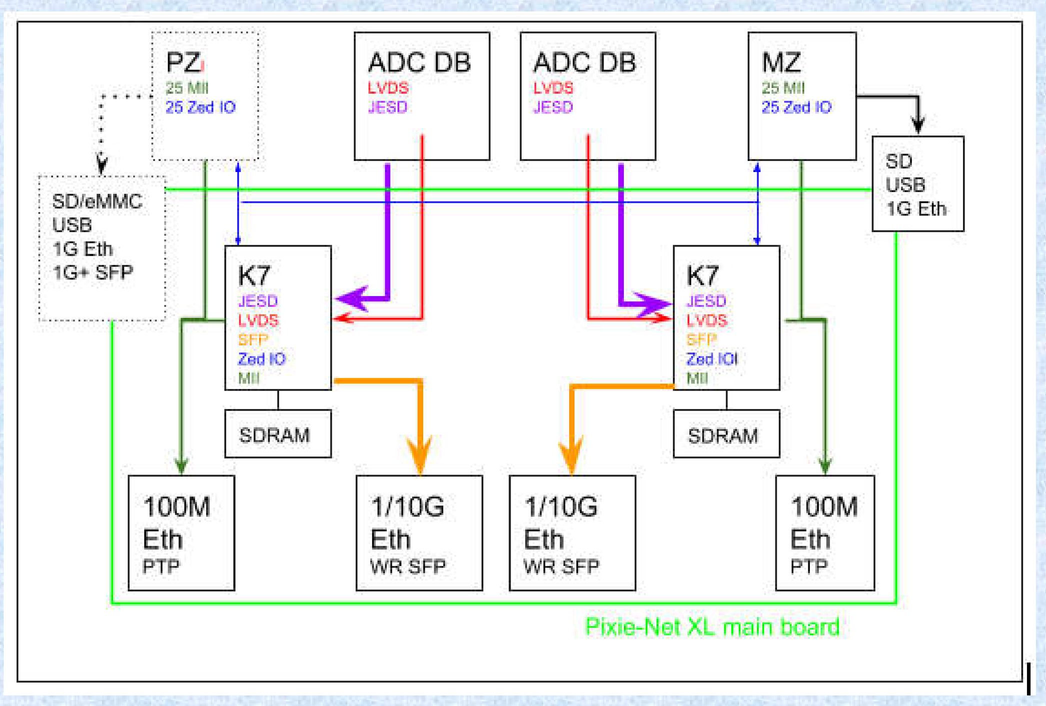


Figure 1. Summary of FWHM time resolution for various signal sources and PTP/SyncE network configurations with Pixie-Net electronics (pictured left)

Pixie-Net XL Hardware design

The electronics hardware design centers on two Kintex 7 FPGAs. 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), a 10/100M PTP compatible Ethernet PHY, and a variety of general purpose I/O connections and other peripherals. In addition, one of the FPGAs is connected to DAC controlled oscillators equivalent to WR reference designs [2].



- **K7:** Main pulse processor board using two Kintex 7 FPGA
- **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
- 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

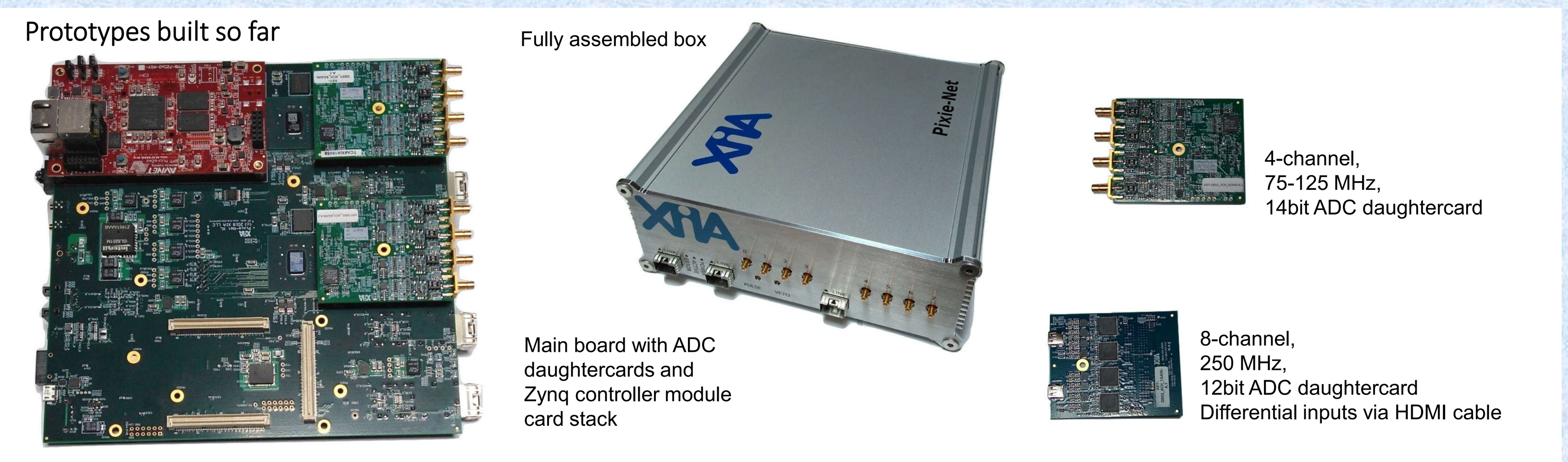


Figure 2. Pixie-Net XL block diagram and pictures

Pixie-Net XL Firmware design

The firmware of each Kintex FPGA is divided into 3 major sections:

1) Detector pulse processing derived from previous Pixie pulse processors [4]
2) Controller I/O with Zynq board to write processing parameters and read out data in slow debug mode, using [5].
3) White Rabbit core [2] with customized Verilog wrapper and GTX pinout matching Pixie-Net pinout.

Detector pulse data is saved with time stamps from WR clock and can be streamed out via WR Ethernet connection (work in progress)

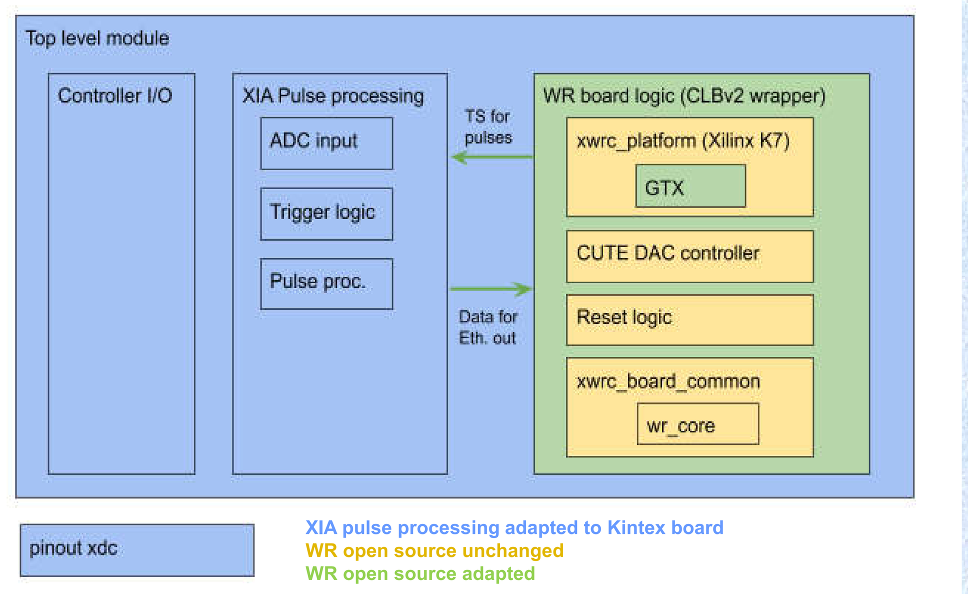


Figure 3. Pixie-Net XL firmware block diagram

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.

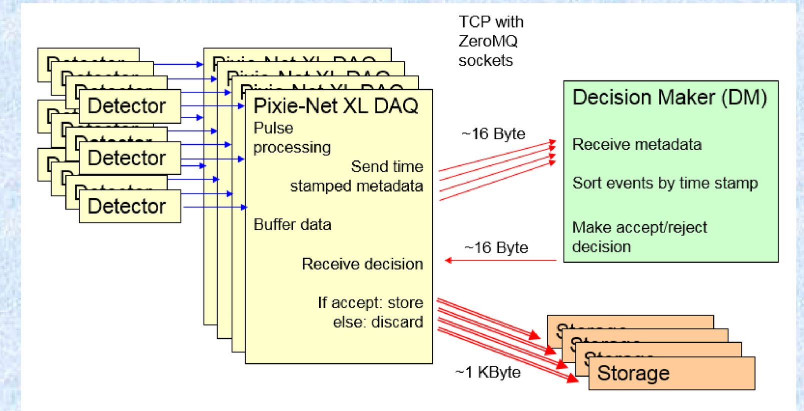
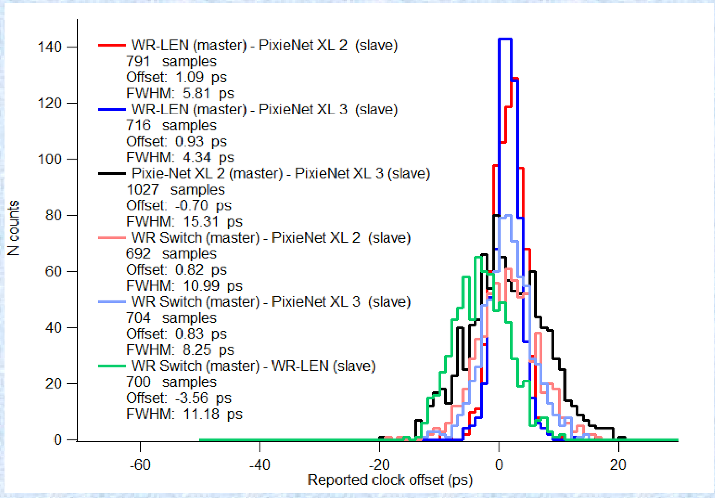


Figure 4. Concept of software triggering, for example to apply coincidence decision during the data acquisition without the need of hardwire logic.

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

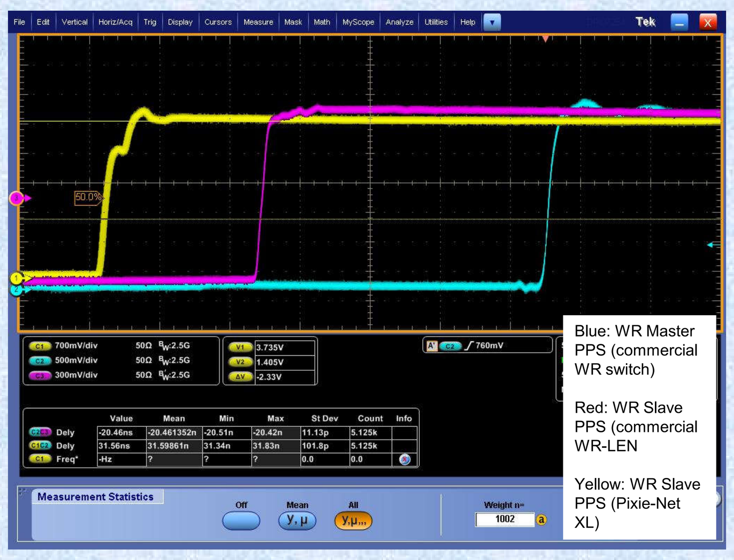


- ➢ Timing resolutions 4.3-15.3 ps FWHM
- ➢ No significant difference between commercial WR modules and Pixie-Net XL

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

Clock jitter tests

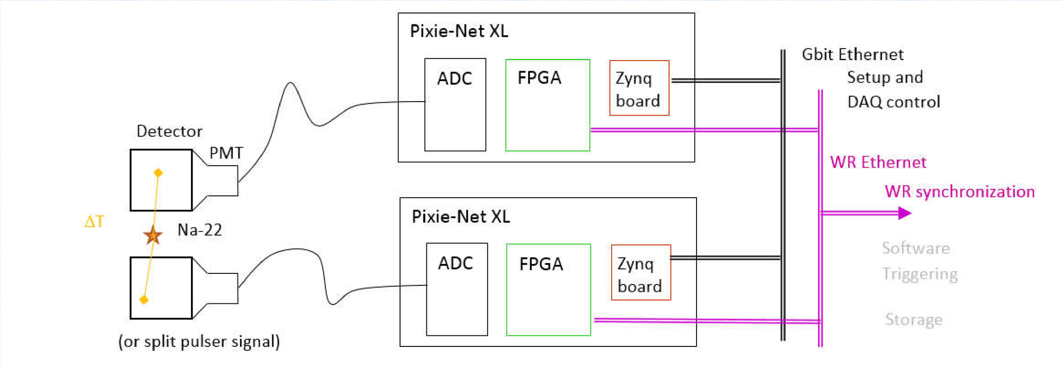
- Probing actual clock or PPS signals on Pixie-Net XL vs PPS reference pulse from WR master (commercial WR switch)
- Oscilloscope reports std.dev. of delay from edge to edge (= "jitter")

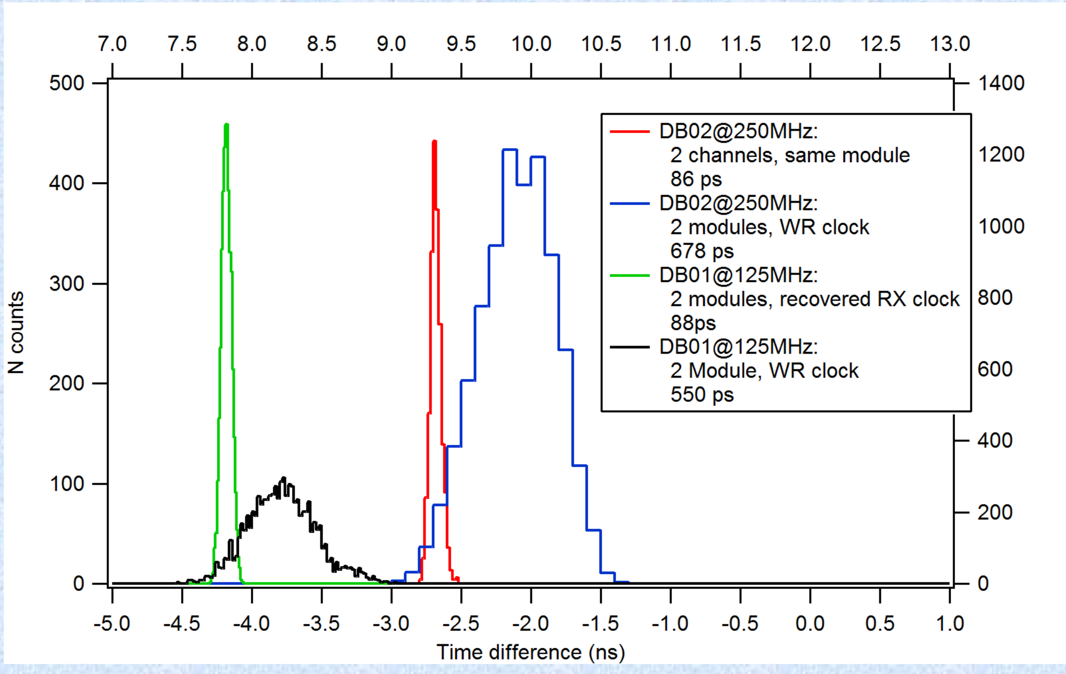


- ➢ Pixie-Net XL jitter is ~100ps, but commercial WR module reaches 10-15ps
- ➢ Further probing shows tuned WR clock on Pixie-Net XL is unusually jittery, and clock fanout for ADCs adds even more jitter (~300ps)
- ➢ But fortunately the Recovered RX Ethernet clock is low jitter (17ps) and can be routed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

Time of Flight (Pulser)

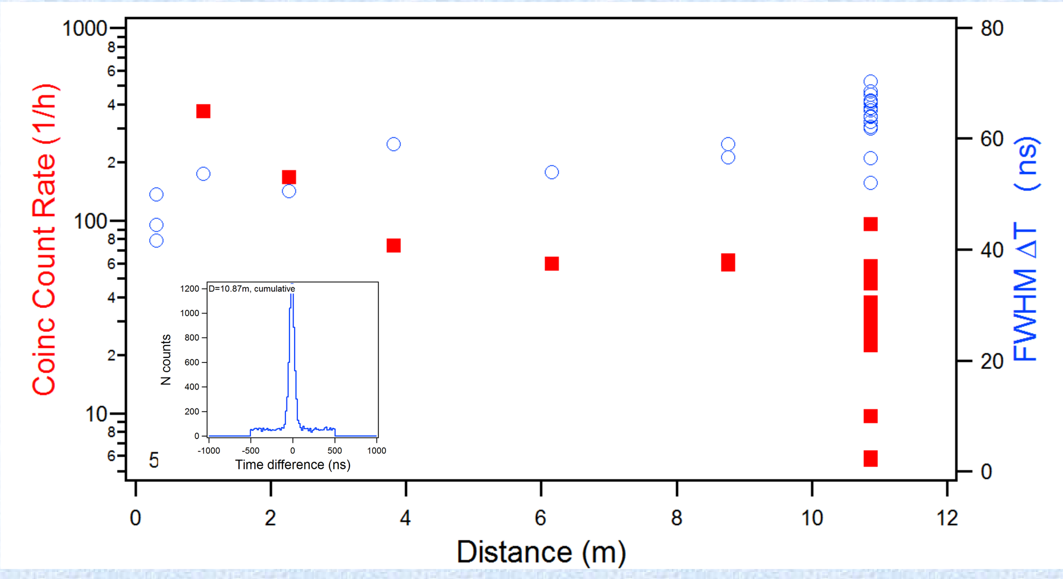
- Two detector signals (or split pulser) connected to two Pixie-Net XL synchronized via WR
- Capture waveforms and timestamps, compute sub-sample time of arrival by interpolation on rising edge [6]
- Histogram the difference of time of arrival ΔT in both modules, apply Gauss fit
- This is the measure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





Cosmic coincidences

- Use cosmic showers as source for coincident radiation separated by large distance.
- Using large (slow) detectors for efficiency.
- Goal is to demonstrate synchronization over long time and large distance (not high precision)
- Only use WR time stamps, not waveform interpolation



- ➢ Background rate ~500 counts/s each detector, recording ~8.5 million records (>1 MeV) per day.
- ➢ Coincidence rate decreases with distance. Hundreds of coincidence events per day at ~11m distance.
- ➢ Timing resolution ~70 ns FWHM

If modules could share trigger information besides clock synchronization, we would not have to record the 99.984% waste data => use Software Triggering

Summary and Conclusions

In summary, we implemented the White Rabbit time synchronization core in a new module of detector readout electronics. Time resolutions in preliminary measurements are 5-15 ps per software output, ~100ps per clock jitter measurements and ~500ps per digitized coincident pulser signal; overall well below 1 ns. The method has been proven suitable for distances of more than 10 m, and there is no reason why it can not scale up with the same precision to distances set by the fiber optic network infrastructure, i.e. 5 km or more.

The test measurements were performed with preliminary versions of software, firmware, and hardware. In particular, there are sources of excessive jitter in the new hardware and workarounds improved the coincidence timing to <100ps. These results are thus not yet quite as good as with commercially available devices or as reported in [7]. In future work, we will debug the jitter issues, finalize the firmware, and repeat the pulser measurements with fast radiation detectors. The software triggering will be used to limit collection of unnecessary data.

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

References and Acknowledgments

[1] W. Hennig, et al, IEEE Trans. Nucl. Sci. 66 (2019), p1182
[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

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Number DE-SC0017223.