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

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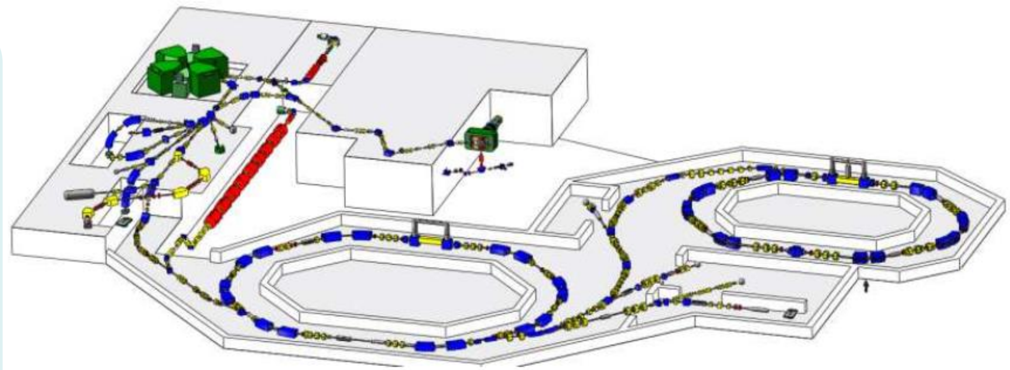
Background



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 dedicated clock and 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

White Rabbit: High Accuracy Profile of IEEE 1588 Precision Time Protocol (PTP)

- Synchronizing time by exchanging data messages over Ethernet
- Clocks as well as time/date … to sub-nanosecond precision
- Precision depends on implementation and network infrastructure

Clocks from two devices, synchronized by standard PTP

=> how well does it work for synchronizing detector readout electronics?

Sub-Nanosecond Time Resolution …

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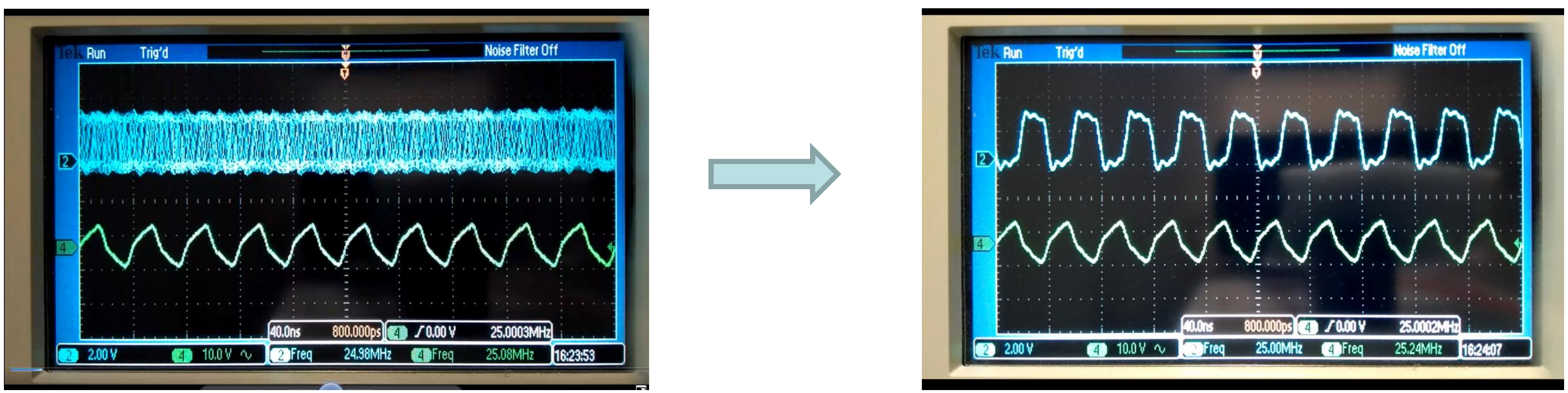


=> how well does it work for synchronizing detector readout electronics?

Sub-Nanosecond Time Resolution …

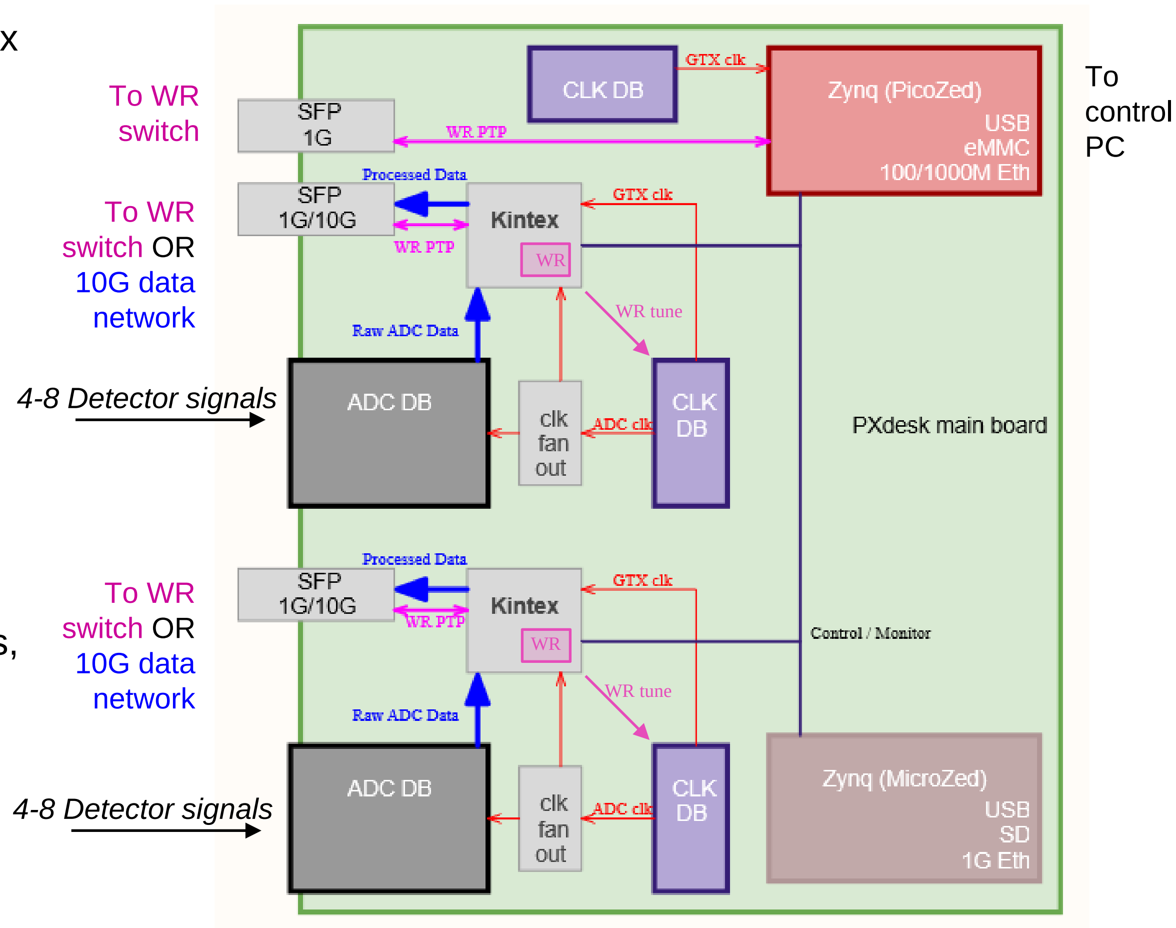
Pixie-Net XL (PXdesk), Revision B

- Pulse processor board using Kintex 7 FPGA
  - Detector pulse processing
  - White Rabbit
  - Ethernet data output (1G or 10G)

- Zynq controller board
  - Linux OS
  - Web interface or terminal
  - DAQ setup and control
  - White Rabbit (option)

- ADC daughtercards for detector readout (flexibility in ADC channels, rate, precision, or non-ADC functions)

- High speed data flow from ADC to FPGA to Ethernet output



Thick border = separate PCB

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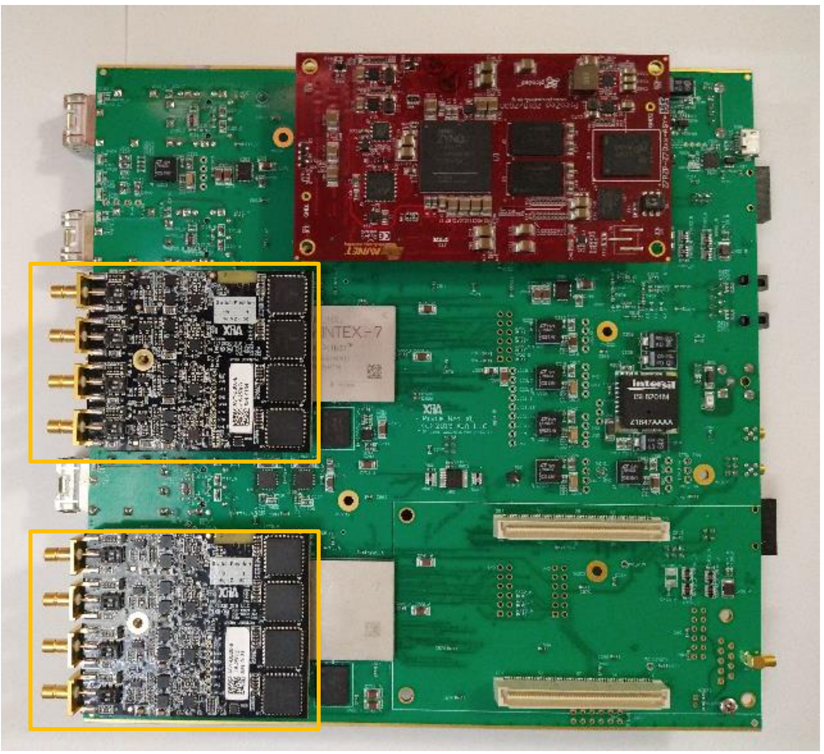
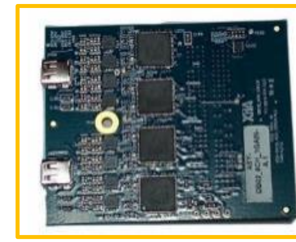
PXdesk main board



Daughtercards

DB01:
4-channel,
12-**14**bit, 75-**125** MSPS ADCs
variable gain/offset, uses ¼ of the I/O pins



DB02:
8-channel,
12-14bit, **250** MSPS ADCs
fixed gain/offset, differential inputs

DB06:
4-channel,
16bit, **250** MSPS or 14bit, 500 MSPS ADCs
2 gains, variable offset

DB04:
8-channel,
12-**14**bit, **250** MSPS ADCs
fixed gain, variable offset, microcoax inputs

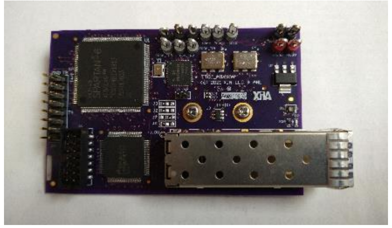
Clocking and Synchronization

WR clocking circuitry on a daughtercard to accommodate different modes of operation for ADC and Ethernet:

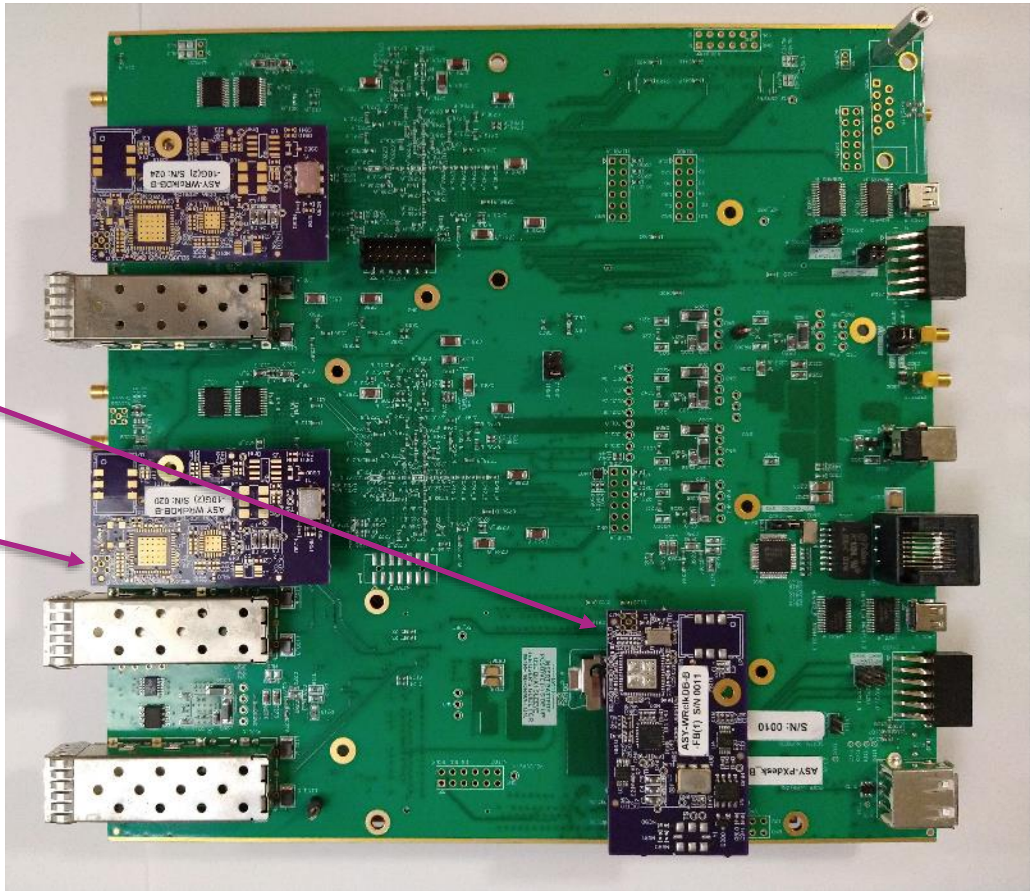
1. **WRclkDB (1G)**:
   WR voltage controlled oscillators, DACs, PROMs
   125 MHz for 1G Ethernet (and ADC)
   option for "low jitter DB" circuitry

2. **WRclkDB (10G)**
   Simple fixed oscillator, no WR sync
   156.25 MHz for 10G Ethernet

3. **TTCL Adapter**:
   Compatibility for DGS, Greta, etc
   "TTCL clock" for ADC
   Separate 156.25 MHz for 10G Ethernet
   (collaboration with ANL, in progress)



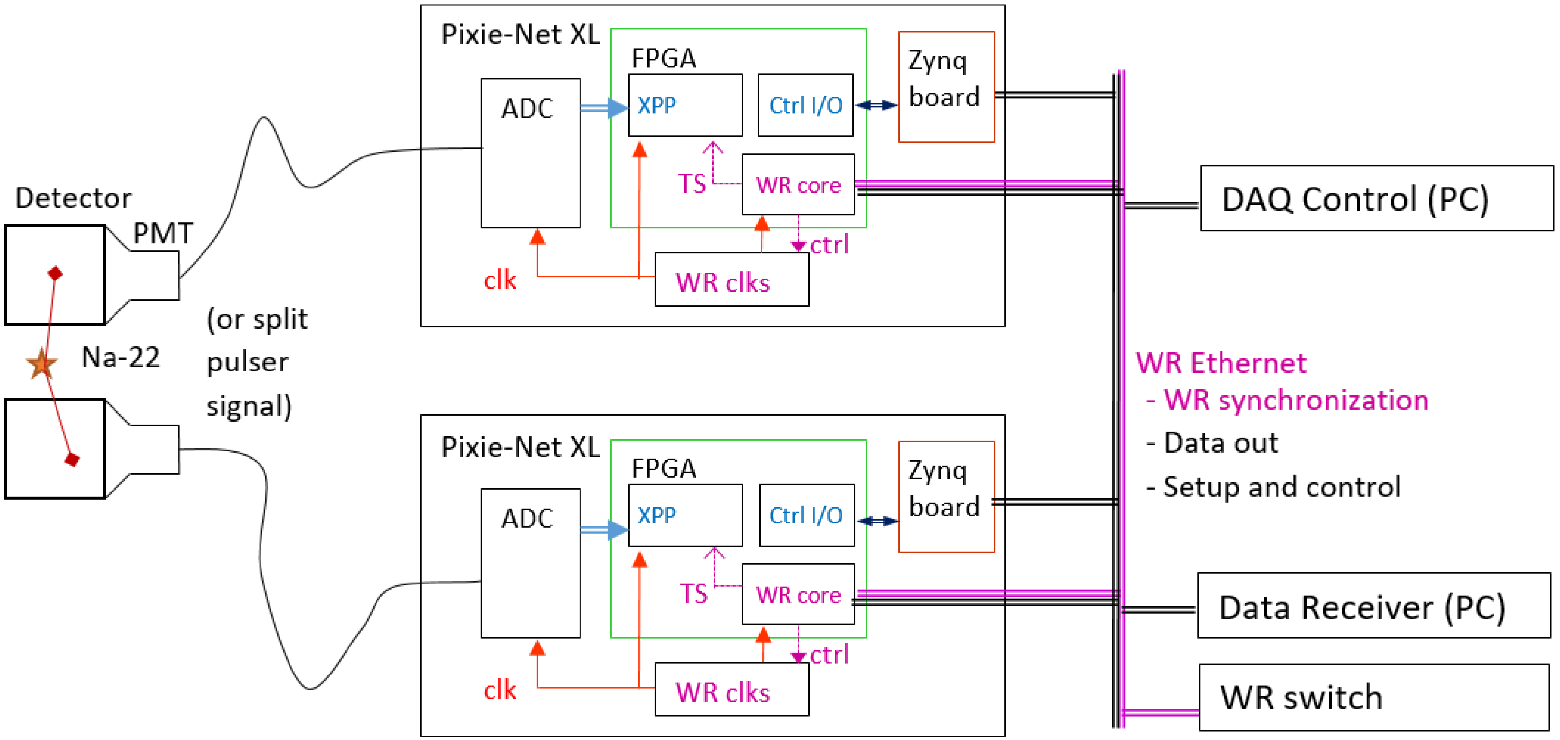
4. **Future 10G WR standard**
   Under development at CERN … 2024?



Main board with clock DBs for Kintex and Zynq

Timing Measurement Setup

- Using coincident radiation as "most useful" method of timing characterization
- Each Pixie-Net captures detector data, timestamps with WR time
- Data sent to Receiver PC as UDP packages



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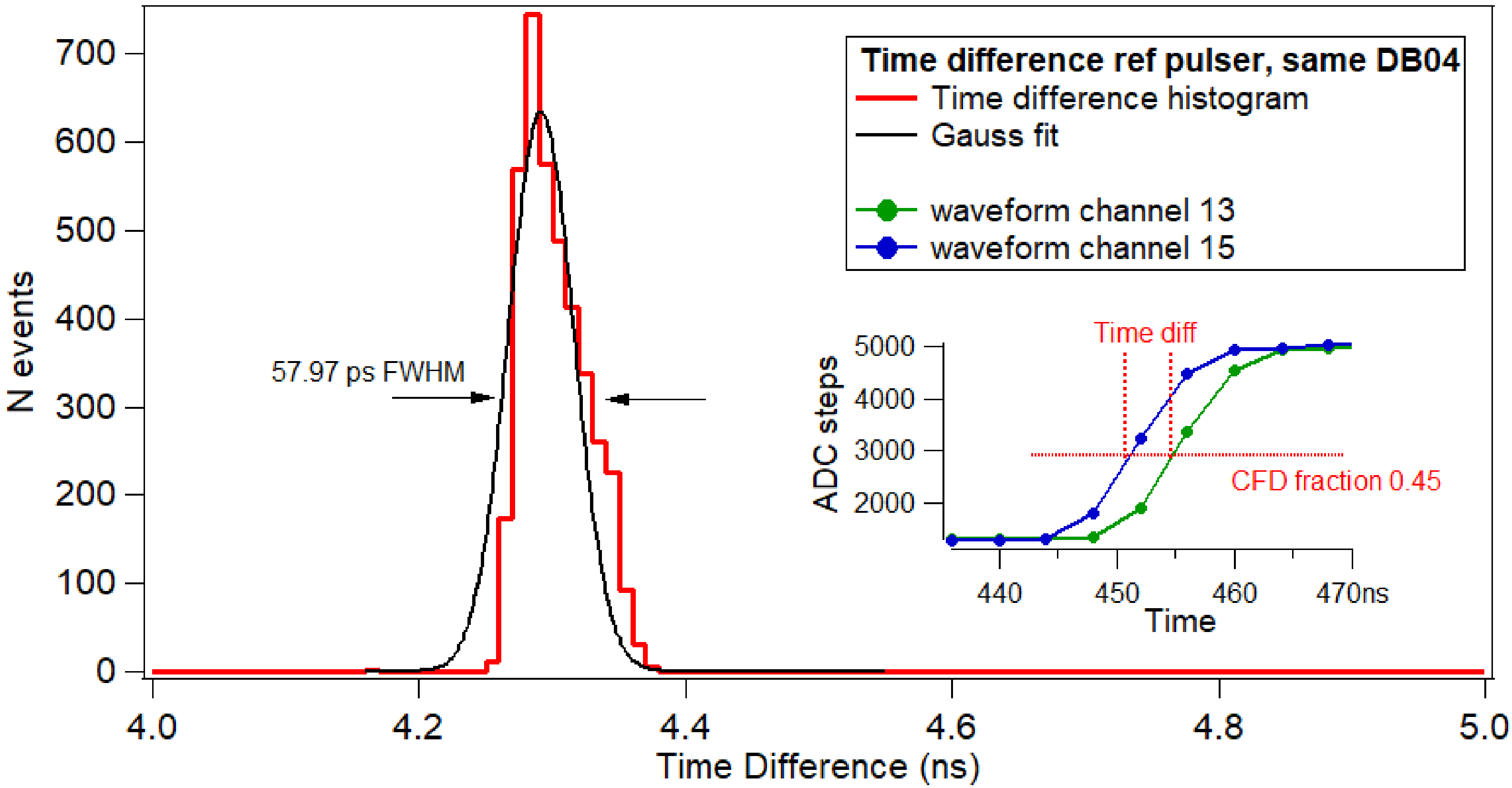
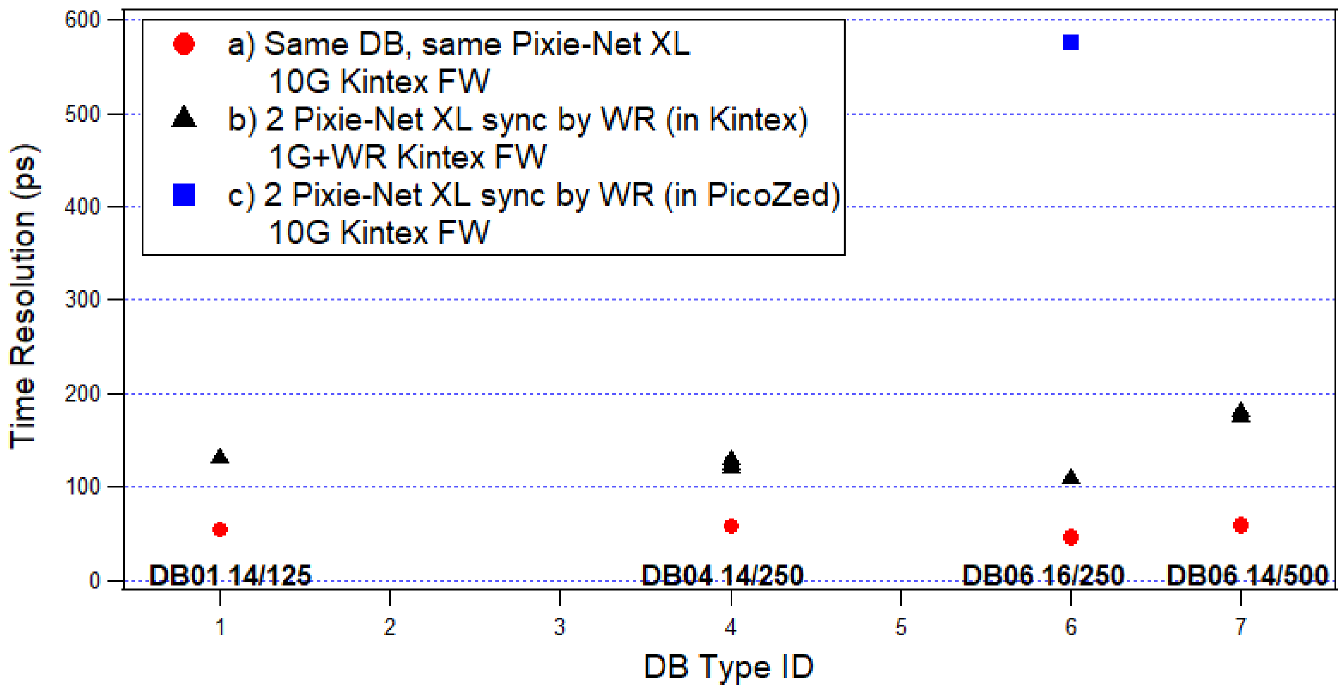
Timing Measurement Analysis

- Offline analysis to apply constant fraction timing
- Compute time-of-arrival difference
- Histogram ~10,000 events



Timing Measurement Conditions

1. Every ADC daughtercard with the reference pulser, 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 Zynq (PicoZed).
2. DB04 daughtercard with pulser shape and amplitude optimized, subsets a) and b)
3. DB04 daughtercard with LaBr3, subsets a) and b)



Pulser measurements, 1a)-c)

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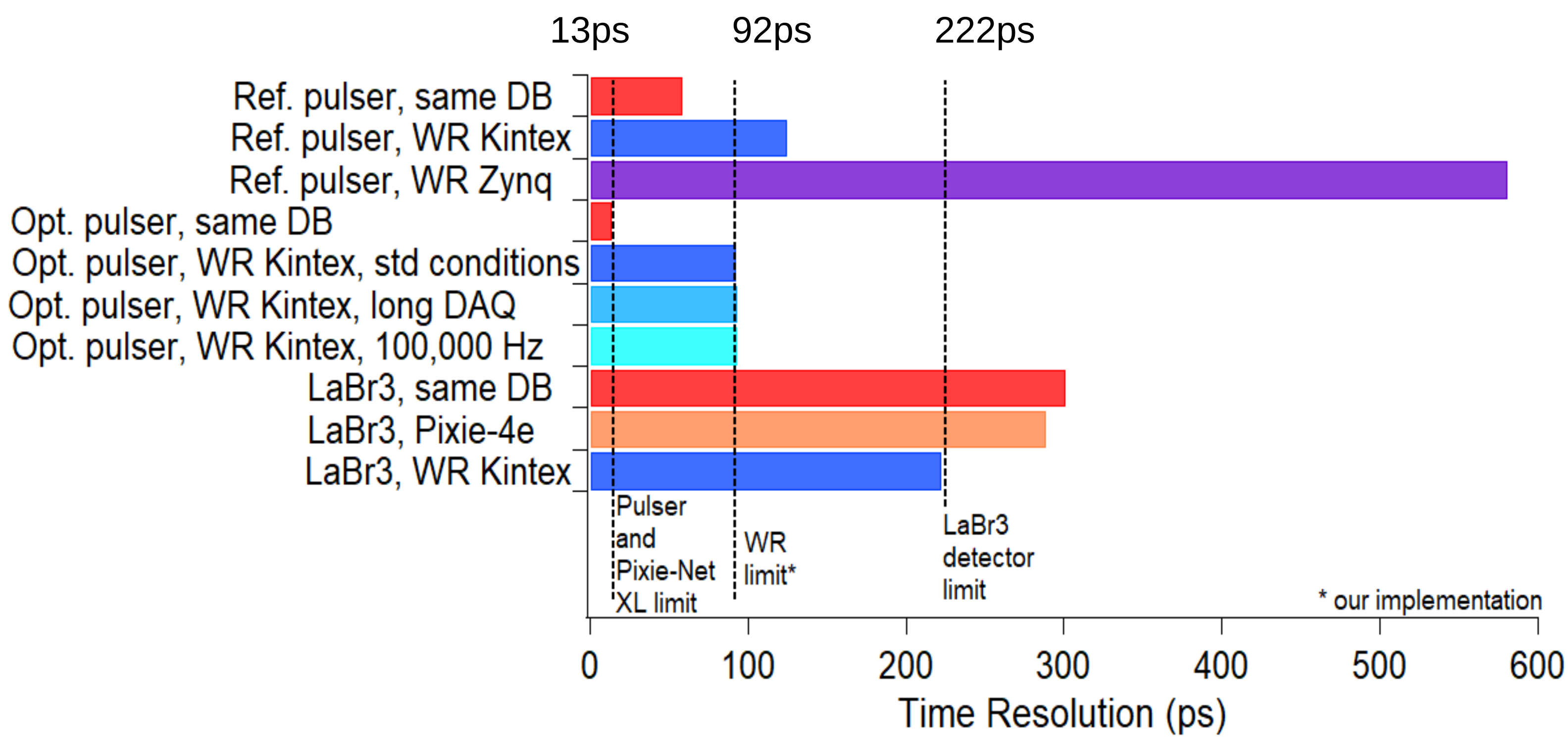
Timing Measurement Results



DB04 measurements, conditions 1, 2, 3; except Pixie-4e and WR Zynq

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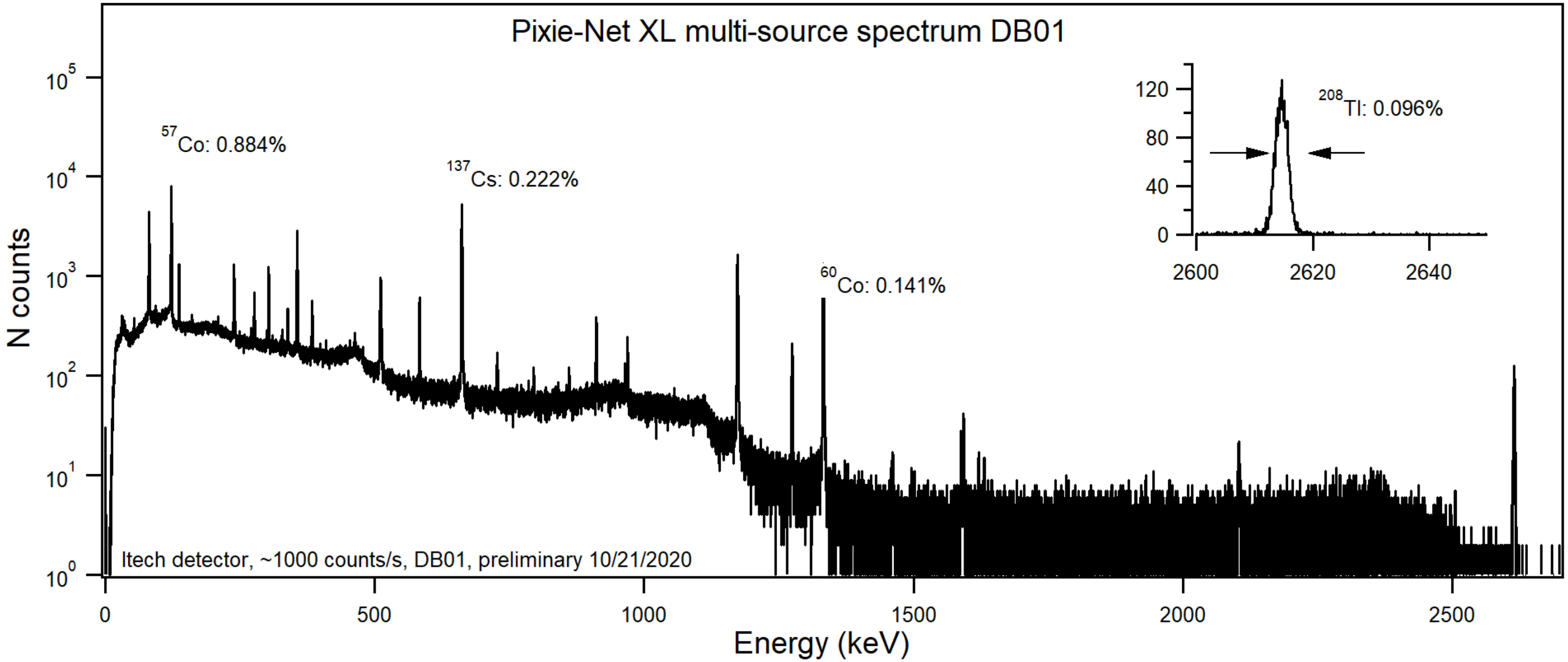
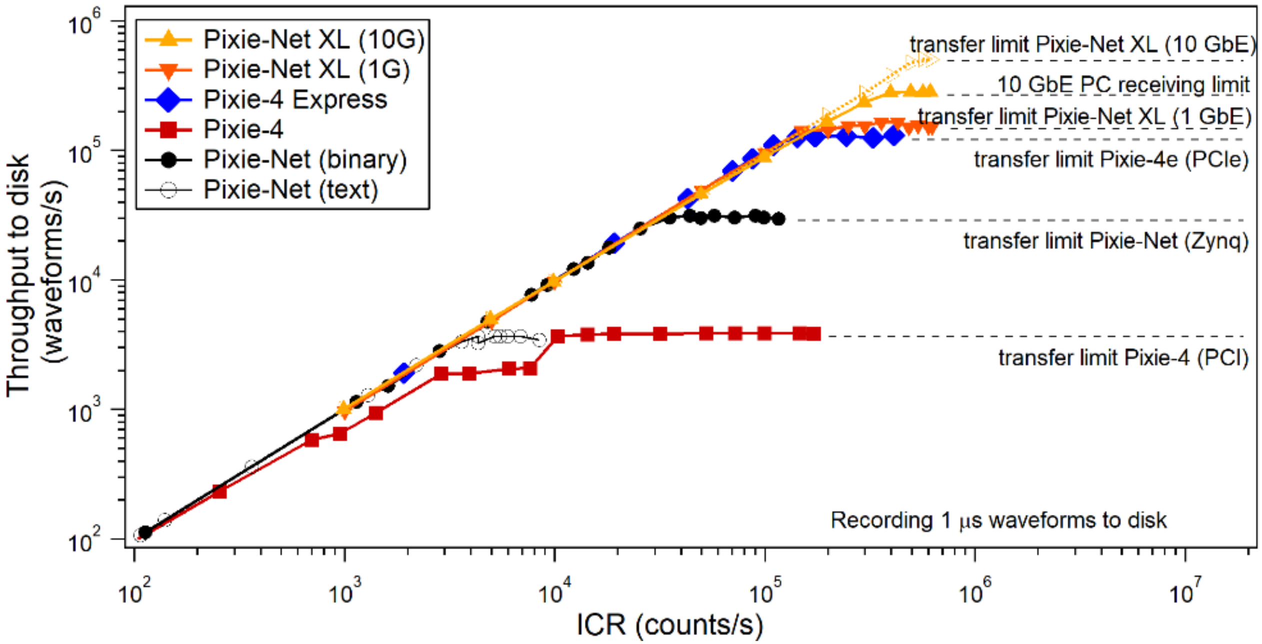
Energy Resolution

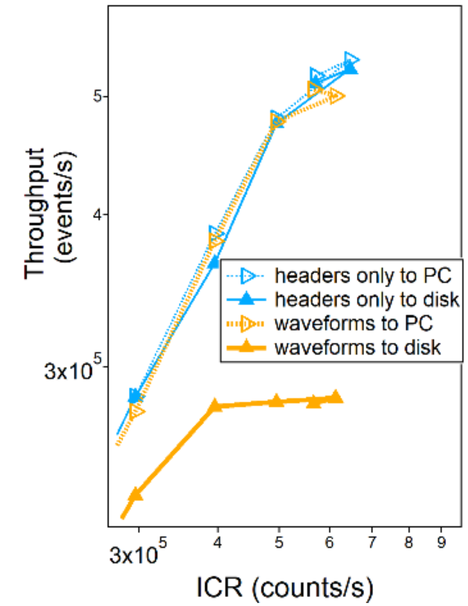


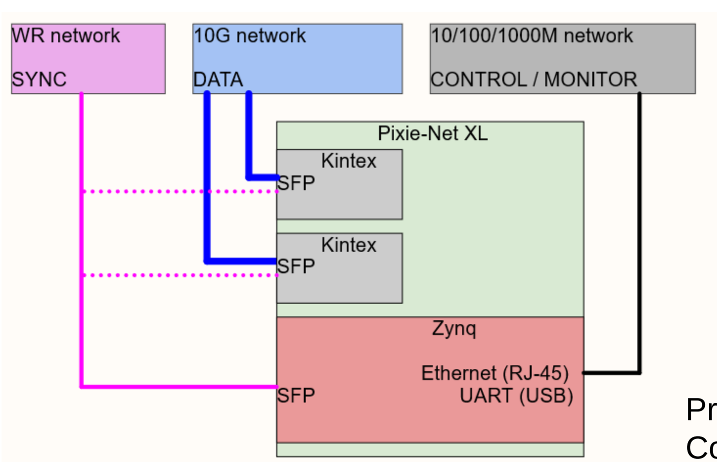
Pixie-Net XL HPGe energy resolution (DB01)

Sub-Nanosecond Time Resolution …

List Mode Data Throughput







- Pixie-Net XL exceeds previous models' throughput for storing event waveforms to disk
- Limited by packets dropped by PC (not by network)
  try multiple PCs?
- Almost 300,000 waveforms/s (or over 500,000 headers/s) per Kintex

Preferred setup architecture uses 3 networks (SYNC, CONTROL, DATA)
Could be all one network, but with lower throughput (two are max 1G)

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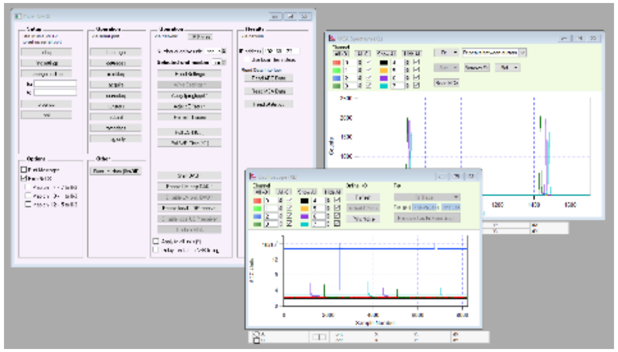
Final Product

Pixie-Net XL

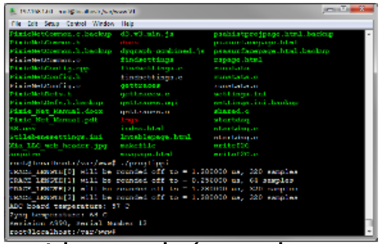
Igor Pro GUI



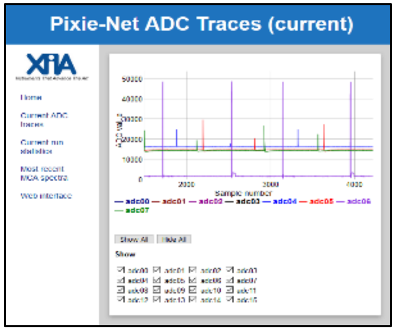
- Buttons replace typing terminal commands (via UART)
- Igor reads webpages to display data (via Ethernet)
- Igor executes *http get* commands to set parameters and start/stop DAQ (using basic "web API")
- Igor xop can receive UDP data

Basic Operation

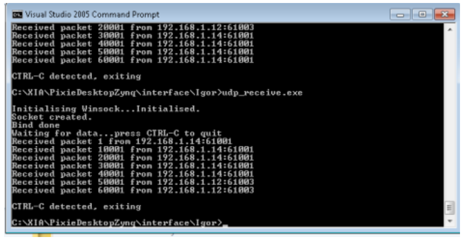
Can use single or multiple PCs for …



… Linux ssh (or webpages) for setup and daq



…webpages to monitor results and status



… receiving UDP data

Sub-Nanosecond Time Resolution …

Commercial Products

- **Pixie-Net PTP**
  PTP only. 4 channel, 12bit, 250 MHz

- **Pixie-Net XL**
  2 ADC daughtercards, 8-16 channels
  Data output 1G WR or 10G, 2x 500k LM events
  WR time synchronization

- **MZTIO**
  Trigger I/O module for XIA's Pixie-16 PXI pulse processor boards with PTP clock option
  (Also available as desktop PTP GPIO module)

- **Pixie Hybrid**
  Update of XIA's 3U PXIe pulse processor board
  WR synchronization and 1G data output possible

- **Pixie-16 x1/x2**
  Update of XIA's Pixie-16 PXI pulse processor board
  "HW ready" for WR + 1G data
  Same ADC daughtercards, up to 32 channels per board

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Open Source Products

- **PZ-TIO**
  - Zynq carrier board (PicoZed 7015)
  - 3 SFP interfaces and ~40 GPIO lines
  - 2 SFP capable of White Rabbit time
  - Linux OS
  - Open Hardware on ohwr.org

- **WRclkDB**
  - WR controlled oscillators on a daughtercard
  - versions with WR ref design, “low jitter” upgrade, non-WR 10G oscillator (156.25 MHz)
  - Open Hardware on ohwr.org

- **Software**
  - ptp-mii-tool to communicate with DP83640 PHY
  - Pixie-Net [XL] software for ARM/Linux
  - host software for Linux and Windows

Sub-Nanosecond Time Resolution …

Summary

- Implemented White Rabbit network time synchronization on new detector DAQ electronics, the Pixie-Net XL
- Easily reaches “sub nanosecond” timing resolution,
  Better than $LaBr_3$ detector limit
  Not quite equal to timing in same unit
- List mode data output via 10G Ethernet
  max. measured output data rate is ~600 MB/s (test mode, one Kintex)
  max. LM data rate **received** is ~360 MB/s max (header only, one Kintex)
- Related products include GPIO trigger/timing boards with PTP or WR
  Some are open hardware
- Can choose network infrastructure to match application’s precision needs
  > 1000 ns standard PTP in normal network
  ~ 10 ns standard PTP in network with PTP switch
  < 1 ns White Rabbit with WR switch

Thank You

Questions?