Network Time Synchronization of the Readout Electronics for a New Radioactive Gas Detection System

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Background

In systems with multiple radiation detectors, time synchronization of the data collected from different detectors is essential to reconstruct multi-detector events such as scattering and coincidences. In cases where the number of detectors exceeds the readout channels in a single data acquisition electronics module, multiple modules have to be synchronized, which is traditionally accomplished by distributing clocks and triggers via dedicated connections.

To eliminate this added cabling complexity in the case of a new radioactive gas detection system prototype under development at the French Atomic Energy Commission (CEA), we implemented time synchronization between multiple XIA Pixie-Net detector readout modules through the existing Ethernet network, based on the IEEE 1588 precision time protocol (PTP) [1]. The detector system is dedicated to the measurement of radioactive gases at low activity. Detecting coincidences will make it possible to identify each radioisotope present in the sample. To allow these identifications at low activities, the Pixie-Net modules must be synchronized to a precision well below the targeted coincidence window of 500-1000 ns. Being equipped with a PTP compatible Ethernet PHY that outputs a locally generated but system-wide synchronized clock [2], the Pixie-Net can operate its analog to digital converters (ADCs) and digital processing circuitry with that clock and match time stamps for captured data across multiple modules.

Detector Prototype

The detector prototype consists of a gas cell surrounded by two large segmented silicon wafers, coupled with two squared NaI(Tl) detectors (Figure 1). The gas cell has a sample volume of 30 cm^3 and the silicon wafers are 500 µm thick with an active surface area of 3600 mm^2. Each wafer is segmented into four silicon pixels (30 x 30 mm^2). This module is sandwiched between two plane-type NaI(Tl) detectors (83 x 263 mm^2 height including photomultiplier tube, 70 x 70 x 40 mm^3 crystal). The thickness of the silicon wafers is sufficient to stop any electron with a kinetic energy less than 400 keV. Geant4-based Monte Carlo simulations showed that such thickness absorbs approximately 18 to 20% of the 30 keV photons, and do not significantly affect photons with energy higher than 80 keV; allowing them to pass through the silicon and to be stopped in one of the NaI(Tl) crystals.

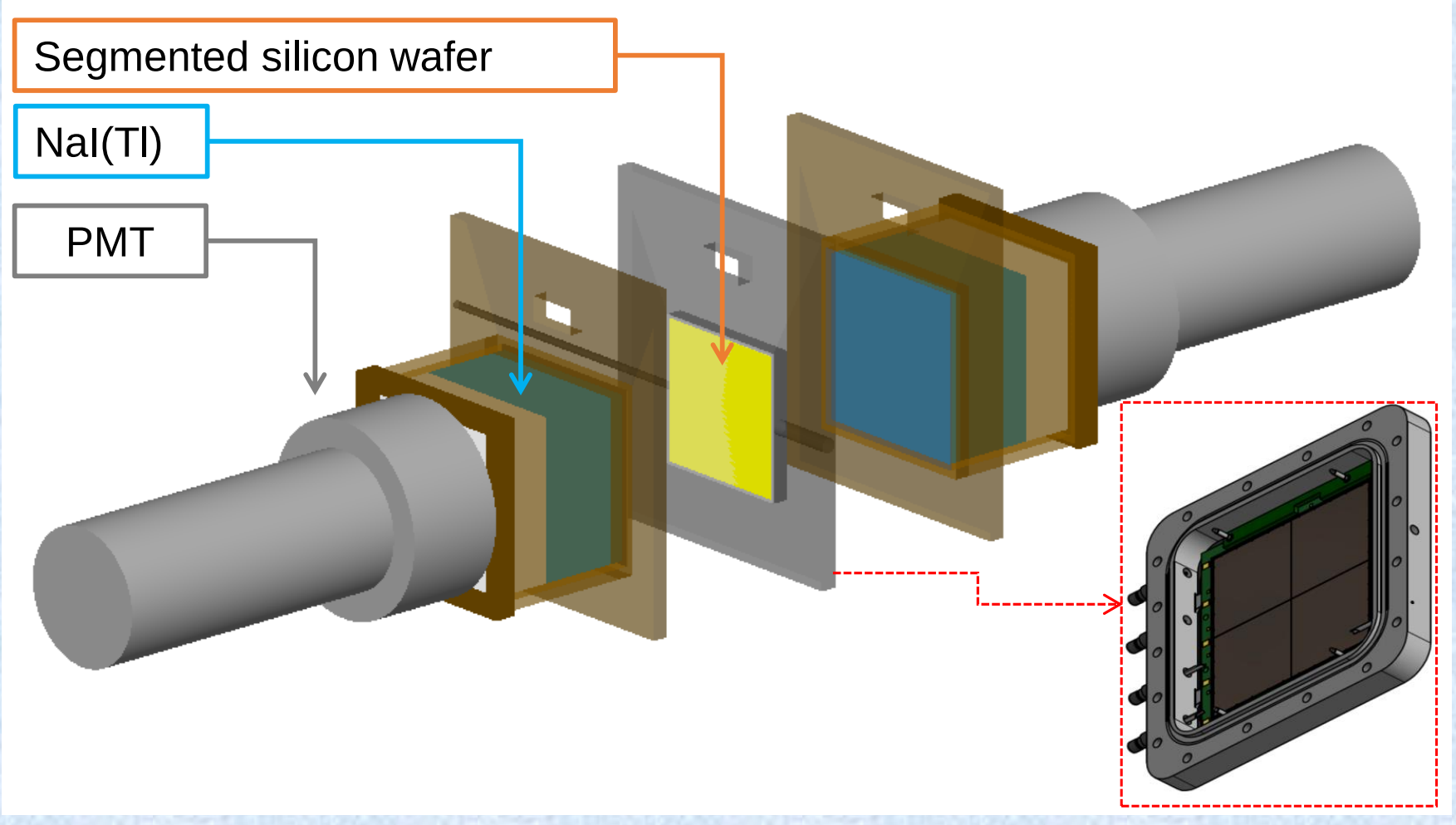

Figure 1: Exploded view of the detector prototype. The radioactive gas sample will be injected inside the central box housing (insert at the bottom right).

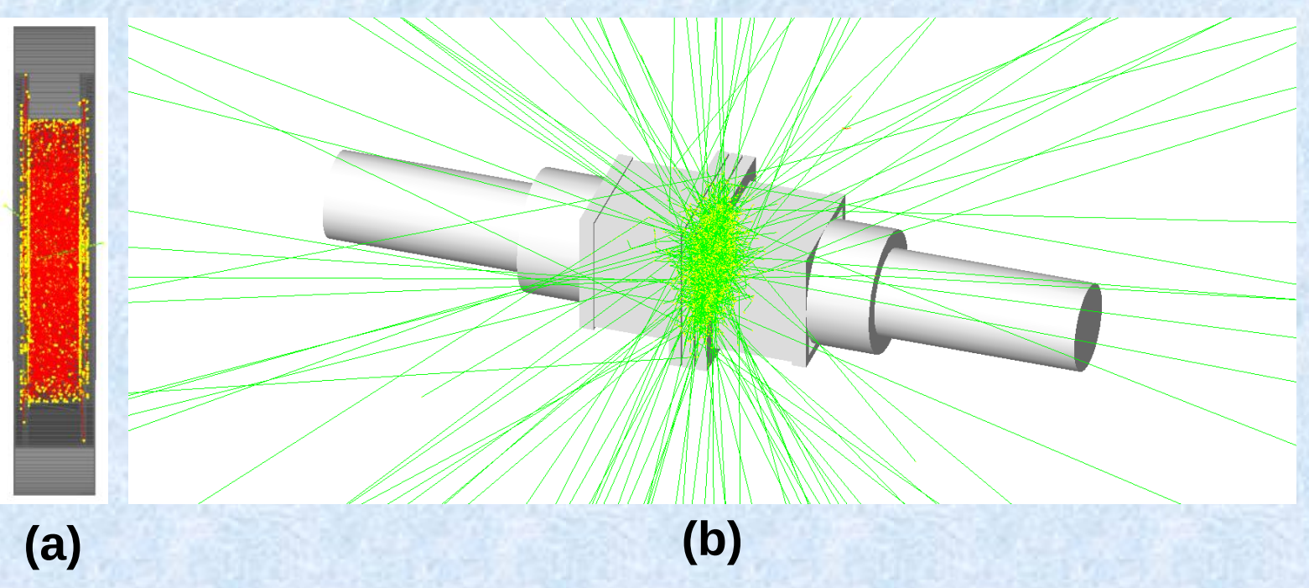

Figure 2: (a) simulation of 100,000 electrons with 200 keV kinetic energy. They all deposit their energy in the silicon wafers. (b) Simulation of 100,000 γ-rays with 200 keV kinetic energy. They pass through the silicon wafers and deposit their energy in the NaI(Tl) crystals.

In order to detect very low activities (1 mBq/m^3) of e.g. radioxenon isotopes, the coincidence measurement technique will be used to drastically reduce environmental background (which masks such activities). In most cases, during the radioactive decay, several particles are emitted almost simultaneously (few picoseconds delay). Measuring at least two particles allows to tag the emitting radionuclide. Thus, a coincidence time window is necessary. The width of this window depends essentially a) on the charge time collection in the detectors (which is approximately 1 µs in this case), and b) on the network configuration if a common clock is used. If two particles are detected within the same coincidence window, then the event is represented by a point in a 2D histogram (Figure 3). After an acquisition, a post-processing analysis identifies radioactive elements that were present in the sample, according to the deposited energies (Figure 4).

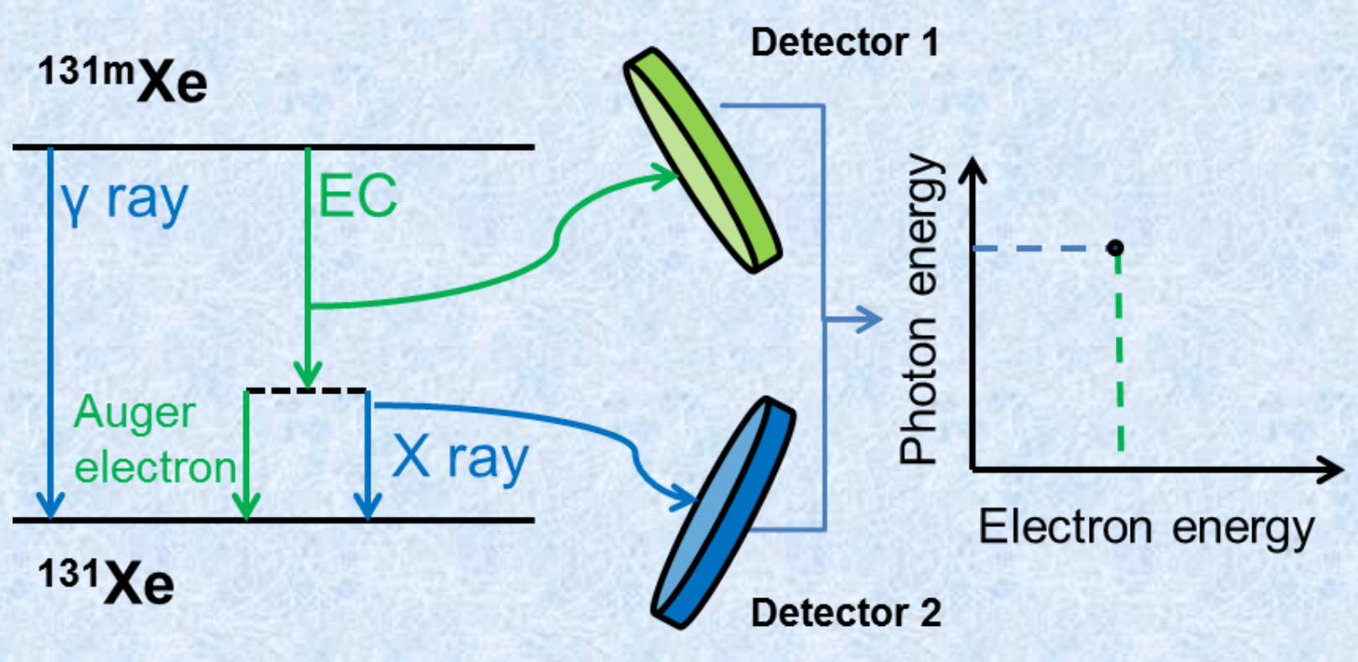

Figure 3: Simplified ^{131m}Xe decay scheme. The main emission consists of a 129 keV conversion electron (CE), followed by a 30 keV X-ray. If the two particles are detected simultaneously, they represent one count on the ^{131m}Xe Region Of Interest on a 2D histogram.

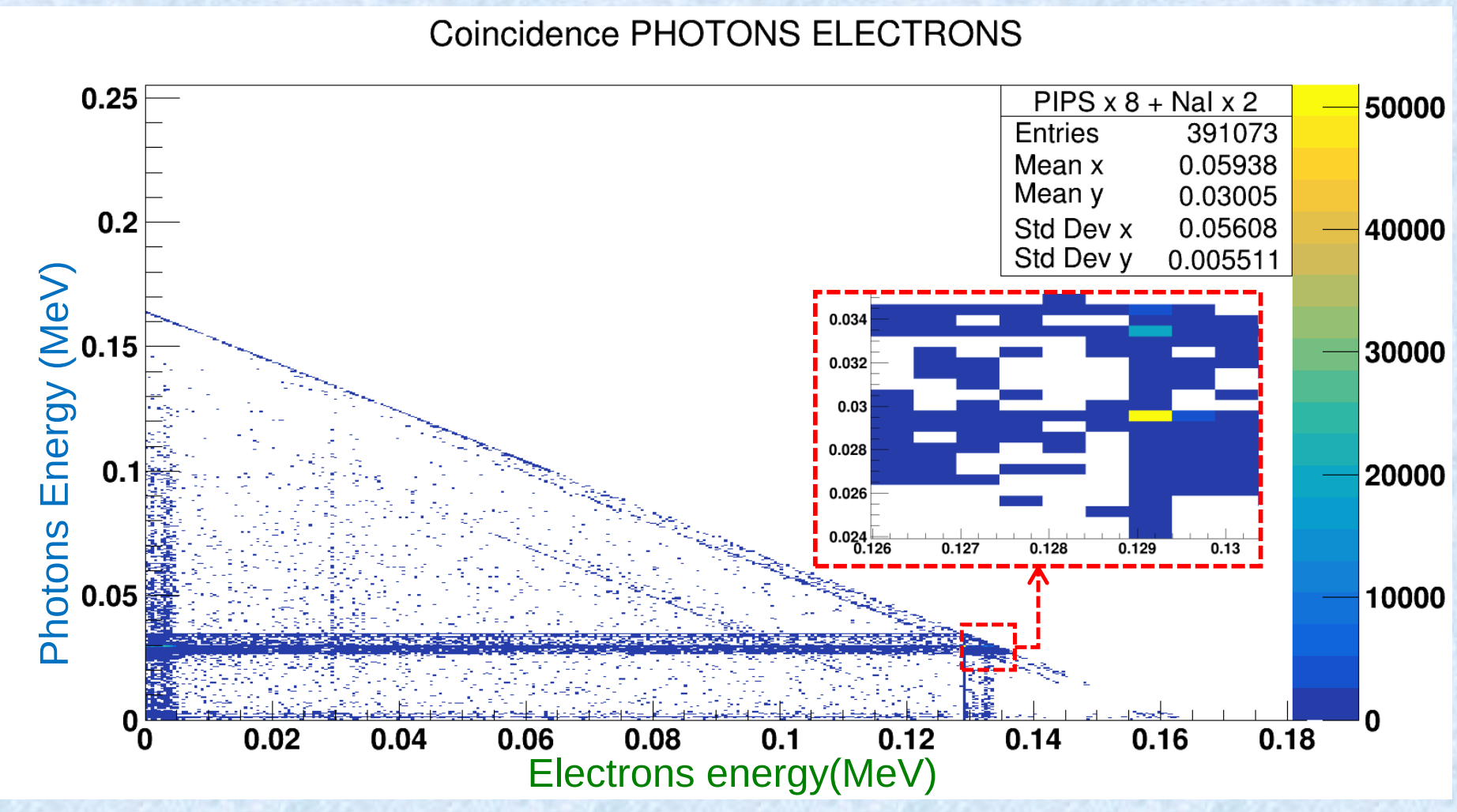

Figure 4: Geant4-based prototype simulation of 1,000,000 ^{131m}Xe disintegrations. Main Region Of Interest (ROI) is shown in the dashed red insert, corresponding to the 129 keV CE emitted in coincidence with a 30 keV X-ray.

In general, the shorter the coincidence window, the more environmental background is rejected, and the more reliable the measurement will be. However, shortening the window to less than the average background event time separation has diminishing returns, and shortening to less than the intrinsic time resolution of the detector will lead to loss of true coincidences. In order to reconstruct coincidences properly during post-processing analysis, clocks and timestamps must therefore be synchronized with sufficient precision between the modules. Preliminary coincidence background measurements (T_{acq}=24 h, no lead shielding) between the two NaI(Tl) detectors, and a Dell PowerConnect 2216 network switch show an accuracy of **260 ns** FWHM (figure 5). This precision minimizes the window width and thus reduces fortuitous coincidences by **34%** in the ^{131m,133m}Xe ROIs, and by **10%** in ^{133,135}Xe ROIs, compared to a "classical" window of the order of 0.8 - 1 µs.

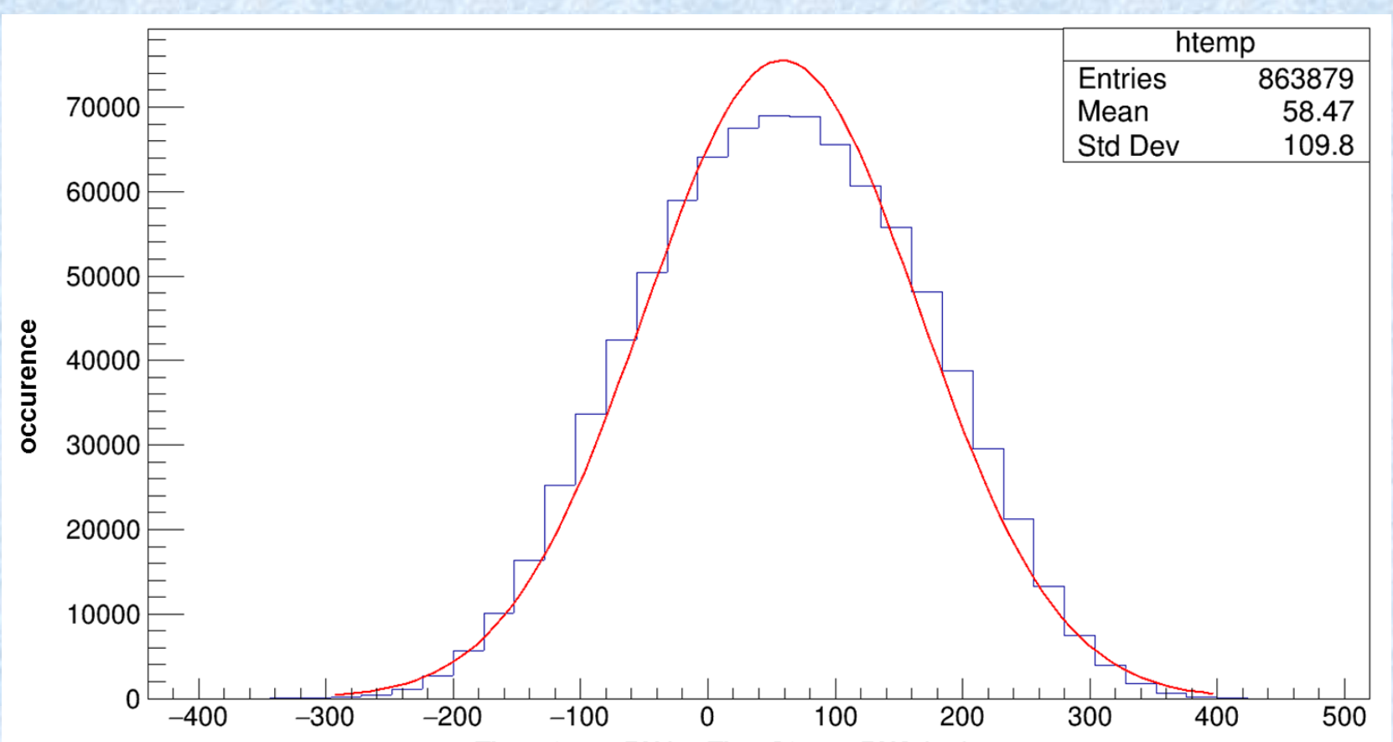

Figure 5. Difference between timestamps recorded by the two PTP synchronized Pixie-Net. The accuracy (FWHM) is 260 ns. Offset between modules is less than 60 ns.

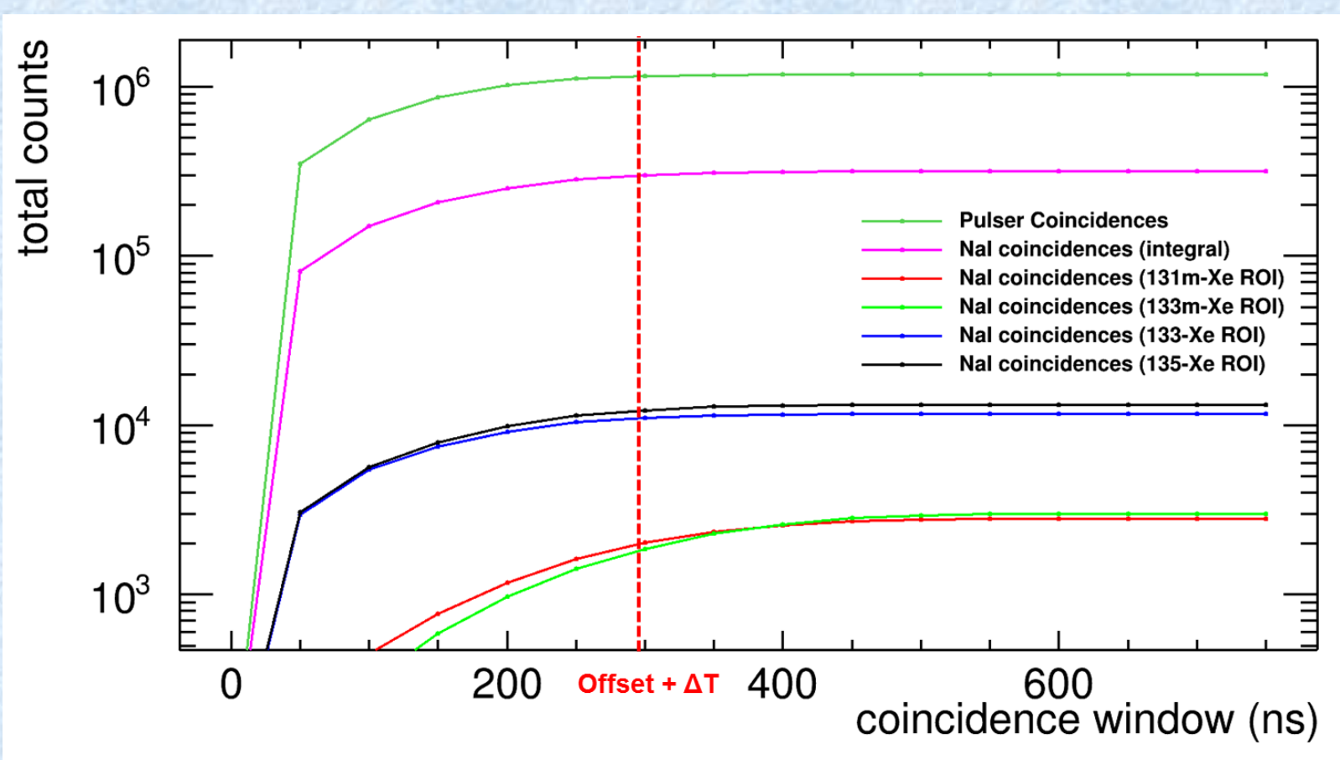

Figure 6. Variations in the number of fortuitous coincidences as a function of the window width. 24-hour background acquisition. True coincidences obtained with the pulser (dark green curve) act as a reference. the dashed red line suggests an optimal coincidence window width of ~300 ns.

References and Acknowledgments

[1] https://en.wikipedia.org/wiki/Precision_Time_Protocol
[2] www.ti.com/product/DP83640/technicaldocuments
[3] http://www.xia.com/Pixie-Net.html
[4] "Zynq-7000 AP SoC", www.xilinx.com
[5] http://linuxptp.sourceforge.net/
[6] https://sourceforge.net/projects/net-tools/
[7] equivalent to A. Fallu-Labruyere et al, NIM A 579 (2007), p247.

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Pixie-Net Readout Electronics

The detector is read out with three 4-channel Pixie-Net [3] modules (2x4 silicon signals and 2 NaI(Tl) signals), as shown in Figure 3. Data is saved in list mode. The Pixie-Net data acquisition includes

- Digitizing detector signals at 12bit, 250 MHz with clock derived from PTP PHY
- Triggering & pulse height measurement in the FPGA fabric of a Zynq "System On Chip" [4]
- Storing of MCA spectra and list mode data on local SD card by Linux C programs in the Zynq ARM
- Generating webpages for remote monitoring
- Managing the PTP Ethernet PHY (using free software LinuxPTP [5] and mii-tool [6])
- Configuring PTP triggers to start/stop acquisition at user defined date/time

For a coordinated data acquisition, the local Linux programs on each Pixie-Net were executed remotely from a Linux PC via SSH calls from a shell script.

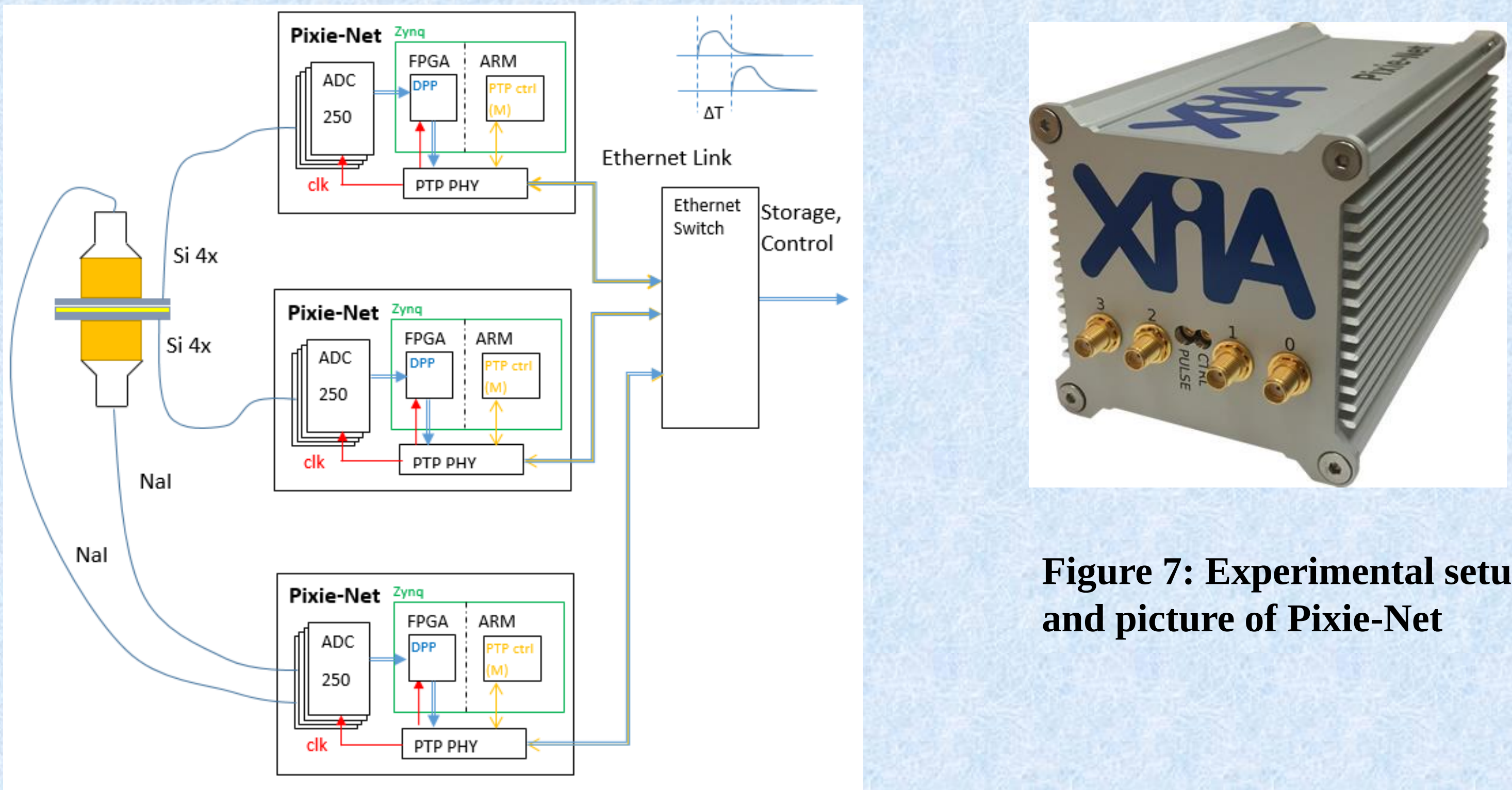


Figure 7: Experimental setup and picture of Pixie-Net

Timing Characterization

In preliminary tests we used two Pixie-Net modules and a pair of $LaBr_3$ detectors instead of the NaI detectors. The Pixie-Net modules were always configured for either synchronization with PTP, SyncE, or both. The network connection was either **non-PTP** (connections through a non-PTP switch [A], [C-F])), or **all-PTP** in which every node runs on a synchronized clock (connecting the two Pixie-Net modules back to back [B] or using a PTP enabled switch [G-I]). When coincident scintillator pulses are captured in the two Pixie-Net modules, with time stamps T1 and T2, there will be a small difference in time stamps ΔT = T2-T1 (from cable delays etc). ΔT is nominally a constant (cables don't change) but with small variations due to imperfect clocking and variations in pulse shape [7].

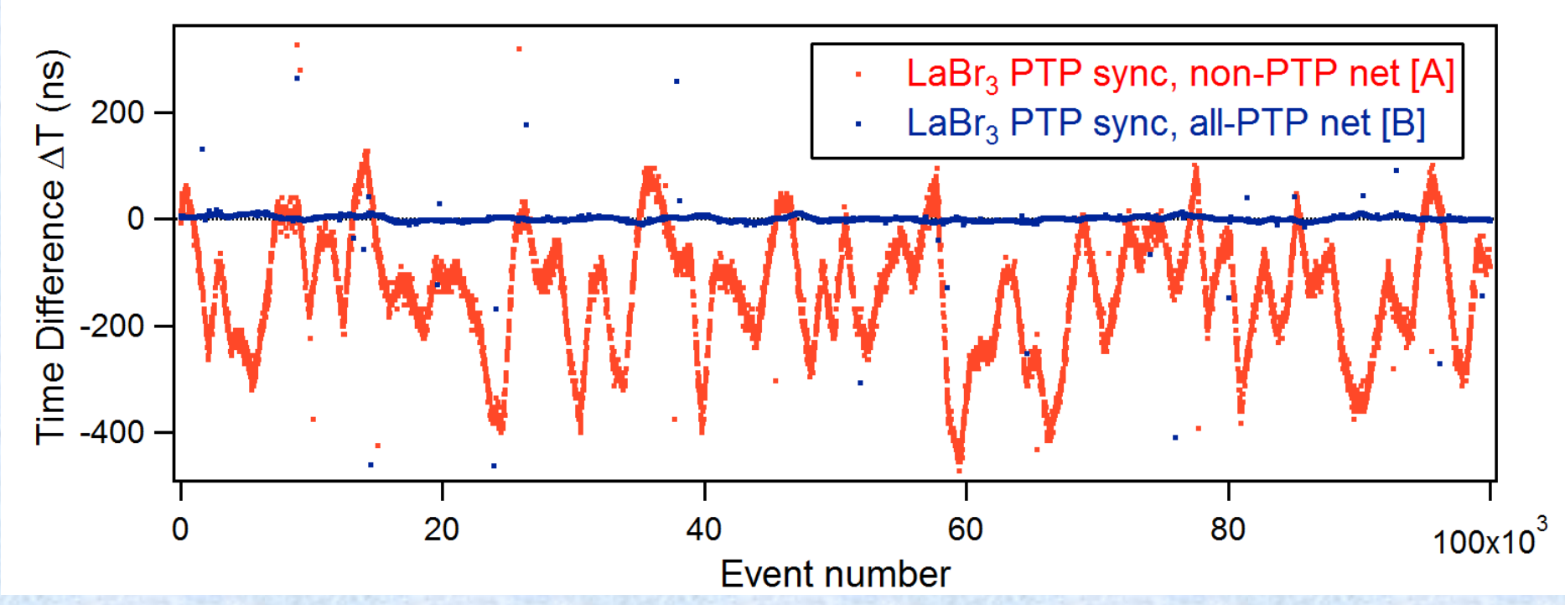
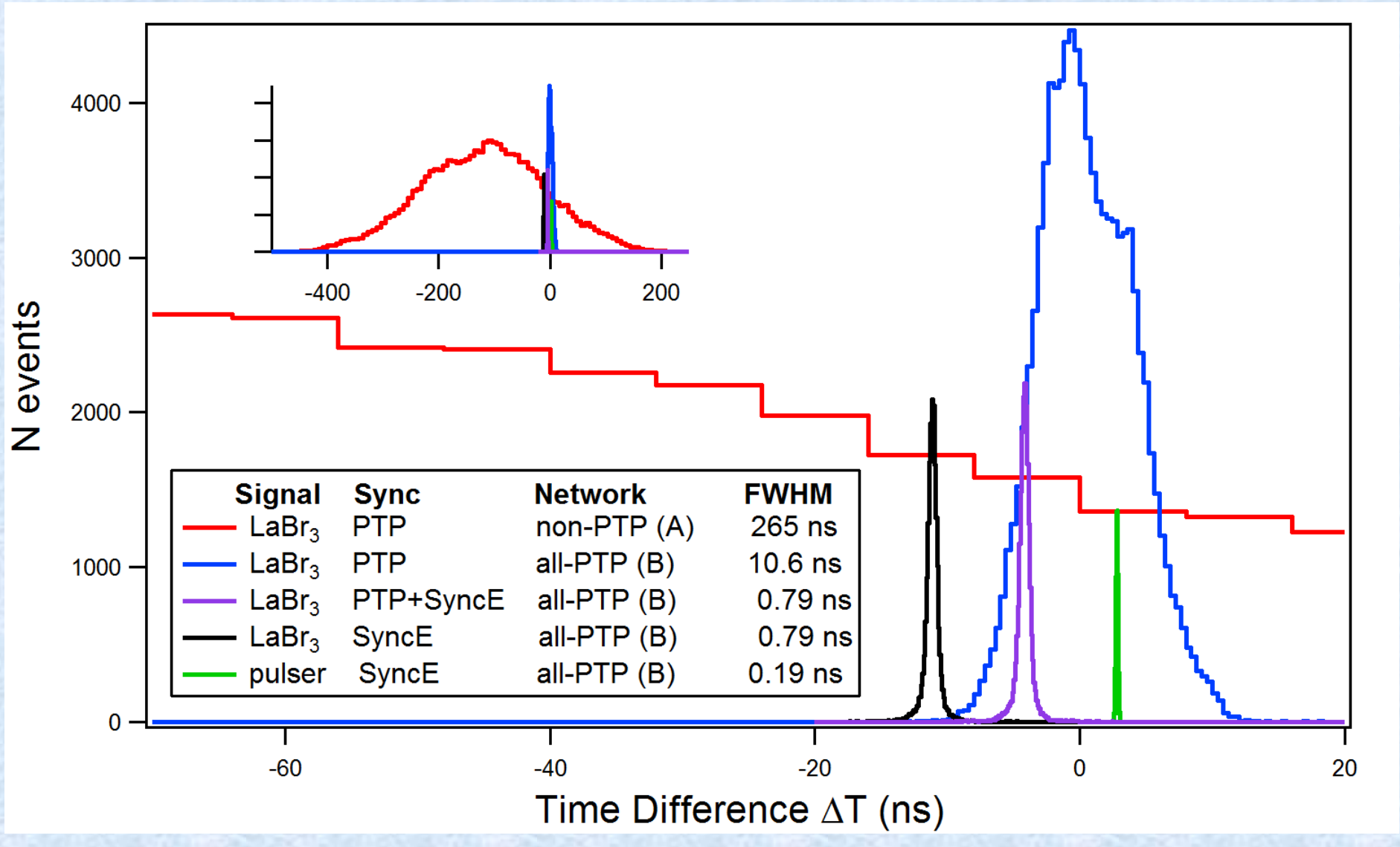
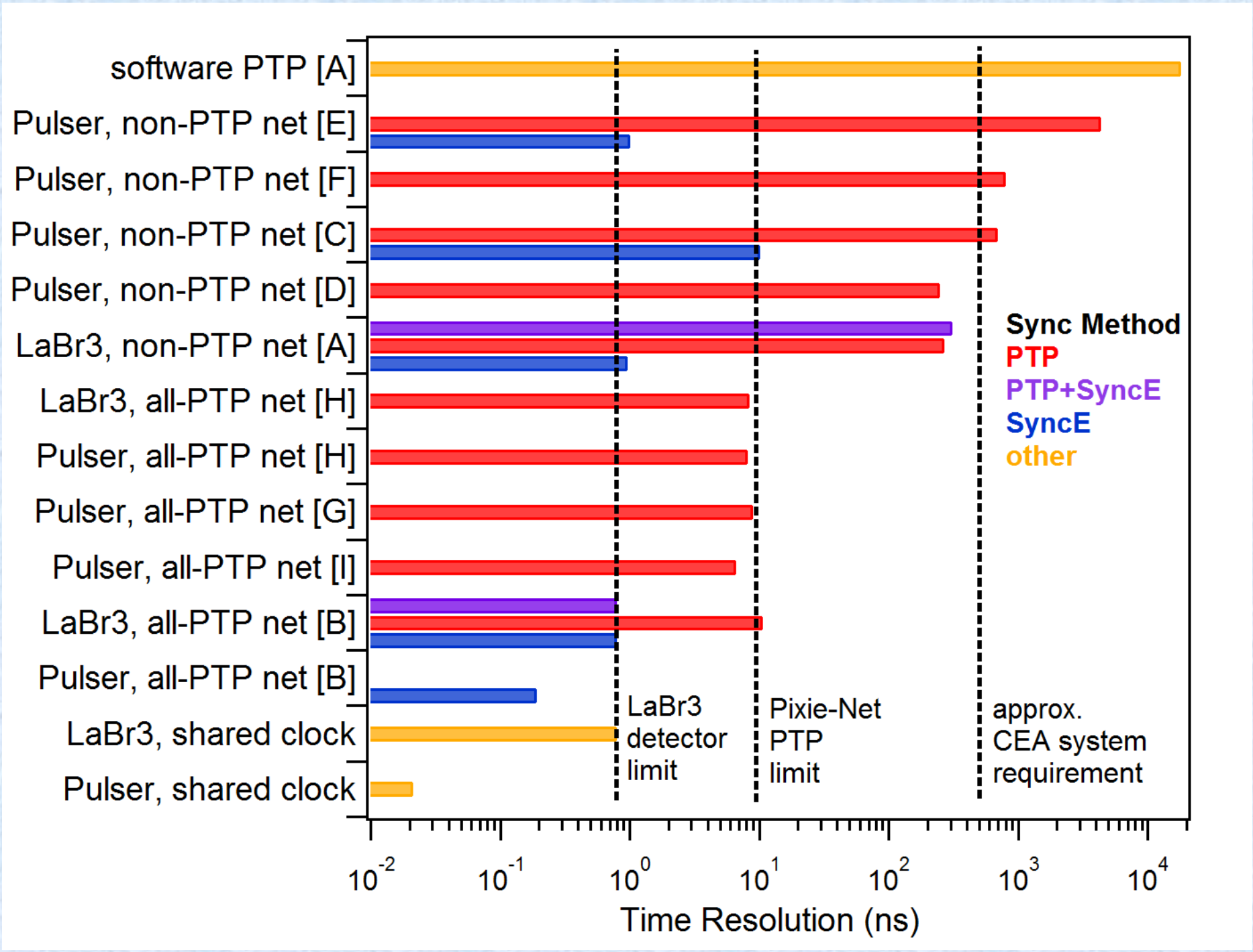


Figure 8. Measured time difference ΔT for coincident detector events acquired by 2 Pixie-Nets, demonstrating how ΔT varies as the PTP software periodically adjusts the clock. This variation is of lower magnitude in the all-PTP (and SyncE) network configuration compared to the non-PTP network.



Signal	Sync	Network	FWHM
$LaBr_3$	PTP	non-PTP (A)	265 ns
$LaBr_3$	PTP	all-PTP (B)	10.6 ns
$LaBr_3$	PTP+SyncE	all-PTP (B)	0.79 ns
$LaBr_3$	SyncE	all-PTP (B)	0.79 ns
pulser	SyncE	all-PTP (B)	0.19 ns

Figure 9. Histograms of ΔT used to compute the FWHM time resolution. (Inset shows full scale of non-PTP histogram.)



Histogramming ΔT from hundreds of thousands of pulses (Figure 9) and applying a Gaussian fit to determine the FWHM distribution is used to characterize the performance of the synchronization technique. (A CFD algorithm is applied in cases where the PTP precision approaches the clock period.

As the PTP control software periodically adjusts the slave clock, measured ΔT tends to drift in the same direction for short periods of time (slave slightly slower or faster than master) until the next adjustment [over]corrects the slave clock again (Figure 8). Overall the ΔT variation results in a FWHM time resolution of ~300 ns in a non-PTP network, and of ~10 ns when all nodes run PTP, see Figure 10. When the PHY is switched to SyncE mode, time resolutions are ~800 ps with a pair of $LaBr_3$ detectors. When detectors are replaced with a periodic reference pulser, time resolutions were ~190 ps (reduced jitter from noise, light collection variations, etc).

In configurations using a network switch, the particular choice is very important. For example, a Netgear ProSAFE GS108 (non-PTP) [C] reached only ~690 ns FWHM while several other non-PTP switches reached below 300 ns FWHM, and several PTP switches reached ~10 ns.

[A] Dell PowerConnect 2216, non-PTP
[B] back to back, PTP
[C] Netgear ProSAFE GS108, non-PTP
[D] Toplink TK 1005G, non-PTP
[E] Linksys EZXS55W, non-PTP
[F] Moxa EDS-405A-PTP, non-PTP (disabled)
[G] Moxa EDS-405A-PTP, PTP
[H] Oregano syn1588, PTP
[I] Artel Quarra 2800, PTP

Figure 10. Summary of FWHM time resolution for various signal sources and network configurations

Summary and Conclusions

A new detector system for radioactive gases is being developed at CEA. The Pixie-Net hardware, firmware and software was adapted to use network time synchronization (PTP or SyncE) to correlate clocks and timestamps in multiple modules.

- While some non-PTP switches add unacceptably large clock uncertainties, other non-PTP switches reach an acceptable precision of ~300 ns FWHM or less.
- All-PTP configurations can reach precisions of ~10ns FWHM, SyncE configurations can reach below 1 ns FWHM. In the sub-ns range, performance is also limited by signal source characteristics (~190 ps with pulser vs ~800 ps with $LaBr_3$, even with shared clock)
- The use of Pixie-Net modules implemented with the PTP protocol, coupled with a Dell PowerConnect 2216 switch allows to obtain a better accuracy than that required for this detection system, while optimizing its compactness and acting as a passive shielding against background noise.

Future work will include performance testing of the detector, Pixie-Net hardware upgrades for compatibility with the White Rabbit technology, and software upgrades to manage coincidence acquisition from a central processor (software triggering).

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