A high speed fully digital data acquisition system for Positron Emission Tomography

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Abstract– **The availability of compact arrays of high speed analog to digital converters and fast field programmable gate arrays allow much of the complex analog signal processing chain in nuclear pulse processing data acquisition to be replaced with digital algorithms. The fully digital approach allows us to evaluate APD based PET detectors and time of flight (TOF) capable fast PMTs using the same digital data acquisition (DAQ) system. We have developed digital processing algorithms for recording the time, position, and energy from a 511 keV photon interaction with a lutetium-oxyortho-silicate (LSO) crystal array coupled to a Position Sensitive Avalanche Photodiode (PSAPD) or to a XP2020 Photonics PMT as the scintillation light photodector. Implementing these algorithms in a Pixie-4 setup, we compared its performance to an analog setup based on NIM electronics modules, and we evaluated its coincidence time performance using utra-fast PMTs. From our initial experiments, the Pixie-4 system performs well in high spatial resolution, high count rate PET applications with our PSAPD detectors and with fast PMTs that are capable of TOF PET applications.**

I. INTRODUCTION

THIS DGF Pixie-4 from XIA LLC [Sunnyvale, CA] is a fully parallel 75 Msps 14-bit 4 channel data acquisition system that can be used as a multi-channel X-ray or Gamma ray spectrometer[1]. We are using the Pixie-4 data acquisition system (DAQ) to characterize our Position Sensitive Avalanche Photodiode (PSAPD) detectors used for high resolution PET systems under development [2] and XP2020 Photonis PMTs of interest for Time of Flight (TOF) PET. The speed of the current generation of ADCs and the density of gates of FPGAs allow most of the standard analog pulse processing circuits to be re-implemented as digital algorithms, which can be quickly reprogrammed for optimization, if necessary. An almost fully digital DAQ system can now reach the density needed for many small to medium channel count nuclear pulse processing applications that have traditionally used NIM racks and modules. We adapted the Pixie-4 system to work in PET nuclear data acquisition with our PSAPD detector and several different LSO crystal arrays. Also, the same DAQ was adapted to work with fast PMT devices that are of interest for TOF PET. We benchmarked the Pixie-4 DAQ performance by comparing PSAPD detector results to those from a NIM electronics setup, and evaluated the coincidence time capabilities using fast PMTs.

II. MATERIALS AND METHODS

We used a ceramic 8x8 mm^2 PSAPD device biased at -1740 V coupled to a 8x8x2 mm^3 slotted sheet LSO crystal and a 8x8x1 mm^3 sheet LSO crystal. We irradiated the crystals using a 70 µCi Na-22 source for flood and coincidence measurements. Cremat-110 preamplifiers were used to AC couple the PSAPD signals into one of two different DAQ setups. We used a 1 cm diameter Hamamatsu PMT coupled to a 2x3x10 mm^3 LSO crystal used for PSAPD coincidence measurements.

For PMT-based coincidence time resolution experiments, we used two XP2020 fast Photonis PMTs coupled to a 2x2x3 mm^3 LSO crystals. The fast PMT signals were Nyquist filtered with a 37.5 ns time constant to allow their fast rise time pulses to be sampled at the Pixie-4's 13.33 ns clock rate.

The first DAQ setup was a NIM analog spectroscopy system comprised of an Ortec-855 Gaussian shaper coupled to two National Instruments 4-channel simultaneous sampling ADC boards. The second DAQ setup was the Pixie-4 digital spectroscopy system. It was comprised of two Pixie-4 PXI 4-channel sampling boards housed in a National Instruments PXI-1002 crate.

We conducted flood acquisitions of the slotted array to determine the crystal identification capabilities of the PSAPD photodetector and the linearity and noise performance of the electronics. Individual array crystal energy resolutions were calculated and compared between the two DAQ systems. We also conducted coincidence experiments using the sheet crystal for coincidence energy resolution and timing measurements and compared this to our earlier published work.

In the Pixie DAQ system, energies are measured by performing digital triangular shaping followed by peak detection and capture. The time pickoff was measured using a digital constant fraction discriminator (CFD) algorithm [2]. This digital CFD algorithm finds the first two points above the noise floor and linearly interpolates the threshold crossing time between them to determine the arrival time.

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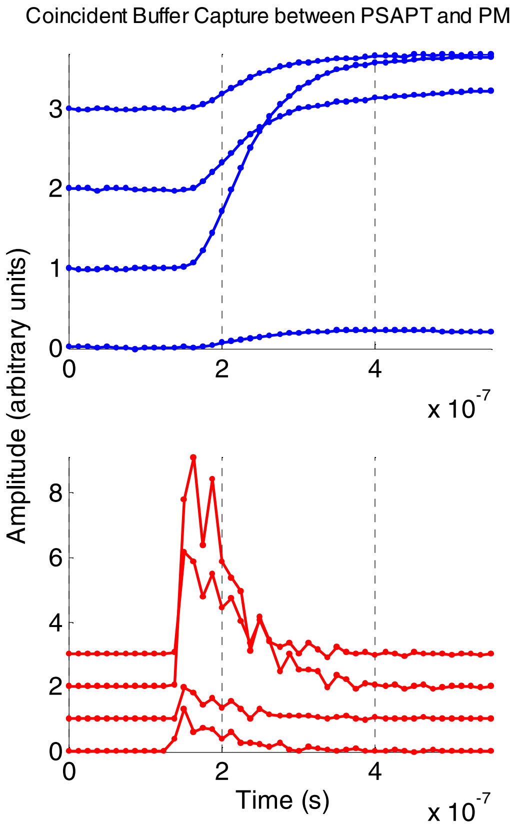

Fig. 1 Raw wave form captures for a PSAPD (**blue, top**) device and a PMT (**red, bottom**) in coincidence. Four separate waveforms are shown displaced by 1 unit.

III. RESULTS

The Pixie-4 75 Mhz sampling rate acquires samples every 13.33 ns. This allows it to sample several points on the nuclear pulse from a scintillation event (see Fig. 1). The Pixie system was able to record good energy spectra from the PSAPD and the PMT (see Fig.2). These results match our earlier results with NIM electronics and sheet crystals [2]. We measured a coincident time resolution of 886ps +/-100ps (662ps +/- 70ps unfolded) for the two LSO XP2020 PMT detectors in coincidence and 3.55ns +/-0.5ns for the LSO-PSAPD-1 cm diameter PMT coincidence experiment (see Fig. 3). The crystal identification performance of the Pixie-4 DAQ, 7:1 peak-to-valley ratio, was better than the NIM DAQ, 4.5 peak-to-valley ratio (Fig. 4).

IV. CONCLUSION

Two PET DAQs were compared: a fully digital integrated DAQ and a "traditional" NIM based DAQ. Equivalent (or better for the sheet crystal) energy resolution and crystal identification were measured. Coincidence timing resolution between the PSAPD and the 1 cm diameter PMT of 3.55 ns (Pixie-4) versus 2 ns ([2] earlier published) is tentative, and needs further evaluation to study the different contributions of noise from the PSAPD to timing. The coincidence timing resolution performance for the two LSO-XP2020 PMT detectors at 886 +/- 100 ps for LSO crystals would give a TOF constrained reconstruction diameter of 26.5 +/- 3 cm for a PET system which would give limited, but useful SNR improvement. The timing resolution of the two XP2020 PMT system may be improved by using slightly faster ADC sampling rate (100 Msps), and a faster scintillation crystal such as Lanthanum-Bromide.

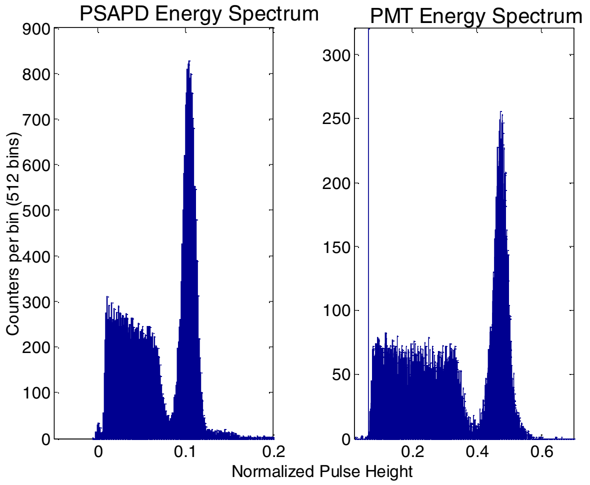

Fig.2. Energy spectra obtained from the Pixie-4 data acquisition system for a LSO sheet crystal in coincidence with a LSO crystal coupled to a 1 cm diameter PMT. The PSAPD energy resolution was 11.2 +/- 1%, and the PMT energy resolution was 10.6 +/- 1%.

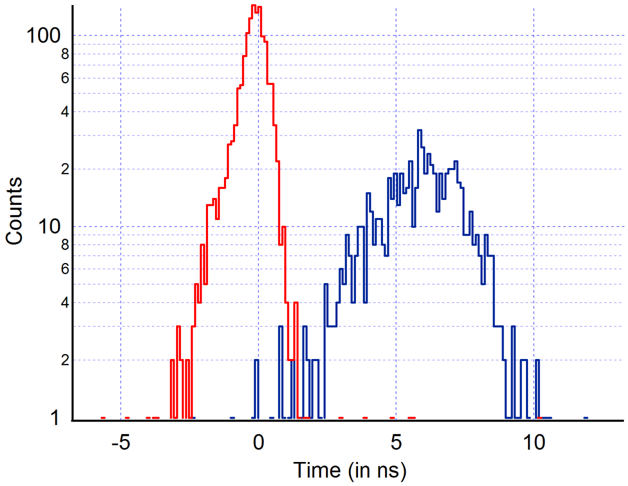

Fig.3. Timing spectra from PSAPD (**blue**) (3.55 +/- 0.5 FWHM) device and XP2020 PMT (**red**) experiments (886ps +/-100ps FWHM).

The entire Pixie-4 system only occupies the size of a small scope, rather than an entire NIM instrumentation rack. On a per channel cost, the Pixie-4 system is more flexible and less expensive than the equivalent NIM DAQ system, hence more scalable for small scale multi-channel nuclear pulse processing applications.

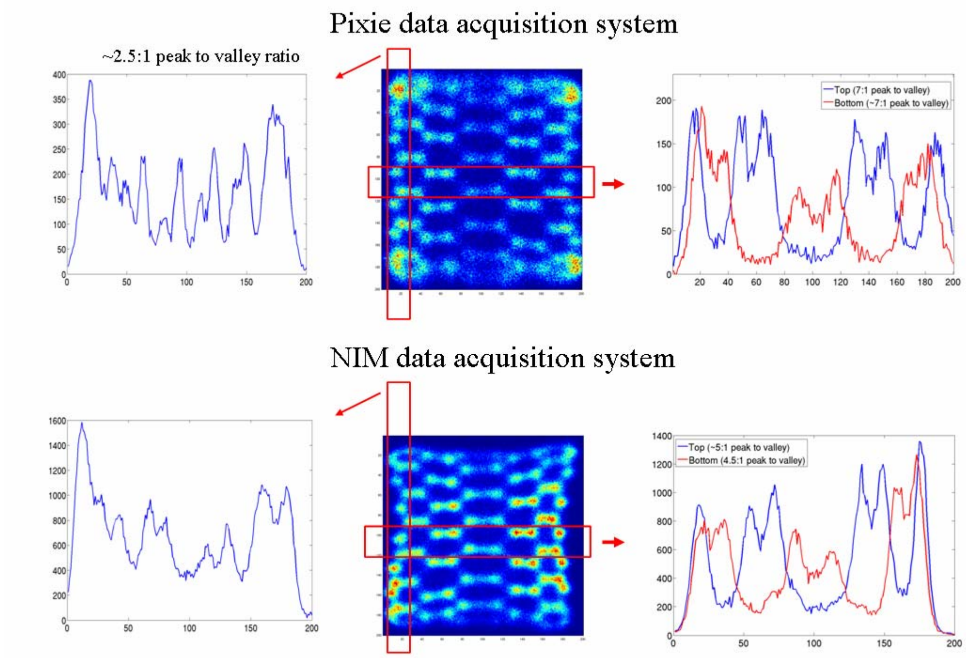

Fig. 4 The two data acquisition systems were compared with high-count rate energy gated polynomial corrected flood histograms taken with a 74 µCi Na-22 point source. 500 µm features of the slotted crystal test the noise and linearity performance of the DAQ system. Crystal identification of the Pixiel-4 system with a 7:1 peak-to-valley ratio is better than the equivalent NIM acquisition system with 4.5:1 peak-to-valley ratio. The Pixie-4 system also had better linearity near the edge of the crystal array and was able to identify all 15 crystals. A better crystal ID will allow for better positioning of the detected interaction.

REFERENCES

[1] W. Hennig et al. “The DGF Pixie-4 spectrometer – Compact Digital Readout Electronics for HPGe Clover Detectors”, presented at the IRRMA IV conference, Hamilton, ON, Canada, June 2005, **submitted to NIM B**.

[2] Levin, C.S. et al., “Investigation of position sensitive avalanche photodiodes for a new high-resolution PET detector design”, Nuclear Science, IEEE Transactions on Vol 51, Issue 3, Part 2, June 2004 Page(s):805 - 810

[3] A. Fallu-Labruyere et al. “Time Resolution Studies using Digital Constant Fraction Discrimination”, presented at the SORMA XI conference, Ann Arbor MI, USA, May 2006, submitted to NIM A.