Development of 500 MHz Multi-Channel Readout Electronics for Fast Radiation Detectors

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***Abstract*–We describe the development of readout electronics for fast radiation detectors that digitize signals at a rate of 500 MHz, process the digital data stream to measure pulse heights, bin the result in on-board MCA spectra, and optionally capture waveforms for pulse shape analysis. The electronics are targeted for applications requiring good energy resolution and precise timing, for example life time measurements on exotic nuclei, timing measurements with fast scintillators such as $LaBr_3$ or BaF_2, or pulse shape analysis with liquid scintillators or phoswich detectors. Upgrading the existing XIA Pixie-4 spectrometer design with a 12-bit, 500 MHz analog to digital converter, we built a prototype of a 4-channel electronics module and evaluated its performance in terms of energy resolution, timing resolution, and improvements in pulse shape analysis.**

I. Introduction

As accelerators are upgraded to reach higher energies and better yields of highly unstable nuclei with shorter lifetimes, and as detectors are improved to generate faster signals, provide higher count rates, and achieve better position, time and/or energy resolution, there is a need for higher speed digital detector readout electronics to match these improvements. Currently available readout electronics typically digitize the detector signal at 40-100 MHz with 12-14 bit precision or 0.5-2 GHz with 8-10 bit precision. The first group provides good energy resolution and is sufficient for microsecond decay times, but is clearly inadequate for the desired nanosecond time regime. The second group provides good timing resolution, but is limited in its energy resolution, and usually does little more than capture waveforms for offline processing, which is not suitable for high count rates.

We therefore developed the prototype of a spectrometer capable of sampling detector signals at a rate of 500 MHz with 12 bit precision. This instrument, derived from the existing XIA Pixie-4 spectrometer digitizing at 75 MHz [1], can not only capture waveforms, but can also process the digital data stream to measure pulse heights, bin the result in on-board MCA spectra, detect pulse pileup, record time stamps, live time and event rates, and perform pulse shape analysis in an on-board digital signal processor (DSP). The on-board firmware can be customized for specific applications and parameter settings can be stored on file for easy switching between applications. A small number of prototype boards (named P500) were built and characterized. In a preliminary performance evaluation of the P500, we obtained the results described below.

Manuscript received November 13, 2009. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-08ER84981.

II. Hardware Development and Test

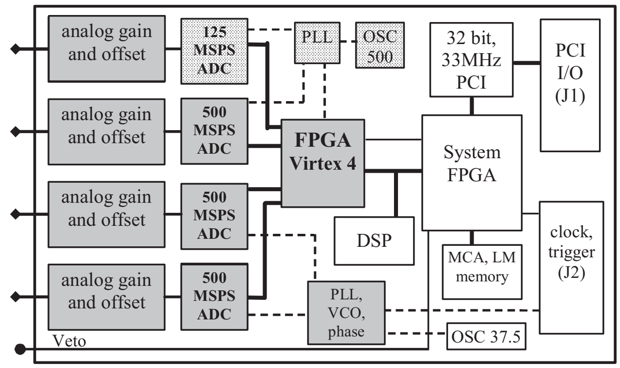

Fig. 1. Block diagram of the P500 prototype. Changes to Pixie-4 are shown in gray. The 125 MHz channel (dots) was added for reference only and will be replaced with a 500 MHz channel in the final electronics.

Fig. 1 shows a block diagram of the P500, a standard 3U CompactPCI/PXI module. It consists of a high speed front end with 500 MHz analog to digital converters (ADC) and a Xilinx Virtex-4 FPGA. In the FPGA input stage, the 12 bit, 500 MHz digital data stream from each ADC is "de-serialized" into a 48 bit, 125 MHz data stream for internal processing. Processing currently implemented includes a) triggering on the rising edge of a detector pulse, b) capture of up to 8K 12 bit samples in a FIFO, c) accumulation of filter sums for reconstruction of pulse height, d) pileup inspection to reject pulses following each other so closely that the filter sums would overlap, and e) recording run statistics such as input counts and live time.

The back end of the module, identical to the Pixie-4 [1], includes a 16 bit DSP that manages the download of filter and trigger parameters to the FPGA and computes the pulse height (energy) from filter sums read from the FPGA. Optionally the DSP can perform pulse shape analysis, e.g. computing rise times and sums over characteristic regions of a pulse from the waveforms captured in the FIFO. MCA spectra and event-by-event list mode data (timestamps, energy, waveforms) are stored in a 256K, 32 bit external memory controlled by a second FPGA and can be read out through a PCI interface. Several of the trigger lines defined by the PXI standard are used to distribute clocks and triggers between modules.

The final Pixie-500 spectrometer will consist of the P500 front end (with minor changes), but the DSP will be upgraded to a 32 bit floating point model and the host interface will be upgraded to the PXI Express standard (PXIe). PXIe combines

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the high speed PCI Express data bus found in modern PCs with additional lines for clock and trigger distribution. This allows high data transfer rates from module to host PC (nominally up to 1GB/s with a PCIe x4 link) and precise synchronization of data acquisition between modules.

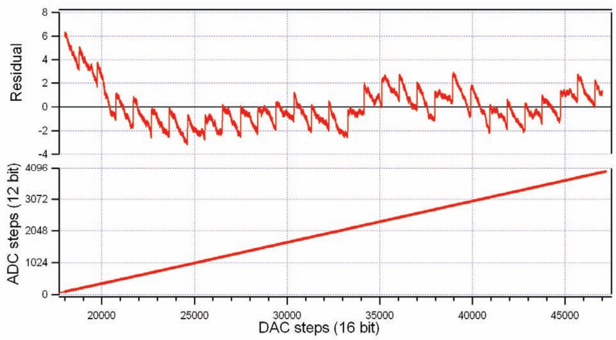

Fig. 2. Measured ADC output as a function of input voltage set by a DAC and residual of linear fit.

The ADC used on the P500 (Texas Instruments ADS5463) has the following specifications: Integral nonlinearity (INL): ± 2.5 LSB maximum, +0.8/ 0.3 LSB typical; differential nonlinearity (DNL) ± 1 LSB; RMS noise about 0.7 LSB; effective number of bits (ENOB) 10.4. For comparison, specifications for the 14-bit ADC used on the Pixie-4 are (in 12 bit LSB equivalent units) typical. INL: ± 0.125 LSB; maximum DNL: +0.375/-0.25 LSB.

Measurements of the noise and the nonlinearity (Fig. 2) largely confirm the looser specifications of the 12 bit ADC. Overall non-linearities in the P500 are substantially worse than in the Pixie-4, although it is understandable that a 12 bit ADC designed for high speed does not match the performance of a 14 bit ADC designed for precision. The non-linearites may distort spectra and worsen energy resolutions in measurements with HPGe detectors, but likely are not significant for faster, lower precision detectors such as $LaBr_3$, which are the primary target application. Processing in the FPGA may be used to reduce the effects of the nonlinearity, e.g. by correcting measured ADC values with calibration data from Fig. 2 contained in a lookup table.

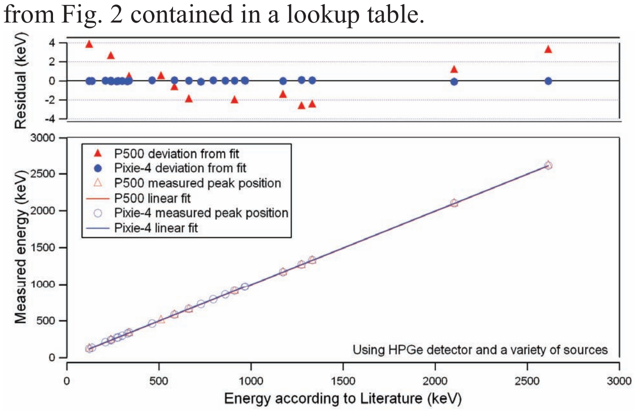

Fig. 3 Measured peak position vs. nominal energy for Pixie-4 and P500 (from offline pulse height analysis)

Available choices for spectroscopy quality, high speed ADCs are still limited; most digitize only at 8-10 bits (about 7 ENOB compared to the 10.4 ENOB of the device used here). One notable exception is a 14-bit, 400 MHz ADC (AD5474) which is pin compatible with our choice. Precision applications may thus benefit from a P500 stuffing variant with this more precise, but somewhat slower ADC.

1. Preliminary Performance Evaluation

A. Energy Resolution

Even though HPGe detectors are not the primary application for the P500, they provide a good test signal for performance evaluation. Pulse processing to measure energies was first implemented offline, then online. Energy resolutions in energy spectra computed offline are generally worse than in those computed online due to a) length limits in waveform capture and b) lack of baselines averaging using data between pulses. Offline processing is also very time consuming.

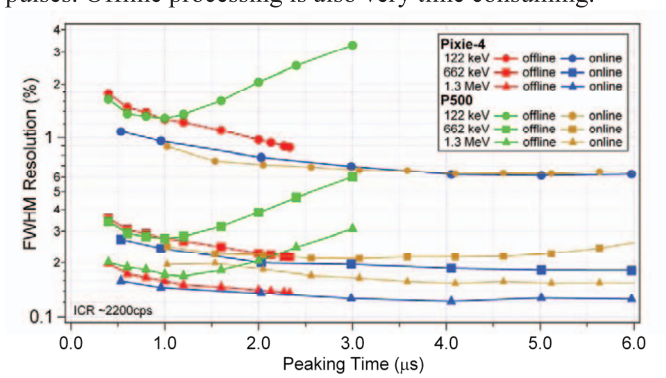

Fig. 4. Energy resolution with HPGe detector as a function of peaking time of the energy filter for Pixie-4 and P500 in online and offline processing.

With online processing, the P500 comes close to the energy resolution of the Pixie-4 and reaches ~2 keV FWHM (0.15%) for the 1.3 MeV peak at a rate of ~2200 counts/s (Fig. 4). However, due to the ADC's nonlinearity, resolutions vary strongly with count rate – resolutions may reach ~1.7 keV (0.13%) at ~1000 counts/s but peaks broaden and/or form double peaks at higher count rates when pulses overlap.

In any case, the performance of the P500 is more than sufficient for fast scintillators such as $LaBr_3$ (Fig. 5), which have lower intrinsic resolutions than HPGe detectors.

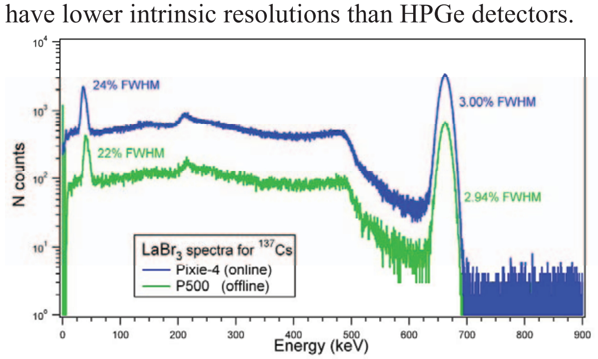

Fig. 5. P500 and pixie-4 energy spectra from $LaBr_3$ crystal and PMT.

B. Timing Resolution

In the Pixie-4, distributed clocks have a frequency of 37.5 MHz and are doubled to 75 MHz inside the FPGAs. In the P500, to simplify prototype development, channels 0 and 1

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are clocked from a dedicated 500 MHz oscillator. Channels 2 and 3 are clocked from a programmable PLL chip that multiplies an incoming 37.5 MHz clock to create a 500 MHz clock. These channels are thus compatible with a Pixie-4 distributed clock and can be used to determine if the clock distribution and multiplication affects the timing precision in a negative way. In the initial tests reported here, the PLL chip was not yet programmed and we characterized timing resolutions in a single channel by measuring the time difference ΔT between the two rising edges of a double pulse with controlled delay (Fig. 6 top). This is similar to the start-stop operation of a TDC. The variation dT of the measured time difference for several hundred pulses is very small: about 53 ps FWHM for $LaBr_3$, and 20 ps or less for a pulser (Fig. 6 bottom). In comparison, for a traditional timing measurement [2] using an analog constant fraction discriminator to measure the delay between coincident pulses from two scintillators/PMTs (BaF_2 and $LaBr_3$), the timing resolution attributed to the $LaBr_3$ channel is reported to be ~140ps FWHM.

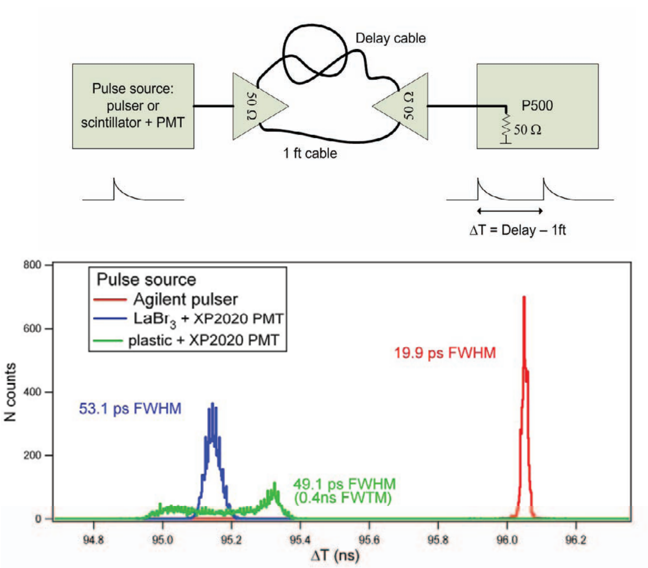

Fig. 6. Histograms of measured time difference ΔT between the two rising edges of a double pulse using P500 prototype (bottom). The double pulse was created with 50 Ω splitters (top). The pulse shape variations in the different sources lead to different ΔT distributions, sometimes non-Gaussian.

C. Submit the Manuscript and Copyright Form

As a sample application for pulse shape analysis (PSA), we used the P500 to capture waveforms from a CsI(Tl)/BC-404 phoswich detector with characteristic fast/slow pulses. Both waveforms in Fig. 7 come from a 662 keV photon scattering from the BC-404 into the CsI, depositing ~180 keV in the BC-404 and ~480 keV in the CsI. The P500 was able to resolve the fast pulse contributions from the BC-404 much better than the Pixie-4 with its slower sampling.

This leads to a much better separation of events with coincident interactions in CsI and BC-404 from events interacting in only one of the scintillators. Part of the PSA calibration process includes measuring the slope of PSA sum P vs. sum C for BC-404 only and CsI only events. As shown in Fig. 8, the slopes are much more orthogonal for the P500. Since the BC-404 contribution extends over so much less time in the P500, the length of P can be reduced from ~100 ns to ~20 ns, i.e. there is hardly any CsI contribution in the sum P.

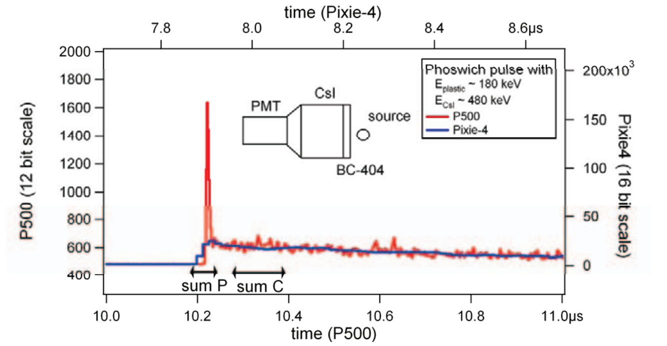

Fig. 7. Waveforms from a phoswich detector captured by Pixie-4 and P500.

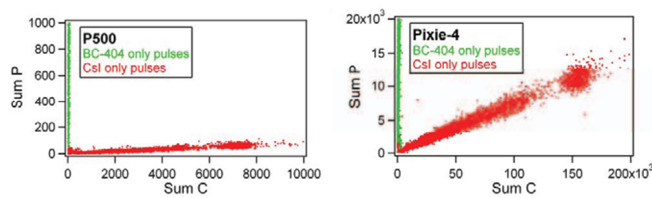

Fig. 8 Scatter plots of sum P vs. sum C computed from phoswich waveforms. Axes are scaled to the same ratio for Pixie-4 and P500 plots.

III. CONCUSIONS

In summary, we updated the design of the existing Pixie-4 spectrometer with a high speed ADC and FPGA to build the prototype of a new high speed spectrometer module, named P500. The P500 obtained good energy resolution (even though the nonlinearities of the ADC are substantially worse than those of the slower 14-bit ADC used on the Pixie-4) and very good timing resolution. Overall, the P500 is well suited for applications with fast scintillators and with limitations even for some HPGe applications, for example gamma ray tracking with segmented detectors that often have resolutions in the order of 2 keV at 1.3 MeV. Further improvements in energy resolution can be expected with a pin compatible 14-bit, 400 MHz ADC.

In future work, we will upgrade the host interface of the prototype to PCI Express, allowing much higher data transfer rates between spectrometer and host PC (nominally up to 1 GB/s with a PCIe x4 link), and develop clock and trigger distribution mechanisms to be able to capture waveforms across channels and modules with high timing precision.

References

[1] [1] W. Hennig, Y. X. Chu, H. Tan, A. Fallu-Labruyere, W. K. Warburton and R. Grzywacz, “The DGF Pixie-4 spectrometer – Compact Digital Readout Electronics for HPGe Clover Detectors”, NIM B, 263 (2007), p175.

[2] [2] M. Moszynski, M. Gierlik, M. Kapusta, A. Nassalski, T. Szczesniak, C. Fontaine, P. Lavoute, ”New Photonis XP20D0 photomultiplier for fast timing in nuclear medicine”, NIM A, 567 (2006), p31.