A modular waveform-sampling data acquisition system for time-of-flight PET

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Abstract– **Paper presents design and initial performance of ROCSTAR – a waveform data acquisition board that is being developed to instrument a dedicated high spatial resolution time-of-flight capable breast PET scanner. The PET detector is PMT-based, uses LYSO scintillation crystals with a cross-section of 1.5 x 1.5 mm^2 & has an average coincidence timing resolution of ~350 ps. The data acquisition design relies on our previous experience in developing a waveform-sampling DAQ based on the Domino Ring Sampler (DRS) integrated circuit. While the core architecture is generalizable, the ROCSTAR board has been customized for the breast scanner detector that has a single dynode and 64 anode signals. To maximize data throughput, the board uses a combination of waveform sampling and traditional flash ADCs. Anode sums are used for event positioning and digitized by flash ADCs, while the dynode signal is used to calculate the energy & timing information and is digitized by the DRS4 chip. Data from both the signal digitization paths are collected by an FPGA which packages & transfers it to a DAQ computer over a Gigabit link. The ROCSTAR board has been designed, and the first boards have been fabricated and assembled. Initial tests indicate the ability to successfully communicate with all the analog & digital portions of the board, simultaneously digitize anode and dynode signals, trigger readout, package, and transmit waveform data to the acquisition computer over Ethernet.**

I. Introduction

We are currently building a dedicated TOF-capable breast PET scanner with timing resolution of ~350 ps [1]. Due to the lack of commercial data acquisitions capable of matching the intrinsic timing resolution of the PET detectors the scanner would greatly benefit from a custom design. Our group at the University of Pennsylvania has previously demonstrated the ability to develop waveform-sampling DAQ using the Domino Ring Sampler (DRS4) [2] integrated circuit for a whole-body TOF PET scanner [3-4]. This paper discusses the design and performance of the modular DAQ being developed for the dedicated breast PET scanner.

II. Materials and methods

The breast scanner PET detector is modular and comprises of a single Hamamatsu H8500 PMT coupled to a 32 x 32 array of 1.5 x 1.5 x 15 mm3 LYSO crystals. The full scanner comprises of two opposing detector heads, each having 8 detectors in a 4x2 arrangement. The H8500 PMT has a single dynode and 64 anode signal outputs. The dynode signal is used for measuring the event energy and timing information, while the anode signals are used only for event positioning. We have previously demonstrated that a row-column sum of the 64 anode signals is sufficient to achieve good crystal separation over the entire crystal array [5]. Hence the data acquisition board for the breast scanner not only digitizes the signals, but also performs the anode data-reduction. We thus call it "ROCSTAR" (ROw Column Signal Timing And Readout) board. The ROCSTAR architecture relies on previous work done in developing a waveform sampling DAQ for a whole-body TOF PET scanner that was also developed at the University of Pennsylvania. The main components of the board include (a) DRS4 chip – waveform digitization at up to 5 Gsps, (b) FGPA, and (c) MicroZed – an off-the-shelf programmable board that includes 1 Gigabit Ethernet. To improve data throughput without sacrificing intrinsic performance, we chose to use a combination of waveform sampling and traditional flash ADCs for the ROCSTAR. Besides signal digitization, the ROCSTAR board also performs pulse shaping and gain equalization. A single ROCSTAR board is used to read a single PET detector. To measure ~300ps timing resolution it is critical to minimize the intrinsic time non-linearity within each DRS4 chip. Hence the ROCSTAR also includes a dedicated oscillator (sine wave) that is multiplexed to each of the DRS4 chips for characterizing & later correcting this non-linearity. The ROCSTAR board also uses multiple DRS4 chips in a "ping-pong" configuration to minimize the dead-time arising from use of the DRS4 chips. Fig. 1 details the architecture of the ROCSTAR board. A Master Coincidence/Control Unit (MCU) serves to synchronize and detect coincidences between the 16 ROCSTAR boards that would be used to readout the entire breast scanner.

III. Results and Summary

Fig. 1 shows the block diagram of the ROCSTAR architecture and Fig. 2 shows a photo of a fully assembled ROCSTAR board highlighting the different sections of the board. Initial firmware development, and high-speed communication between the ADCs, MicroZed has been successfully established. Initial board evaluation was performed with a custom board that was developed to generate pulses with a fast rise time and exponential decay to mimic

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scintillation pulses. Fig. 3 (*top*) shows a single pulse (*blue*) that was simultaneously fed to the anode and dynode inputs of the board. Fig. 3 (*top*) also shows the test pulse digitized by the DRS4 chip at 4 Gsps after undergoing shaping (*red*). The dynode shaping circuitry for ROCSTAR has been optimized to maintain the fast rise-time, but reduce the pulse decay time for LYSO scintillator. The test pulse used for testing however has slightly longer decay time than LYSO. Nevertheless, the circuitry helps in reducing the pulse decay time that is noticed at the output of the DRS4 chip. The leading edge of the pulse is preserved (*Fig. 3 top inset*) demonstrating the benefit of fast sampling. The periodic spikes seen is a well-known artifact of the DRS4 chip and will be eliminated once DRS4 calibrations are performed. Fig. 3 (*bottom left*) also shows pulse-sample information from 4 channels of the analog 100 Msps ADCs sampling anode pulses that will eventually be used for position estimation. The trigger signal is derived using a separate custom shaping circuit on the dynode signal and provides an ~100 ns Gaussian pulse which is sampled by a separate 100 Msps ADC to generate an event trigger. Fig. 3 shows digitized information from the trigger pathway (*bottom right*). The ability to simultaneously digitize analog (anode), digital (dynode) and trigger pulses, generate a corresponding event trigger via the FPGA, and package and transmit digital data from anodes, dynode and trigger pathways presents a significant milestone.

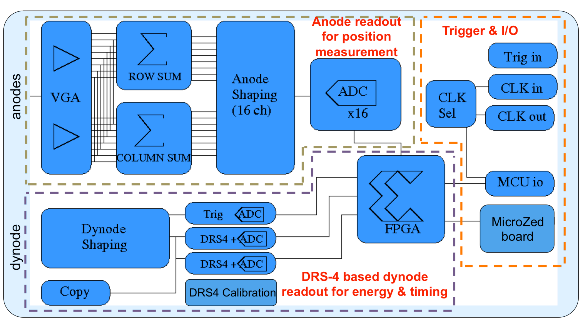

Fig. 1. Block diagram describing architecture of the ROCSTAR board. Multiple DRS4 chip's, FPGA and Gigabit Ethernet form the core of each DAQ board. The ROCSTAR has been customized to readout the Hamamatsu H8500 PMT used in the breast scanner. A separate Master Controller board will be used to control and detect coincidences between all 16 ROCSTAR boards that will be used to readout the full breast PET scanner.

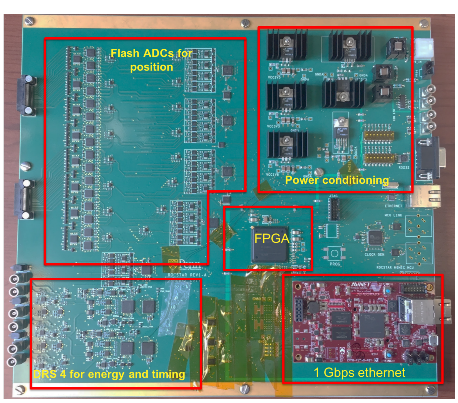

Fig. 2. Photo of a fully assembled ROCSTAR board outlining the different sections of the board.

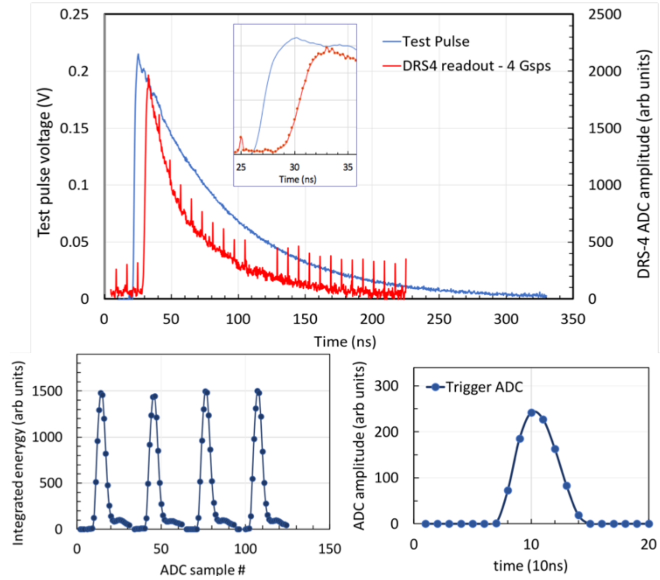

Fig. 3. *Top*: A single test pulse mimicking a scintillation pulse was simultaneously fed to the anode and dynode inputs of the board (*blue waveform*). The pulse is successfully digitized by the DRS4 chip (*red waveform*). Inset shows a zoom-in over the leading-edge of the pulse to demonstrate the ability of the ROCSTAR board to digitize fast pulses. *Bottom*: Sample data from four channels of the analog ADCs sampling the anode signals (*left)* used for event-position measurement, and trigger ADC data used to generate event trigger from the dynode signal (*right*).

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