Waveform-Sampling Electronics for Time-of-Flight PET Scanner

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***Abstract*—Waveform sampling (WFS) is an appealing technique for instruments requiring precision time and pulse-height measurements. Recent advances in switched-capacitor-array ASICs such as the Domino Ring Sampler (DRS4) have made WFS affordable for large systems. LaPET is a whole-body time-of-flight PET scanner using 38880 $LaBr_3$(5% Ce) scintillator crystals of dimension $4 \times 4 \times 30\ \mathrm{mm}^3$, imaged by 432 Photonis XP20D0 PMTs, grouped into 24 identical detector modules. High light yield (61000 photons/MeV) and fast decay time (20 ns) make $LaBr_3$ an excellent scintillator for TOF PET. Our group previously reported coincidence timing resolution 315-330 ps (fwhm) in benchtop measurements and 375 ps in full-system measurements using semi-custom electronics. This contribution reports on a complete redesign of the LaPET electronics, trigger, and data acquisition system. Our design uses 240 DRS4 chips to obtain oscilloscope-quality sampling of each PMT waveform at 2 GSPS. The 7 PMTs with which each crystal's scintillation light is collected map cleanly into the 8 analog inputs of a DRS4 chip, facilitating a redundant and nearly deadtime-free (at clinical rates) trigger design, in spite of the $\sim 3\ \mu$s required for DRS4 readout. An FPGA-based trigger using analog pulse shaping and 100 MSPS sampling provides coarse energy and timing measurements used to detect coincident pairs and to select DRS4 chips for readout. Simulation studies show that oscilloscope-quality readout of each PMT signal will permit more flexible handling of detector calibrations, PMT waveform baseline offsets, and pulse pile-up effects. We thus expect the upgraded electronics to permit system-level performance that more closely approximates single-module benchtop results and to preserve that performance at clinical count rates. Our goals are both to explore the feasibility of WFS for a large scanner and to improve the overall performance of the LaPET research scanner. We present initial tests using prototype units of our redesigned electronics.**

I. Introduction

Waveform Sampling offers three key advantages for LaPET: flexibility in handling channel-to-channel calibration effects such as gain variation and timing offsets; flexibility in handling pile-up effects; and ease with which new pulse-processing techniques can be investigated in a complete research scanner. In recent years, there has been considerable community interest in the use of waveform sampling for TOF PET [1], [2], [3], [4], [5], [6].

Our group has previously reported benchtop single-module tests that predict system timing resolution of 315-330 ps, while measured system timing resolution is 375 ps [7]. A key difference between a benchtop setup and a full system is the handling of large numbers of channel-by-channel timing and gain variations. *In situ* measurements suggest that present LaPET system timing resolution is limited by such effects.

We have performed benchtop measurements of $LaBr_3$(Ce) crystals and Photonis XP20D0 PMTs (1.5 ns rise time) using conventional discriminator/TDC/ADC modules, using commercial digitizer modules, and using DRS4 [8] evaluation modules. (See Fig. 1.) For cases studied, DRS4 evaluation modules perform equivalently to commercial digitizer modules, at an order of magnitude lower cost per channel. Thus, a DRS4-based design can affordably (about $30 per channel of DRS4+ADC) equip the full LaPET scanner to provide WFS PMT-by-PMT.

	NIM/ CAMAC	digitizer board	DRS4 eval board
⊙	225 ps	210 ps	199 ps

Fig. 1. Coincidence time resolution measured using conventional NIM/CAMAC electronics (discriminator, TDC, ADC), commercial digitizer board (2 GSPS, 8-bit), and DRS4 evaluation board (5 GSPS, 11-bit). All measurements used ⌀14mm×18mm $LaBr_3$(5%Ce) cylinder centered on Photonis XP20D0 PMT. DRS4 compares favorably with commercial digitizer, and in all cases studied, WFS performs at least as well as conventional electronics.

Numerous authors have devoted considerable creativity to the handling of the pile-up effects that limit scanner performance at high count rates. Our design combines conventional analog pulse shaping with 2 GSPS WFS. Analog shaping cancels the exponential tail of each scintillation pulse, allowing nearby pulses to be more cleanly separated. WFS facilitates both subtraction of baseline offsets caused by earlier pulses and detection of overlap pulses whose shape does not match a single-pulse template. Detailed simulation studies show that pileup identification using WFS can preserve timing and position resolution at and beyond clinical count rates. While the DRS4 chip is capable of 5 GSPS sampling, we sample at 2 GSPS to reduce readout time and to extend the 1024-sample DRS4 memory (and consequently the allowable trigger latency) from 200 ns to 500 ns.

The flexibility provided by a full readout system using WFS electronics is an asset for a research scanner such as LaPET. Whereas the pulse processing for conventional electronics is largely hard-wired into the circuit-board design, with modifications requiring at minimum many weeks to re-solder analog filter components, the pulse processing for the DRS4-

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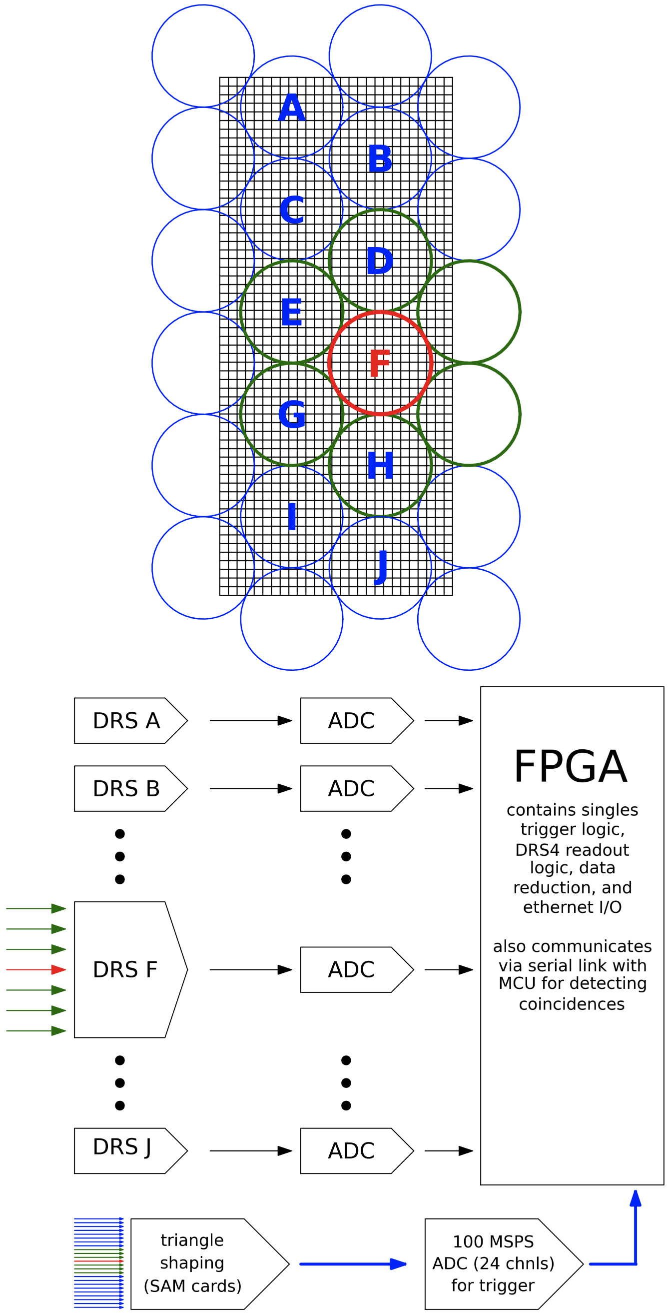

Fig. 2. Detector module geometry (upper) and block diagram of Module Readout Board (lower), which instruments $\frac{1}{24}$ of LaPET. The FPGA communicates via ethernet link with the data acquisition PC to transmit accepted photon data and via ad-hoc gigabit serial link with the Master Coincidence Unit to check that a coincident photon pair has been identified before initiating DRS4 readout. One DRS4 records each 7-PMT trigger zone, as illustrated for Zone F. The bottom of the figure indicates the trigger path, which combines analog filtering with continuous 100 MSPS digitization of each of the 24 PMT signals, in order to identify photon candidates for possible DRS4 readout.

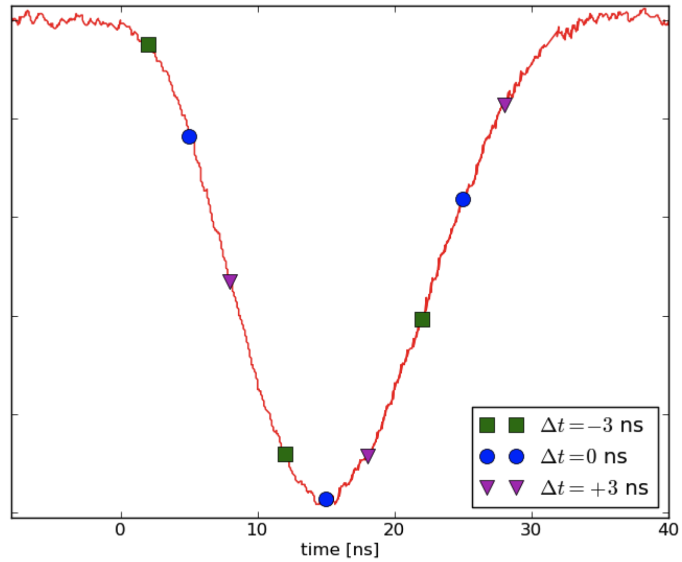

Fig. 3. The MRB trigger path shapes each PMT waveform into a quasi-triangular pulse, then samples it at 10 ns intervals to obtain an energy sum and a time centroid. The solid curve shows a PMT pulse after the analog filter has shaped it into a "triangle." Each of the three sets of points (square, circular, triangular) shows a sequence of 10 ns samples for a different pulse arrival time (-3 ns, 0 ns, $+3$ ns) with respect to the 100 MHz sampling clock, to illustrate the time centroid measurement used for coincidence detection to initiate DRS4 readout.

based system is performed in FPGA firmware. Implementing (and reversing) a modified pulse-processing algorithm for full-system study becomes as straightforward as loading updated firmware into the FPGAs that control LaPET's readout.

II. Design

In our redesigned electronics, each of LaPET's 24 detector modules is read out by one Module Readout Board (MRB). An MRB contains 10 DRS4 chips, corresponding to the 10 trigger centers labeled A-J in Fig. 2. A DRS4 samples (nominally at 2 GSPS) each of the 7 PMTs forming a trigger zone (6 PMTs for edge zones A and J), as Fig. 2 illustrates for zone F. An eighth DRS4 channel samples a reference clock. (The trigger zone concept is explained in detail in Ref. [7]. Briefly, LaPET's Anger-logic encoding scheme spread's a given $4 \times 4 \times 30\ \mathrm{mm}^3$ crystal's light with FWHM ≈ 50 mm, so that a 7-PMT ring collects nearly all light from a given crystal. PMTs in module-boundary columns are not trigger centers because light is not shared across detector module boundaries.) When readout of a trigger zone is desired, the corresponding DRS4 is stopped for digitization at 33 MSPS by an 8-channel AD9222 ADC. We digitize a region of interest (nominally 100 samples, or 50 ns) sufficient to measure a pre-pulse baseline offset, a leading-edge time, an integrated charge, and a pulse-shape goodness criterion.

Because DRS4 readout renders a trigger zone dead for $\sim 3\ \mu$s, the trigger must be both selective and redundant to eliminate system deadtime. The MRB trigger path (shown at the bottom of Fig. 2) digitizes all PMT waveforms at 100 MSPS to select a trigger zone and to provide coarse energy and time measurements. Analog circuitry shapes PMT pulses

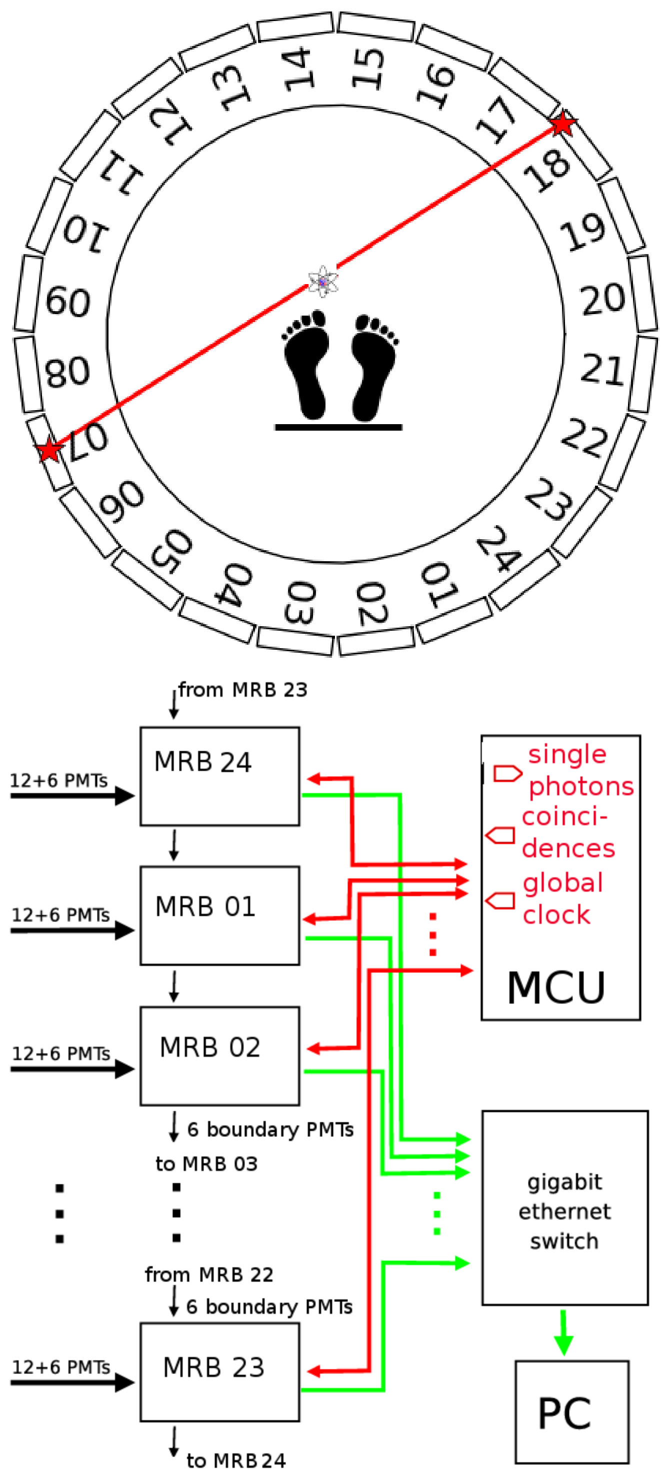

Fig. 4. System block diagram. New electronics consist of 24 MRBs. MRB/PC link uses 100/1000 Mbps ethernet for data fan-in of accepted pairs. Coincidence logic is pure digital, using Category 7 twisted-pair cable for synchronous data link between each MRB and Master Coincidence Unit. The MCU receives single-photon time-stamp inputs from all 24 MRBs and transmits to each MRB both a global clock and a flag indicating (with fixed latency) that a coincidence has been detected. Red lines indicate MRB/MCU communication, while green lines indicate ethernet-based readout of accepted photon pairs. The trigger path has energy resolution sufficient for clean separation of photopeak from Compton scattering and timing resolution better than 1 ns, which is sufficient to define a coincidence gate for initiating readout.

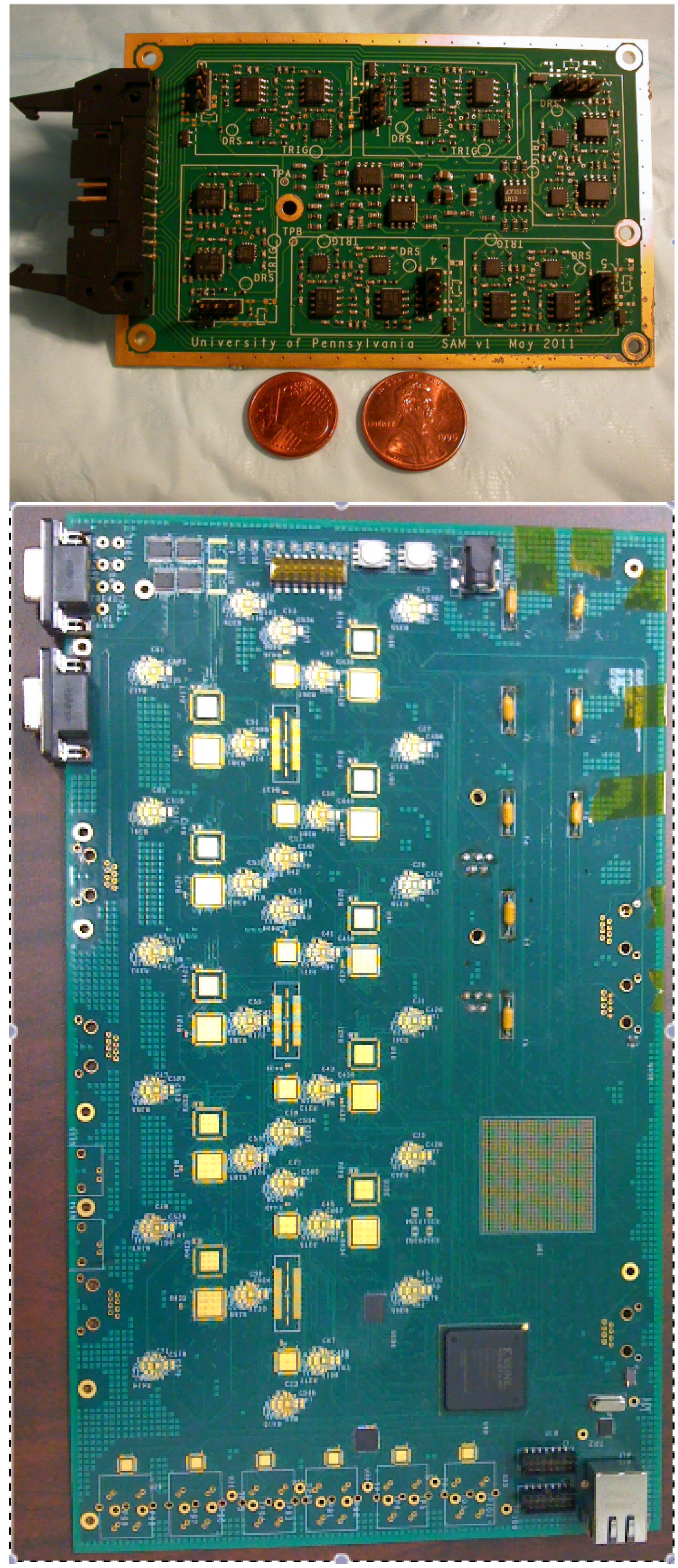

Fig. 5. Shaper/Analog Mezzanine card (upper) and Module Readout Board (lower) prototypes exist and are currently being assembled and tested. Three SAM cards will be mounted on each MRB.

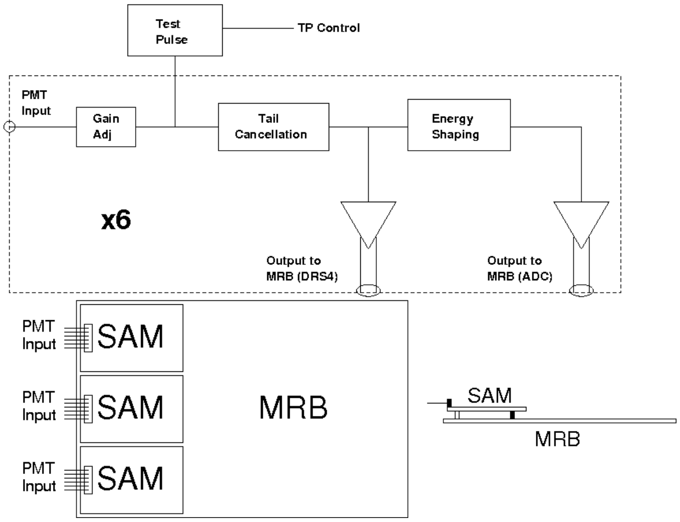

Fig. 6. Each SAM card performs analog signal processing on six PMT signals, producing two outputs per PMT—one shaped for final DRS4 readout and one shaped for the 100 MSPS trigger scheme. Each MRB hosts three SAM (Shaper/Analog Mezzaine) cards.

into roughly triangular pulses that rise+fall in $\sim 15+15$ ns, such that three consecutive samples provide a timing centroid sufficient to form the (nominally 6 ns) coincidence gate. (See Fig. 3.) We chose the 100 MSPS AD9287 after a survey of cost and power consumption of available moderate-speed ADCs. Every 10 ns clock cycle, FPGA-based trigger logic combines three successive samples from the 7 PMTs in each trigger zone, applies an energy window (nominally 400-600 keV), and may identify one available trigger zone as a single-photon candidate. The energy is estimated by simple addition, $E = \sum_i Q_i$, where the sum is over three successive 10 ns samples for all PMTs in the 7-PMT trigger zone. Similarly, a time offset with respect to the 10 ns clock edge is estimated for the 7-PMT ring as $\Delta t = \sum_i t_i Q_i / E$, where t_i is -1, 0, $+1$ for the three successive 10 ns samples. The above Δt sum is then adjusted for a programmable PMT-by-PMT timing offset. If an MRB finds an acceptable single-photon candidate, it sends a 6-bit time stamp (0.3125 ns binning) to the Master Coincidence Unit (MCU) for confirmation. Each 10 ns cycle, the MCU checks for photon pairs whose difference in timing and in azimuth are consistent with positron annihilation within the scanner's transaxial field of view; the MCU accepts or rejects each single-photon candidate with fixed latency $\sim$ 200 ns. For an accepted trigger, each corresponding MRB stops the selected DRS4, processes the 7 PMT waveforms in FPGA logic, and transmits ~ 100 bytes of summary data via Ethernet link (UDP protocol) to a PC for further processing and storage. (See Fig. 4 for a system block diagram.) Deadtime is negligible in detailed simulation studies at nominal clinical conditions of $\sim$ 20 MHz single-photon trigger rate and $\sim$ 700 kHz prompt coincidence rate and remains below 1% at ~ 50 MHz simulated single-photon rate.

III. Results

Our system design has been vetted with a combination of benchtop data and simulation studies. Prototype Shaper/Analog Mezzanine cards exist and have been successfully tested. Prototype MRBs have been fabricated and are currently being assembled and tested. (See Fig. 5 for photos.) The Master Coincidence Unit exists in the form of C and Verilog models; its algorithm will be prototyped for $\frac{2}{24}$ of the scanner using existing MRB hardware. The Ethernet/UDP readout scheme has been prototyped using commercial FPGA evaluation boards, a commercial Ethernet switch, and a Linux PC. The data-acquisition software will write list-mode events compatible with existing reconstruction software and will reuse calibration algorithms that measure detector quantities. Further software development will be needed for event collection and for electronics calibration. We plan to re-instrument the full LaPET scanner during calendar year 2012.

IV. Summary

Progress in TOF PET timing resolution continues to improve the clinical benefit of PET imaging. One challenge in scaling from a small detector on a benchtop to a whole-body TOF PET scanner is the control of channel-to-channel gain and timing offsets. A key challenge in operating a whole-body TOF PET scanner at clinical count rates is to preserve excellent timing, energy, and position resolution in the presence of pile-up interactions. We have designed and are currently implementing for the LaPET scanner new electronics that address these challenges. By processing individual PMT signals digitally, we maximize available handles for controlling calibration effects. Using high-speed waveform sampling facilitiates our handling baseline offsets and pile-up pulses at clinical count rates. We are currently testing prototypes of the circuit boards with which we will re-instrument the LaPET whole-body research scanner.

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