Abstract—LA PET is a LaBr$_3$-based whole-body time-of-flight PET scanner. We previously reported coincidence timing resolution 315-330 ps (fwhm) in benchtop measurements and 375 ps in full-system measurements. We are currently testing prototype units for a complete redesign of LA PET’s electronics, aimed at improving the full-system timing performance and at preserving that performance at high count rates. We report on four facets of the new design. First, PMT-by-PMT high-voltage control at two points per dynode chain permits both gains and timing offsets to be equalized across the scanner. Second, analog pulse shaping reduces the duration of each PMT pulse from 75 ns to 35 ns, leading to a pile-up effect. Third, custom circuit boards use the DRS4 waveform-sampling ASIC to provide oscilloscope-quality readout of each PMT signal, enabling digital processing of PMT waveforms. Finally, an FPGA-based trigger provides the coarse energy and timing measurements used to detect coincident pairs. Tests are underway of prototype High Voltage Control boards, Shaper/Analog Mezzanine cards, and the DRS4-based Module Readout Board; the Master Coincidence Unit design is in progress.

I. INTRODUCTION

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 [1]. We have designed and are implementing new electronics that address these challenges for the LA PET research TOF PET scanner.

LA PET [2] is a whole-body time-of-flight PET scanner using 38880 LaBr$_3$ (5% Ce) scintillator crystals of dimension $4 \times 4 \times 30 \text{mm}^3$, imaged by 432 Photonis XP20D0 PMTs (Fig. 1). High light yield (61000 photons/MeV) and fast ($\tau \approx 20 \text{ ns}$) decay time make LaBr$_3$ an excellent scintillator for TOF PET. Our group previously reported coincidence timing resolution 315-330 ps (fwhm) in single-module benchtop measurements and 375 ps in full-system measurements using semi-custom electronics. We are currently testing prototype units for a complete redesign of LA PET’s electronics, aimed at improving the full-system timing performance and at preserving that performance at clinical count rates ($\sim$ 20 MHz single-photon trigger rate and $\sim$ 700 kHz prompt coincidence rate).

This contribution reports on four facets of the redesigned electronics. First, PMT-by-PMT high-voltage control at two points per dynode chain permits both gains and timing offsets to be equalized across the scanner, eliminating a significant contribution to timing resolution [3]. Second, analog pulse shaping reduces the duration (5% to 5% of peak) of each PMT pulse from 75 ns to 35 ns, reducing the severity of pulse-pileup effects at high count rates. Third, custom circuit boards use the Domino Ring Sampler (DRS4) [4] waveform-sampling ASIC to provide oscilloscope-quality readout of each PMT signal, enabling digital signal processing techniques to implement more flexible handling of detector calibrations, PMT waveform baseline offsets, and pulse-pileup effects. Finally, an FPGA-based trigger using analog pulse shaping and 100 MSPS sampling provides a flexible implementation of the coarse energy and timing measurements used to detect coincident pairs and to select DRS4 chips for readout. Tests are underway of prototype High Voltage Control (HVC) boards [5], Shaper/Analog Mezzanine (SAM) cards, and the DRS4-based Module Readout Boards (MRB) [6]; a preliminary design exists for the Master Coincidence Unit needed to coordinate trigger processing for the full scanner’s 24 detector modules.

The principal goal for the new electronics is for the full scanner’s performance to meet or exceed at clinical count rates the 315-330 ps performance obtained for single-module benchtop tests. A secondary goal is to provide an adaptable platform for further development of the LA PET research scanner.

II. DESIGN

Our design combines targeted analog solutions to well-understood performance issues (PMT gain variation, PMT timing offsets, exponential pulse tail) with the flexibility of waveform-sampled readout and a fully digital trigger.

The HVC board is a digitally programmable power supply capable of independently controlling the dynode and photocathode biasing voltages for each of 18 PMTs (Fig. 2). The full scanner requires 24 HVC boards.
Each of LAPET’s 24 detector modules will be read out by one MRB (Fig. 3,4), whose 10 DRS4 ASICs sample PMT waveforms 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, such that a single DRS4 contains all PMT waveforms needed to reconstruct a given 511 keV photon. Waveform sampling allows shape-based discrimination of clean pulses from pile-up pulses (Fig 5). In addition, early digitization facilitates ad hoc handling of performance issues that we may encounter once the full system is reinstrumented.

Three SAM cards provide analog shaping for each MRB (Fig. 6,7). One shaping path (“readout shape” in Fig. 6) shortens the exponential ($\tau \approx 20$ ns) tail of each PMT pulse, while preserving the fast leading edge for TOF measurements. The motivation is to reduce the time interval that must be digitized in order to separate cleanly the pulse of interest from earlier pulses. A second SAM shaping output (“trigger shape” in Fig. 6) rises+falls in 15+15 ns, such that 100 MSPS from earlier pulses. A second SAM shaping output (“trigger shape”, as shown in Fig. 6) function as designed. SAM card measurements also show that in the absence of pile-up, a 30 ns integration window is sufficient to preserve energy resolution (Fig. 12). Hence, the SAM card meets the goal of permitting the integration window to be shortened.

Benchtop tests using a partial LAPET detector module have demonstrated the methods of the upgraded electronics, using a real HVC board, a real SAM card, and a commercial DRS4-based digitizer (Fig. 13): the result is a flood map in which individual crystals are clearly distinguished. In the coming months, these results will be extended to two sectors of the real LAPET scanner, using two prototype MRBs. The Master Coincidence Unit exists in the form of C and Verilog models; its algorithm will be prototyped for $\frac{A}{3}$ of the scanner using existing MRB hardware. The Ethernet-based readout scheme is in use for MRB bench tests. We plan to re-instrument the full LAPET scanner during calendar year 2013.

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. Redesigned high-voltage control (HVC board) and analog shaping (SAM card) address well-understood performance issues (PMT gain variation, PMT timing offsets, exponential pulse tail). By processing individual PMT signals digitally, we maximize available handles for controlling calibration effects. Using high-speed waveform sampling facilitates 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.

REFERENCES


Fig. 1. LAPT's 38880 crystals are separated azimuthally into 24 detector modules and imaged by 432 PMTs (51 mm²). The new electronics obey the same 24-fold symmetry, sharing edge PMT data between neighboring sectors.

Fig. 2. Schematic illustration of PMT gain and timing control (left), and High Voltage Control (HVC) boards on scanner (right). HVC boards have stably powered 2/24 of LAPET (as shown in photo) for several months. HVC controls and programmably adjusts PMT-by-PMT gain and timing.

Fig. 3. New electronics consist of 24 Module Readout Boards (MRB). 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.

Fig. 4. Block diagram of Module Readout Board (MRB). Letters A through J indicate PMTs on which trigger zones are centered. Scintillation light from the 7 PMTs (only 6 PMTs for zones A and J) in each zone is collected by 7 analog inputs of the corresponding DRS4 chip. (An eighth analog input for each DRS4 chip records a reference clock for timing alignment.) A separate data path digitizes all 24 PMT signals at 100 MSPS for FPGA-based triggering.

Fig. 5. Waveform sampling at 2 GSPS enables flexible definition of leading-edge timing and of integrated light collected by PMT, from a single data stream. Digital baseline restoration and shape-based pile-up detection help to preserve performance at high count rates. The Module Readout Board provides DRS4-based readout for LAPET.
Fig. 6. SAM card input and filtered outputs. PMT pulse (black curve) recorded by oscilloscope, before and after shaping by SAM card. Green curve shows tail cancellation that reduces pile-up effects. Red curve shows pulse shaped for 100 MSPS trigger processing. The “readout shape” (green) sent to DRS4 for 2 GSPS sampling, preserves fast leading-edge timing while canceling slow tail of PMT pulse. The “trigger shape” (red) makes rise and fall times roughly equal, so that trigger ADC and FPGA logic can determine coarse energy and timing (via centroid algorithm) for coincidence detection, to select DRS4 chips for readout.

Fig. 7. Shaper/Analog Mezzanine (SAM) cards have been assembled, tested, and used to record data both with MRB prototype and with commercial DRS4-based DAQ.

Fig. 8. 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.

Fig. 9. Benchtop tests of prototype Module Readout Board. Each MRB hosts three SAM cards (two are shown in photo). The full scanner requires 24 MRBs.
Fig. 10. PMT pulses recorded by prototype MRB. Waveforms have had baselines subtracted and leading-edge times aligned in software.

Fig. 11. Energy spectrum from positron decay (from $^{22}$Na source), triggered and recorded by prototype MRB.

Fig. 12. Single-crystal energy resolution (blue) and response (red) vs. integration time, for pulses recorded after SAM “readout” shaping. Goal is to optimize tradeoff between energy resolution (long integration) and high-count-rate pile-up minimization (short integration).

Fig. 13. Partial flood map obtained on test bench using HVC board, SAM cards, and commercial DRS4-based digitizer.