A Multi-Threshold Sampling Method for (TOF) PET Signal Processing

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Abstract—As an approach to realizing all-digital data acquisition for positron emission tomography (PET), we have previously proposed and studied a multi-threshold (MT) sampling method to generate samples of a PET event waveform with respect to a few user-defined amplitudes. By analyzing digital samples generated by this method, one can then extract both the energy and timing information for an event. In this paper, we report our prototype implementation of this sampling method in electronics and the performance results obtained with this prototype. The prototype consists of two multi-level discriminator boards and a time-to-digital converter (TDC) board. Each of the multi-level discriminator boards takes one input and provides up to 8 threshold levels, which can be defined by users, for sampling the input signal. The TDC board employs the CERN HPTDC chip that determines the digital times of the leading and falling edges of the discriminator output pulses. We connect our prototype electronics to the outputs of two Hamamatsu R9800 photomultiplier tubes (PMTs) that are individually coupled to a 6.25mm×6.25mm×25mm LSO crystal. By analyzing data samples generated by using two thresholds on the leading edge and four thresholds on the trailing edge, we obtain a coincidence timing resolution of about 341 ps and an ~18% energy resolution at 511 keV. We are also able to estimate the decay-time constant from the resulting samples and obtain a mean value of 44 ns with an ~9 ns FWHM. In comparison, by analyzing digitized pulses obtained at a 20 GSPs sampling rate for the same LSO/PMT modules we obtain ~300 ps coincidence timing resolution, ~13% energy resolution at 511 keV, and ~4 ns FWHM for the estimated decay-time constant. Our results therefore have solidly demonstrated the practical value of the MT sampling method.

I. INTRODUCTION

RECENTLY, there are increasing interests in deriving relevant PET event information from the digitally sampled event waveform [1][2][3], and we have investigated the potential benefits of employing such digital technologies in determining the event time [4][5]. We observed that one practical challenge with the popular digitizing scheme that samples the waveform at a regular time interval is the need for having higher than 1 GSPs (10^9 samples per second) sampling rate in order to properly capture the start time of the fast event pulses generated with modern scintillators such as LSO. This high sampling-rate requirement creates practical concerns about the cost, power consumption and heat dissipation. Toward addressing this challenge, we have also proposed a multi-threshold (MT) sampling method that samples the event waveform with respect to a few amplitude thresholds, and found the method to be capable of generating reasonably good timing resolution for time-of-flight (TOF) PET imaging. In this paper, we present our prototype implementation of this MT sampling method in electronics. We also extend our analysis method to generate from the digitized waveform samples not only the event time, but also the event energy and the decay time constant. Our results indicate that by employing 4 thresholds the MT sampling method can yield results that are useful for PET and TOF-PET imaging. It is noted that our results were obtained by using no preamplifiers to optimize the signal-to-noise ratio (SNR) at sampling. In this digital data-acquisition (DAQ) architecture, all relevant information is derived from digital data generated in a single sampling channel (conventionally, event time and energy are processed by separate electronics channels), and several components often found in current PET DAQ electronics, including the constant fraction discriminators (CFD) and analog-to-digital converter (ADC), can be eliminated. More advanced digital signal processing (DSP) techniques may also be explored for generated improved results from the obtained digital samples. The simplified and unified approach, plus the possibility to explore advanced DSP technologies, may result in cost saving and improved event detection.

II. METHODS

A. Prototype

Fig. 1 shows our prototype implementation of the MT sampling method. The prototype consists of two multi-threshold discriminator boards and a TDC board.

We have developed multi-threshold discriminator boards by using the ADCMP582 comparators. The board provides eight programmable voltage thresholds from 0 to 700 mV (Fig. 1). It connects directly to the PMT output with no pre-amplification applied. Currently, we have two multi-threshold boards and installed four comparators on each board. For digitization of the timing, the outputs of discriminators were connected to High Performance TDC(HPTDC) which was developed at European Organization for Nuclear Research(CERN)[6]. HPTDC provides 8 channels with 24.4 ps/bit resolution.

B. Experimental Setup

Our setup for testing the prototype is depicted by Fig. 2. Two Hamamatsu R9800 photomultiplier tubes (PMTs) coupled with LSO crystals (6.25×6.25×25mm^3) were spaced at 5.0cm...
Figure 1. A multi-threshold discriminator board (left) and the HPTDC board (right). The discriminator can provide up to 8 thresholds for sampling its input signal. Currently, four channels have been implemented. The discriminator outputs are connected to the HPTDC chip on the TDC board. The HPTDC chip, developed at CERN, can provide 8 TDC channels at 24.4-ps bit resolution. Therefore, currently we can employ a TDC board to support two multi-threshold boards.

apart, and a Na-22 positron source was placed in between the two PMTs. Both PMTs are operated at -1300V to obtain a nominal gain of about $10^6$. Each PMT output was directly connected to one multi-threshold discriminator board. The discriminator board currently provides 4 threshold levels and they were set typically at 50, 100, 200 and 300 mV. The HPTDC chip on the TDC board took the 8 discriminator outputs from the two multi-level discriminator boards and determined the digital times when these output pulses made transitions between the high- and low-voltage levels.

In addition, the full waveforms of PMT signal and discriminator output were also taken by the Tektronix TDS6154C oscilloscope running at a 20GSps sampling rate. These sampled waveforms were analyzed to investigate the timing characteristics of the multi-threshold board, and to evaluate the performance characteristics of the prototype.

C. Analysis of the digital samples

Using the eight samples generated by the multi-threshold board with four thresholds, we investigate the accuracy and precision in reconstructing the event pulse shape from these eight samples. The three thresholds currently considered are 50, 100, 200, and 300 mV. Figure 3 shows the input PMT signal to the multi-threshold board, the eight sampled points generated by the board (after time corrections using measurements obtained above), the line fitting to the four sampled points on the rising edge of the pulse, and the exponential-curve fitting to four samples points on the decay portion of the pulse. The event time and energy are determined from 8 sampled points as follows: (a) the intersection of the fitting line on the rising edge with the zero-voltage level is defined as the event time of the pulse; (b) the total area under the fitted line and exponential curve gives the event energy. The event time and energy are similarly determined from the event waveform digitized at 20 GHz. The decay portion of this waveform is also fitted with an exponential function to obtain the scintillation decay constant.

III. Results

A. Timing characteristics of the discriminator board

Figure 4 shows measured time differences between two discriminator outputs on the same discriminator board due to the difference in the signal path lengths from the input to the discriminators. In this measurement, a pulse generator output was used for the input to the board. The thresholds were set at 100 mV for all channels. The measured time differences between channels were used for the timing corrections in results reported below. The time differences have been measured for all installed channels on both boards; the average time resolution was estimated to 13.3 ps in FWHM for a single discriminator channel.

B. Energy resolution

Figure 5 compares the pulse-height spectra obtained by using the multi-threshold method with four thresholds and by using the waveform digitized at 20 GHz. The results indicate a 18% energy resolution in FWHM at 511 keV with the former method, and 13% energy resolution in FWHM with the latter. Thus, the use of only three thresholds can already acceptable energy resolution for PET imaging.

C. Decay time constant

Figure 6, on the other hand, shows the scintillation decay constants obtained. Using the digitized waveform, we obtain a mean value of 45 ns, with a width of ~4 ns FWHM. In
Figure 4. A sample histogram showing the time offset between the outputs of two channels on the same multi-threshold board. The peak position gives the time offset between the two channels and the width shows the timing jitter, which is ~16.8 ps in FWHM in this case. The width of the other channel combination shows similar values, and the average timing jitter is ~13.3 ps in FWHM.

Figure 5. Integrated charge distribution of reconstructed pulse(red). The integrated charge for original PMT pulse is also superimposed for comparison(blue).

D. Coincidence timing resolution

We also measured the coincidence timing resolution that can be achieved by using only two thresholds, setting at 100 and 200 mV, on each of the two multi-threshold boards. Figure 7 shows the histogram of the differential time determined. The result shows a coincidence time resolution of about 350 ps in FWHM. This result can be compared to the previously reported ~300 ps of time resolution using the conventional analog CFD.[5]

Figure 7. Time difference of coincidence events. The event time was decided using timings from 100 and 200 mV thresholds for each PMT signal.

IV. Conclusion

The multi-threshold discriminator board was built to implement the sampling PET signal at the voltage domain. Timing outputs of the multi-threshold board with 4 thresholds were read out by HPTDC. The event timing and energy information was extracted from the reconstructed pulse shape using eight sampling points. With the multi-threshold method, we obtained 18% of energy resolution and ~350 ps coincidence timing resolution. These results can be compared to 13% of energy resolution and ~330 ps timing resolution with 20 GS/s waveform. The multi-threshold sampling with 4 thresholds contributes ~20 ps degradation to coincidence timing and 5% degradation in energy resolution. The further improvements in timing can be expected by threshold level optimization and fitting methods. The current results shows that the multi-threshold sampling is a promising method for implementing digital PET data acquisition.

REFERENCES