論文の内容の要旨

Study on Front-End Electronics for High Spatial Resolution PET System
（高分解能 PET システム用フロントエンド回路の研究）

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1. Introduction

Positron emission tomography (PET) is a nuclear medicine imaging technique, which utilizes positron-emitting radionuclide labeled molecules to reveal biological and physiological information of human body or animals.

Before PET scan, a short-lived positron-emitting tracer isotope is injected into the living subject. The tracer is chemically incorporated into a biologically active molecule. As the radioisotope undergoes positron emission decay, it emits a positron. After traveling up to a few millimeters the positron encounters an electron, and the two particles annihilate, producing a pair of 511 KeV gamma-ray photons moving in opposite directions. These two gamma-rays, if detected by surrounding detectors of the PET scanner within a timing window, will be recorded as a line of response (LOR). Thus, after many LORs are collected, the original distribution of the radiopharmaceutical could be obtained and corresponding biological information could be analyzed.

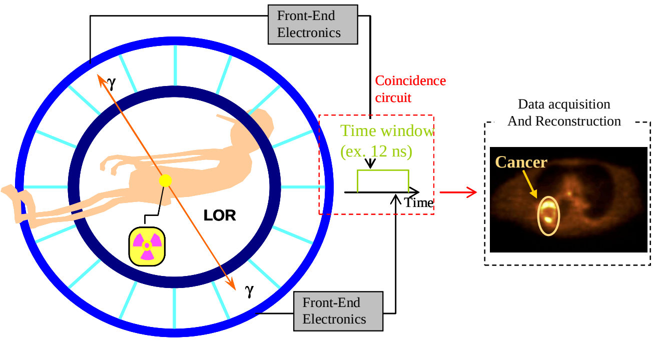


Fig.1 Principle of PET Imaging

As a unique molecular imaging tool in cancer diagnosis, radiation therapy and small animal imaging, PET system with high spatial resolution and high sensitivity is demanded in both clinic and research applications. The most important factors affecting spatial resolution of PET system are detector pixel size and electronic readout method. Therefore, we have proposed two front-end electronics themes which could be used for individual readout for pixellated detector based PET system to achieve high spatial resolution (<2 mm).

2. Detectors for high resolution PET

There are mainly three types of radiation detectors available for PET system, Gaseous detector, Semiconductor detector and Scintillation detector coupled to a photodetector.

TABLE 1
COMPARISON OF PET DETECTORS

	Gaseous Detectors	Scintillation Detectors	Semiconductor Detectors
Price	Cheap	Moderate	Expensive
Energy Resolution	Poor	Moderate	Good
Spatial Resolution	Good	Moderate	Good
Timing Resolution	Good	Good	Poor

Based on all overall characteristic we recommend to use scintillator and photodetector for high resolution PET system since the 2 mm pixel size are already available in mature commercial products. Both phoswich and one to one coupling scheme with pixellated scintillator array and pixellated APD could achieve the desired spatial resolution.

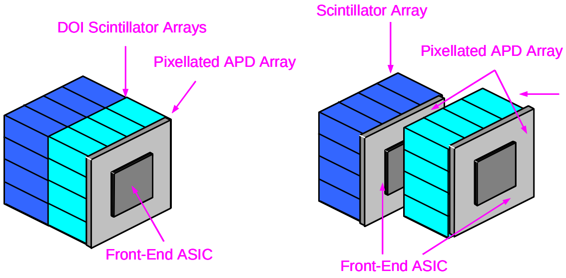


Fig. 2 Proposed high resolution PET detector

3. Front-end scheme for high resolution PET

As it was concluded, the most effective method to improve spatial resolution of PET system is to reduce the detector pixel size and use individual readout method [1]. However this will make the PET system require a very large scale multi-channel readout system, whose cost, power consumption and reliability become a big challenge.

Therefore, we have proposed two front-end electronic themes for proposed PET detector. The waveform sampling based front-end electronics is able to perform PSD function [2]. Therefore it is suitable for phoswich detectors. At the meantime, time-over-threshold method is able to achieve much higher channel density, which is suitable for one to once coupling type detectors.

3.1 Waveform Multiplexing

Although all channels within multi-channel system are usually designed with same configurations, characteristics variation always exists. This can be caused by fabrication process or detector uniformity. Therefore it is feasible to use some variable design parameters for tagging waveforms and multiplex signals from different channels. The demultipelxing function can be performed by analyzing the tag information. Parameters like rise time, decay time and gain polarity can be used as tag information for this purpose.

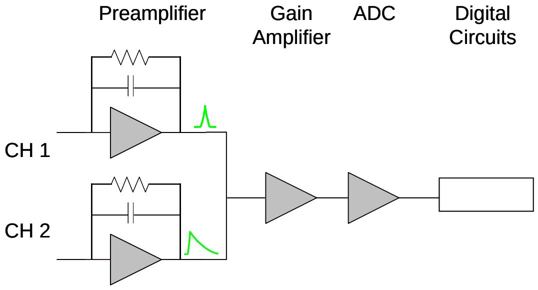


Fig. 3 Scheme of Waveform Multiplexing

The multiplexing method we have implemented has chosen decay time as tagging information. The multiplexed preamplifiers are charge sensitive preamplifiers, and the decay time can be varied by adjusting the feedback resistance. These preamplifiers are connected together, amplified by a gain amplifier, digitized by an ADC, and then encoded by digital circuits. The digital signals will be analyzed by FPGA to identify decay time given by

$$T_{tag} = T_{peak} - T_{threshold}$$

Where Tpeak is the peaking time and Tthreshold is the time of half peak in decay edge.

While this structure is simple to implement, the noise degradation will happen because noise components from multiplexed preamplifier will accumulate. Assuming there is no correlation noise, the equivalent noise charge (ENC) is give by

$$ENC_{mux} = \sqrt{N_{mux}} \times ENC_{preamp}$$

3.2 Pulse-width based readout method

3.2.1 Time-over-Threshold method

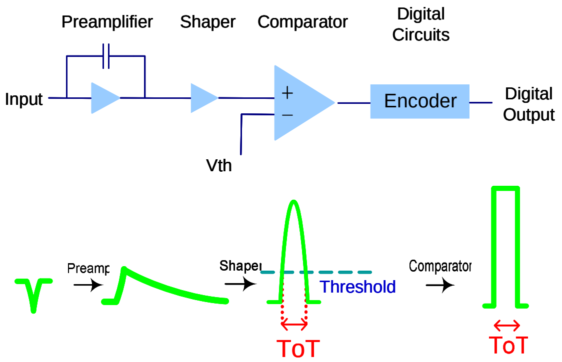


Fig. 4 Scheme of Time-over-Threshold

In time-over-threshold (ToT) readout approach, the charge signals from detectors are amplified by a charge-sensitive preamplifier and then shaped by a semi-Gaussian shaper. The shaper output, the peak amplitude, is a linear function of Q [3]. If the signal at the shaper output is sent to a comparator with a preset threshold (Vth), a pulse is generated at the output of comparator, whose width is equal to the time during which the shaped signal exceeds the threshold. ToT has fast signal processing, easy implementation and less transmission lines. The Data Acquisition (DAQ) System is easy to implement with just FGPA instead of ADC. What is more, the output signal is already digital signal, which enables more digital processing feature.

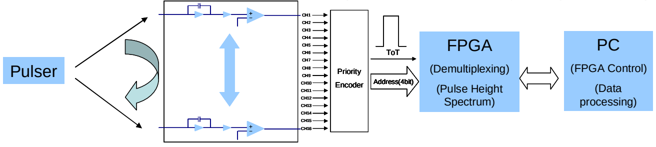


Fig. 5 ToT implementation with digital multiplexing

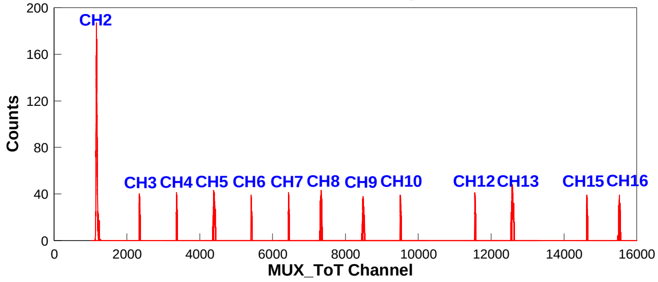


Fig. 6 Experiment result with ToT readout

3.2.2 Dynamic Time-over-Threshold

During the study of ToT, we have noticed that the linearity of ToT is a limitation of this powerful method. Therefore we have proposed an improvement for this method.

In the new approach Dynamic ToT, once shaper output surpass the base threshold level (Vref). The monostable multivibrator will be triggered by comparator output and feedback to threshold voltage through RC circuits, which leads to a rapid increase for threshold voltage. With this method, we have realized a self triggered multi-level ToT without extra encoding or decoding because the Dynamic ToT signal could be processed same as normal ToT signal.

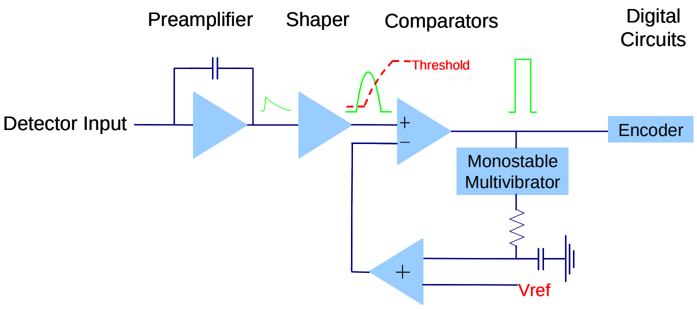


Fig. 7 Scheme of
Dynamic Time-over-Threshold

There are two important factors of using Dynamic ToT method. First, there must be a delay time for threshold increase, which was achieved by multivibrator. Without this delay time, the low amplitude signals cannot be recognized because the threshold voltage will immediately increase to a quite high level. Second, the shaper output width and threshold increase timer (τ = RC) must match so that the threshold increase is significant before the shaper signal decay to a low level.

4. Experimental Results

4.1 Waveform Multiplexing

We have characterized the 32-channel multiplexing preamplifier ASIC and tested it with 2 mm pixel LYSO-APD detector. The two multiplexed preamplifier was set with 10 µs (fast preamp) and 30 µs decay time (slow preamp).

When used for readout LYSO-APD detector irradiated with Na-22 source, the two preampllifer output was captured by digital oscilloscope separately, and the waveform length is clear enough for pulse shape discrimination.

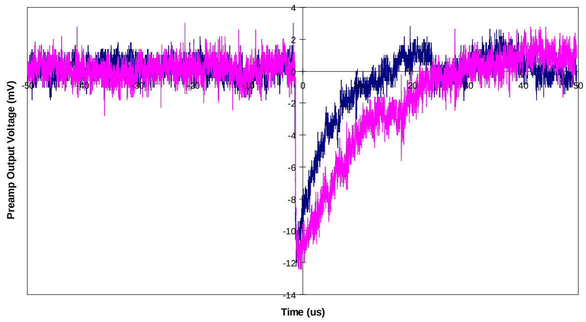


Fig. 8 Waveforms of multiplexed channel for reading out APD detctor

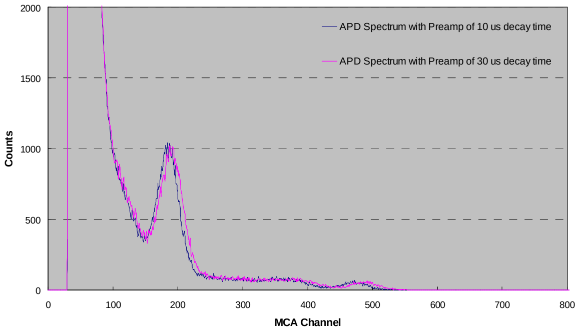


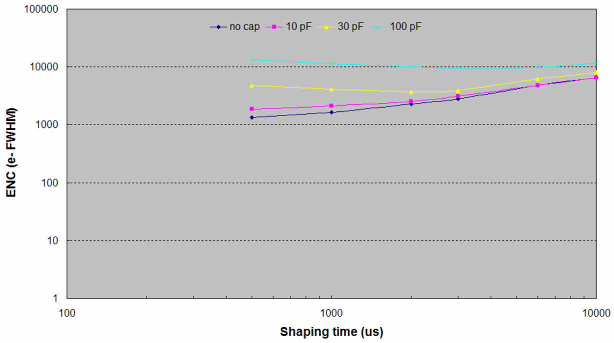
Fig. 9 Na-22 spectrum with APD biased at 380 V with both preamplifier

When testing the gain linearity with ORTEC 419 pulse generator, the two multiplexed channel has showed 0.84 mV/fC for slow preamp and 0.9 mV/fC for fast preamp and the linearity is < 0.5% for both preamplifiers.

The rise time with no input capacitance was 35 ns for preamplifier with 10 us decay time and 40 ns for preamplifier with 30 us decay time. When applied a 10 pF input capacitance, the rise time is 48 ns and 60 ns correspondingly.

The Na-22 spectrum was obtained when APD was biased at 380 V (gain ~ 70) and shaping time was set at 0.5 µs. The energy resolution of 511 keV annihilation peak was 16.8% for fast preamplifier and 18.3% for slow preamplifier.The optimum ENC with no input capacitance was 1225 e- FWHM for preamplifier with 10 us decay time, and 1334 e- FWHM for preamplifier with 30 us decay time. It is obtained with 0.5 us shaping time.

The noise characteristics with different detector capacitance were also measure for both preamplifiers. (Fig. 10) The noise slope is 81e-/pF at 0.5 us shaping time for fast preamplifier and 120 e-/pF for slow preamplifier.



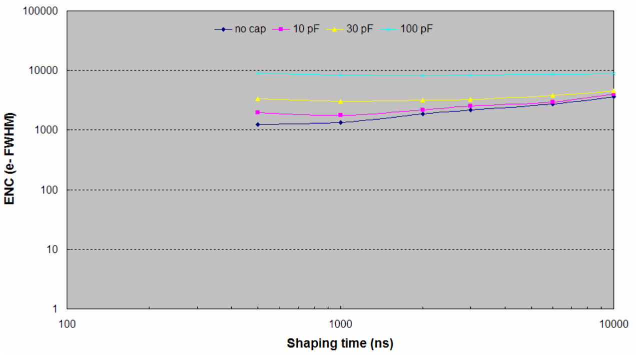


Fig. 10 noise characteristics of 2 preamplifier within multiplexing preamplifier ASIC

The multiplexing waveform sampling ASIC has been tested to verify the function of waveform multiplexing. Of the two multiplexed preamplifier, one is set to have an 800 ns decay time (fast channel), while the other is set to 1.6 μs decay time.

By injecting same voltage step pulse, gain linearity of both slow channel and fast channel have been measured separately. The gain is 0.94 mV/fC for fast channel and 0.96 mV/fC for slow channel. Nonlinearity of both channels is 2.5%.

The digitized signals were record by logical analyzer and then reconstructed by computer program. As is shown in Fig. 11, the decay time of fast channel and slow channel can be identified and hence the channel information can be obtained.

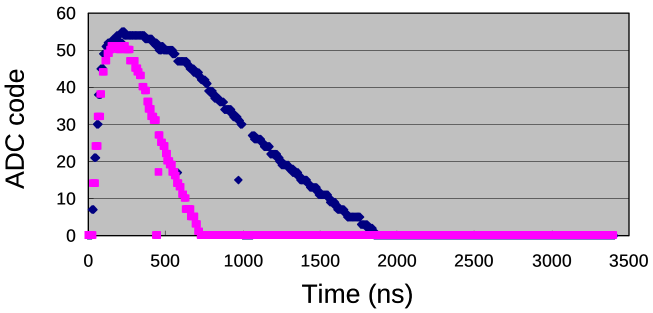


Fig.11 Reconstructed waveform from waveform multiplexing ASIC

4.2 Dynamic Time-over-Threshold

For linearity measurement, a pulser was used to inject charge through a 1 pF input capacitor. The charge signal was processed by ASIC charge sensitive preamplifier and shaped by semi-Gaussian shaper, which were set with same parameters as M-MSGC readout. The gain of ASIC preamplifier is ~ 0.75 mV/fC, and the shaper has a gain of ~ 25 while the shaping time was 3 μS.

According to the experiment results, the linearity of Dynamic ToT has shown significant improvement over normal ToT method in the over all dynamic range. When input charge was from 10 fC to 100 fC, the coefficient of determination (R-Squared) for DToT linearity (Vth = Dynamic) is ~ 0.94.

We have also used our dynamic ToT method to readout a MSGC plate, which was irradiation by 5.9 keV X-ray. The reconstructed spectrum has clearly show both the photon peak and escape peak (Fig. 13).

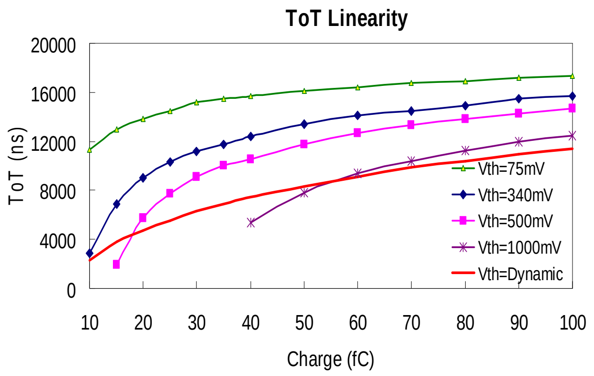
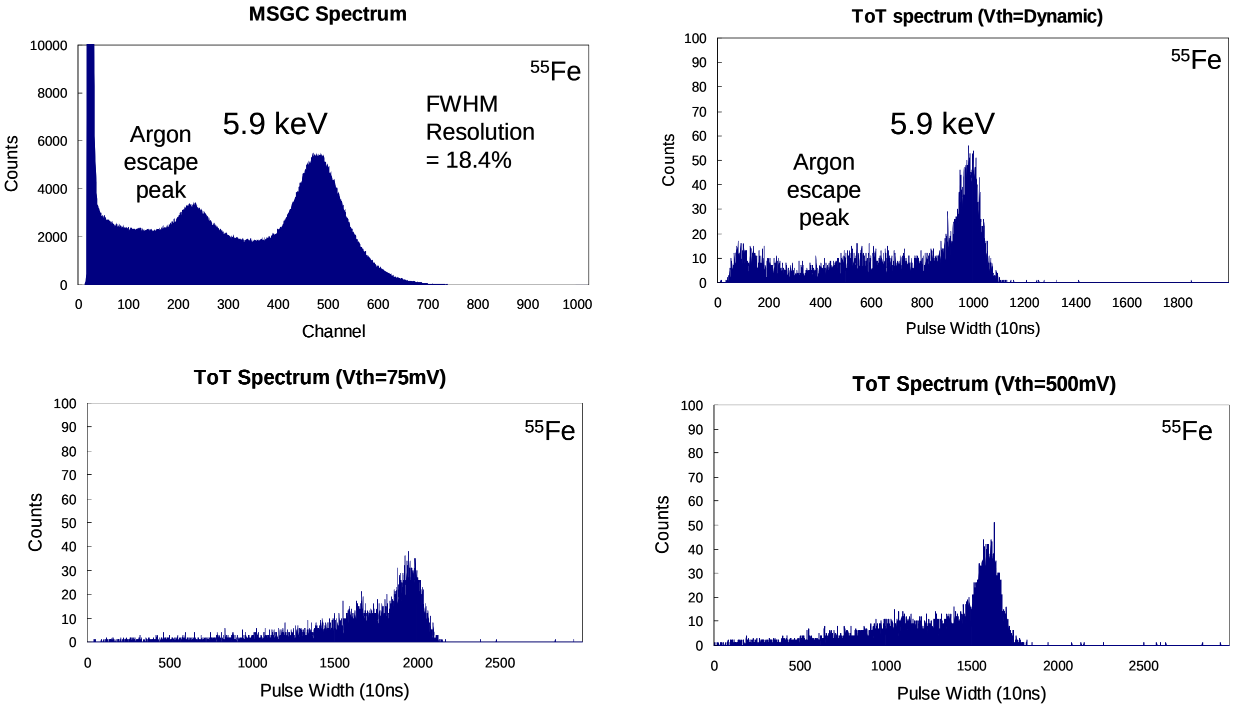


Fig. 12 Linearity of ToT and DToT



^{55}Fe source, 70% Ar + 30% CH_4 gas, Gas Gain ~ 1000

5. Summary and Conclusion

Waveform multiplexing has been successfully implemented and demonstrated with 2-to-1 multiplexing on front-end ASIC. This method is very effective on improving front-end ASIC designed for phoswich detected based high spatial resolution PET system.

Time-over-Threshold method with digital multiplexing has been validated, which has great potential on high spatial resolution PET system.

Dynamic Time-over-Threshold method has been proved. This method is effective on improving the linearity and dynamic range. Dynamic ToT has the potential to replace ADC in front-end signal processing.

Reference:

[1] W.W. Moses and S.E. Derenzo, "Empirical observation of. performance degradation in positron emission tomographs utilizing block detectors," J. Nucl. Med., Vol. 34, pp. 101, 1993.

[2] J. Y. Yeom, K. Shimazoe, H. Takahashi and H. Murayama, "A waveform sampling front-end ASIC for readout of GSO/APD with DOI information," Nucl. Instr. Meth. A, Vol. 571, pp. 381-384, 2007.

[3] I. Kipnis and T. Collinis, "A Time-over-Threshold Machine: the Readout Integrated Circuit for the BABAR Silicon Vertex Tracker," IEEE Trans. Nucl. Sci., Vol. 44, pp. 289-297, 1997.