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A new approach for improved time and position measurements for TOF-PET: Time-stamping of the photo-electrons using analogue SiPMs

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ABSTRACT

Measurement of the Time-of-Flight (TOF) of the 511 keV gammas brings an important reduction of statistical noise in the PET image, with higher precision time measurements producing clearer images. The common method of coupling a photodetector to scintillating crystals is to have two matching matrices, with a one-to-one coupling between the crystal and the photodetector. We propose a new geometry based on analogue strip SiPMs reading out a scintillator cut into slabs. This technique allows the time stamping of individual photo-electrons and extracts the best time resolution using a specific algorithm. Here we present the results from the first 'slab module' test.

1. Introduction

PET images are generated by detecting back-to-back 511 keV gamma photons from a positron annihilation. If the time of the interaction of the gamma in the detector is precisely measured, the location of the position annihilation along the line connecting the two detection positions is constrained; this constraint is tightened with improving time resolution. Currently, scintillating crystals, together with Silicon Photo-Multiplier (SiPM) photosensors are the best choice for a PET system design, if high sensitivity and precise timing measurement is the major goal.

The SiPM consists of a matrix of Silicon Avalanche Diodes. Each diode is biased such that it operates in Geiger mode; thus a single photon can trigger a Geiger breakdown in a diode and produce a detectable signal; thus these diodes are known as Single Photon Avalanche Diodes (SPAD). This feature makes this device especially interesting when it is coupled to a scintillating crystal. The passage of a charged particle in a scintillating crystal produces a burst of light with a characteristic rise and fall time. The photo-electrons created in the photo-sensor trigger the Geiger breakdown. Precise timing can be studied by observing the statistics of the detected photoelectrons. A Poisson time distribution predicts that the best time resolution is obtained with the timestamp of the earliest photoelectron; however the rise-time, the decay-time of the scintillator and the Gaussian time response of the SiPM itself modifies this. Further time distortions are introduced due to the light travelling through the crystal via multiple reflections. In these situations, simulation models have shown that the best time resolution is given by the time of arrival of a subsequent photoelectron [1] when all effects of time jitter are taken into account.

For a TOF-PET detector, it is of course necessary to have the best time resolution, but equally important is to have high detection capability for the 511 keV gamma photons. The family of Lutetium Silicates are one of the popular choices of scintillating crystals. The radiation length is 12 mm; thus for a reasonable sensitivity, it is important to have at least a 15 mm crystal length. A measurement of the depth of interaction (position along the axial direction of the crystal) is critical if a Coincide Time Resolution (CTR) of 100 ps is to be realised.

Previously, we have proposed a new strip geometry for the SiPM [2] (also known as the Multi-Pixel Photon Counter (MPPC)). The strip is read out at each end, with each end coupled to an individual TDC (time to digital converter). The time difference is related to the position of the firing SPAD along the length of the strip, while the average of the two times gives the time of the hit. The strip geometry implies that the ends of the strip are at the edge of the photodetector device; this allows both the anode and the cathode to be accessed and thus a differential signal can be sent to the front-end electronics. These are the principles of the new strip geometry design that is discussed before. Here we propose a new method for coupling a scintillating crystal to this new geometric design of MPPC. We present our preliminary and very encouraging results, highlighting the high spatial resolution (i.e. the ability to determine the interaction location of the gamma ray in the detector to a small spatial volume) and the excellent timing resolution.

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2. Detector design

The typical method of coupling a photodetector to scintillating crystals is to have two matching matrices, with a one-to-one coupling between the crystal and the photodetector. We propose a new geometry based on the Strip SiPM [3] with the scintillator cut into slabs. Fig. 1 shows how each slab will be coupled to the Strip SiPM. The SiPM are also known as Multi Pixel Photon Counters (MPPC), since Hamamatsu has fabricated the Strip SiPM, hereafter we refer to it as Strip MPPC. In this figure we show 16 strips reading out a single slab; however it should be noted that the number of read-out strips per slab still needs to be optimised. Sixteen strips allows the time-of-arrival of 16 photons to be measured independently, so that an algorithm can be derived to extract the best time resolution using these 16 values. In addition, the amount of light falling on each strip can be measured so that the depth of interaction could be estimated from this information; however the front-end electronics used for these measurements measures the input charge with a Time-over-Threshold (ToT) technique and this was not sufficient to estimate the depth of interaction.

3. Results from prototype test setup

A slab module of six LFS[1] crystals (each slab is $3\times11\times15\ mm^3$) has been glued to a 16 Strip MPPC array; this is shown in Fig. 2. A ^{22}Na source was mounted between the “slab module” and a reference detector consisting of a $3\times3\times15\ mm^3$ LFS crystal coupled to a $3\times3\ mm^2$ MPPC. This setup is shown in Fig. 3. The Strip MPPCs were readout with the NINO ASIC [4], an ultra fast amplifier-discriminator. The NINO threshold is set at the amplitude of half a photoelectron. The strips were read out at each end, thus 32 channels of NINO were used for the slab module readout. The LVDS output signals from the NINO were converted to NIM logic signals using in-house electronics. These NIM logic signals were fed to the WaveCatcher system [5] that uses a switched capacitor array to record the input waveform. A 5 ps time resolution was obtained. Both the leading and trailing edge of the NINO output were recorded.

Signals from each strip, discriminated by the NINO creates two ‘time-stamps’ (one from each end); the average of the time-stamps provides the ‘hit-time’; while the time difference gives the position along the strip where the pulse of light was registered. Events were triggered by a large energy deposit in the reference crystal and the slab module. The amplitude of the light pulse was estimated by the NINO asic with Time-over-Threshold technique and this controlled the width of the output LVDS signal. Typical ToT spectra for 16 strips and the reference detector are shown in Fig. 4. A ToT cut of 2× sigma of the gaussian fit of the two back-to-back 511 keV gamma was applied to the data. For each event, the following data is produced: (a) for the slab module: 16 hit times, 16 positions, 16 ToT values and (b) for the reference, the hit time and a single ToT value.

These 16 hit times were sorted into time order; the CTRs (with respect to the reference counter) are presented in Fig. 5. In Fig. 6 the CTR obtained when the earliest seven time-stamps are averaged.

The reference counter was aligned to be back-to-back with slab 4 in the centre of the module as shown in Fig. 3. The time difference between the two ends can be used to obtain the location along the strip length where the light pulse has been observed: this corresponds to the slab where the 511 keV gamma photon interacted. In Fig. 7 we show the averaged time difference for the 16 strips. Clearly the correct slab can be identified owing to the excellent position resolution offered by Strip MPPC.

4. Conclusions and outlook

The Strip MPPC has been developed with the idea that multiple individual photo-sensors can be attached to a scintillating crystal. This allows the time-stamping of first arriving photons. The 16 measurements of the amplitude of the light could be used to identify the position of the 511 keV interaction (including the depth of interaction); however we need to implement a better measurement of the light amplitude than offered by the simple ToT of the NINO asic.

The strip array used in this study is the first prototype of this device. To extract the full potential with this technique, more performant Strip MPPCs are needed. In particular there is a 200 μm dead region between each strip that reduces the overall photon detection efficiency. New prototypes have been recently fabricated and are under test.

The technique presented here, depends on the time stamping of

[1] Lutetium Fine Silicate manufactured by Zecotek Photonics Inc.

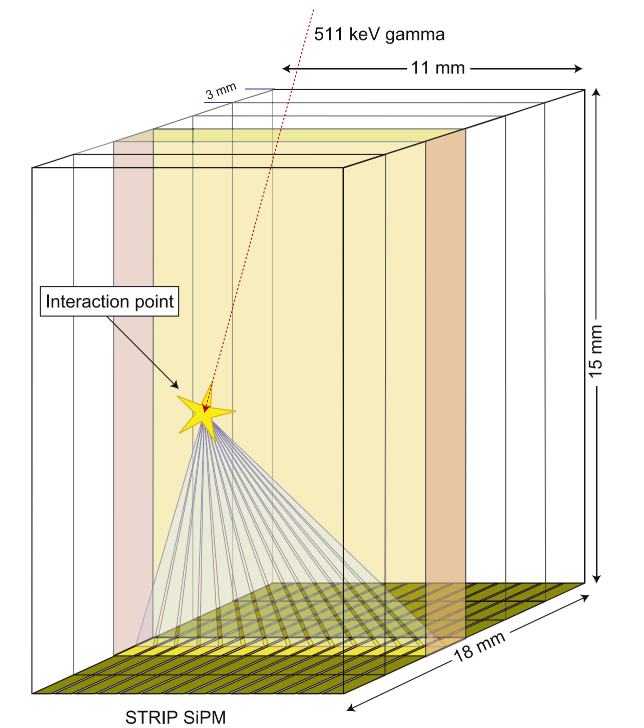

Fig. 1. Schematic representation of coupling of strip-SiPMs to an array of slab scintillating crystals.

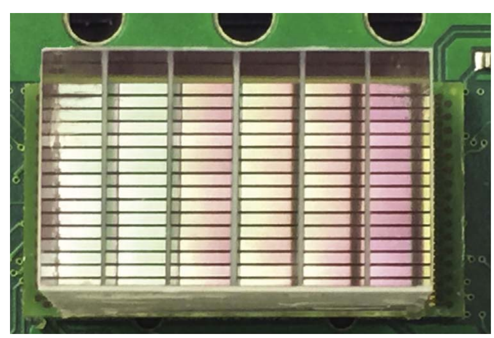

Fig. 2. Photograph of six LFS slabs glued onto a 16 strip MPPC array.

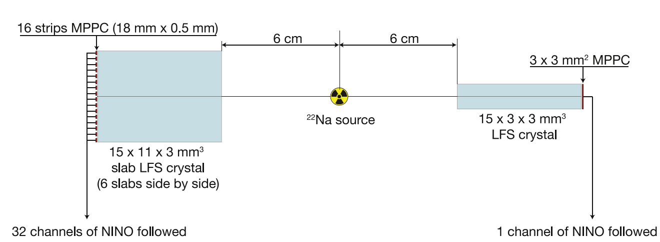

Fig. 3. The coincidence time resolution measurement setup.

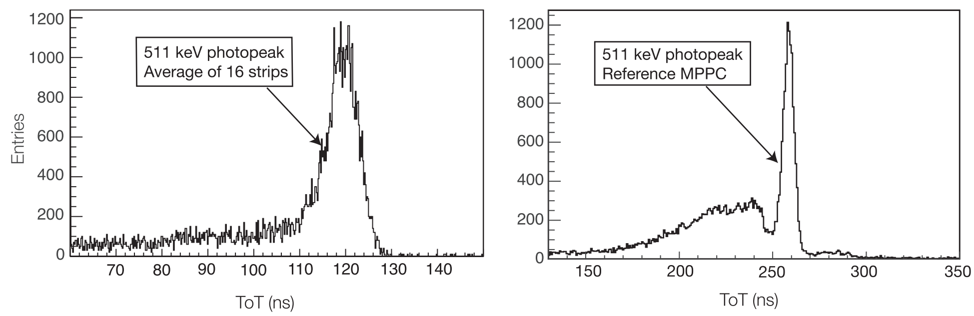

Fig. 4. Typical spectra obtained with two detectors on each side of a ^{22}Na source: The plot on the left corresponds to the average ToT spectrum of 16 strips. The reference detector consisted of a HFF-MPPC attached to a 3×3×3 mm^3 LFS crystal; the ToT plot is shown on the right.

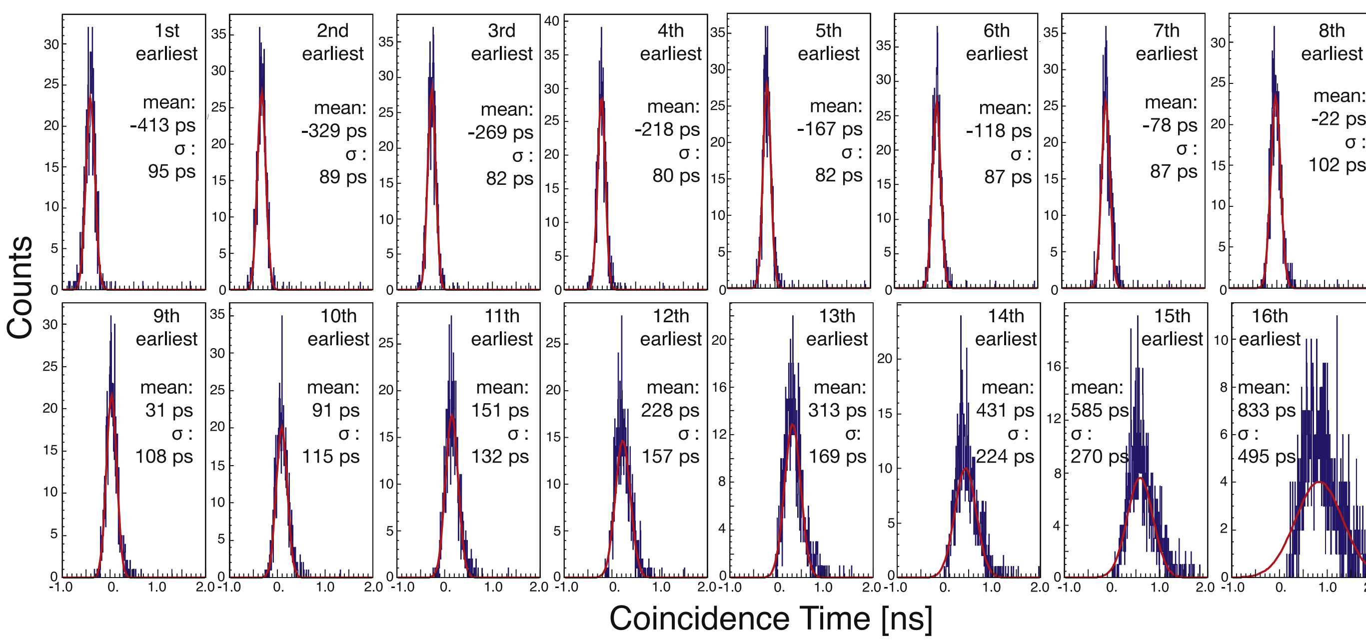

Fig. 5. Coincidence time resolution of the strip MPPCs coupled to the slab-module, arranged in time order.

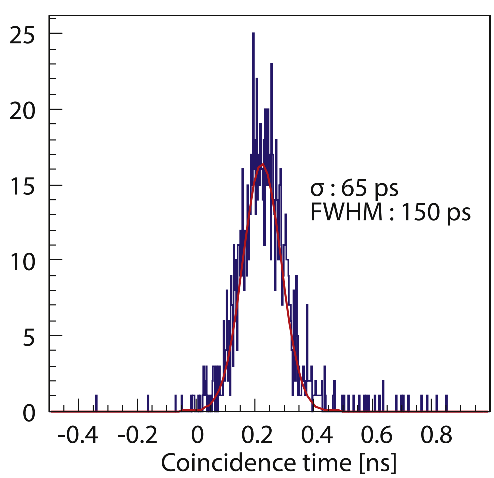

Fig. 6. Time spectra created by averaging the earliest n times (n=7).

individual photo-electrons. However, the NINO ASIC has not been optimised for the high capacitance of the MPPC and thus the bandwidth of the first stage is reduced. The effect of this is that the NINO fires on an average time of arrival of the initial photoelectrons (rather than the first) [2]. A new front-end ASIC is under design, that will also have an improved amplitude measurement circuitry.

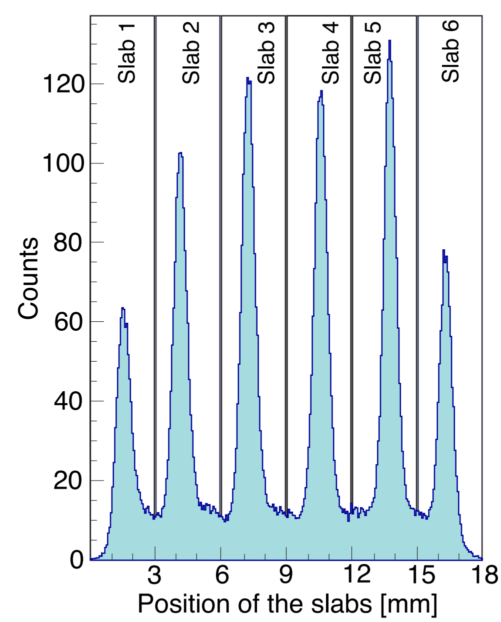

Fig. 7. Position of light pulse along the strip obtained from the average of 16 time differences.

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