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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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 Diods. 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 Diods (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 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.
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
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.

![Typical spectra obtained with two detectors on each side of a $^{22}\text{Na}$ 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.](image1)

Fig. 4.

![Coincidence time resolution of the strip MPPCs coupled to the slab-module, arranged in time order.](image2)

Fig. 5.

![Time spectra created by averaging the earliest $n$ times ($n=7$).](image3)

Fig. 6.

![Position of light pulse along the strip obtained from the average of 16 time differences.](image4)

Fig. 7.
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References