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On the comparison of analog and digital SiPM readout in terms of expected timing performance

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ABSTRACT

In time of flight positron emission tomography (TOF-PET) and in particular for the EndoTOFPET-US Project (Frisch, 2013 [1]), and other applications for high energy physics, the multi-digital silicon photomultiplier (MD-SiPM) was recently proposed (Mandai and Charbon, 2012 [2]), in which the time of every single photoelectron is being recorded. If such a photodetector is coupled to a scintillator, the largest and most accurate timing information can be extracted from the cascade of the scintillation photons, and the most probable time of positron emission determined. The readout concept of the MD-SiPM is very different from that of the analog SiPM, where the individual photoelectrons are merely summed up and the output signal fed into the readout electronics. We have developed a comprehensive Monte Carlo (MC) simulation tool that describes the timing properties of the photodetector and electronics, the scintillation properties of the crystal and the light transfer within the crystal. In previous studies we have compared MC simulations with coincidence time resolution (CTR) measurements and found good agreement within less than 10% for crystals of different lengths (from 3 mm to 20 mm) coupled to SiPMs from Hamamatsu. In this work we will use the developed MC tool to directly compare the highest possible time resolution for both the analog and digital readout of SiPMs with different scintillator lengths. The presented studies reveal that the analog readout of SiPMs with microcell signal pile-up and leading edge discrimination can lead to nearly the same time resolution as compared to the maximum likelihood time estimation applied to MD-SiPMs. Consequently there is no real preference for either a digital or analog SiPM for the sake of achieving highest time resolution. However, the best CTR in the analog SiPM is observed for a rather small range of optimal threshold values, whereas the MD-SiPM provides stable CTR after roughly 20 registered photoelectron timestamps in the time estimator.

1. Introduction

Highest time resolution in scintillator-based detectors is becoming more and more important in applications for high energy physics and medical diagnostics [1]. Several commercial whole-body TOF-PET scanners have demonstrated that already ~500 ps in coincidence time resolution (FWHM) can give clear improvements in image signal to noise ratio (SNR) and contrast [3,4]. However, CTRs smaller than 100 ps FWHM are necessary to improve image SNR to the level that scanning times and radiation exposure to the patient can be significantly reduced. In PET, L(Y)SO crystals are commonly used to detect the 511 keV gammas and to produce scintillation photons to be sensed by photodetectors. Silicon photomultipliers (SiPMs) are promising candidates to achieve excellent time resolution [5–8]. In an analog SiPM signals from individual photon avalanche diodes (SPADs) are summed up, and the timing information is commonly derived from leading edge discrimination as can be seen in Fig. 1.

Another technique to detect the scintillation photons is to employ multi-digital SiPMs (MD-SiPMs) [2] as shown in Fig. 2. In these purely digital devices every photoelelectron detected in a SPAD is registered with its own timestamp, thus providing the maximum information of the scintillation photon rate. This idea was first commercialized by Philips [9]. However, it should be noted that the Philips device only has one TDC for a larger array of SPADs and is therefore essentially different from the MD-SiPM discussed in this work. In previous studies it was shown that the proper combination of all photoelectron timestamps obtained in the MD-SiPM noticeably improves the CTR [10–13]. However, the analog SiPM, with its characteristic leading edge discrimination, intrinsically performs such a combination as well, which is nothing but the average of the preceding photoelectron

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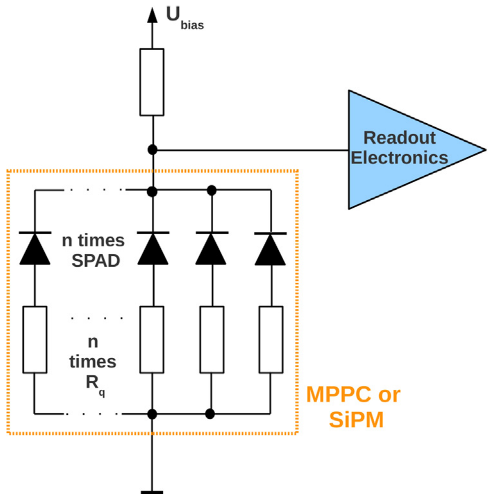

Fig. 1. In the analog SiPM the SPAD (microcell) signals are summed up and the positron emission time is estimated via leading edge discrimination.

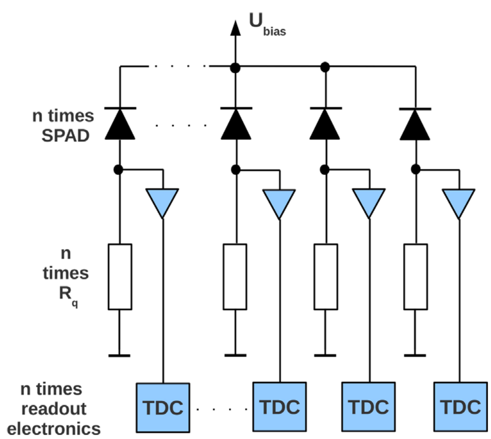

Fig. 2. In the multi-digital SiPM the timestamp of every photon detected is recorded with its own time to digital converter (TDC).

timestamps. It is therefore interesting to investigate and understand the inherent limitations in the highest possible time resolution for both the analog and digital readout of SiPMs. Because of the not yet available MD-SiPM measurements this is only possible within the framework of sophisticated Monte Carlo simulations.

\In this paper we will compare the analog and digital readout of SiPMs in terms of their expected timing performance in a TOF-PET system. After a detailed description of the positron emission time estimator derived in the analog SiPM we will introduce two different time estimators in the digital SiPM, i.e. a simple average of the gathered photoelectron timestamps and a maximum likelihood method taking into account the full covariance matrix of the system. Using our previously developed Monte Carlo (MC) tool [14] we are able to compare the best time resolution possible in a system employing an analog or a multi-digital readout of SiPMs. We follow with a discussion of the Cramér–Rao lower bound [11] of the time resolution and compare the calculated lower bound of the CTR with simulation results obtained for the analog and MD-SiPM.

2. Methods of estimating the positron emission time

2.1. Analog SiPM

In the analog SiPM a number of single photon avalanche diodes are connected in parallel, i.e. 3600 for the Hamamatsu S10931-050P MPPC. Each SPAD gives rise to a characteristic signal if an incident photon is being detected at time D_i. The SiPM output signal is the sum of all fired, single SPAD signals. If the SPAD signal is well described by a bi-exponential function with a rise time component of the order of a few 100 ps and a fall time component of several nanoseconds, then the overlap of the single SPAD signals will happen at the onset of the bi-exponential function. This assumption is justified on the grounds that a LSO scintillator gives a photon detection rate of typically 100 photoelectrons per nanosecond. Furthermore it should be noted that low pass filtering or bandwidth limitation of the electronics can enlarge the SPAD signal rise time value significantly. Within these limitations the SPAD signals can be approximated by a straight line, and the summed SiPM output signal is the sum of these linear slopes, as can be seen in Fig. 3 and as described in Eq. (1). The Heaviside function Θ ensures the SPAD signal to be zero before detection. The timestamp D_i denotes the time of the i-th photoelectron being detected and k is the gradient of the SPAD signals. The sum in Eq. (1) sums over all detected photoelectrons n':

$$V = \sum_{i=1}^{n'} k(t-D_i)\Theta(t-D_i). \tag{1}$$

The leading edge discrimination with a threshold value of V_{th}, performed by the analog readout, can be described by setting Eq. (1) equal to the threshold value V_{th} (see Eq. (2)). The resulting crossing time $\widehat{\theta}_{analog}$ is the analog time estimator of the positron emission time as stated in Eq. (3):

$$V_{th} = \sum_{i=1}^{n_{V_{th}}} k(\widehat{\theta}_{analog} - D_i)$$
$$V_{th} = n_{V_{th}} k \widehat{\theta}_{analog} - \sum_{i=1}^{n_{V_{th}}} kD_i \tag{2}$$

$$\Rightarrow \widehat{\theta}_{analog} = \frac{V_{th}}{n_{V_{th}} k} + \frac{1}{n_{V_{th}}} \sum_{i=1}^{n_{V_{th}}} D_i. \tag{3}$$

In Eq. (3) it can be seen that the analog SPAD signal pile-up with leading edge discrimination effectively is the average of the photoelectron timestamps. The term $n_{V_{th}}$ indicates that the number of photoelectrons averaged is dependent on the applied threshold V_{th}. The first term in Eq. (3) describes a constant offset, which is dependent on the number of photoelectrons averaged (threshold) and on the slope of the SPAD signal. It implies that a higher bias overvoltage and a higher number of detected photons lead to an earlier threshold crossing time. Because $n_{V_{th}}$ is a function of the photon emission rate and thus dependent on light yield fluctuations its variance is assumed to be not exactly zero.

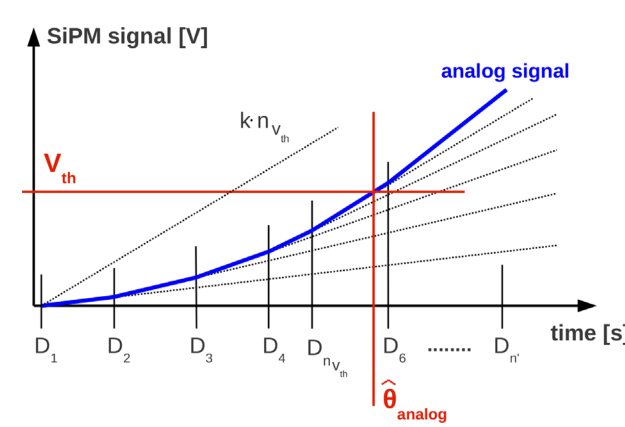

Fig. 3. The SPAD signal pile-up in the analog SiPM with leading edge discrimination leads to an effective average of the preceding photoelectron timestamps seen in the analog time estimator $\widehat{\theta}_{analog}$. The time of each photoelectron detected is denoted as D_i with a total number of photoelectrons being detected n'.

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