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Systematic study of new types of Hamamatsu MPPCs read out with the NINO ASIC

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ABSTRACT

Over the last decade there have been commercial TOF-PET scanners constructed using Photo-Multiplier Tubes (PMT) that have achieved ~500 ps FWHM Coincidence Time Resolution (CTR). A new device known as the Silicon PhotoMultiplier (SiPM) has the potential to overcome some of the limitations of the PMT. Therefore implementing a SiPM based TOF-PET scanner is of high interest. Recently Philips has introduced a TOF-PET scanner that uses digital Silicon PhotoMultipliers (d-SiPMs) which has a CTR of 350 ps. Here we will report on the timing performance of two Hamamatsu $3 \times 3\ mm^2$ analogue-SiPMs read out with the NINO ASIC: this is an ultra-fast amplifier/discriminator with a differential architecture. The differential architecture is very important since the single-ended readout uses the ground as the signal return; as the ground is also the reference level for the discriminators, the result is high crosstalk and degraded time resolution. However differential readout allows the scaling up from a single cell to a multi-cell device with no loss of time resolution; this becomes increasingly important for the highly segmented detectors that are being built today, both for particle and for medical instrumentation.

We obtained excellent results for both the Single Photon Time Resolution (SPTR) and for the CTR using a LYSO crystal of 15 mm length. Such a crystal length has sufficient detection efficiency for 511 keV gammas to make an excellent PET device. The results presented here are proof that a TOF-PET detector with a CTR of 175 ps is indeed possible. This is the first step that defines the starting point of our SuperNINO project.

1. Introduction

During the last decade there have been significant advances in the field of precise timing. This has largely been triggered by the invention of the Multigap Resistive Plate Chamber (MRPC) [1] and its implementation for the ALICE Time-of-Flight (ToF) barrel array [2]. It should be noted that this ToF system is highly segmented consisting of 160,000 channels covering 150 m^2.

There was an intense R&D phase [3] to optimise the timing performance of the MRPC. To achieve the best possible time resolution, the front-end electronics has to have minimal noise, since noise creates additional time jitter. A differential read-out architecture reduces cross-talk (an important contribution to noise) and cuts common mode noise; in our opinion such an architecture is obligatory for precise timing [4]. Thus, for the ALICE-TOF, a fully differential, ultra fast front-end amplifier/discriminator was designed [5]: this is the NINO ASIC.

Nowadays, there is growing interest with the Silicon Photo-Multiplier (SiPM) developed through the pioneering work of Golovin [6] and Sadygov [7]. This device has high detection efficiency; the ability to detect a single photon; the potential for excellent timing; and is insensitive to magnetic fields.

A SiPM device has a typical active area in the range between 1 and 20 mm^2. The thickness, including a substrate, is some millimetres. With increasing area, the capacitance of the device increases (making it difficult to extract the fast signal) and there is an increase in the rate of random dark counts (DCR). These effects limit the maximum area that is practical for ultra-precise timing to below 20 mm^2. This small device size implies that any detector fabricated with SiPMs will be highly segmented. This high density of detector cells will exasperate crosstalk. If ultra-precise timing is the primary goal, a differential architecture and a differential amplifier/discriminator is a necessity.

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Table 1
Characteristics provided by Hamamatsu for the two MPPCs.

MPPC type	SPAD size (μm)	Fill factor (%)	Overvoltage for 1.5×10^6 gain (V)	C_{Total} (pF)	Crosstalk at 1.5×10^6 gain (%)	Dark counts at 1.5×10^6 gain
HFF-MPPC	50	81	2.6	320	50	2 MHz
LCT-MPPC	50	60	2.2	320	12	200 kHz

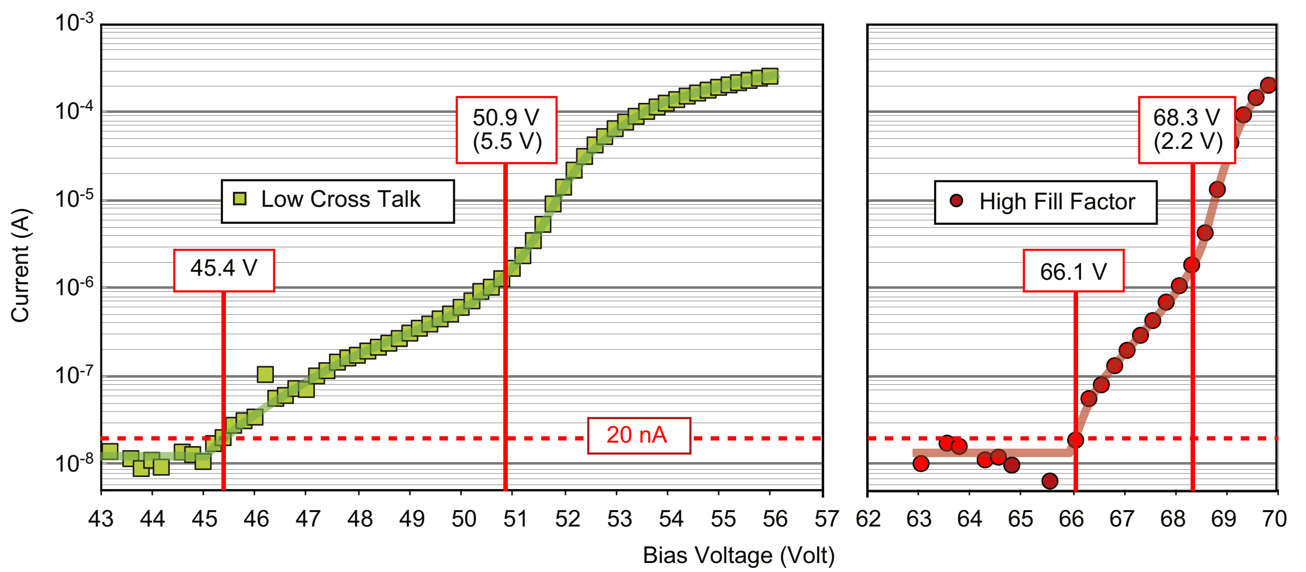

Fig. 1. The current drawn by the MPPC plotted against the applied voltage. The MPPC device is reverse biased. The breakdown voltage is where the current draws more than 20 nA. The upper voltage is chosen to be the point where the current starts increasing rapidly.

We will now discus the details of the SiPM. It is fabricated from a matrix of small avalanche photodetectors (with a typical size of $50 \times 50\ \mu m^2$). Thus a SiPM device of $3 \times 3\ mm^2$ active area would typically contain 3600 avalanche photodetectors. A voltage is applied across the avalanche photodiode; if this voltage is increased then the avalanche triggers a Geiger breakdown. Thus a single photon can initiate a Geiger breakdown and produce a detectable signal; for this reason, these individual avalanche photodiodes are known as Single Photon Avalanche Detectors (SPADs).

Due to the finite number of SPADs, light pulses with a large number of photons will saturate the SiPM (i.e all SPADs are fired); this effect does not allow an accurate measurement of the amplitude of large light pulses. This could be alleviated by having smaller SPADs more densely packed; however each SPAD is surrounded by a dead region consisting of a grid supplying the voltage and a quenching resistor to quench the Geiger breakdown. Thus an increase in SPAD density will lead to a decrease of the active area and a corresponding reduction of the Photon Detection Efficiency (PDE). The best timing signal is given by the time of arrival of the first photoelectrons. Therefore for precise timing, it is necessary to have the highest possible PDE (and of course, the brightest crystals). Thus the goal of excellent timing (i.e. employing large SPADs to improve PDE) will compromise the energy measurement (that requires a high number of SPADs). Our choice is to balance these opposite effects to obtain the best time resolution together with an acceptable measurement of the light amplitude: to this end, we have concentrated our efforts on SiPMs fabricated with SPADs on a 50 μm pitch.

The energy resolution is further compromised by optical cross-talk between SPADs. When an SPAD fires, the Geiger breakdown generates photons that can travel into the neighbouring SPADs and

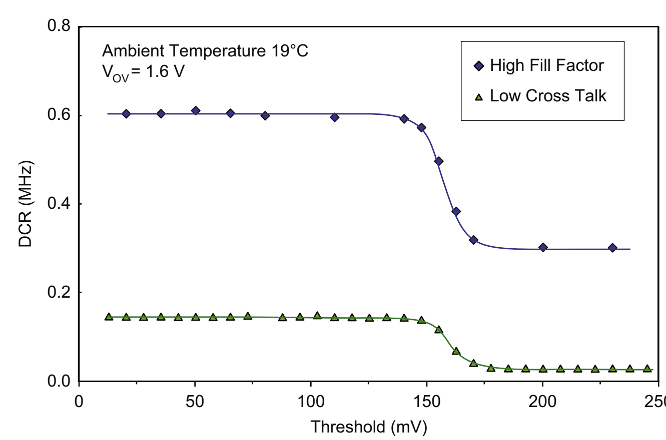

Fig. 2. The Dark Count Rate (DCR) is plotted versus the NINO threshold for the two MPPC devices tested.

cause them also to fire. This is not a small effect and can easily be higher than 50 %; this limits the effective number of SPADs. A technique to alleviate this crosstalk problem is to insert non-transparent 'trenches' down into the silicon between each SPAD; these trenches impede light generated in the Geiger breakdown of one SPAD from travelling to the neighbours. However these trenches do increase the dead region surrounding each SPAD.

Hamamatsu have recently produced two new types of SiPM. One that is named the 'High Fill Factor' (HFF-MPPC) where the polysilicate quenching resistor has been replaced with a metal film resistor transparent to light, thus decreasing the dead area around each SPAD. The other is termed 'Low Cross-Talk'

(LCT-MPPC) and has trenches between each SPAD. We tested the LCT-MPPC some months after the HFF-MPPC. In Table 1 the characteristics supplied by Hamamatsu for these MPPC devices are shown.

2. I–V curve

To identify the breakdown voltage, the current as a function of the applied voltage (reverse biased) is measured. The I–V curves for the two MPPCs are shown in Fig. 1. We define the V_{BD} as the voltage where the MPPC draws 20 nA. At an ambient temperature of 19 °C, the breakdown voltages, V_{BD}, are 66.1 V for the HFF-MPPC and 45.4 V for the LCT-MPPC. Above V_{BD}, there is a clear difference concerning the increase in current with applied voltage; the rise is much slower for the LCT-MPPC with the non-transparent trenches between the SPADs. We define the maximum operation voltage as the knee of rapid current increase (these voltages are marked in Fig. 1). The LCT-MPPC can be operated at 5.5 V above V_{BD} compared to 2.2 V for the HFF-MPPC. We use the term over-voltage (V_{OV}) as the voltage applied to the MPPC above its V_{BD}.

3. Dark count rate versus threshold

An important measurement is the Dark Count Rate (DCR). The MPPCs are mounted in a temperature controlled dark box and the counting rate measured. A plot of the DCR versus the NINO threshold is shown in Fig. 2. It should be noted that this value of threshold refers to the differential voltage applied to the threshold input of the NINO ASIC. This plot is important in order to understand the threshold; we need to know if we are firing the discriminator on the first photoelectron or the second: however there are three other details that can be extracted from this plot; these will be discussed below.

When an SPAD fires it generates a signal that is equal to the capacitance of the SPAD multiplied by the over-voltage, V_{OV}. Precise Silicon fabrication processes ensure equal capacitance for all SPADs and equal breakdown voltage; thus the signal produced by a single detected photon is the same irrespective of which SPAD fires. Thus, in the DRC versus the threshold plot, there will be an abrupt drop at a certain threshold. This step is evident in Fig. 2.

The DCR measurement for thresholds below this step corresponds to one or more SPADs firing; the DRC measured for threshold values above the step corresponds to two or more SPADs firing. The reason that two or more SPADs fire simultaneously in the dark is due to SPAD-SPAD crosstalk; the crosstalk ratio is given by

$$Crosstalk = \frac{DCR\ with\ two\ or\ more\ SPADs\ firing}{DCR\ with\ one\ or\ more\ SPADs\ firing}. \quad (1)$$

At 1.6 V over-voltage, the HFF-MPPC has a crosstalk of 0.5, while the LCT-MPPC has 0.18.

Another detail that can be extracted from the plot is the sharpness of the step. This sharpness is given by two terms: the uniformity of the signals from each SPAD and the noise in the front-end amplifier/discriminator. If we assume that the

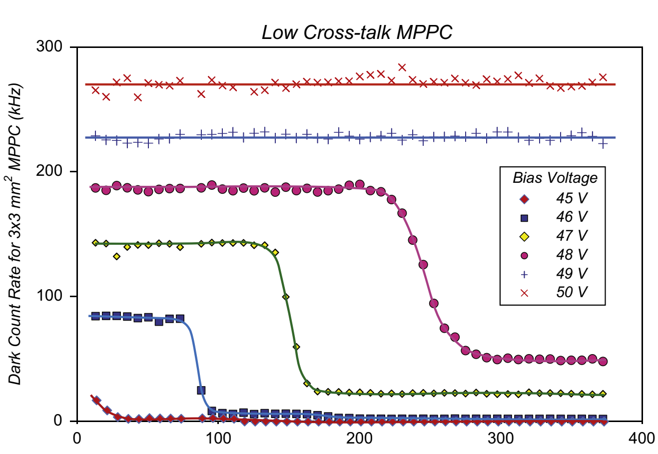

Fig. 3. The Dark Count Rate (DCR) versus the NINO threshold for various bias voltages for the LCT-MPPC.

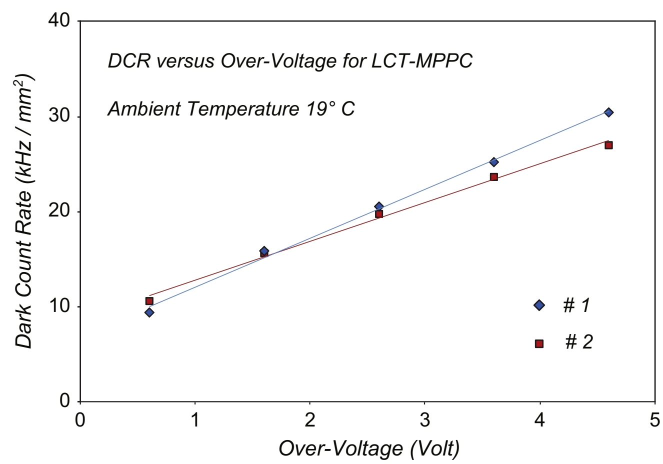

Fig. 4. The Dark Count Rate (DCR) versus over-voltage for two samples of the LCT-MPPC.

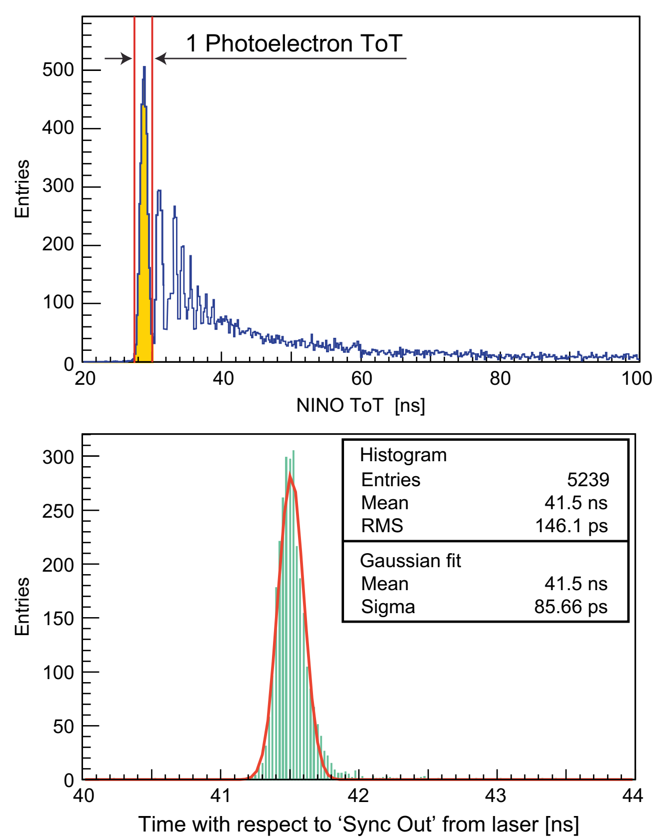

Fig. 5. Typical SPTR plots obtained for the HFF-MPPC with V_{OP}=68.8 V and $V_{THRESHOLD}$=30 mV. The upper plot shows the ToT spectrum. The one photoelectron peak is selected. The time difference between the output signal from the NINO and the 'Sync Out' pulse from the laser driver (i.e. the SPTR) is shown in the lower plot.

response from each SPAD making up the MPPC is exactly the same, then we can extract the Signal to Noise Ratio (SNR): SNR=(mean of signal)/(r.m.s. of the noise). The SNR is about 36 for both MPPCs. Often this ratio is quoted for an over-voltage of 1 V, so that the SNR is $22.5 \times V_{OV}$. It should be noted that this is a lower limit of the SNR since the assumption was made that the response of all SPADs making a MPPC device is perfectly uniform.

The final piece of information is that the step for these devices occurs at the same threshold; this implies that the gain is the same for both the LCT-MPPC and the HFF-MPPC. Since the gain is just the capacitance multiplied by the over-voltage, this implies that the capacitance of the SPADs is the same for both devices.

In Fig. 3 the DCR versus Threshold is plotted for increasing bias voltage for the LCT-MPPC. For 49 V and above, the step is outside the range of threshold for the NINO; however it is important to notice the low value of DCR. The DCR versus over-voltage is plotted in Fig. 4 for the LCT-MPPC.

4. Single photon time resolution

The Single Photon Time Resolution (SPRT) is the time response of the MPPC when a single photoelectron (p.e.) is detected. A pulsed laser illuminates the surface of MPPC. This laser light pulse is then attenuated so that a signal is seen only $\sim 15\%$ of the time. The NINO amplifier/discriminator is connected to the MPPC: the leading edge of the LVDS output signal from the NINO gives the timing, while the width (ToT) is related to the input charge. A typical ToT spectrum is shown in the upper plot of Fig. 5. Note that the number of events in the peaks associated with two p.e. and above does not follow a Poisson distribution, but is dominated by the cross-talk between the SPADs of the MPPC.

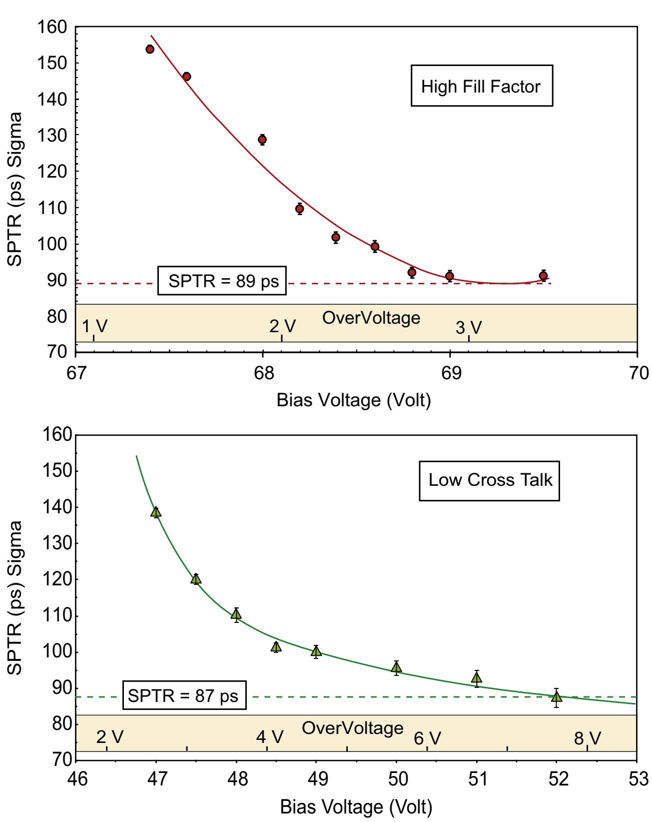

Fig. 6. The Single Photo-electron Time Resolution (SPTR) is detected for the two types of MPPC as a function of applied voltage. The NINO threshold was set to 30 mV. We also show the value of V_{OV}.

A cut is made to select events where only one SPAD fires as shown in Fig. 5. The time of the leading edge of the LVDS signal from the NINO is then measured with respect to the 'Sync-Out' signal from the laser. The result is shown in the lower plot of Fig. 5. A Gaussian fit is made and the SPTR is the sigma of this fit.

In Fig. 6, the SPTR is plotted for the MPPCs against applied bias voltage. The SPTR is important for Cherenkov detectors where single photons are detected; however the SPTR measurement also gives the basic time resolution of the MPPC and the front-end electronics. The time resolution of detected 511 keV gammas for TOF-PET (discussed in the next section) not only does have a dependance on the SPTR but also has an important contribution from the crystal itself and other parameters such as Photon Detection Efficiency (PDE).

As shown in Fig. 6, the time resolution improves with increasing over-voltage. For a comparison, the SPTR should be compared for an over-voltage that corresponds to a working voltage of the

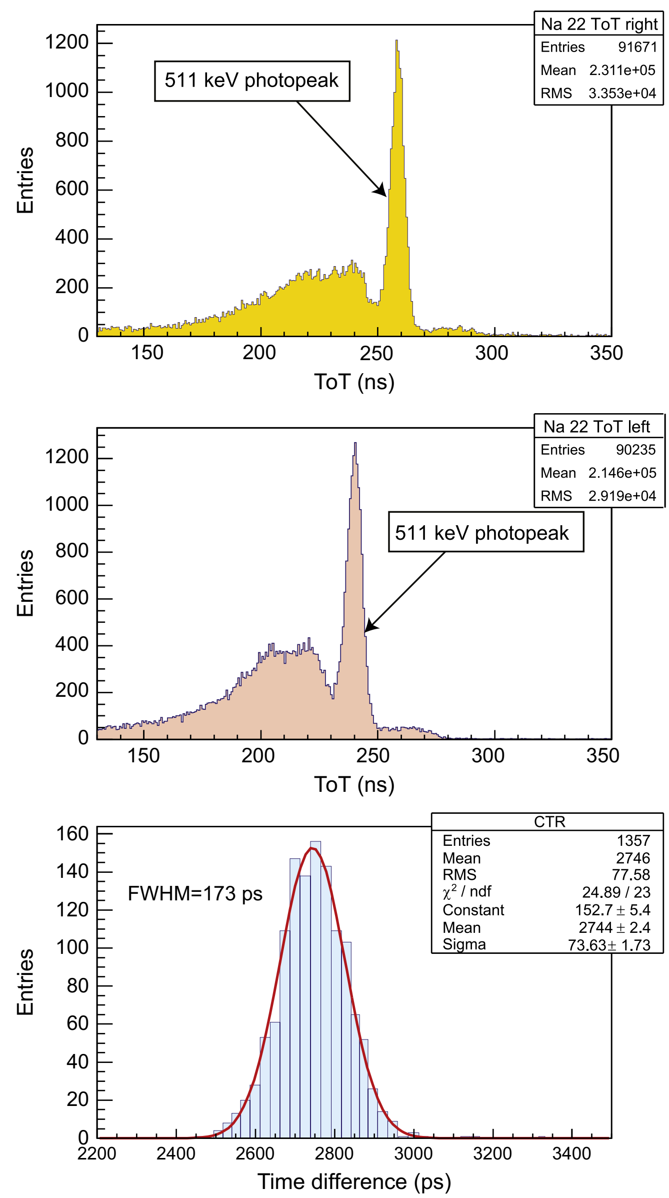

Fig. 7. Typical spectra obtained with two detectors on each side of a ^{22}Na source: each detector consisted of a HFF MPPC attached to a $3 \times 3 \times 15$ mm^3 LYSO crystal. The upper two plots correspond to the ToT spectrum obtained from each detector. The lower plot shows the coincidence time resolution after making a ToT cut to select the 511 keV photo peak.

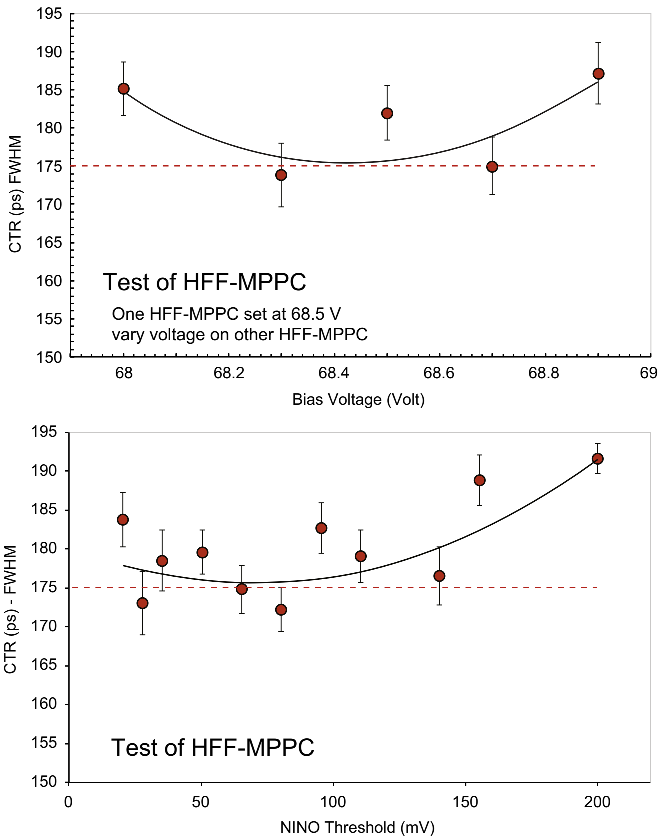

Fig. 8. The Coincidence Time Resolution (CTR) of two detectors on each side of a ^{22}Na source: each detector consisted of a HFF MPPC attached to a $3\times3\times15$ mm^3 LYSO crystal. In the upper plot, the voltage of one MPPC was fixed at 68.5 V while the voltage on the other MPPC was varied in the range plotted. The lower plot shows the effect of varying the threshold: the voltage on both MPPCs was set at 68.5 V.

MPPC in question. We assign a working over-voltage for the HFF-MPPC to be 2.5 V, and 5.5 V for the LCT-MPPC. This gives an SPTR of 100 ps for the HFF-MPPC, and 95 ps for the LCT-MPPC.

5. Coincidence time resolution

For tests of the Coincidence Time Resolution (CTR) we attach crystals to the MPPCs and mount them on each side of a ^{22}Na source. The MPPCs are read out with the NINO ASIC; the LVDS output from the NINO was connected to an 'in-house' LVDS-NIM converter; and the NIM signals were then sent to an oscilloscope.

LYSO crystals of dimension $3\times3\times15$ mm^3 were used for these measurements. The HFF-MPPCs were first tested. Typical spectra are shown in Fig. 7. The upper two plots show the ToT spectra for the two detectors, with a peak corresponding to the 511 keV photo peak. Note that saturation effects modify the signal produced by the MPPC due to the finite number of SPADs (3600); this makes the ToT 511 keV peak narrower than for a photodetector with an infinite number of pixels. A cut on the ToT is used to select the 511 keV photopeak; the lower histogram in Fig. 7 is the time difference between the two detectors. The ^{22}Na source is a point source, thus this is the Coincidence Time Resolution (CTR) of the system; the CTR is quoted as a FWHM. In Fig 8, the CTR for the HFF-MPPCs as a function of bias voltage (upper panel) and threshold (lower panel) is shown.

Finally we tested the LCT-MPPC: two MPPCs were glued to LYSO crystals of $3\times3\times15$ mm^3. The CTR plotted versus the bias voltage is shown in Fig. 9.

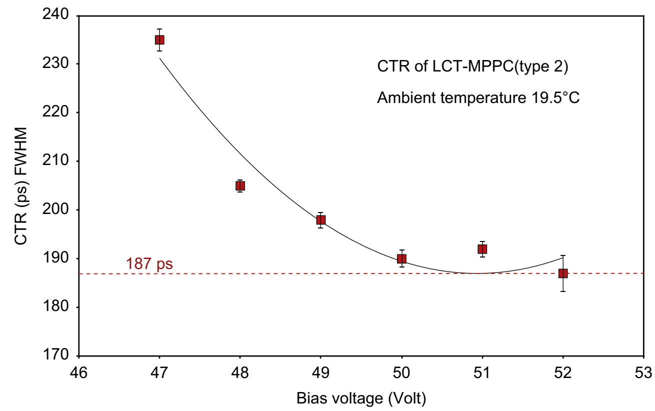

Fig. 9. The Coincidence Time Resolution (CTR) for the LCT-MPPC: the two detectors on each side of a ^{22}Na source: both detectors are coupled to a similar LYSO crystal of $3\times3\times15$ mm^3.

6. Conclusion

The purpose of our present work was (and is) to obtain the results needed for the implementation of the SuperNINO Project. To this end, we have tested two new types of MPPCs produced by Hamamatsu. The measurement of the DCR as a function of discriminator threshold proves that the fabrication of the MPPCs is exceptionally uniform. The NINO readout is also well suited for these devices and has a high SNR. It is clear that trenches reduce crosstalk between SPADs and allow operation at a much higher over-voltage.

There are two important measurements: (a) the Single Photon Time Resolution (SPTR) that is crucial for the timing of Cherenkov photons and (b) the Coincidence Time Resolution (CTR) that is important for TOF-PET or pre-shower detectors for calorimeters in particle physics. Both these MPPC devices could be used, although the exceptionally low DCR favours the LCT-MPPC in many circumstances.

For TOF-PET, not only are the timing aspects critical but also there has to be sufficient detection efficiency of the 511 keV gammas to make a viable PET detector. LYSO crystals of 15 mm in length (Gamma absorption length of 11 mm) are sufficient, thus the 175 ps CTR measurement presented in this paper indicates that indeed a TOF-PET with sub 200 ps is viable.

The results presented are the first step towards a TOF-PET device with much improved time resolution. This is the first step to build front-end electronics specifically designed for Silicon PhotoMultipliers: "The SuperNINO project". Further improvements are also foreseen by mounting the amplifier/discriminator ASIC directly on the back of the MPPC substrate.

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