Comparative timing measurements of LYSO and LFS to achieve the best time resolution for TOF-PET.

K. Doroud, A. Rodriguez, M.C.S. Williams, A. Zichichi and R. Zuyeuski

***Abstract*—There are research reports available presenting a Coincidence Time Resolution (CTR) below 150 ps; however often these measurements are made with short crystals of 3 or 5 mm in length. Such crystals have limited efficiency for the detection of the 511 keV gammas resulting from a positron annihilation, therefore are not really practical for a TOF-PET imaging device. We present our setup and measurements using 15 mm length crystals; a length we regard as reasonable for a TOF-PET scanner. We have used a new series of Silicon Photo Multipliers (SiPM) manufactured by Hamamatsu. These are the high Fill Factor (HFF) and Low Cross Talk (LCT) Multi Pixel Photon Counters (MPPC). We have compared two types of crystal, LFS (supplied by Zecotek) and two samples of LYSO (manufactured by Saint Gobain and CPI). We have obtained an excellent value of 148 ps for the Coincidence Time Resolution (CTR) with two LFS crystals (15 mm long) mounted on each side of a ^{22}Na radioactive source with the HFF-MPPCs at 3.3 V over-voltage. This is in comparison to a CTR of 180 ps measured with the LYSO crystals.**

I. Introduction

THE precise measurement of time and charge of 511 keV gamma is nowadays a major challenge for TOF-PET scanners. The timing performance of Silicon Photo-Multipliers (SiPM) is being developed, for both particle physics experiments and medical physics. The high detection efficiency and the ability to detect a single photon make this device potentially suitable for excellent timing. The performance of the latest MPPCs (Multi-Pixel Photon Counter) manufactured by Hamamatsu, the Low Cross Talk (LCT-MPPC) and High Fill Factor (HFF-MPPC) have been tested previously [1]. Here we report on the timing measurement made when we attach these MPPCs to two types of scintillating crystals.

The performance of a Lutetium Fine Silicate (LFS) crystals is compared to LYSO ($Ce_x(Lu,Y)_{1-x}SiO_5$) crystals: all crystals are 15 mm long with a 3 $\times$ 3 mm^2 cross section. The samples of LYSO crystals were supplied by CPI and Saint-Gobain. According to the manufactures, the Yttrium content is about 5% for the CPI LYSO and about 10% for the Saint-Gobain LYSO [2]. The nominal Cerium doping level is 0.2% for the CPI LYSO, and is less than 1% for the Saint-Gobain LYSO. The LFS crystal was produced by Zecotek; the sample tested was the LFS-3. LFS is a commercial name of the set of Ce-doped silicate scintillation crystal comprising of Lutetium and crystallised in the monoclinic system, spatial group C2/c, Z = 4. The patented LFS-3 compositions is $Ce_xLu_{2+2y-x-z}A_zSi_{1-y}O_{5+y}$, where A is at least one element selected from the group consisting of Ca, Gd, Sc, Y, La, Eu and Tb. The parameters related to these crystals are provided in table I; the values are obtained from the Zecotek [4] and the Saint Gobain [6] catalogues.

TABLE I
Comparison between LYSO and LFS crystals

Crystal	LYSO	LFS-3
Density (g/cm^3)	7.1	7.35
Melting point (°C)	2050	2000
Attenuation length for 511 keV (cm)	1.12	1.15
Moliere Radius (cm)	2.2	2.09
Hygroscopicity	no	no
Luminescence (nm) at peak	428	416
Decay Time (ns)	41	36
Light Yield (% w.r.t. NaI)	80	80-85
Refractive index	1.81	1.81

The best timing signal is given by the time associated to the first photoelectrons. Therefore for precise timing, it is necessary to have photodetectors with the highest possible Photon Detection Efficiency (PDE). For good timing, the crystal also has to instantaneously produce a burst of photons: the time structure and the intensity of this burst of photons depends on the crystal. Table I has the most important parameters. A critical parameter is the light output (this is quoted as a percent normalised to NaI crystal); in this case this is similar for both crystals, $\sim$ 80 %. The decay time of the LFS is shorter than the LYSO and this implies that the LFS emits more photons at the beginning of the light pulse, and this aids the time resolution. Crystals with shorter decay times have the peak of the luminescence shifted to shorter wavelengths [5]. The PDE of the Hamamatsu MPPCs peaks at $\sim$ 420 nm, thus crystals with very short decay times may suffer from lower PDE. However, in this case the wavelength of the emitted light is close to the maximum of the PDE of the MPPCs.

II. Experimental Technique

Two Hamamatsu Silicon PhotoMultipliers were tested, one was termed the High Fill Factor (HFF-MPPC) that has a fill

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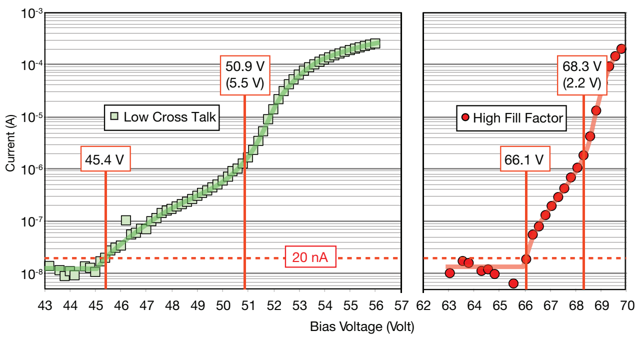

Fig. 1. The current drawn by the MPPC plotted against the applied voltage. The MPPC device is reverse biased. The breakdown voltage is where the current draws more than 20 nA. The upper voltage is chosen to be the point where the current starts increasing rapidly.

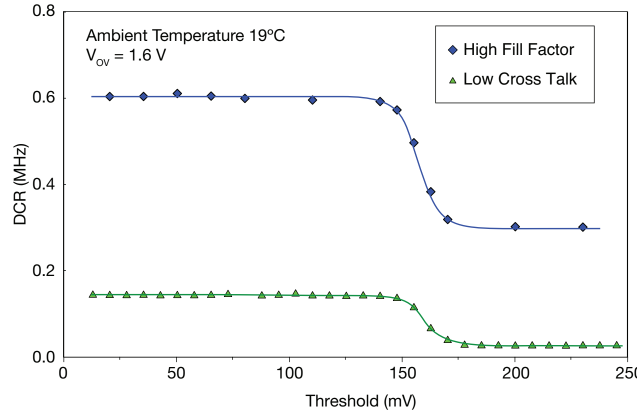

Fig. 2. Comparison of the dark count rate as a function of the NINO threshold setting for the two MPPCs. The dark count rate is 65 kHz/mm^2 for the HFF compared to the 20 kHz/mm^2 for the LCT.

factor (FF) of 81 % and the other is a Low Cross Talk (LCT-MPPC); this has a FF of 60 % and has been fabricated with trenches. The current versus voltage (I-V curve) is shown in fig. 1. The maximum working voltage is defined to be the voltage where the current starts rising more rapidly: this is at an over voltage of 2.2 V for the HFF-MPPC and 5.5 V for the LCT-MPPC. A big difference is measured with the dark count rate (DCR); 65 kHz/mm^2 for the HFF compared to the 20 kHz/mm^2 for the LCT. The DCR versus threshold voltage applied to the NINO asic is shown in fig. 2.

The NINO asic [7] (an ultra-fast amplifier/discriminator) is used to read out the MPPC. The leading edge of the output signal from the NINO contains the timing information, while the width is the time-over-threshold and is related to the input charge. The output signal from the NINO is LVDS; this is first converted to a NIM signal with an in-house built converter. The NIM signal was either sent to an oscilloscope or a CAEN VME TDC (type 1290N). For measurements made with the VME TDC, the contribution of the intrinsic TDC time resolution (sigma of 36 ps between two time sources) was subtracted quadratically.

Various measurements were performed: the Single Photon Time Resolution (SPTR); the Coincidence Time Resolution by mounting the two crystals on each side of a Na^{22} source; and the number of SPADs that fire corresponding to the light generated by a 511 keV gamma interaction (photopeak). The technique for these measurements are discussed below.

A. Single Photon Time Resolution (SPTR)

The SPTR has been previously measured for these two MPPCs [1] and is presented here for completeness. A pulsed picosecond blue laser (405 nm) was used at a fixed repetition rate (400 Hz). A neutral optical attenuator was placed in front of the MPPC to reduce the laser light intensity such that each laser pulse created on average less than 1 photoelectron (p.e.). The time difference between the "Sync-Out" from the laser and the output pulse from the NINO was measured with the HPTDC system. Off-line, a selection of events corresponding to single photo-electrons was made by making a cut on the

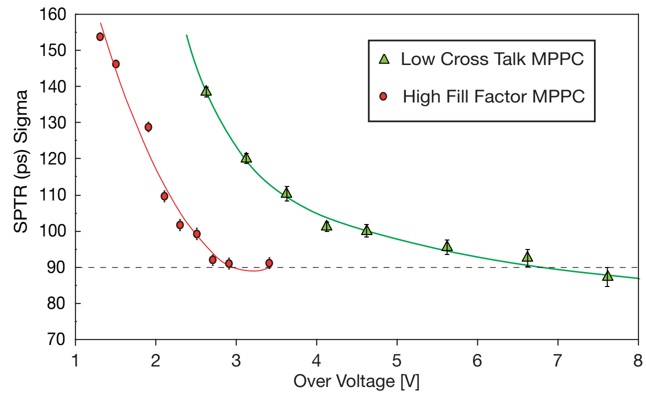

Fig. 3. The Single Photo-electron Time Resolution (SPTR) is detected for the two types of MPPC as a function of over-voltage (voltage above breakdown voltage). The NINO threshold was set to 30 mV.

Time-over-Threshold (ToT). The SPTR is measured to be close to 90 ps for these two MPPCs. The SPTR as a function of V_{OV} is shown in fig. 3, where V_{OV} is the voltage above the breakdown voltage. The breakdown voltage for LCT MPPC is 45.4 V, while the HFF-MPPC breakdown voltage is 68.1 V as shown in fig. 1.

B. Coincidence Time Resolution (CTR)

To measure the Coincidence Time Resolution (CTR), pairs of crystals of type: 'LYSO-Saint Gobain', 'LYSO-CPI' and 'LFS-Zecotek' were glued to the pair of LCT-MPPC sensors. The crystals have a dimension 3×3×15 mm^3; the MPPC had an active area of 3×3 mm^2. Two such assemblies were mounted on each side of a ^{22}Na source. A schematic drawing is shown in fig. 4.

A trigger was formed by demanding a ToT from each crystal of greater than 100 ns. Typical ToT spectra and a coincidence time spectrum are shown in fig. 5. The CTR as a function of the applied bias voltage is shown in fig. 6.

The LFS crystal was then mounted on the HFF-MPPC; the CTR as a function of applied voltage is shown in fig. 7. A

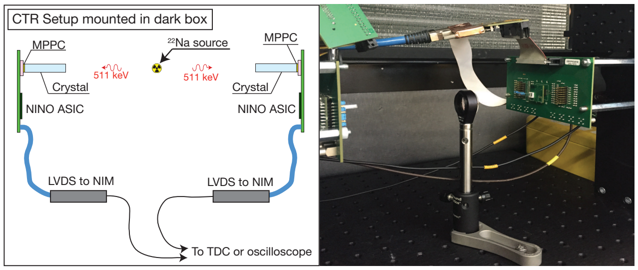

Fig. 4. A schematic drawing of the setup for the Coincidence Time Resolution (CTR). Crystals of size 3×3×15 mm^3 are glued onto the MPPC. Two such crystal/MPPC devices are mounted each side of a ^{22}Na source. The differential signal from the MPPC is input to the NINO ASIC. The LVDS output signal from the NINO is converted to a NIM signal, which are then sent to an oscilloscope or a VME TDC

CTR of 148 ps was achieved; this was at a voltage of 3.8 V above breakdown.

The Fill Factor (FF) of the HFF is 81 % compared to the 60 % of the LCT. The CTR is expected to improve with the square root of the number of photoelectrons: i.e. $\sqrt{81/60}$ = 1.16. The difference between the CTR for these two MPPCs is only 6 %. The reason for the good performance of the LCT-MPPC is that the high over voltage enhances the quantum efficiency of the MPPC.

C. Relative Luminesence

A critical parameter concerning the timing is the number of photoelectrons that we observe in the MPPC corresponding to the 511 keV photopeak. This depends on the photon detection efficiency (PDE), the coupling of the crystal to the MPPC and the number of photons generated within the scintillating crystal.

It is difficult to measure the light yield with a SiPM for the following reasons:

- The finite number of SPADs: there are 3600 SPADs for the 3×3 mm^2 SiPM devices used in this test. When an SPAD fires it is insensitive until the voltage on the diode is restored. Thus the SiPM response becomes saturated.
- Crosstalk between SPADs: photons are emitted during the Geiger breakdown process: these photons can pass to the neighbouring SPADs and cause them to fire. The Low Cross Talk (LCT-MPPC) tested here has metal-filled trenches between SPADs to inhibit crosstalk.
- After-pulses: charge carriers can get trapped, and these eventually decay emitting a photon that can trigger an after-pulse. If the quenching resistor is made very large, the recharge time is long and this reduces the probability after pulses.
- Recharge of SPAD: if the quenching resistor is made small, then the SPAD can be recharged within 20 ns, as an example, and be ready to fire again. This counteracts the saturation discussed above.

The anode of MPPC under test was connected directly to an oscilloscope with a 50 Ω termination. A laser was used to illuminate the MPPC and the intensity increased until the signal from the MPPC is saturated; the oscilloscope was triggered

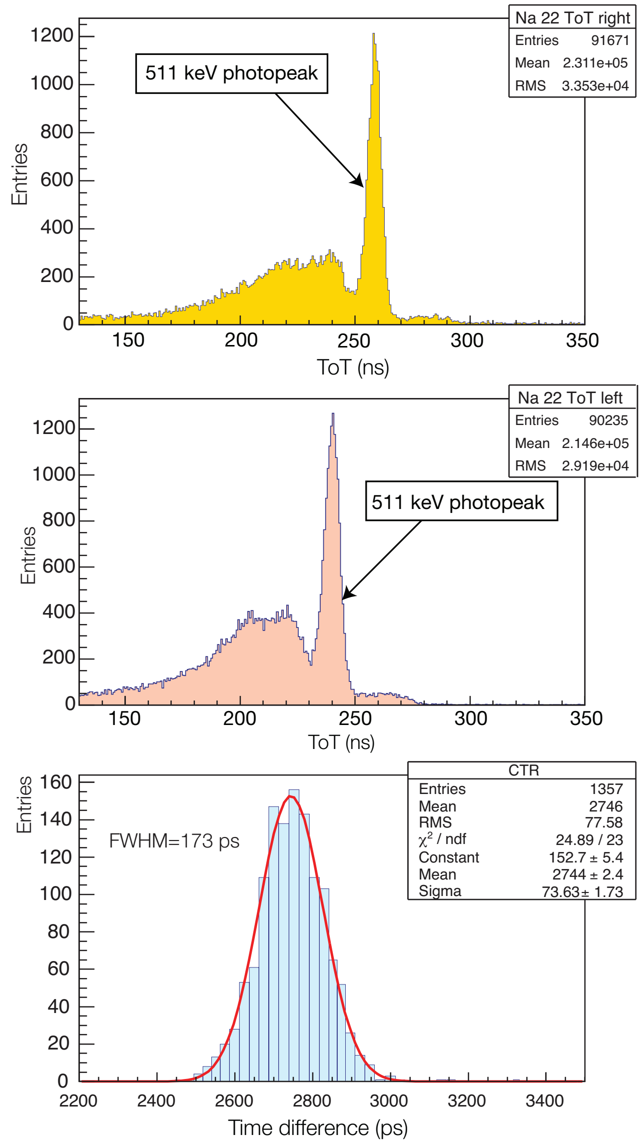

Fig. 5. Typical spectra obtained with two detectors on each side of a ^{22}Na source: each detector consisted of a HFF-MPPC attached to a 3×3×15 mm^3 LYSO crystal. The upper two plots correspond to the ToT spectrum obtained from each detector. The lower plot shows the Coincidence Time Resolution after making a ToT cut to select the 511 keV photo peak.

with the laser "Synch out". The area of the signal is measured with the oscilloscope within a 5 μs window (thus if there are after pulses they will be included as well). To measure the zero signal level, the trigger point of the oscilloscope was delayed by 5.5 μs such that the MPPC response to the laser light was outside the oscilloscope measurement window; the measurements of the area were then again taken with the oscilloscope. The differences in the area was then assigned to be the charge produced when 3600 SPADS fire.

A ^{22}Na source was then placed close to the crystal with the oscilloscope trigged on the MPPC signal itself (as shown in fig. 8). The value corresponding to the 511 keV peak was selected and equated to a number of SPADs firing. The number

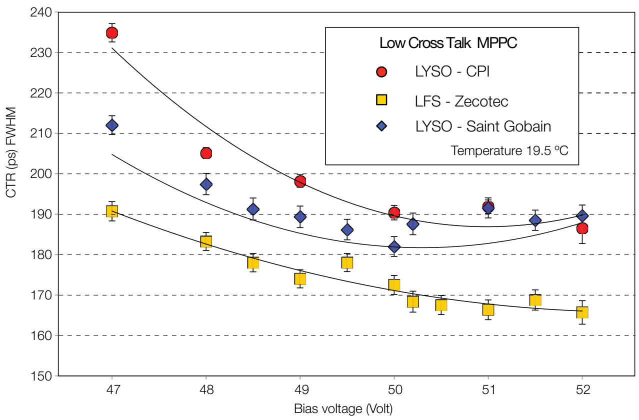

Fig. 6. The Coincidence Time Resolution (CTR) as a function of the reverse bias voltage for three types of scintillation crystals of size $3{\times}3{\times}15$ mm^3 mounted on a pair of LCT-MPPCs. The NINO threshold was set to 30 mV.

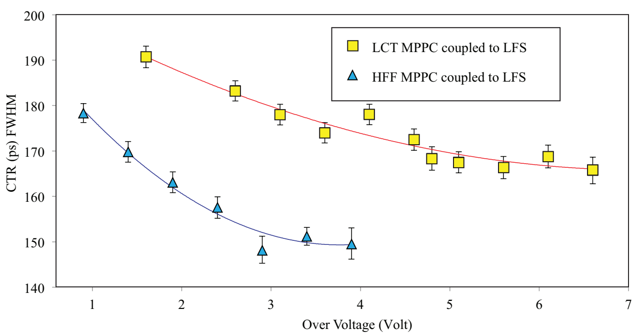

Fig. 7. The Coincidence Time Resolution (CTR) as a function of the reverse bias voltage for two types of MPPCs attached to $3{\times}3{\times}15$ mm^3 LFS crystals. The NINO threshold was set to 30 mV.

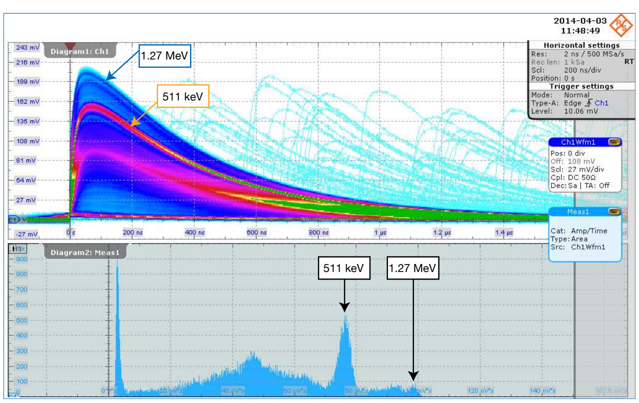

Fig. 8. Snap-shot of oscilloscope display: the upper panel displays the signal with the oscilloscope set on infinite persistence; there are visible bands corresponding to the 511 keV and 1.27 MeV gamma energies. The lower panel shows a histogram of the area of the signal.

of SPADs firing can not be translated directly into the number of initial photo-electrons due to the cross-talk inherent to the SiPM. Note also that the fraction of crosstalk decreases as the number of SPADs that fire increases. The plot shown in fig. 9

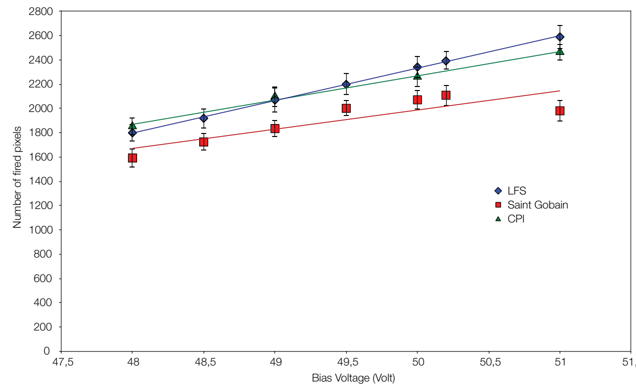

Fig. 9. Number of pixels fired by the scintillating light from the crystals. Three different crystals are tested using the method described in the text.

III. Conclusion

The timing performance and the relative luminosity of a two types of crystals have been compared using the latest MPPCs of the Hamamatsu (LCT and HFF). The LFS crystals give an excellent CTR of 148 ps (FWHM) compared of 180 ps (FWHM) of LYSO. A CTR of 148 ps was achieved at a voltage of 3.8 V above breakdown; at this voltage the current starts to increase rapidly with applied voltage. The CTR is expected to improve with the square root of the number of photoelectrons: i.e. SQRT(81/60) = 1.16. The difference between the CTR for these two MPPCs is only 6 %. Therefore this excellent CTR can be due to a) the shorter decay time of the LFS compared to the LYSO crystals and b) the high Fill factor of the HFF (81 %) compared to the 60 % of the LCT.

Acknowledgment

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