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Comparative timing measurements of LYSO and LFS-3 to achieve the best time resolution for TOF-PET

K. Doroud [a,*], M.C.S. Williams [a,c], A. Zichichi [a,b,c], R. Zuyeuski [a,b]

[a] CERN Geneva, Switzerland
[b] Museo Storico della Fisica e Centro Studi e Ricerche E. Fermi, Roma, Italy
[c] INFN and Dipartimento di Fisica e Astronomia, Università di Bologna, Italy

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ABSTRACT

The best Coincidence Time Resolution (CTR) obtained so far – with very short crystals of 3–5 mm in length – reach values between 100 and 150 ps. Such crystals are not really practical for a TOF PET imaging device, since the sensitivity is quite small for the detection of the 511 keV gammas resulting from a positron annihilation. 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 three different crystals, LFS-3 (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-3 crystals (15 mm long) mounted on each side of a ^{22}Na radioactive source with the HFF-MPPCs at 3.3 V over-voltage. Our results are148 ps obtained with LFS-3 and 170 ps with LYSO crystals using identical SiPMs and electronics.

1. Introduction

The precise measurements of the time and the energy of 511 keV gammas interacting in scintillating crystals are nowadays the 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 measurements obtained when we attach these MPPCs to three types of scintillating crystal.

The performance of a LFS-3 (Lutetium Fine Silicate) crystal is compared to two types of LYSO ($Ce_x(Lu,Y)_{1-x}SiO_5$) crystals: all crystals are 15 mm long with a 3×3 mm^2 cross-section. The two types of LYSO crystals were supplied by CPI and Saint-Gobain. According to the manufactures [2], the yttrium content is about 5% for the CPI LYSO and about 10% for the Saint-Gobain LYSO. The nominal cerium doping level is 0.2% for the CPI LYSO, and is less than 1% for the Saint-Gobain LYSO. So the Saint-Gobain LYSO has higher content of yttrium and cerium; we see (Fig. 9) that the light yield of the two LYSO crystals is different, while the decay time is the same as reported in Table 1. The LFS-3 crystal was produced by Zecotek; LFS is a commercial name of the set of Ce-doped silicate scintillation crystal comprising of lutetium and crystallized in the monoclinic system, spatial group $C2/c$, $Z=4$. The composition is specified in a patent [3] as $Ce_xLu_{2+2y-x-z}A_zSi_{1-y}O_{5+y}$, where A is at least one element selected from the group consisting of Ca, Gd, Sc, Y, La, Eu and Tb. The parameters of the LYSO and LFS-3 crystals are obtained from the manufacturers [4,5] and reported in Table 1.

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 1 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, ~80%. The decay time of the LFS-3 is shorter than the two types of LYSO; this implies that the LFS-3 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 [6]. The PDE of the Hamamatsu MPPCs peaks at ~420 nm, thus

* Corresponding author.
E-mail address: Katayoun.Doroud@cern.ch (K. Doroud).

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crystals with very short decay times may suffer from lower PDE. However, in this case the wavelength of the emitted light from both types of crystal is close to the maximum of the PDE of the MPPCs.

2. Experimental technique

Two Hamamatsu Silicon Photo-Multipliers were tested, one was termed the High Fill Factor (HFF-MPPC) that has a Fill 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 for the same over-voltage, V_{OV}. The over-voltage is the applied voltage above the breakdown voltage.

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) [8]. 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 ^{22}Na 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 is discussed below.

Table 1
Comparison between LYSO and LFS-3 crystals.

Crystal	LYSO, Saint Gobain and CPI	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

2.1. 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. The time difference between the “Sync-Out” from the laser and the output pulse from the NINO was measured with the CAEN V1290 TDC system. Off-line, a selection of events corresponding to single photo-electrons was made by making a cut on the 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.

2.2. Coincidence Time Resolution (CTR)

To measure the Coincidence Time Resolution (CTR), pairs of crystals of type: ‘LYSO-Saint Gobain’, ‘LYSO-CPI’ and ‘LFS-Zecotek’

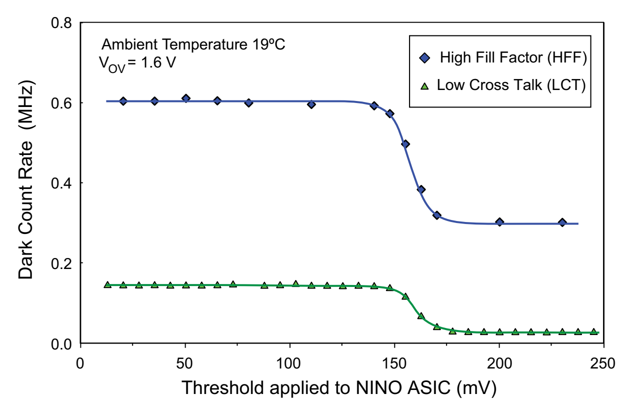

Fig. 2. Comparison of the Dark Count Rate as a function of the NINO threshold setting for the two MPPCs. Both MPPCs were operated at the same voltage above the breakdown voltage, the over-voltage, V_{OV}. The dark count rate is 65 kHz/mm^2 for the HFF compared to the 20 kHz/mm^2 for the LCT.

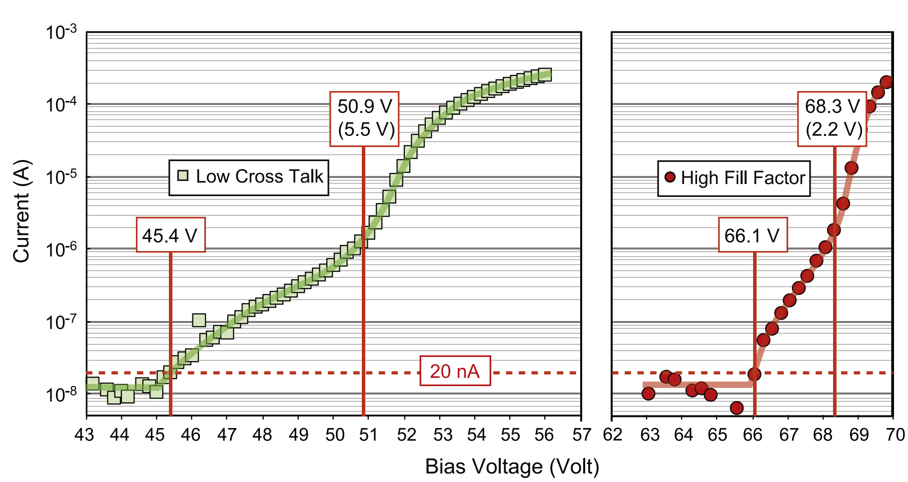

Fig. 1. The current drawn by the MPPC plotted against the applied voltage. The MPPC device is reverse biased. The breakdown voltage is where the current draws more than 20 nA. The upper voltage is chosen to be the point where the current starts increasing rapidly.