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Application of the Micro Pixel Photon Counter to calorimetry and PET(*)

N. D'Ascenzo(1)(2)(**), A. Eggemann(2), E. Garutti(2) and A. Tadday(3)

(1) *University of Hamburg - Edmund Siemens Allee 1, D-20146, Hamburg, Germany*
(2) *DESY - Notkestr. 85, D-22607 Hamburg, Germany*
(3) *University of Heidelberg - Heidelberg, Germany*

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Summary. — Technological solutions are being investigated, in both fields of calorimetry and positron emission tomography, to increase the granularity of the detectors and achieve a better imaging resolution. The Geiger-mode avalanche photodiode looks a promising photo-detector for these compact designs. Up to now, the main limit of its application was the detection of the scintillation light, mostly ranging in the blue region: the traditional Geiger-mode avalanche photodiode is green sensitive. Hamamatsu has recently released a photo-detector of the same family, the Micro Pixel Photon Counter (MPPC), with a high photo-detection efficiency in the 420 nm spectral region, opening a new scenario for the scintillator-based systems. The direct readout performances of a MPPC directly coupled to a plastic organic scintillator and to an inorganic scintillator (LSO) are systematically studied. Possible applications in highly granular calorimeters and positron emission tomography detectors are discussed.

PACS `29.40.Vj` – Calorimeters.
PACS `29.40.Mc` – Scintillation detectors.
PACS `29.40.Wk` – Solid-state detectors.
PACS `87.57.uk` – Positron emission tomography (PET).

1. – The motivations of this study

Imaging detectors are a growing field of investigation and technological development. Their application usually allows a better understanding of the phenomena under study. This family of detectors needs to be compact, easily adaptable to several shapes and highly granular. The Geiger-mode avalanche photodiode [1-3] is the natural candidate

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(**) E-mail: `nicola.dascenzo@desy.de`

to read out such systems. It is a $1 \times 1\,\mathrm{mm}^2$ silicon photo-detector, with a typical gain of $\sim 10^6$ reached with a bias voltage ranging between 30 V and 70 V, typically 2 V above breakdown voltage. The traditional photo-detection efficiency of this photo-detector ($\sim$ 15–30%) is peaked in the green spectral region, and decreases significantly outside of it. Hamamatsu has recently released the Micro Pixel Photon Counter, a Geiger-mode avalanche photodiode which extends a good photo-detection efficiency also in the blue spectral range [4]. High-energy physics and medical applications are intensively developing imaging detector designs. The future International Linear Collider and the positron emission tomography are two significative paradigms of a wider opportunity of applications which nowadays extends in several more fields of physics.

The future International Linear Collider (ILC) [5] is a e^+e^- collider intended to investigate the electroweak symmetry breaking process and the predicted new physics beyond the Standard Model. As many final states will be characterized by high-energy multi-jet signatures, an extremely good jet energy resolution ($30\%/\sqrt{E}$) is required in order to perform precision measurements [6]. The particle flow approach [7], which utilizes the joint information of each sub-detector in order to reconstruct each single particle within the jet is expected to reach this goal. The hadron calorimeter design plays a critical role in the particle flow concept. It is thought of as a highly granular imaging detector [8]. In addition, many interesting channels of physics beyond the Standard Model are identified with characteristic missing energy signatures. This requires a detector with very good hermeticity. To achieve best performance and hermeticity, the whole detector has to be inserted into the magnetic coil, this translates into strong requirements on detector compactness. The option for an analog hadron calorimeter as proposed by the CALICE Collaboration for the ILC [9] is a sampling calorimeter alternating 0.5 cm thick scintillator layers with 2 cm thick steel absorbers. The suggested optimal layout of the sensitive layer consists of a texture of $3 \times 3 \times 0.5\,\mathrm{cm}^3$, resulting in several million channels in the whole detector and in an unprecedent high granularity. A prototype of the analog hadron calorimeter was built: it has 38 layers fully equipped and is currently tested at CERN. The SiPM, produced by MEPHI (Moscow Engineering and Physics Institute) in collaboration with the Pulsar enterprise, is successfully used as a readout of the scintillator tiles [10]. Its size allows a direct installation on the tile. However, the SiPM is a green-sensitive photo-detector and the coupling to the blue-emitting scintillator is obtained via a green wavelength shifting fiber installed in a groove on the scintillator itself. This configuration improves the light collection uniformity at the photo-detector, but increases the complexity of the system. The blue-sensitive MPPC would allow to investigate the direct coupling of the scintillation tile, with a consequent simplification of the design. The first purpose of this study is hence to evaluate the response of a plastic scintillator, directly read out by the most recent MPPC by Hamamatsu, to a minimum ionizing particle (m.i.p.).

The second aim of this study is to investigate the possible application of MPPC to Positron Emission Tomography (PET). A possible design of a PET apparatus with Geiger-mode avalanche photodiode readout is already proposed [11] and many others are under discussion. They generally consist of an array of crystals coupled with a photo-detector which matches its size. The small size of the crystal allows an improvement of the image resolution. As the spectral emission of the crystal is in the blue and ultraviolet region, the photo-detector has to have a good photo-detection efficiency in this range. This improves the energy resolution of the system with a consequently more efficient discrimination between photoelectric and Compton-scattered background photons. Furthermore, the image reconstruction algorithms benefit from the reduction of the random

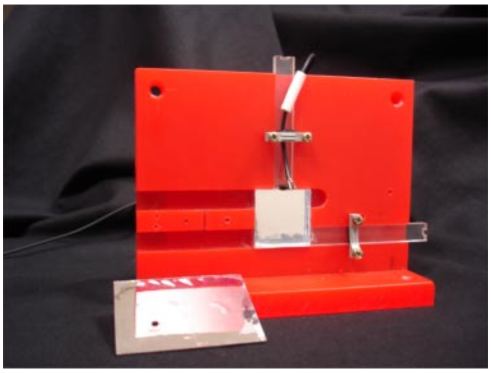


Fig. 1. – Set-up for the direct coupling. The scintillator is installed in a specific housing. The MPPC is fixed at one end of a plastic holder which can be located in two different positions. The coupling is reproducible at a 3% level.

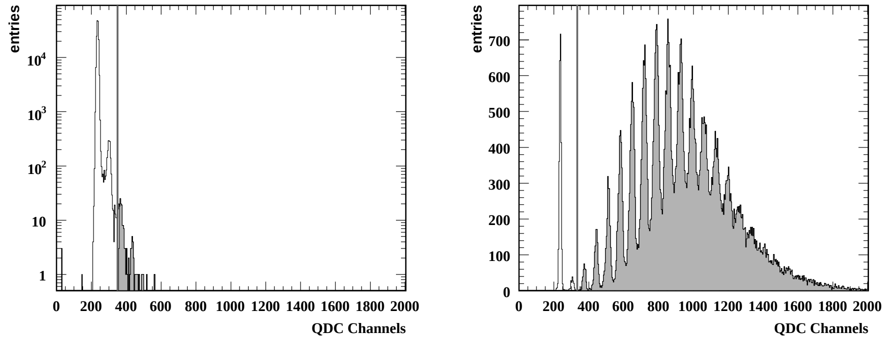
coincidences obtained with a short coincidence window: this depends on the response time of the photo-detector. A fast photo-detector would allow the design of a time-of-flight PET, where a good time resolution contributes to a more precise localization of the signal source. The systematic investigation of the energy and time resolution, for 511 keV photons, of a $1 \times 1 \times 15\,\mathrm{mm}^3$ and a $3 \times 3 \times 15\,\mathrm{mm}^3$ LSO crystals directly coupled with the MPPC is proposed as a starting point for design considerations for a prototype of a Positron Emission Tomography device.

2. – The available MPPCs

This study is based on 5 samples of $1\,\mathrm{mm}^2$ MPPCs (400 pixels), 5 samples of $1\,\mathrm{mm}^2$ MPPCs (1600 pixels) and 5 samples of $3\,\mathrm{mm}^2$ MPPCs (3600 pixels). The active silicon is protected by a special plastic package. The suggested operation voltage is, respectively, 76 V, 78.1 V and 69.9 V with a spread of 0.1 V between the 5 pieces of each sample. The dark rate at 0.5 pixels is estimated respectively to be 220 kHz, 50 kHz and 3 MHz. The gain of the devices ranges between 2×10^5, for the 1600 pixels MPPCs, and 7×10^5 for the others. An initial characterization of the devices confirms the parameters indicated in the data sheets.

3. – Tests for the application of Hamamatsu MPPC to hadron calorimetry

3·1. *Description of the set-up.* – Two $3 \times 3 \times 0.5\,\mathrm{cm}^3$ plastic organic scintillator tiles (produced by *Uniplast* enterprise in Vladimir, Russia) are used. In one a 1 mm diameter green wavelength shifting fiber (Kuraray multi cladding WLS fiber Y11(200)) is installed. The scintillators are wrapped in a Super-radiant VN2000 foil (3M). A special set-up is designed in order to guarantee the reproducibility of the measurement (fig. 1). The scintillator is installed in a fixed housing, in the middle of a robust main structure. The MPPC is secured at one end of a plastic bar. Two grooves are carved in the main structure, one starting from the middle of the side of the tile, one from the center and they host the MPPC holder. This allows to couple the MPPC to the scintillator in two positions. In the direct readout set-up, a window of $3 \times 3\,\mathrm{mm}^2$ is open in the reflective coating, in front of the MPPC. Its holder is then completely guided in the casing and

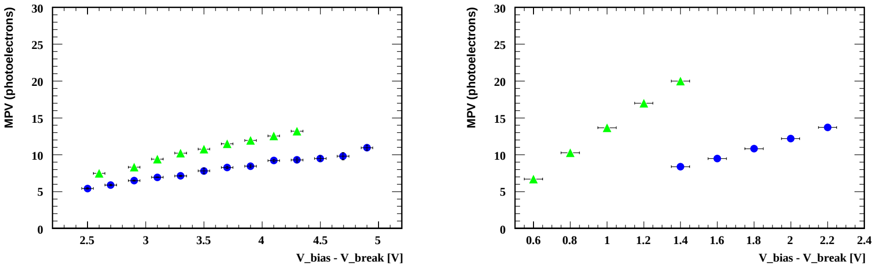


(a) (b)

Fig. 2. – Scintillator crystal read out by a 400 pixels MPPC. A threshold (the vertical line in the figure) is defined from the pedestal, so that the noise above is 3 kHz (grey area in (a)). This threshold in amplitude defines the efficiency of the collection of the signal (b): in gray is the part of the signal above the cut, which is 98% of the total, after subtracting the pedestal contribute.

the MPPC plastic coverage is in contact with the scintillator: this improves the coupling between scintillator and photo-detector. The distance between the sensitive region of the MPPC and the surface of the scintillator is $\sim 2\,\mathrm{mm}$. In the green wavelength shifter mediated design, the scintillator equipped with fiber is installed in the dedicated housing and the green light is directly read out by the MPPC, hold by the same bar. In both designs, no specific optical coupling is used. The response of the system to a β^- source (^{106}Ru) is investigated. A trigger plate, made with a $5 \times 5 \times 1\,\mathrm{cm}^3$ plastic scintillator, read out with a traditional photomultiplier tube, is put behind the scintillator/MPPC system. The signal of the MPPC is amplified with the wide-band voltage amplifier Phillips Scientific 6954. The integration is performed by the QDC Lecroy 1182, in a gate of 80 ns, produced in coincidence with the trigger. The set-up allows to reproduce the measurement within a systematic error of ±3%.

3˙2. *Main results.* – The typical noise and m.i.p. signals registered by the MPPC are shown in fig. 2. The area of each Gaussian single peak is evaluated and plotted as a function of the peak number, then a simple Gaussian fit is performed to determine the most probable value of the m.i.p. signal. This operation has been repeated for various bias voltages and the resulting MPV voltage dependence is shown in fig. 3, for the direct coupling and green wavelength shifter readout mode. It can be noted that in the WLF fiber mediated design the 1600 pixels MPPC provides a light yield ranging between 8 and 14 pixels per m.i.p. and the 400 pixels up to 20 pixels per m.i.p. The latter samples would even provide higher yield when increasing the bias voltage further, but the dark rate increases at higher voltage. For the hadron calorimeter prototype the MEPHI SiPM is optimized to provide a light yield of 15 pixels per m.i.p. (15 ± 2 measured in the operation of the prototype). The MPPC could provide a comparable response. The similar performances of the SiPM and MPPC in the wavelength shifter mediated readout induces to think that the MPPC has in addition a similar photo-detection efficiency in the green spectral region. Far from being an absolute statement, this is a suggestion for

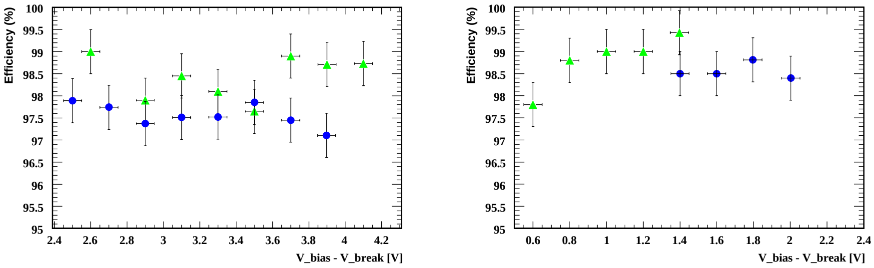


(a) (b)

Fig. 3. – Most probable value of a m.i.p. spectrum detected by a 1600 pixels (a) and a 400 pixels (b) MPPC. The dots correspond to the direct coupling, while the triangles to the wavelength shifting mediated readout.

further precise measurements of photo-detection efficiency, where the difference of this parameter in the detector can be quantitatively quoted. The MPV in the blue coupling ranges around 6-9 pixels per m.i.p. in the 1600 pixels MPPCs and 7-12 pixels per m.i.p. in the 400 pixels MPPCs. The light yield measured in the two positions on the tile side is in agreement within the systematic error. The good signal obtained with the direct readout indicates that the photo-detection efficiency in the blue region is reasonably increased with respect to the old generation SiPMs, where a light yield of less than 3 pixels per m.i.p. is commonly observed [12]. At the same overvoltage a light yield twice as large can be extrapolated from the 400 pixel MPPC measurements, in agreement with the data sheet. The better light yield in the traditional readout configuration is due to the well-established light collection techniques, studied systematically during the commissioning of the CALICE hadron calorimeter prototype. The direct readout is a new concept and no light yield optimization study has been attempted so far. More studies are needed in order to quantify the maximum light yield possible by the direct readout of the scintillator. The best readout position with respect to the tile and the uniformity of the light collection are still to be investigated.

In the highly granular calorimeter m.i.p. signals are used as a reference for the calibration. The Most Probable Value (MPV) of the signal sets the energy scale of each channel. A threshold on the amplitude defines the discrimination between the noise and the physics signal. The normalized integral of the m.i.p. signal above the noise threshold is the m.i.p. detection efficiency. All signals, with amplitude above threshold, constitute a hit in the calorimeter. The threshold is fixed from the pedestal spectrum (fig. 2a) such that the noise rate above threshold is 3 kHz. This requirement corresponds to an occupancy of less than 10 accidental hits on the whole 8000 channels of the calorimeter prototype with $\sim$ 200 ns integration time. For the ILC detector, one aims at an occupancy of 10^{-4} during one beam crossing interval ($\sim$ 300 ns), which translates into a tighter requirement of 300 Hz noise above threshold for a single photo-sensor. The MPPC shows always a m.i.p. detection efficiency better than 97% (fig. 4). The typical threshold, depending on the bias voltage, ranges between 1.5 and 2.5 pixels. In the test beam prototype the measured m.i.p. collection efficiency is 95%, with the noise cut set at $\sim$ 7.5 pixels (0.5 m.i.p.). The high m.i.p. collection efficiency obtained with MPPC even in the direct readout configuration is a consequence of their low cross talk and dark



(a) (b)

Fig. 4. – Signal collection efficiency for the 1600 pixels (a) and 400 pixels (b) MPPCs. The points correspond to the direct coupling, while the triangles refer to the wavelength shifting mediated readout.

rate with respect to the traditional SiPMs: the pedestal drops rapidly as the threshold is increased as is shown in fig. 2a.

This test indicates that the Hamamatsu MPPCs are a possible candidate for hadron calorimetry in the direct readout configuration. The required performance is accomplished by the 1600 pixels device in the biasing region 2.5–3.5 V over breakdown, with an expected light yield of 6-7 pixels per m.i.p. and ∼ 97% m.i.p. efficiency, with a noise threshold imposed at ∼ 1.5 pixels. The 400 pixels MPPCs operated at 1.5–1.8 V over breakdown have a very high m.i.p. collection efficiency and light yield. However, the limited dynamic range makes the device not optimal: the restriction to signals below 400 pixels is too tight for a hadron calorimeter, where the linear dynamic range has to reach order of 100 m.i.p.'s per tile. It has to be noted that in both MPPCs the dark rate drops rapidly as the threshold is increased, such that for the tighter requirements of the ILC a threshold of 2–4 pixels would be sufficient to keep the occupancy small. In this case it is possible to operate at an overvoltage which preserves the m.i.p. efficiency above 95%. If thinner scintillator, *e.g.*, 3 mm instead of 5 mm thickness is to be used, better coupling or larger sensitive area of the photo-detector has to be investigated. A possible solution could be the application of the new $3 \times 3\,\mathrm{mm}^2$ MPPC, but more systematic studies are needed.

4. – The application of MPPC to PET

4˙1. *Description of the set-up.* – The investigation of a possible application of MPPC to PET requires considering two parameters: energy and time resolution of LSO crystals directly readout with a MPPC. Two pairs of $1 \times 1 \times 15\,\mathrm{mm}^3$ and $3 \times 3 \times 15\,\mathrm{mm}^3$ LSO crystals (Hilger) are wrapped in a 2 mm thick teflon layer. One end of the crystal (fig. 5) is left free and coupled with optical grease to a MPPC of equal active area. Two holders for the photo-detector with a guideline for the crystal allow to fix the MPPC relative position. A groove is carved in the main support and a ^{22}Na source is positioned in the middle of it. The detector holders are free to move along it and are kept in this way always aligned with the source. The precision of the system is 0.5 mm and the systematic error of the resulting measurement is quoted to be 3% for the $3 \times 3\,\mathrm{mm}^2$ detectors and 10% for the $1 \times 1\,\mathrm{mm}^2$ ones. Without using any amplification, the signals from the MPPC

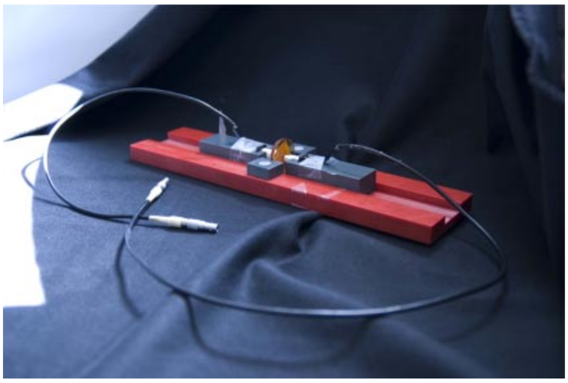
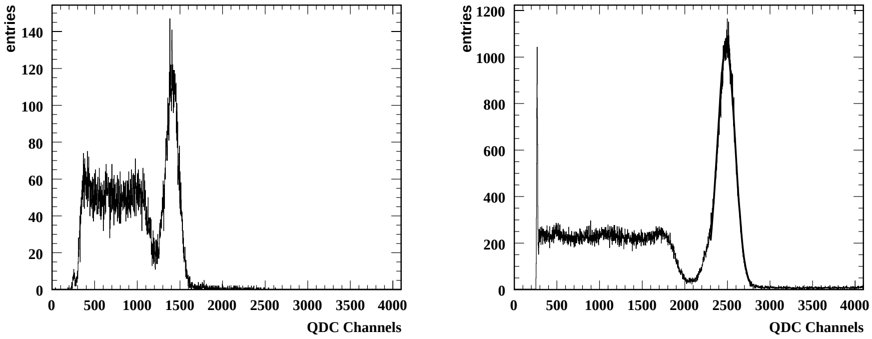


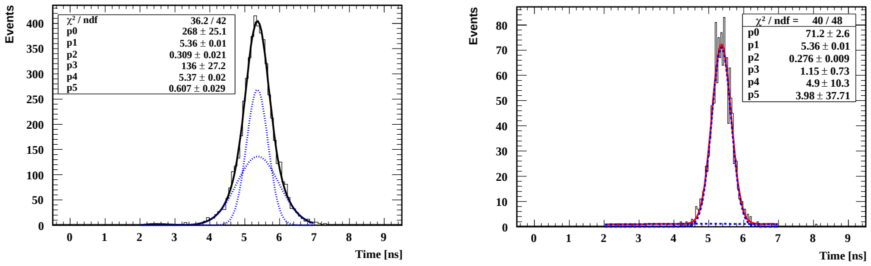
Fig. 5. – Set-up for the energy and time resolution measurements of LSO crystals. The scintillators (white) are directly read out by the MPPC and aligned with a ^{22}Na positioned in the middle. The set-up allows a reproducibility of the measurements of 3% for the $3 \times 3\,\text{mm}^2$ detectors and 10% for the $1 \times 1\,\text{mm}^2$ ones.

are integrated by the VME QDC Lecroy 1182, in a gate generated when the signals are in coincidence using NIM logic modules. The time resolution measurement is performed with a 4 GHz oscilloscope (TDS7404B by Tektronix). The two signals from the detector elements are directly sent to the inputs of the oscilloscope. The coincidence logic is internally set in the oscilloscope. When both exceed a predefined amplitude (V_1), the trigger of the oscilloscope is generated. The timing is calculated using the on-line jitter analysis software, provided by tektronix. The times at which the signals cross a second predefined threshold (V_2) are evaluated by the software and the difference between them is computed. The oscilloscope provides a sampling rate of 20 Gs/s, resulting in a time resolution of 50 ps.



(a) (b)

Fig. 6. – Energy response to a ^{22}Na source of (a) $1 \times 1 \times 15\,\text{mm}^3$ LSO crystal coupled with a $1 \times 1\,\text{mm}^2$ MPPC (400 pixels) and (b) $3 \times 3 \times 15\,\text{mm}^3$ LSO crystal coupled with a $3 \times 3\,\text{mm}^2$ MPPC (3600 pixels).



(a) (b)

Fig. 7. – Timing resolution of two LSO crystals detecting in coincidence the 511 keV emission of a ^{22}Na source. A background is superimposed to the clean signal, worsening the FWHM from 700 ps to 1.4 ns (a). When rising the coincidence amplitude threshold to 50 photoelectrons the background disappears and a clean signal with FWHM 650 ps is observed (b).

4·2. *Energy resolution.* – Using the $3 \times 3 \times 15\,\text{mm}^3$ LSO crystals, an energy resolution of 10% is obtained for 511 keV photons (fig. 6a), while the $1 \times 1 \times 15\,\text{mm}^3$ crystals show 14% (fig. 6b). The higher systematic uncertainty of the latter measurement, due to the technical reproducibility and optimization of the coupling, indicates possibility for improvements. The measured energy resolution would allow an efficient separation between the photoelectric peak and the Compton scattered events. It was previously shown [13] in a similar experiment that the traditional SiPM provides a resolution of $\sim 35\%$, due to the poor photo-detection efficiency in the blue spectral region. Furthermore, the same crystal usually shows $\sim 10\%$ energy resolution at 511 keV, if read out by a traditional photomultiplier tube [14]: LSO has an intrinsic energy resolution of 9% [15]. The obtained result is, hence, in agreement with expectations and gives indications that the MPPC provides energy resolution for PET application competitive with that of traditional PMT with the advantage of an easy direct coupling to a small crystal.

4·3. *Time resolution.* – The time resolution is defined as the distribution of the time difference between the two signals generated by the detection of two back-to-back 511 keV photons. The trigger to compute the time difference is provided by the two signals coincidence obtained with a threshold lower than that at which the signals timing is measured. Figure 7a shows the typical time resolution spectrum with V_1 set to 10 mV (~ 10 photoelectrons) and V_2 set to 2 mV (~ 2 photoelectrons) (^{1}). The total FWHM is 1.4 ns. Performing a double Gaussian fit on the spectrum it is possible to separate two contributes: a signal with 700 ± 60 ps FWHM and a large background (1.41 ± 0.07 ns FWHM), which worsens the resolution. The background can be identified in these events for which one signal is generated via photoelectric effect and the other by Compton scattering. The leading edge of the two signals has a different slope and this worsens the time resolution. The probability of getting these background events is high in this measurement as the coincidence threshold is set to 10 photoelectrons, much lower than the photoelectric

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(^{1}) Here and in the following, the correspondence between signal amplitude in mV and number of photoelectrons is only intended as an indication. The number of firing pixels is strongly related only with the total charge of the signal.

peak amplitude, estimated as 300 photoelectrons. Rising V_1 to 50 photoelectrons, the background disappears (fig. 7b) and a timing resolution of 650 ± 20 ps FWHM is measured. Further studies on the systematics introduced by V_1 and V_2 are needed.

It is quoted that a time resolution of 500 ps (FWHM) would be enough to twice enhance the signal-to-background ratio of the reconstructed image [16]. A similar value is shown for LSO crystal read out by a photomultiplier tube [14]. The measurements with MPPC are not far from what is needed and indicate a promising optimization study in order to achieve a competitive result with the traditional designs.

5. – Conclusions and remarks

The MPPC by Hamamatsu has been tested for direct readout of both organic and inorganic fast scintillators. The light yield of the MPPC coupled with an organic scintillator, in the detection of a m.i.p., allows a signal collection efficiency of more than 97%, making this photo-detector competitive with the standard SiPM used in the CALICE hadron calorimeter prototype.

The direct readout of LSO crystals shows a promising application to positron emission tomography. An energy resolution of 10% and a time resolution of 650 ps FWHM are reached. These results suggest that the MPPC can compete with the standard well-established photo-detectors used in this field.

This study is however based on few samples, from which only an indication can be extracted. On one side, for the application of MPPC to the hadron calorimeter, one needs to quote the light collection uniformity and its impact in the energy resolution, the required dynamic range and the control of the large-scale production parameters determining the quality of the photo-detectors. In this respect the scintillator tile electromagnetic calorimeter developed in the CALICE Collaboration integrates also the direct readout with MPPC and will show the effects of this technique in a real prototype [5]. On the other side, the extension of MPPC to PET requires manufacturing MPPC matrices with the same performances of the single piece. The next step would be to demonstrate with a small prototype the advantages with respect to the traditional light sharing techniques currently in use in many PET systems.

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