Application of novel Silicon-based photo-detector to calorimetry and medical physics.

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***Abstract*—Various samples of newly produced Micro-Pixels Photon Counters have been characterized and their properties are compared. The samples differ in the total number of active pixels as well as in the total detector area. The application of these devices for the next generation of highly granular calorimeter readout is discussed. Their enhanced blue sensitivity allows to consider direct coupling to plastic scintillator tiles as an alternative to the traditional readout mediated by a wavelength shifter fiber. The spin-off application for time resolution PET readout is considered. First measurements are presented of energy and time resolution obtained with a test system consisting of two inorganic scintillator crystals coupled to MPPC readout.**

I. Introduction

RECENT developments in photo-detector technology have introduced the family of multi-pixel silicon-based photo-detectors operated in Geiger-mode [1], [2], [3]. Such sensors are extremely compact, robust and easy to operate, and immediately found broad application in the design of highly granular imagine detectors.

Silicon-photomultipliers (SiPM) are generally 1x1 mm^2 in size and consist of a variable number of pixels between 100 and 2000. The Geiger mode operation ensures a high gain around 10^6 comparable with that of traditional photomultiplier tubes. The spectral sensitivity of these devices is typically peaked in the green region, at about 500 nm.

A new version of such photo-detectors became recently available with an enhanced sensitivity to the blue spectral region. This makes them a natural candidate for direct coupling to organic and inorganic scintillators.

This work summarizes the characterization studies performed on three samples of the new Micro-Pixels Photon Counters (MPPC, from Hamamatsu). Emphasis is given to two possible applications of MPPC in highly segmented detectors such as calorimeters for high energy physics and detectors for positron emission tomography application.

A prototype hadron calorimeter for the International Linear Collider (ILC) has been developed by the CALICE collaboration[1]. It consists of a sampling structure of 38 layers laterally segmented in cells as small as 3x3 cm^2. A total of 8000 SiPM is employed to readout individually each plastic scintillator tile constituting a calorimeter cell. The physics requirements for the calorimeter cells are a good signal to noise ratio (>7) and a high detection efficiency (>95%) for minimum ionizing particles (MIP). Furthermore, a dynamic range up to 100-500 MIP is desirable. The photo-detector have to be insensitive to magnetic fields of about 4-5T.

In addition to the advantages of SiPM for this application, the enhanced blue sensitivity of MPPC allows direct readout of scintillators offering possible improvement and simplifications for the system design.

In Positron Emission Tomography (PET) the 511 keV photons produced through e^+e^- annihilations inside a living organism are detected. The positrons are introduced in the organism via a tracer marked with β^+ radio-nuclei. The two emitted photons travel back to back away from the source along a straight line known as Line Of Response (LOR). The 3D reconstruction of several LOR enables to determine the exact shape and position of the source.

To minimize the number of LOR required for an accurate reconstruction, and therefore the radioactive dose to the patient, the sensitivity and efficiency of the PET detector has to be optimized. The Time of Flight method in conjunction with traditional 3D reconstruction methods allow to improve the space resolution of a PET detector. The blue sensitivity of MPPC in this case is essential to achieve high energy resolution, providing a high light yield in direct crystal readout. The very fast and stable signal response from MPPC should enable a good time resolution for application in ToF-PET. The reduced size and cost of MPPC offers the possibility on ultra-high granularity in a reasonable volume which should significantly improve the detector space resolution.

II. Characterization of MPPC

The MPPC is a silicon photo-detector with variable size between 1x1 mm^2 and 3x3 mm^2. It consists of an array of p-n junction pixels biased above the breakdown voltage. Each pixel is passively quenched with an external resistor. Its response is a fixed amount of charge for each impinging photon, hence not proportional to the photon energy. The MPPC signal output is the sum of the charges of all pixels, which is proportional to the incident flux of photons. The gain of the device ranges from 10^5 to 10^6. The MPPC shows a high sensitivity in the 420 nm spectral region, with a photo-detection efficiency ranging between 25% and 65% depending on the pixel size. The typical low dark current ($< 1\ \mu$A), the low bias voltage ($\sim$ 70V) and the high gain largely simplify

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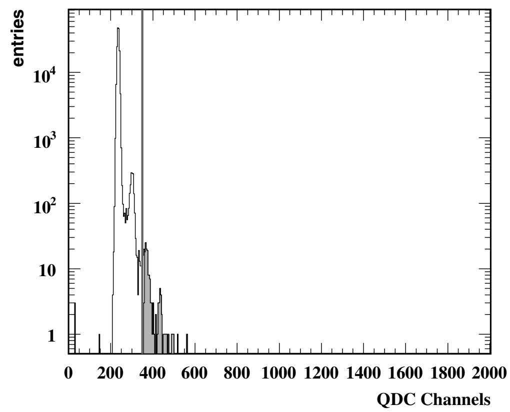
[1]The CALICE collaboration home page can be found at: http://llr.in2p3.fr/activites/physique/flc/calice.html

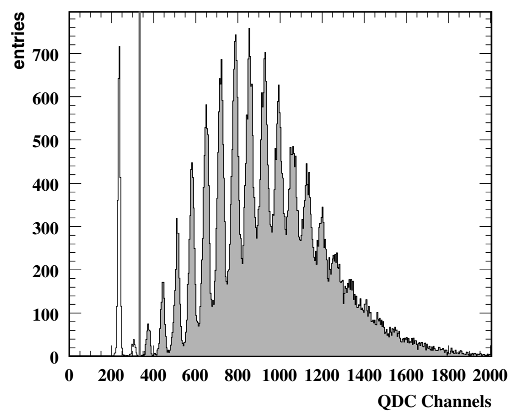
the readout electronics.
This study is based on five samples of 1x1 mm^2 MPPC 400 pixels, five of 1x1 mm^2 MPPC 1600 pixels, and five samples of 3x3 mm^2 MPPC 3600 pixels. The active silicon is protected by a special plastic package and can be easily handled. The suggested operation voltage ranges between 70 V and 78 V, with a spread of 0.1 V between the five pieces in each sample. The result of the characterization measurements at operation voltage for gain and dark rate (DR) above a certain threshold (0.5 and 1.5 pixels) are reported in Table I.

size [mm^2]	N. pixel	Bias [V]	Gain [10^5]	DR>0.5pix [kHz]	DR >1.5pix [kHz]
1x1	400	76	7.4-7.5	220-250	9-10
1x1	1600	78	2.6-2.7	50-60	0.05-0.1
3x3	3600	70	7.4-7.5	3200-3300	320-330

TABLE I
RESULTS OF THE CHARACTERIZATION OF 3 SAMPLES OF FIVE MPPC.



a)



b)

Fig. 1. a) Noise spectrum of a MPPC 400 pixels, the gray area above the 1.5 pixels threshold amounts to less then 3 kHz. b) MIP spectrum from a MPPC 400 pixels directly couple to a 3x3x0.5 mm^3 scintillator tile. The gray area above 1.5 pixels threshold amounts to 98% of the total MIP signal. The thresold cut has to be tuned for different bias voltage.

III. CALORIMETRY APPLICATION

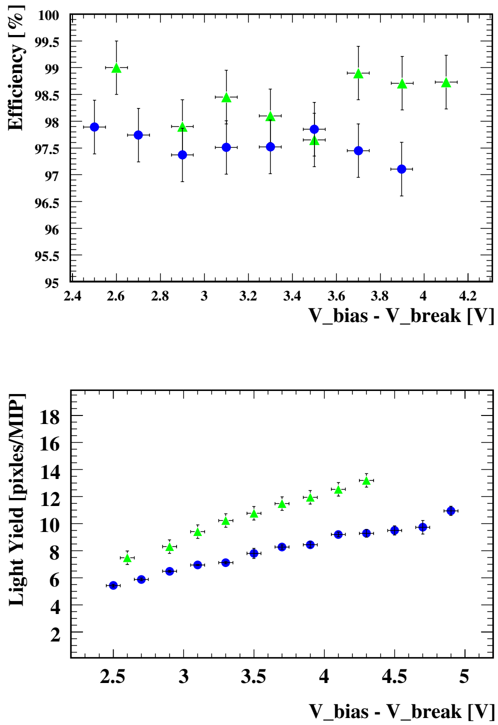
The state of the art analog calorimeter for future HEP detectors consists of highly segmented scintillator tiles individually read out by multi-pixel silicon-based photo-detectors. Present designs envisage 3x3 cm^2 tiles, 0.5 cm thick, read out via SiPM (produced by MEPHI/PULSAR[2]). Due to the green sensitivity of the SiPM a wavelength shifter (WLS) fiber is embedded on the tile, which collects the scintillation photons and guides them green shifted to the photo-detector. With this method a light yield of 15 photo-electrons per MIP is achieved for a tile-SiPM system.
One of the next steps in calorimetry R&D is to simplify the system design possibly by direct coupling of the photo-detector to the scintillator tile. MPPC with 400 and 1600 pixels are possible candidates for this application. Their small size of 1x1 mm^2 (3x4 mm^2 including package) and their enhanced blue sensitivity (with a peak at 420 nm) allow direct installation on a scintillator tile.
In a laboratory setup several combinations of tiles and MPPC have been studied. Tiles with or without WLS fiber are wrapped in reflector foil (Super-radiant VN2000 from 3M). About 0.5 mm plastic from the package separate the silicon from the scintillator surface, no optical grease is used. The signal of reference for the study is provided by a β^- source (Ru^{106}). The signal of the MPPC is amplified by a wide-band voltage amplifier (Phillips Scientific 6954) and integrated by a VME QDC (Lecroy 1182) using a gate of 80 ns. The reproducibility of measurements performed with this setup is at the 3% level.
Fig. 1 a) shows a noise spectrum from a MPPC 400 pixels. The peaks above the electronic noise one are caused by thermally induced noise and inter-pixel optical cross-talk. A threshold cut is tuned to obtain a dark rate of less then 3 kHz. For the same cut the fraction of a MIP signal collected is evaluated using measured MIP spectra as shown in Fig. 1 b).

[2]Moscow Engineering and Physics Institute and PULSAR enterprise, Moscow, Russia.

The extracted efficiency values weakly dependent on voltage as shown in Fig. 2a) for a MPPC 1600 pixels. A detection efficiency larger than 97% can be reached for both direct and WLS fiber mediated readout. With MPPC 400 pixels detection efficiency larger than 98% are possible.
The light yield for a MIP signal as delivered by a 3x3x0.5 mm^3 scintillator tile coupled to a MPPC 1600 pixels is shown in Fig. 2b) as a function of voltage above breakdown. The WLS fiber mediated readout yields about 40% more light than the direct readout system, but both solutions are acceptable for the scope of a calorimeter (sufficiently large signal to noise ratio). In comparison, the system with MPPC 400 pixels offer a light yield up to 70% larger (7-20 pixels per mip with WLS fiber and 8-14 pixels per mip without in the tested voltage range) but the dynamic range is strongly reduced and maybe not sufficient for analog calorimeter readout.

IV. PET APPLICATION

The basic setup for tests of PET readout consists of two inorganic scintillator crystals coupled to two photo-detectors, constituting two PET cells. The two cells are positioned face



a)

b)

Fig. 2. a) MIP detection efficiency above threshold cut and b) Light yield for a MIP signal, as a function of voltage above breakdown for a tile-MPPC 1600 pixels system. The dots correspond to direct coupling, the triangles to WLS fiber mediated readout.

to face on a mechanical holder. In the middle of the two cells a Na^{22} source is used to generate the back to back scattered photons. In this way the energy resolution of both cells to 511 keV photons is tested, which depends on the crystal quality, the crystal light insulation, the crystal to photo-detector coupling, the photo-detector efficiency and several other parameters. Also several sizes of crystals can be tested in this configuration as well as several type of photo-detectors. For this study MPPC 3600 pixels and MPPC 400 pixels have been used. Crystals of $1 \times 1 \times 15$ mm^3 and $3 \times 3 \times 15$ mm^3 were directly coupled to a MPPC with an active area of the same size. The performances of LSO (Lutetium Orthosilicate, or Lu_2SiO_5, from Heilger Crystals) and LFS-7 (Lutetium Fine Silicate, developed by General Physics Institute, Moscow [4]) were compared.

As a preliminary result from this setup an energy resolution of $(10 \pm 0.3)\%$ is obtained for 511 keV photons using the $3 \times 3 \times 15$ mm^3 LSO crystals coupled to MPPC 3600 pixels. A comparable resolution is obtained using a LFS system of the same size, as shown in Fig. 3. When using crystals of smaller cross section, $1 \times 1 \times 15$ mm^3 coupled to MPPC 400 pixels, one gets a somewhat worse energy resolution of $(14 \pm 1.4)\%$. Note that the pixel pitch is the same for MPPC 3600 and 400 pixels; thus photo-detection efficiencies are expected to be the same. The worse energy resolution of the $1 \times 1 \times 15$ mm^3 system must come from the crystal itself or from the alignment precision in the coupling, but not from the photo-detector. The rather large systematic uncertainties of the $1 \times 1 \times 15$ mm^3 system measurements are due to a still imperfect setup of the test system; improvements are possible especially concerning the technical reproducibility and the crystal-MPPC coupling. The measured energy resolution allows an efficient separation

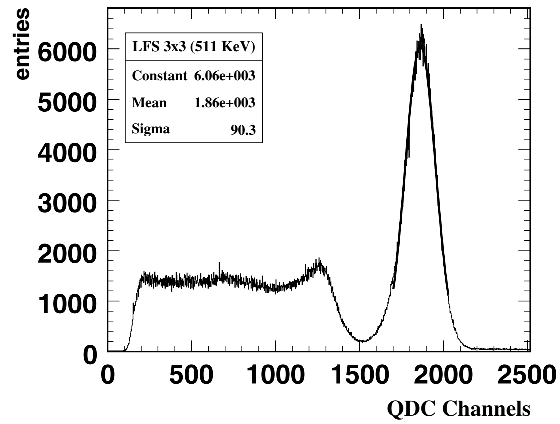


Fig. 3. Energy response to a ^{22}Na source of a $3 \times 3 \times 15$ mm^3 LFS crystal coupled to a 3×3 mm^2 MPPC 3600 pixels.

between the photoelectric peak and the Compton scattered events. In a similar experiment [5] it was previously shown that the traditional SiPM provides a resolution of $\sim 35\%$, due to the poor photo-detection efficiency in the blue spectral region. Furthermore, LSO crystals show $\sim 10\%$ energy resolution at 511 keV when read out by a traditional photomultiplier tube [6] (LSO intrinsic energy resolution is $\sim 8\%$ [7]). The results obtained indicate that the MPPC provides a energy resolution for PET application which is competitive with that of PMT with the advantage of an easy direct coupling to a small crystal.

Due to its limited number of pixels the MPPC has a non-linear response. The effect of the non-linearity of MPPC on

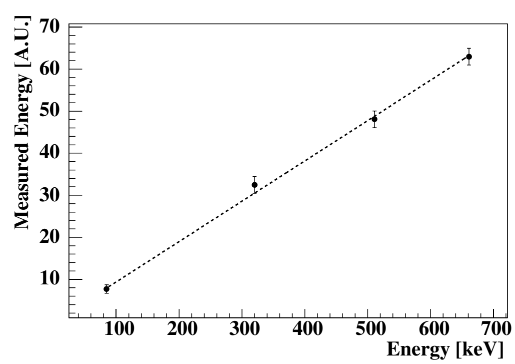


Fig. 4. Response of a MPPC crystal system to γ sources of various energy: Ba^{127}, and Na^{22}, Cs^{137}.

the 511 keV signal is checked in Fig. 4, where the response of the system to photons from Ba^{133}, Cs^{137} is measured to check the linearity in the energy range of interest. Within the uncertainty of the measurement no non-linearity is observed. This is a combined effect of the fast recovery time of MPPC, $\sim$4 ns, and the slow emission of the crystals, $\sim$120 ns FWHM.

The same setup has been used for measurements of time resolution of the system using a 4-GHz True-Analog Bandwidth oscilloscope (TDS7404B by Tektronix). The two signals from the detector elements are directly sent to the inputs of the oscilloscope, where they are discriminated if above a tunable threshold. This threshold is kept as low as possible, just above the oscilloscope electronics background $\sim$ 4 mV (or $\sim$13 pixels). After discrimination a logic coincidence is formed

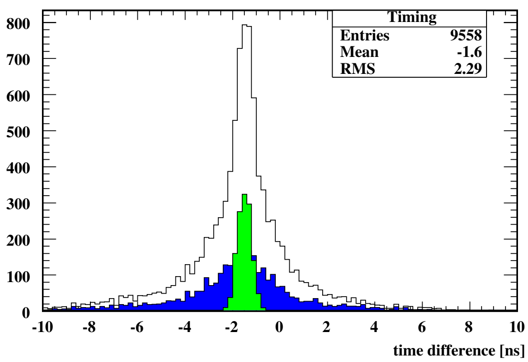


Fig. 5. Time difference between the two signals from MPPC 3600 pixels coupled to LSO crystals obtained detecting coincidences between the two 511 keV photons from a ^{22}Na source. The light gray histogram is a subsample of the total obtained with a energy cut of $\pm 1\sigma$ around the photo-electric peak.

and used as trigger to store the waveforms of the signals. In acquisition mode the oscilloscope provides a sampling rate of 20 GS/s, resulting in an intrinsic time resolution of 50 ps. The acquisition rate is quite poor ($\sim$ 1 Hz), but storing the waveforms allows large flexibility in the subsequent studies.
The analysis of the waveforms is then performed offline. An energy cut is applied to each of the signals to reject Compton events. This cut rejects in average 10-15% of the total events, but significantly improves the time resolution. Fig. 5 illustrates the improvement of time resolution obtained when applying an energy cut of $\pm 1\sigma$ around the photo-electric peak value.
The time resolution is defined as the FWHM of the time difference at a give threshold between the two signals generated by the detection of two back to back scattered photons. Two methods have been tested useing either a fix-amplitude or a constant-fraction threshold. The methods yield comparable time resolutions. Results are presented in Fig. 6 as a function of the fix-amplitude threshold in pixels. The improvement in the observed time resolution due to the energy cut is almost a factor of 2. The best time resolution achieved with the lowest threshold is 650 ps FWHM. This result is limited by the noise of the readout and data acquisition system which does not allow to trigger at the single pixel level. A significant improvement is expected if one can lower the threshold further. It is quoted that a time resolution of 500 ps (FWHM) would be enough to double the signal to background ratio of the reconstructed image [8]. A similar value is shown for LSO crystal read out by a photomultiplier tube [6]. The measurements with MPPC show that the time resolution is at least close to what is needed for PET application; a further

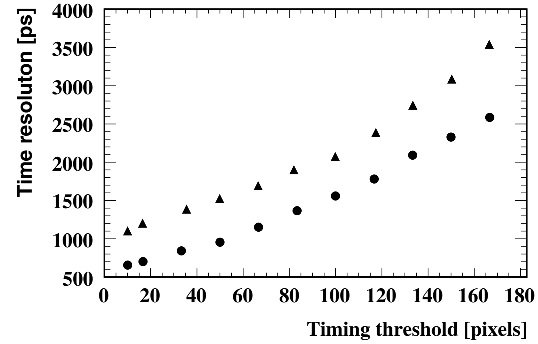


Fig. 6. Time resolution for a system of two $3 \times 3 \times 15$ mm^3 LSO crystals coupled to 3×3 mm^2 MPPC 3600 pixels using fix-amplitude threshold. Results obtained with (points) and without (triangles) energy cut are shown.

optimization of the test setup is planed and may yield results competitive to traditional PET systems.

A. Small size prototype

The next step after establishing a single channel readout scheme is the construction of a small size prototype consisting of two matrices of 6x6 crystals each, for a total of 72 channels with individual readout. The purposes of such prototypes are manifold. On one side the channel-to-channel homogeneity and reproducibility of the concept has to be tested. A solution for the necessary multi-channel readout has to be found which is scalable to a larger prototype for commercial use. The calibration and monitoring requirements of a multi-channel detector need to be addressed as well as the stability of operation. On the other side, a small prototype will give the opportunity to test the improvement of time resolution in the 2D and maybe 3D spacial reconstruction of a non-point-like radioactive source.

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