IL NUOVO CIMENTO Vol. 34 C, N. 5 Settembre-Ottobre 2011
DOI 10.1393/ncc/i2011-10925-7

Communications: SIF Congress 2010

Feasibility study of a ToF PET prototype with MRPCs

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(ricevuto il 31 Dicembre 2010; approvato il 2 Marzo 2011; pubblicato online il 2 Agosto 2011)

Summary. — Multigap Resistive Plate Counters (MRPCs) were used to investigate their time resolution to 511 keV gamma rays in view of possible biomedical applications such as Time-of-Flight Positron Emission Tomography (ToF-PET). Using a ^{22}Na source the Time-of-Flight information of annihilation gamma rays has been measured to calculate the MRPC time resolution to 511 keV photons pairs and resulted to be about 145 ps.

PACS 87.57.Q- – Computed tomography.
PACS 87.57.uk – Positron emission tomography (PET).

1. – Introduction

Positron Emission Tomography (PET) is one of the most powerful *imaging methabolic* techniques that gives 2D or 3D functional images of a living body both for clinical purposes and scientific studies.

It is based on the injection of a β^+ radio emitting tracer into the living body and on the detection and recording of the emitted radiation. The emitted positron will travel in the body tissue surrounding the emitting point, losing energy as it scatters along the path, before annihilating with an electron and producing two photons. To a first approximation the positron can be considered at rest, so the energy and momentum conservation law implies that photons must be collinear and their energy must be 511 keV.

In a PET scanner a ring of detectors collects these photons pairs. For each coincidence an ideal line of response (LOR) can be drawn throughout the tomograph and, from the total of them, by means of image reconstruction algorithms, an activity map of the injected radionuclides can be obtained.

Hence, the goal of the PET technique is to detect the annihilation photons and to reconstruct the tomographic image. To increase the signal-to-noise ratio and to improve the image quality, the ToF information of the two photons can be used [1]. To exploit

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this feature, the use of fast detectors with a very good time resolution (less than 1 ns) is mandatory.

The ToF-PET idea is not new but it has been proposed since the early eighties [2], and currently some ToF-PETs [3] have been developed using conventional detectors such as LYSO and $LaBr_3$.

The idea of using MRPC detectors in a ToF-PET has been proposed quite recently [4, 5], and is based on the fact that these gaseous detectors have affordable prices and good time resolution.

2. – Time of Flight

The idea of a Time-of-Flight PET was born with the development of fast crystals detectors such BaF_2 or CsF, now replaced by crystals with a higher light output such as LYSO, LSO and $LaBr_3$.

Time-of-Flight information refers to the possibility of measuring the time arrival difference of the two coincidence photons.

It is possible to understand why such information is so important. As previously said in a PET tomograph, for every coincidence, the computing algorithms assign a Line of Response (LOR) and the annihilation point can lie anywhere along this line. Using ToF information it is possible to reduce the uncertainty Δx on the event position along the LOR with respect to the tomograph axis (provided that $\Delta x \ll D$, where D is the dimension of the object to be imaged), according to the relation [3]:

$$\Delta x = \frac{c\Delta t}{2}\,, \tag{1}$$

where Δt is the time resolution which depends on the particular detector used, while c is the light velocity. The Time-of-Flight information reduces the uncertainty in the reconstruction and the noise in the final image. This causes an improvement in the signal-to-noise ratio (SNR), that corresponds to a sensitivity increase. The sensitivity is defined as the number of the events detected by the apparatus per unit of radioactive concentration into the scanned object. The gain in the signal-to-noise ratio (S/N_{gain}) of a TOF-PET with respect to a standard PET can be calculated to be [6]:

$$\frac{S}{N_{gain}} = \frac{S/N_{TOF}}{S/N_{PET}} = \left(\frac{\Delta x^2}{D^2}\right)^{-1/4} = \sqrt{\frac{2D}{c\Delta t}}\,. \tag{2}$$

The image quality is heavily affected by the sensitivity, because it determines how many data will be avaiable for a fixed amount of tracer. Since the dose given to a patient cannot exceed a fixed value, it means that a low-sensitivity scanner will produce images with a low S/N ratio.

Hence the gain in S/N ratio can be translated into a gain in sensitivity: it is possible to demonstrate [6, 7] that the gain in sensitivity is equal to:

$$G_{sensitivity} = \alpha\frac{2D}{c\Delta t}\,, \tag{3}$$

where α is a coefficient related to the image reconstruction algorithm.

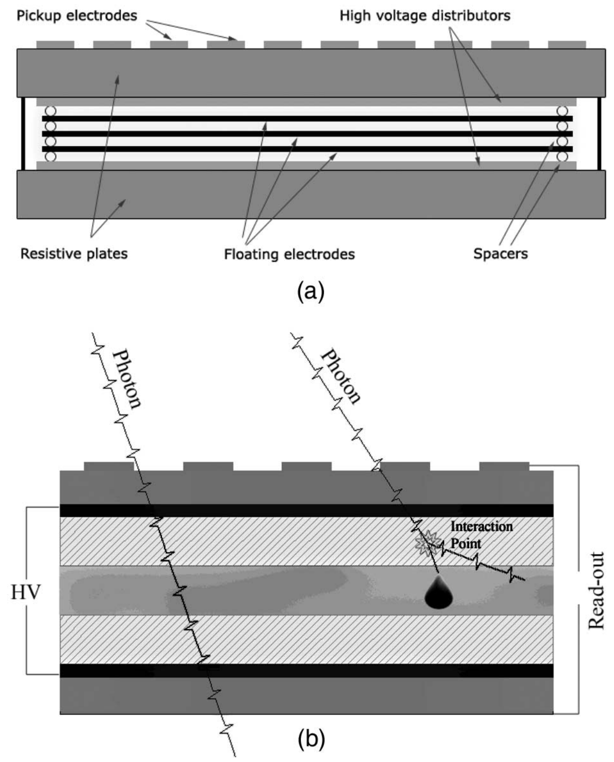


Fig. 1. – (a) Schematic layout of a MRPC with four gaps; (b) photon detection in a MRPC with a single gap. For the energies we are interested in ($\approx 500\,\text{keV}$) a photon interaction (Compton or photoelectric) into a resistive layer produces an electron. If the extracted electron has enough energy it can reach the gap and ionize the gas, producing an avalanche.

The gain therefore increases with the dimension D of the scanned object and the improvement of time resolution.

Our group is studying the possibility of using Multigap Resistive Plate Counters (MRPCs) in ToF-PET applications.

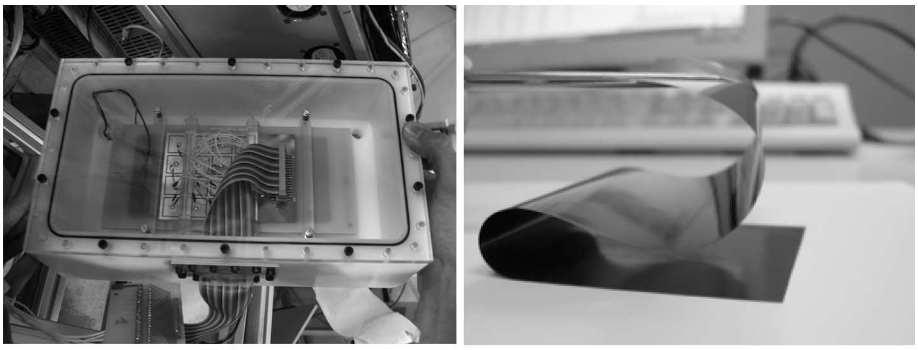
3. – MRPC and gamma radiation

The Multigap Resistive Plate Counters (MRPCs) are gaseous devices used for charged-particles detection in high-energy physics. They have been proposed in 1996 [8,9] and can reach a time resolution of 50 ps. A MRPC consists of a stack of resistive planes (made of glass) equally separated by insulating calibrated spacers; the outer plates are connected with the electrodes, while the inner layers are kept electrically floating (fig. 1).

A high voltage is applied through a thin layer of semiconducting material. Gaps (from 200 to 300 μm wide) are filled with an appropriate gas mixture.

These detectors are based on the physical principle of gas ionization by means of charged particles.

Therefore, in case of gamma detection, a preliminary conversion (with electron extraction through Compton, photoelectric effect or pair production) into the resistive layers



(a) (b)

Fig. 2. – (a) The MRPC prototype; (b) the semiresistive polymeric film that distributes the high voltage.

is needed, since the direct ionization into the gas is very unlikely. If the produced photo-electrons have enough energy to reach the glass/gas interface, they can eventually ionize the gas (primary ionization) starting the development of an avalanche. The motion of this charge cloud into the gas gap induces a current signal on the external pick-up electrodes. Due to all these processes it is easy to expect a low gamma efficiency. However it is possible to modify it by increasing the number of resistive layers.

4. – The MRPC prototype

The basic idea of our project is to develop a modular PET prototype with MRPC detectors. The detectors are placed in a teflon box (with external dimension $335 \times 195 \times 100\,\text{mm}^3$). A gas mixture (at 15 l/h) composed by iC_4H_{10} (5%), SF_6 (10%) and $C_2H_2F_4$ (85%) was used.

The multigaps are made of a stack of 5 glasses $200 \times 100\,\text{mm}^2$ area and $400\,\mu$m thickness, separated by a nylon wire, $250\,\mu$m diameter, that defines 4 gaps (fig. 2).

Two thin semiresistive films ($70\,\mu$m thickness and surface resistivity $\sim$ 20–30 MΩ), applied on the external surface of the first and the last glass, define the HV and ground planes. The glass stacks are closed externally by two fiberglass plates (Printed Circuit Board—$220 \times 100\,\text{mm}^2$). The glasses are manually aligned during assembling and are mantained in position by applying a compression force to the stack, obtained using plexiglass bars and kept under stress with springs.

The MRPC modules are designed to mantain a high flexibility in terms of future modifications.

The signals were read out by 16 pads ($16 \times 16\,\text{mm}^2$) pick-up electrodes and sent to a *front-end* electronics for the preamplification stage.

5. – Experimental setups and results

We carried out measurements of MRPC time resolution to 511 keV photons with two different setups.

5˙1. *Preliminary measurement with one MRPC and scintillators.* – [10] A ^{22}Na source (fig. 3) was located in front of a MRPC. A pair of plastic scintillators placed at a distance

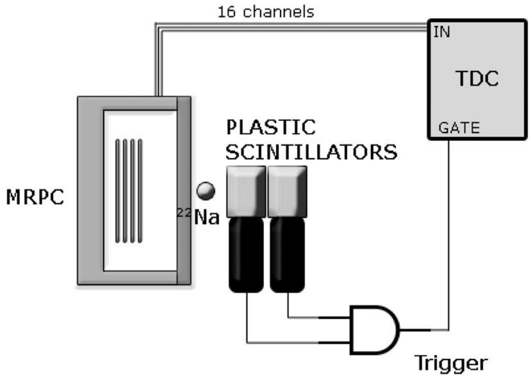


Fig. 3. – Experimental setup for the measurement with one MRPC and two plastic scintillators: signals from the 16 pads fed a TDC module. A signal from the *AND* of the scintillators defined the trigger to the TDC.

of 10 cm defined the trigger. Their coincidence was sent to the input trigger of a CAEN $V1290A$ TDC and signals from any of the 16 readout pads were looked for into the trigger window gate.

Figure 4 shows the distribution of the variable $\Delta t = t_{ch} - t_{tr}$, where t_{ch} is the *time stamp* of the first hit in the time window opened by the trigger at the instant t_{tr}.

A characteristic delay is associated to each channel, so the values are distributed in a wide gap (almost 25 ns): in this window three noticeable peaks appear, corresponding to the delays of each group of channels. The first peak corresponds to the fastest channels; performing a Gaussian fit on this peak we obtained a value of $\sigma \approx 713$ ps. By subtracting the contribution of the electronics (70 ps) and that of the scintillators (≈ 550 ps) the MRPC time resolution was calculated to be $\sigma_\gamma \approx 450$ ps. Even if this value is lower compared to the most common crystals (700 ps) it does not represent the best performance of a MRPC to gammas, since it also depends on the experimental setup [11, 12].

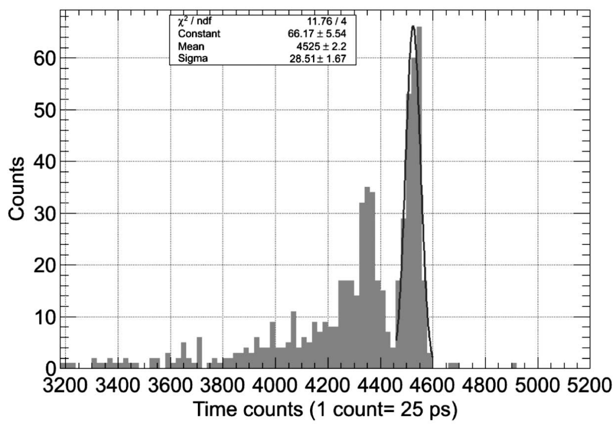


Fig. 4. – First time resolution measurement: data represent the time difference between one readout pad and the trigger while multiple peaks are associated with the characteristic delays of each channel. The higher peak represents the group of the fastest channels.

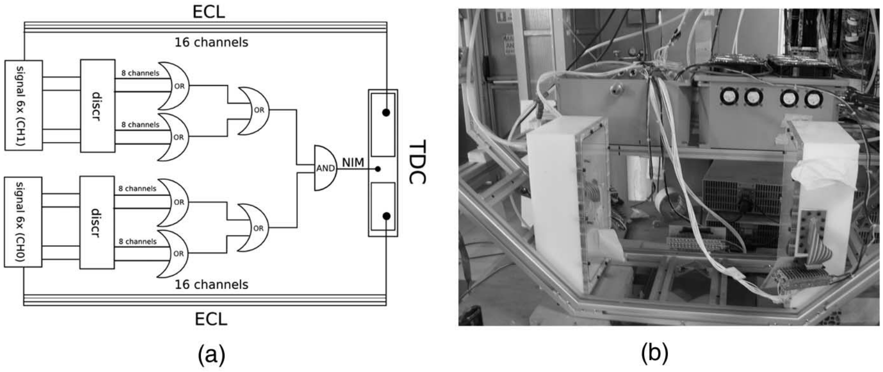


Fig. 5. – Acquisition chain scheme (a) and experimental setup (b) for the new measurement.

5˙2. *Measurement with two MRPCs.* – The previous measurement was performed without a time correction map due to the relative delays associated to each channel and with two auxiliary scintillators with a poor time resolution. To refine the time resolution measurements it is necessary to change the setup. In this new measurement (fig. 5) a pair of MRPCs was placed at a distance of 35 cm and a ^{22}Na source was positioned in front of one of them, 5 cm from the glass stack of one detector and 40 cm away from the other. The position of the source (*i.e.* not equidistant from the two detectors) allowed to introduce a chronological order in the expected sequence of the hits.

Any coincidence signal between the two MRPCs defined a trigger signal sent to the CAEN V12906 TDC. As in the previous measurement, the *time stamp* of each event and the corresponding channels were recorded within the time window defined by the trigger. During the analysis, all the possible LORs associated to the hits belonging to each detector were reconstructed. In fig. 6 the time difference Δt associated to the fastest LORs is plotted.

It shows a peak superimposed to a wider distribution that corresponds to the gamma scattering on the MRPC surrounding material. The signal peak and the scattering

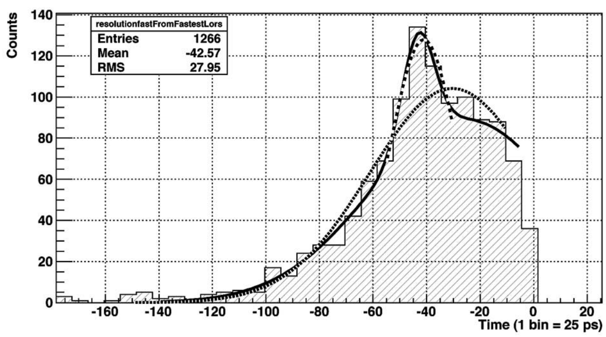


Fig. 6. – Time distribution of the fastest LORs. The lines correspond to the Gaussian fits of the background (dotted line) and the peak (dashed line), while the the continuous line corresponds to their sum.

distribution were modeled with two Gaussians and a fit was made. The single Gaussians and their sum have been superimposed.

A peak value at bin −43.1 (1 bin = 25 ps) was found that corresponds to a difference of photons time of flight of 1.08 ns. This value, multiplied by the light velocity, corresponds to about 35 cm, the distance between the two detectors. The observed time resolution ($\sigma_{oss} = 150\,\text{ps}$) includes the physics of the two detectors (σ_{MRPC}), the contribution of the electronics and channels synchronization ($\sigma_{el\&ch} \approx 20\,\text{ps}$). This can be written as

$$\sigma_{oss}^2 = \sigma_{MRPC}^2 + 2\sigma_{el\&ch}^2. \tag{4}$$

Subtracting these contributions to the observed sigma we obtain $\sigma_{MRPC} \simeq 145\,\text{ps}$. We notice that this value corresponds to the time resolution for a couple of photons and hence contains the time contribution of both detectors (the time resolution for a single MRPC can be calculated to be $\frac{145}{\sqrt{2}} \simeq 103\,\text{ps}$). This value confirms that MRPCs have very good timing properties not only for charged particles but also in photons detection.

This value is lower than that of the commercial chrystals (FWHM ≈ 500 ps) and close to that of $LaBr_3$ (FWHM ≈ 300 ps)(1).

The results are very promising and suggest that MRPCs can be attractive candidates for the development of TOF-PET tomographs. However, our measured value does still not represent the achievable lower limit.

6. – Conclusions

The theoretical lower limit to 511 keV photons pair time resolution, achievable with two Multigap Resistive Plate Counters (MRPCs), has been investigated through a simulation.

The second experimental setup used for the measurement has been simulated through a full Geant4 simulation: detectors position, surrounding materials, kind of source, number of glass electrodes have been accurately reproduced. Both gamma propagation and electron scattering inside each detector have been studied, neglecting any contribution from the avalanches development in the gas gaps. We found that the lower limit to the time resolution on photons pairs weakly depends on chamber distance, applied high voltage or kind of source. However it is strongly influenced by the source position and by the number of resistive electrodes. This contribution (of the order of about 70 ps) has to be added in quadrature to that due to the avalanche dynamics (50 ps). We consider the resulting value of 84 ps the achievable theoretical lower limit.

Since we have measured $\sigma \sim 103\,\text{ps}$ (for one MRPC), this is an indication that we can still ameliorate the setup and further improvements have to be expected.

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(1) Where FWHM = 2.35 σ.

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