Development of a TOF-PET scanner based on Multi-gap Resistive Plate Chambers

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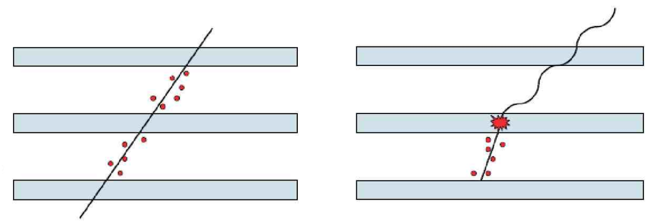
***Abstract*—Based on a benchmarked sensitivity simulation study, a Multigap Resistive Plate Chamber (MRPC) PET scanner has been designed at the TERA foundation. The MRPC detector is based on a cheap production technology and makes use of a limited number of readout channels. The time of flight capability of such a gaseous detector would give a huge improvement on the signal to noise ratio of the reconstructed image, by constraining the lines of response (LOR) drastically. The main application foreseen is the monitoring of the dose deposition during hadron-therapy oncological treatment.This project is partly supported by the European Project ENVISION Grant Agreement No. 241851. An R&D phase has started to develop a prof of concept of this technology. A small dual head detector ($10 \times 7 \times 0.4\ cm^3$) has been produced and is under commissioning. Here are reported the latest results off this development.**

I. Introduction

Nowadays positon emission tomography (PET) is one of the most common technique used to diagnose cancer by injecting FDG tracer to the patient. Since 2008, PET is also foreseen as a modality for quality assurance in hadrontherapy treatment allowing to follow the dose deposition during irradiation of the patient by means of the beam-induced $\beta+$ activity [1]. Up to now, most of the commercially available PET scanners are based on crystal technology. Addition of a time-of-flight (TOF) capability to the scanner would enhance the image reconstruction, by imposing a constraint along the lines of response. The TERA foundation in the framework of the European project ENVISION aims to develop a TOF-PET scanner based on gaseous detectors to overcome these difficulties. The technology under development is based on multi gap resistive plate chambers (MRPC) which has been implemented in CERN high energy physics experiments with a time resolution less than $50\ ps$ (ALICE TOF-LHC) [2]. Compared to charged particle detection, the use of such a device to detect $511\ keV$ gammas emitted by $\beta+$ annihilation is challenging. Indeed as the gamma Compton conversion take place in the glass plates, the charge multiplication will only occur in one of the gaps (Figure:1).

II. MRPC design

The multi-gap resistive plate chamber (MRPC) is composed of five glass plates separated by $300\ \mu m$ gaps (Figure:2.a). The externals plates are coated with a resistive polyimide layer to supply the high voltage which polarizes the chamber. The electric field in the gap is on the order of $10\ kV/mm$. Pure gaseous freon (R134A) is circulated inside these gaps to operate with charge multiplication by cascaded ionization. Those charges are being read out differentially by copper strips surrounding the MRPC ($4\ mm$ pitch). As explained before, the $511\ keV$ gamma needs first to be converted in the glass plate by Compton scattering and second for an energetic electron to enter into the gas volume, leading to avalanche multiplication. In practice, the conversion efficiency is rather low, which is why we take advantage of the multi-gap structure to obtain 0.4% efficiency over the whole chamber thickness. Then, for a PET application, we have simulated heads of 60 to 120 MRPCs in order to obtain a sensitivity close our benchmark commercial scanners. The material budget of the MRPC has been optimized in order to improve the efficiency of the stacked MRPC scanner head.



(a) (b)

Fig. 1. MRPC detection of: (a) charged particles, (b) $511\ keV$ gamma.

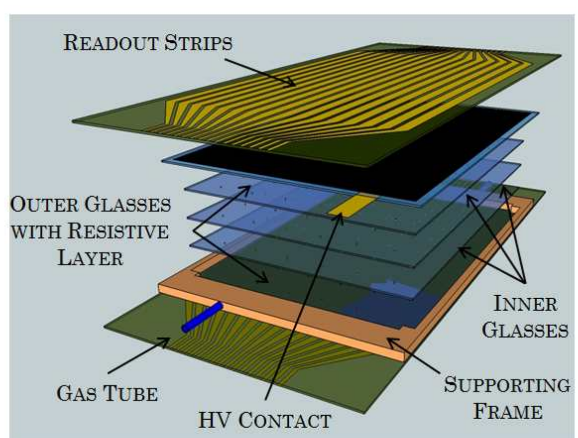


Fig. 2. Schematic view of the multi gap MRPC .

III. ELECTRONIC READOUT

A custom differential readout board have been designed and implemented at both ends of the strips. This board is based on the NINO chip, a 8 channel fast amplifier-discriminator developed at CERN for high energy physics [4]. The outputs produce LVDS pulses, and their width corresponds to the time over threshold. The rising edge obtained is close to 1 ns. All channels are individually connected to the latched entries of an FPGA to determine which channel is fired (Figure:3.b). Simultaneously, the time measurement is performed between the Fast-OR outputs using a 3.5GHz bandwidth oscilloscope. Both kind of data are merged into a dedicated Labview acquisition to be saved on disk an analyzed.

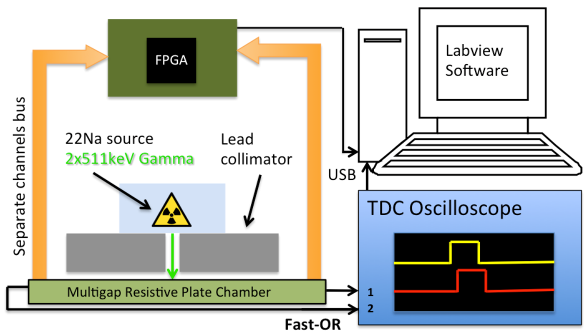


Fig. 3. Readout chain scheme for one MRPC.

IV. TIME RESOLUTION MEASUREMENTS

The real improvement of the MRPC PET scanner should come from the ability of doing time-of-flight with an unprecedented resolution. However, obtaining a resolution less than 50 pss like the previously cited CERN experiment is not straight forward [3]. Because the avalanche only occurs in one gap in the case of gamma detection, four times less charge is produced in the chamber. Nevertheless the multiplication process occurs at the same speed, meaning that a very good time resolution can still be obtained. Special care has been taken when designing the readout electronic board to maximize the signal-to-noise ratio. One should know that the time resolution which can be obtained on a fully instrumented detector is the quadratic sum of three contributing factors, namely: the charge multiplication process stability, the amplifier and discriminator resolution, and the time to digital conversion accuracy (TDC).

$$\sigma = \sqrt{\sigma_{MRPC}^2 + \sigma_{Amplifier}^2 + \sigma_{TDC}^2}$$

A. Position-time resolution

The position along the strip is obtained by measuring the propagation delay. This has the advantage of allowing to increase the sensitive area simply by scaling the strip and chamber lengths using the same number of channels. As the input capacitance of each preamplifier could be slightly different, a time offset must be added on each channel to align them in time (i.e. space). This correction offset is obtained by calibrating each detector thanks to our slit-collimated ^{22}Na gamma source, the slit width is 1 mm (Figure:4-5).

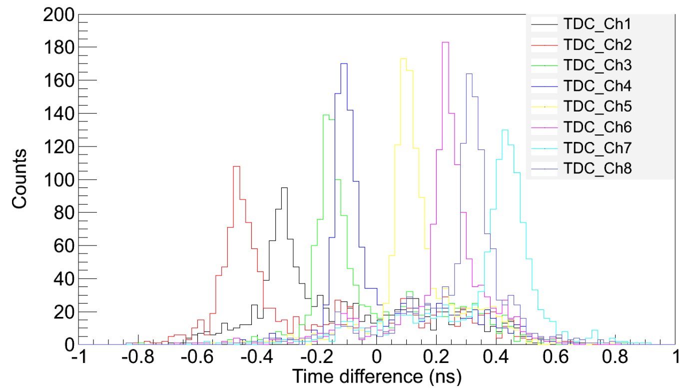


Fig. 4. Time difference distributions before calibration.

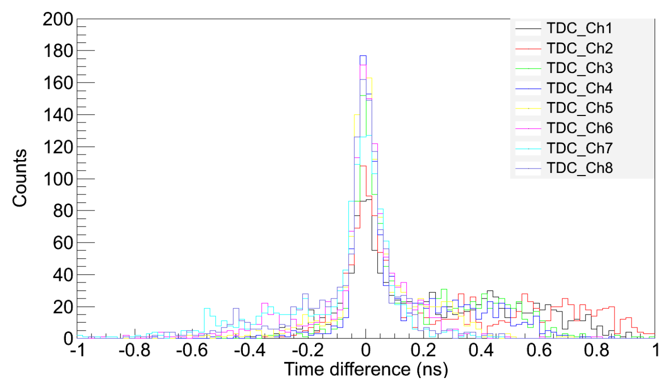


Fig. 5. Time difference obtained after offset correction.

The global time resolution obtained across eight strips after this calibration procedure has been measured to be $\sigma = 38\ ps$ at different positions. This measurement corresponds to the contribution of the two factors: $\sigma_{Amplifier}$ and σ_{TDC} in the previous equation.

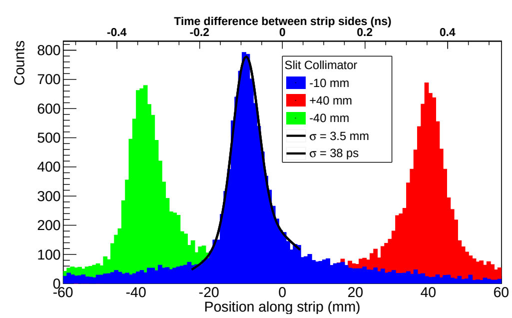


Fig. 6. Position resolution along the strip obtained by timing.

In terms of position along the strip, considering a signal speed of 225 mm/ns, we end up with a resolution

$\sigma_{along\ strips} = 3.5\ mm$ (Figure:6). The position resolution across the detector is determined by the strips width ($4\ mm$) the resolution is $\sigma_{across\ strips} = 4/\sqrt{12} = 1.15\ mm$. You can appreciate the spatial homogeneity that we obtained on the reconstructed image of the slit collimated source (Figure:7).

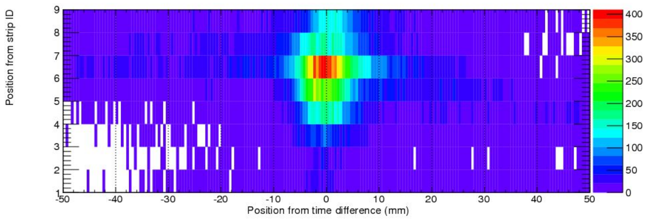


Fig. 7. Image reconstruction of the slit collimated source (plot area: $32 \times 100 mm^2$).

B. *Time of flight resolution*

The previous setup was extended to host a second detector in order to measure the time of flight capability of the MRPC detector (Figure:8). The use of the slit allow to fire only a limited area off the detectors and thus avoid to be subject to misleading position reconstruction along the strip for this measurement.

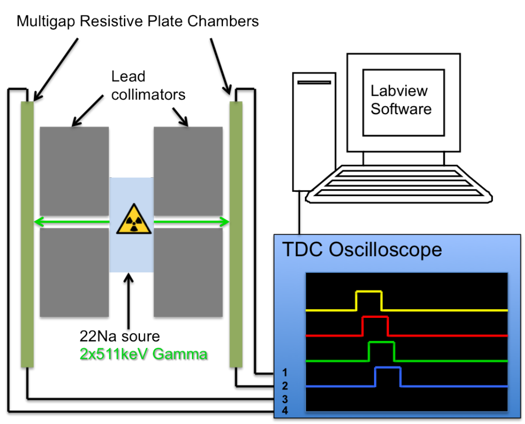


Fig. 8. Time of flight measurement setup.

The gaussian fit of the time of flight distributions give a resolution $\sigma_{TOF} = 240\ ps$ (Figure:8.b). Which means that each of the two MRPC accounts for $\sigma = 240/\sqrt{2} = 170\ ps$. If we refer to the detector time resolution equation introduced before, we can see that the main contribution degrading the time of flight resolution comes from the MRPC pulse formation. Indeed the position-time calibration has shown that the electronics only contribute by $\sigma = 38\ ps$. One explanation could be the following: as this previous measurement (position-time) was done on both ends of the strips the pulse widths out of the NINO were almost the same. In the case of the time of flight measurement both MRPC pulse width can be different, this point out the need of slewing rate correction. Establishing this correction is not straight forward, and not done yet. This is the next step of our development together with optimizing the MRPC chambers for better stability. Indeed, experience as proven that the grounding scheme and impedance matching into the detector plays an important role as soon as you start to deal with pico second range measurement.

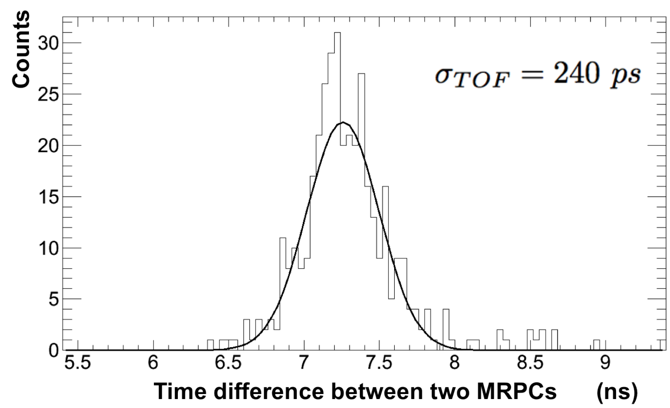


Fig. 9. Time of flight distribution between a pair of MRPCs (only one strip connected on each).

V. Conclusion

After a preliminary calibration procedure, the spatial resolution along and across the strips of the MRPC have been demonstrated to be quite accurate. As you may know, spatial resolution is a key aspect in order to get an accurate PET image reconstruction. In addition, a fair time of flight resolution has been obtained with a pair of those detectors. This time of flight capability should give a huge improvement on the S/N ratio that we can obtain out of such a MRPC-PET scanner. Those first results are quite encouraging, specially knowing that they can be improved soon by time-walk correction. As a second result from this development, a new MRPC version integrating some ideas of improvement is actually under fabrication process. We hope to present soon the results of their commissioning.

References

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