MPPC Response Simulation and High Speed Readout Optimization

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***Abstract*–A Monte-Carlo simulation of the Multi-Pixel Photon Counter (MPPC) response has been developed by the T2K collaboration. Its purpose is to understand how MPPCs affect the overall detector performances. The same MPPCs can be used in numerous applications including Positron Emission Tomography. The performances of MPPCs coupled to LYSO crystals are investigated by comparing data to simulations. The measured timing resolution is well reproduced by simulations.**

I. Introduction

The T2K near detector [1] utilizes about 60,000 Multi-Pixel Photon Counters (MPPCs) [2]. MPPCs are coupled to 1 mm diameter wavelength shifting (WLS) fibers. The WLS fibers are inserted into plastic scintillator bars. The fibers absorb the scintillation photons produced by charged particles going through the scintillator bars and reemit photons at a different wavelength. A fraction of the reemitted photons travel along the fiber to the MPPCs. T2K is the first physics experiment to use MPPCs. Extensive test were performed in order to assess whether or not the MPPC behavior affect the overall detector performances. A Monte-Carlo simulation code was written to account for all the known processes that have been identified. Such simulation program is a very useful tool to predict the detector performances within T2K but also for other applications.

It is of interest to investigate the MPPC response when coupled to LSO/LYSO crystals. Indeed, LSO/LYSO is a very good crystal for Positron Emission Tomography, with a short attenuation length (12 mm at 511 keV), a large light yield (32 photons/keV) and relatively fast decay constant (~41 ns) [3]. Furthermore, the LSO/LYSO emission wavelength corresponds to the peak of the MPPC photo-detection efficiency. MPPCs being insensitive to magnetic field are a very promising photo-sensor to equip PET scanners that can work within Magnetic Resonance Imaging (MRI) systems. Understanding the pros and cons of using MPPCs for PET applications is the purpose of these proceedings. We will use T2K Monte Carlo simulations to understand how to optimize a system based on LSO/LYSO coupled to MPPCs.

II. Using T2K MPPC for PET Application

Hamamatsu photonics produced a set of MPPCs specifically for the T2K experiment. Their active area is 1.3 by 1.3 mm^2. A lead occupies a corner of 150 by 150 μm^2. MPPCs are an array of diodes, segmented into pixel, 50 by 50 μm^2 in this case. The active area is segmented into an array of 667 pixels. Every diode operates in Geiger mode. Free carriers created in the diode depleted region are sufficiently accelerated to produce additional carriers by impact ionization. This phenomenon leads to an avalanche, i.e the rapid generation of a large number of free carriers, which stops only when the voltage across the diode falls below a typical voltage called breakdown voltage. The breakdown voltage is the limit above which avalanches occur. A resistor in series with every diode is used to quench the avalanche. The voltage drop due to current flowing through the resistor brings the voltage across the diode down to the breakdown voltage.

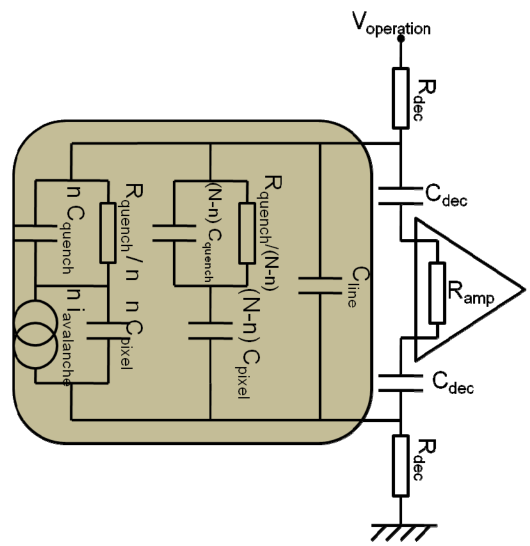

Fig. 1. Schematic of a MPPC and associated electronics. The MPPC is enclosed in the brown box. The model is inspired from [4].

In the T2K experiment, MPPCs are used to detect charged particles, which produce about 30 photo-electrons (PE). While 30 PEs is large enough to ensure 100% detection efficiency, it is too small to achieve sub-nanosecond timing or energy resolution better than 20%. On the other hand, PET applications require excellent timing and energy resolution, which can be achieved thanks to the large light yield of the LSO/LYSO crystals. In order to investigate, the performances of T2K MPPC for PET applications, we built a specific test setup with a new set of electronics.

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Fig. 2. Picture of the test setup. The source was inserted in the central slot. The LYSO crystal were enclosed in Teflon. The MPPC are connected directly to the amplifier boards visible on either side of the picture.

A schematic of the MPPC and associated electronics is shown in Fig 1. A LTC6400-26 differential high speed amplifier was used. It provides a time 30 gain with a 50 Ω input (R_{amp}) impedance. The output of the amplifier was connected directly to a Lecroy WavePro 7 Zi (4GHz, 20 GSample/sec) oscilloscope that allowed recording each waveform. The test setup is shown in Fig 2. Two LYSO crystals from Saint Gobain [5] were coupled to MPPCs. The crystal dimension was 1.5×1.5×30 mm^3, which arguably is too long for achieving optimum performances. The MPPCs were operated about 150 mV above Hamamatsu nominal operating voltage (providing a gain of 7.5 10^5).

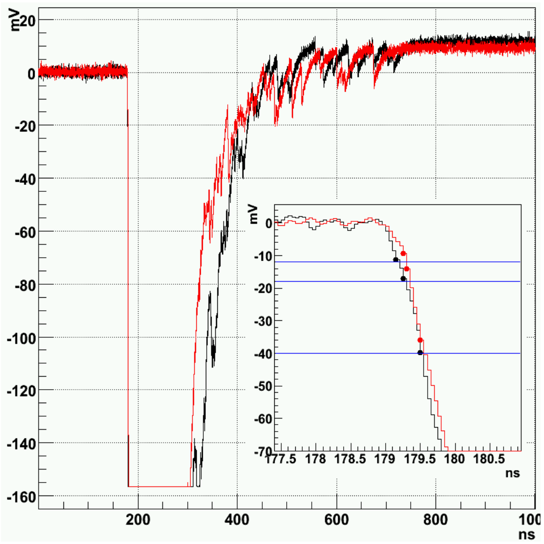


Fig. 3. Typical waveform recorded when both pulse height fall within the 511 keV window. The inset shows a zoom along the rising edge of the pulse. The lines show the location of the thresholds used to estimate the time, -40 mV, -18 mV and -12 mV from bottom to top.

A typical event corresponding to two photons depositing their full 511 keV energy is shown in Fig 3. The saturation of the waveform is due to the oscilloscope limited dynamic range. The energy is estimated by calculating the over-shoot level between 800 and 100 ns. The energy resolution achieved this way is 18% Full Width Half Maximum (FWHM). The single channel timing resolution is 365 ps, 398 ps and 482 ps FWHM, for the -12 mV (~2PE), -18 mV (~3 PE) and -40 mV (>6PE) thresholds respectively. The timing resolution achieved with this setup is not as good as results reported by other groups because of the smaller number of detected photons, which is estimated to be 700. The T2K MPPC response simulation code can be used to demonstrate this point.

III. MPPC Response Simulation

MPPCs have a number of features that can potentially affect the overall detector response. Most of the phenomena affecting the MPPC response are driven by the over-voltage. The over-voltage is the difference between the operating voltage set by the user across the MPPC diodes and the breakdown voltage. The features accounted for in T2K Monte Carlo code are as follow:

- Gain. The gain dependence with over-voltage is C ΔV, with C the diode capacitance and ΔV the over-voltage. The gain fluctuations are modeled by a single parameter σ_G which scales quadratically with the number of pixel avalanching. σ_G/G as found to be roughly independent of ΔV.
- Photo-detection efficiency. It is the probability that a photon hitting the MPPC generates a free carrier in the depleted region. The PDE dependence with over-voltage is parameterized by a quadratic function, which is more or less linear below 1.5Vover-voltage and then saturates.
- Dark noise rate. It is the rate at which thermal free carrier are generated in the diodes. The dark noise rate dependence with over-voltage is parameterized by a linear function. Dark noise is the only quantity that shows strong temperature dependence at constant over-voltage.
- Cross-talk. It is the probability that an avalanche in one pixel triggers an avalanche in a neighboring pixel. It increases quadratically with over-voltage.
- After-pulsing. When an avalanche occurs in a pixel, there is a certain probability that some free carriers become trapped by impurities. They will be released at a later time potentially triggering a new avalanche. This phenomenon is called after-pulsing and can be measured as described in [6]. Fig 4 shows after-pulsing measured for 4 different T2K MPPCs. Two different after-pulsing time constants were found which suggests that there are two different types of impurity with two different band gaps. The after-pulsing probability increases quadratically with over-voltage.
- Recovery. After an avalanche, the voltage across the diode drops down to the breakdown voltage. The voltage recovers back to the operating voltage with a time constant given by the pixel capacitance and quenching resistor. It is 13 ns for T2K MPPCs. Each time an avalanche occurs within a MPPC, the voltage of all the pixels drop by a small amount because the avalanching pixel recover by drawing charge from the other pixels and from the external circuit as well. This phenomenon is only partially simulated in the code that was used in these proceedings.
- Pulse shape. For each avalanche occurring at time t with a gain G, a pulse shape is added. The MPPC pulse shape is calculated running a SPICE simulation based on the schematics shown in Fig 1. The recovery phenomenon can also be studied using the SPICE simulation, but it is difficult to implement when multiple pixels avalanche at different times.
- Electronics noise. Because electronics noise is difficult to simulate accurately, it is extracted from data taken just

below the MPPC breakdown voltage. It is added to the simulated waveforms at the very end.

A key feature of T2K simulation code is that it accounts for recovery. Several processes can generate free carriers: photon hitting the MPPC, dark noise, cross-talk and after-pulsing. However, free carriers do not always generate avalanches. Indeed, at the time a free carrier is released, the given pixel over-voltage may be less than the nominal over-voltage because of a prior avalanche. Taking this into account requires sorting the free carriers in time and generating avalanche or not according to the pixel voltage at the time the free carrier is released. Such algorithm provides a straightforward way to simulate the saturation when a lot of photons hit the MPPC. It also simulates the quenching of after-pulses.

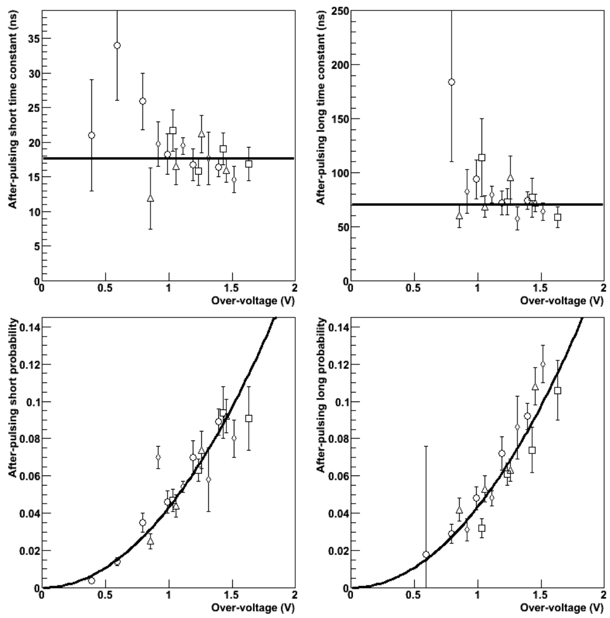


Fig. 4. After-pulse measurement. Each symbol represents a different MPPC. The average time constants are 17 and 70ns. The probabilities follow roughly the same dependence $0.04\times\Delta V^2$.

IV. MPPC And LYSO Simulation

When simulating coupling a MPPC to a LYSO crystal we do not attempt to simulate the scintillation photon propagation. The light hitting the MPPC is assumed to be uniformed. The photons are generated assuming a 41 ns time constant. The rise time is neglected. The number of photons hitting the device is adjusted to match the data. Two typical simulated waveforms were compared to the data in Fig 5 and 6. The data and simulations are in good qualitative agreement. The fine features, such as the pulses on the tail of the waveform do not have to agree as those are random processes. Nevertheless, the shape of the tail is not perfectly reproduced by the simulation relying on the SPICE calculated pulse shape, which can be due to either a too low after-pulsing probability or a discrepancy between the SPICE calculated pulse shape and the data. The empirical function is the one that best match the measured single pixel avalanche pulse shape, however it cannot be justified theoretically.

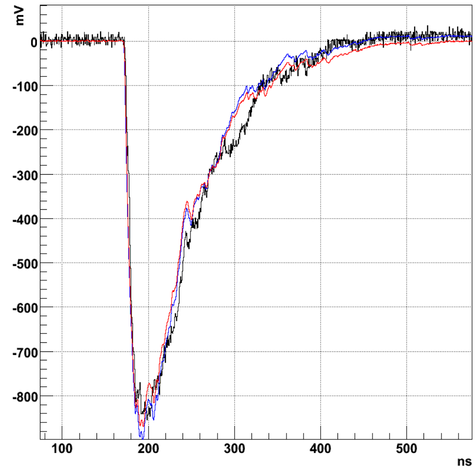
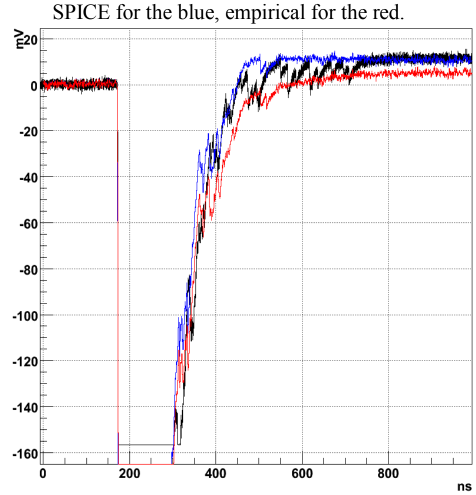
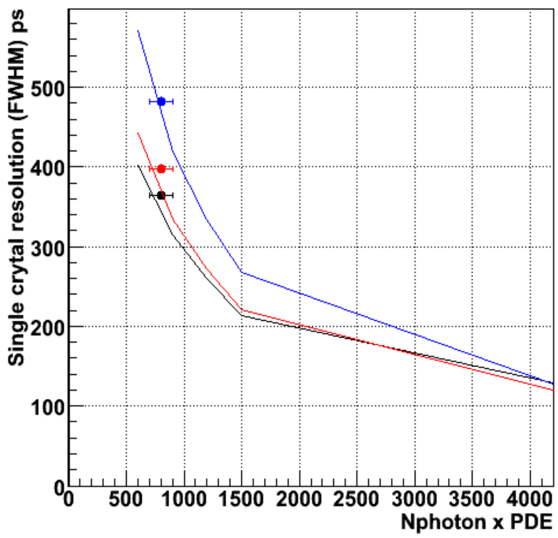


Fig. 5. Comparison of waveform for data (black) and simulations (blue and red). Two different pulse shape were used for the simulated waveforms: SPICE for the blue, empirical for the red.



. Fig. 6. Comparison of waveform for data (black) and simulations (blue and red). Two different pulse shape were used for the simulated waveforms: SPICE for the blue, empirical for the red.

The timing is measured in the simulation exactly as in the data by calculating the time at which the waveform crosses a given threshold. It is not necessary to simulate two channels in the simulation since the “measured” time can be directly compared to the generated time. A comparison between the timing resolution obtained in the data and simulation is shown in Fig 7. The simulated curve is calculated between 0 and 4000 potential photons. The number of potential photons corresponds to the number of photons hitting the MPPC time the photo-detection efficiency. The number of pixel avalanching is potentially very different because of the MPPC saturation, which effectively lowers the photo-detection efficiency. After-pulse and cross-talk have the opposite effect as they add avalanches to the ones triggered by photons.



. Fig. 7. Comparison of the timing resolution obtained in data (points) and simulations (lines). The colors correspond to 3 different thresholds. 40 mV (>6PE): blue, 18 mV (3 PE): red, 12 mV (2 PE): black.

The simulations predict that the timing resolution can be as low as 150 ps FWHM if the number of potential photon is 4000. The Delft University of Technology group has shown as indeed such resolution can be achieved using a 5 mm long LSO crystal coupled to a 3 by 3 mm^2 MPPC [7]. The simulations is also in agreement with the timing resolution obtained by the Siemens group which achieved about 350 ps FWHM for around 1,200 potential photons [8].

V. Conclusion

The T2K collaboration has developed a MPPC response simulation code that can accurately predict the performance of MPPC coupled to LSO/LYSO crystal. It is hence a very useful tool for understanding how to optimize the detector performance.

MPPCs are becoming a mature technology, which fulfill all the requirements for Positron Emission Tomography applications. However, the performances obtained to date have been achieved using readout electronics that can hardly scale because they are too bulky and power hungry. The simulation code provides insight on how to optimize the electronics or alter the MPPC itself to achieve the desired performances while meeting the space and power requirement of the system.

A possible solution may be to decrease the quenching resistor, which increases the peak current and hasten the pixel recovery. The drawback of hastening the pixel recovery is to increase after-pulsing of up to 25%. The advantage is increased effective photo-detection efficiency when the MPPC saturate. Increasing the peak current improves the signal to noise. For example the single avalanche pulse height measured on a 50 Ω termination, such as an oscilloscope go from 0.425 mV with the nominal 150 kΩ quenching resistor to 0.95 mV with a 50 kΩ resistor. However, lowering the quenching resistor down to 50 kΩ may not be possible because the avalanche may no longer be fully quenched.

MPPCs are complex devices with a number of processes that come into play. Assessing which process really matter is difficult because MPPCs are new devices that have not been extensively operated. We have demonstrated that the MPPC response simulation code developed by the T2K collaboration is hence a very useful tool for designing new detector system, and especially detector for Positron Emission Tomography.

Acknowledgment

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