

# Impact of After-pulse, Pixel Crosstalk and Recovery Time in Multi-Pixel Photon Counter<sup>TM</sup> response

M.A.Ward<sup>†</sup>, A.Vacheret<sup>\*</sup>

<sup>†</sup> *Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom*

<sup>\*</sup> *High Energy Physics Group, The Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*

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## Abstract

The photon detection efficiency (PDE) and response linearity of Multi-Pixel Photon Counter (MPPC) is presented at 470 nm and at 500 nm coupled with wavelength shifting fibre. It is found that crosstalk and after-pulse increase artificially the PDE between 4 – 20% as device gain is increased. A empirical fit based on simple statistical assumptions is being developed and allows for some prediction of the fraction of nuisance parameters in the linearity response although experimental conditions are not completely modelled and are in the process of being tuned using a Monte Carlo simulation.

*Key words:* neutrino detector, MPPC, SiPM, Geiger Mode APD

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## 1. Introduction

Tokai to Kamioka (T2K) [1] is a long baseline neutrino experiment aimed at discovering the last oscillation parameter  $\theta_{13}$ . T2K will employ a set of near detectors 280m (ND280) downstream of the target to measure the neutrino beam flux and background interaction cross-sections before oscillation. Most of the sub-systems that composes the near detectors are based on plastic scintillator bars with embedded wavelength shifting (WLS) fibres with a total of 60 000 optical channels. A 1.3 x 1.3 mm Multi-Pixel Photon Counter<sup>TM</sup> (MPPC) developed by Hamamatsu has been chosen to readout the WLS fibres.

## 2. Using MPPC in T2K

The MPPC device is a pixelated array of avalanche photodiodes operated in Geiger mode. Each pixel is connected to a common readout plain via a quenching resistor such that if a pixel undergoes Geiger discharge, the current flow causes a voltage drop across the resistor. The recovery time of the pixel once quenched is governed by a RC constant of the order of 12 ns. More details about MPPC characteristics can be found in [2]. T2K will be the first experiment using the MPPC to read out WLS fibre light and it is therefore crucial to understand accurately the MPPC response and signal resolution for calibrating the detector and Monte Carlo simulations. MPPC are subject to some level of cross-talk and after-pulse. Although these are limited they impact the response of the MPPC and increases the excess noise factor. Cross-talk is the consequence of optical photons produced during the avalanche process reaching other pixels and triggering further avalanches. After-pulsing is caused by electron from the avalanche being trapped in intermediate energy levels that are released during or after the pixel is

reset. After-pulse and cross-talk probabilities have been measured in [3]. We report here a study of these effects on the photon detection efficiency, the signal response and resolution.

## 3. MPPC photo-detection efficiency

The photo-detection efficiency of the MPPC is analogous to the quantum efficiency (QE) of a Photo-multiplier tube, representing the effective conversion factor between incident photons and photo-electrons produced by the device. Unlike the QE of a photo-multiplier the PDE is a function of the QE, avalanche probability ( $P_a$ ) and geometrical efficiency (GE) as follows,

$$\text{PDE} = \text{QE}(\lambda) \times P_a(V) \times \text{GE} \quad (1)$$

QE is dependant on the properties of the silicon and is dependant on the wavelength of incident photons.  $P_a$  is dependant on the electric field strength inside the device and thus is dependant upon the applied over-bias to the MPPC. The GE of is the ratio of sensitive to insensitive area and thus depends on the design and layout of the pixels only, and is thus fixed.

In the following sections we discuss methods of extracting the PDE of an MPPC and a method of correcting for additive effects such as crosstalk and after-pulsing.

## 4. Measuring mean number of photo-electrons

A low intensity flash of photons will cause a discrete number of pixels to undergo Geiger discharge. This number is related to the number of incident photons. A pixel that has undergone Geiger discharge is susceptible to after-pulsing and causing neighbouring pixels to discharge via optical crosstalk. These two effects artificially increase the charge output of the MPPC and charge distribution will as a result be artificially weighted to higher numbers of photo-electrons.

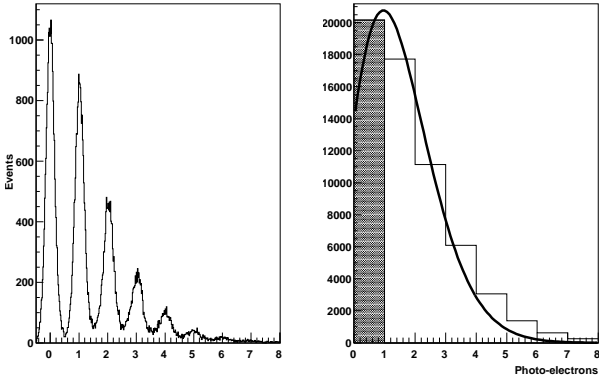


Figure 1: *Left* MPPC charge spectrum normalised to photo-electrons. *Right* MPPC charge spectrum in integer bins with Poisson fit applied. The shaded area is  $N_{Zero}$  as used for calculation of the mean photo-electrons free from crosstalk and after-pulse expressed in equation 2

There are two methods of extracting the mean number of photo-electrons: fitting and counting. The fitting method rebins the charge distribution of the MPPC into integer photo-electrons and apply a Poisson distribution to the spectrum, the mean number of photo-electrons is then given by the  $\mu$  parameter. This method is affected by the shape of the spectrum and is thus the mean including crosstalk and after-pulses. The counting method assumes a Poissonian distribution of photo-electrons, and estimates the mean from the fraction of pedestal to total events as follows,

$$\begin{aligned}
 P(n, \lambda) &= \frac{\lambda^n e^{-\lambda}}{n!} \\
 P(0, \lambda) &= e^{-\lambda} \\
 \Rightarrow \lambda &= -\ln\left(\frac{N_{Zero}}{N_{Total}}\right)
 \end{aligned} \quad (2)$$

This method only counts events in the spectrum that represent zero pixels fired. Thus these events are unaffected by crosstalk and after-pulses, and such the mean is equally unaffected. In order to extract the PDE, charge distributions are taken for a range of photon intensities between 0 and 10 photons. The mean number of photo-electrons is plotted against the expected number of photons and the gradient extracted.

## 5. Experimental procedure

The experimental setup consists of a blue LED pulser, diffuser, filter holder, a Newport 1835C optical power meter and Peltier temperature control on which an MPPC is mounted. The LED pulser used has been developed for use in the ANTARES experiment for calibration of PMTs. It is based on a pulser developed by Kapustinsky et al [4] and delivers a high intensity flash of light with a 2 ns rise time and FWHM of <5 ns with low pulse to pulse variation. At a distance of 80 mm from the LED a diffuser and window are positioned. A filter holder is positioned directly behind the window. This arrangement is to

ensure only photons that pass through the filter holder are incident on the MPPC. The temperature control consists of an aluminium plate, Peltier heat pump and copper heat-sink. The ceramic packaging of the MPPC is held against the aluminium plate and a temperature probe positioned in close proximity.

The LED the pulse profile is measured by applying a small aperture to the optical power meter and measure the optical power at different heights and angles. This study allows alignment of the LED and components on the optical rail and is an important step in understanding the difference in acceptance of the optical power meter and MPPC. Calculations are made by integrating the area under the LED profile for the circular and square active areas of the optical power meter and MPPC at a chosen LED-detector separation.

In order to calibrate the LED, the optical power meter is fixed at a desired distance from the LED and the number of photons per pulse calculated using :

$$N_\gamma = \frac{P(W)}{R(Hz)} \frac{hc}{\lambda(m)} A \quad (3)$$

where P is the power measured by the optical power meter, R is the pulse rate of the LED,  $\lambda$  is the mean wavelength of the LED and A is the acceptance ratio for the set LED-detector separation. The optical power meter is then replaced with an MPPC at the same distance from the LED.

In order to examine the MPPC in conditions similar to ND280, the above experiment is also carried out with the addition of a wavelength shifting fibre and connector designed for use in ND280.

In both arrangements A Lecroy 6100 Oscilloscope is used to integrate the trace from the MPPC on the LED flash for 200 ns. The oscilloscope is set to produce a spectrum of pulse area and control the bias supply through a preselected range of bias voltage. The total number of photons reaching the MPPC is controlled by adding neutral density filters behind the diffuser window. It is possible to expose the MPPC to both high and low intensity flashes using this arrangement.

## 6. Results

Left figure 2 is the PDE is plotted against gain for a 400 pixel MPPC at a wavelength of 470 nm. The difference between the PDE extracted using the mean of a Poisson fit is clearly elevated over that extracted from the counting method. The gradient of the two relationships are also different, showing the effect of Crosstalk and After-pulsing on the PDE. At 470 nm the PDE is increased by 6.2% (absolute) at a gain of  $6.0 \times 10^5$  and 10% (absolute) at a gain of  $8.7 \times 10^5$ .

Right figure 2 shows the PDE of an MPPC coupled to a WLS fibre. The PDE of the MPPC is lower at the photon wavelength emitted by the fibre than at the wavelength produced by the LED. At a gain of  $7.5 \times 10^5$  the total reduction of PDE is approximately 9%. The reduction of PDE from the MPPC catalogue from Hamamatsu [5] shows 5.6% fall for the same photon wavelengths using PDE extracted by current leakage. The extra

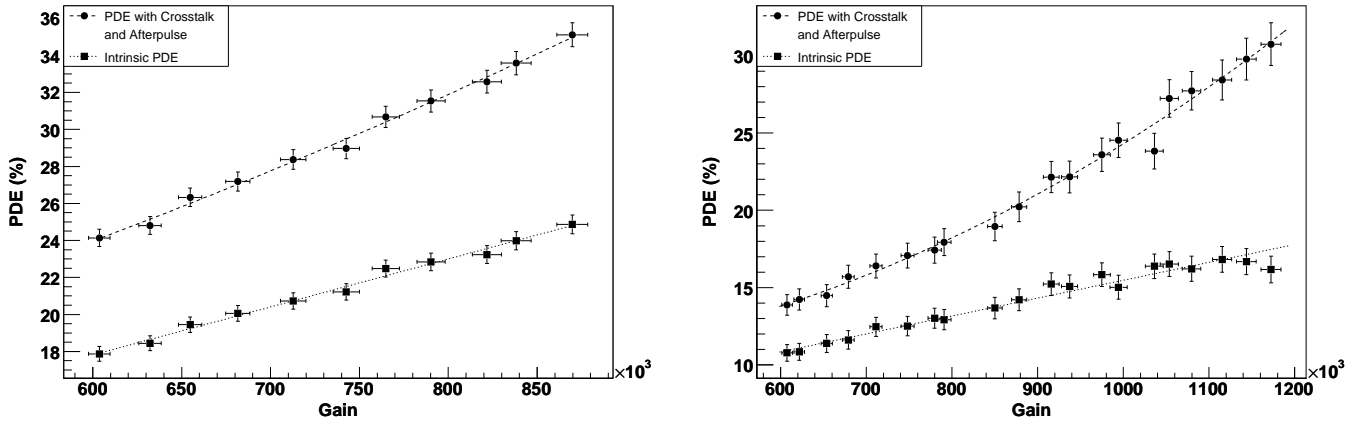


Figure 2: (Left) PDE against device gain for a S10362-11-050 MPPC using 470 nm LED pulse, (Right) PDE against device gain for a 1.3 x 1.3 mm MPPC coupled to WLS fibre.

loss in PDE is likely the result of coupling quality between the MPPC and fibre.

## 7. MPPC response linearity

The dynamic range of an MPPC is limited by the total number of pixels of the active area. Non-linear behaviour to increasing photon intensity occurs when the density of photons is a significant fraction of the pixel density. As photon intensity is increased, so does the probability of two or more photons striking a single pixel. This causes nonlinear behaviour as a consequence of Geiger mode operation, as two or more incident photons triggering one pixel result in only one unit of charge from the MPPC. Response linearity is of great importance when considering the response of an MPPC under experimental conditions if the number of true photons or the energy of an input pulse is required over a large dynamic range. The goal of this study is to produce an empirical fit using MPPC parameters to reproduce MPPC response.

In order to study MPPC linearity, the experimental apparatus is setup as described in section 5, however the photon intensity is controlled using lower optical density filters. LED flashes of up to  $\sim 2000$  photons are applied to the active area of the MPPC and experiment carried out as described previously.

### 7.1. Empirical fit

The number of pixels triggered as a function of the incident number of photons can be described by a simple model assuming Poisson statistics of photons with same arrival time onto the array (independent of recovery effects) :

$$N_{trigger} = N_{pixel} \left( 1 - e^{-\frac{N_{\gamma}\epsilon}{N_{pixel}}} \right) \quad (4)$$

where  $N_{\gamma}$  is the number of photons incident on the MPPC,  $N_{pixel}$  is the number of pixels of the active area and  $\epsilon$  is the PDE. As stated previously, all MPPC pixels are subject to crosstalk and

after-pulses, during a high intensity flash, these effects are extremely important as they artificially increase the output signal by a potentially large amount causing less linear response than expected. Crosstalk ( $\epsilon'$ ) is added as an addition to the PDE term. It appears in this manner as crosstalk increases the total number of pixels triggered during a flash. After-pulses is added to the expression as a probability based on the number of pixels that are triggered during a flash. This form is given because After-pulses do not increase the number of triggered pixels but increases the charge output of a single pixel. The number of pixels triggered by  $N_{\gamma}$  is the product of  $N_{\gamma}$  and  $\epsilon$  however all avalanche processes occurring within the MPPC give the probability of optical crosstalk and thus  $\epsilon'$  is added to the term. Equation 4 then becomes :

$$N_{trigger} = N_{pixel} \left( 1 - e^{-\frac{N_{\gamma}(\epsilon + \epsilon')}{N_{pixel}}} \right) + N_{\gamma}(\epsilon + \epsilon')P_{AP} \quad (5)$$

### 7.2. MPPC response to 470 nm LED pulse

Under high intensity light pulses, MPPC charge output is Gaussian distributed, and contains no visible single photo-electron structure. Thus in order to convert the spectrum into photo-electrons, a single photo-electron spectrum at the same gain is used to provide the charge of a single photo-electron against which to rebin. Gaussian fits are applied and the mean and sigma extracted.

Response linearity is shown in figure 3 for LED photons at a wavelength of 470 nm. Here the MPPC response remains closely linear in the 0 to 200 photon region and becomes increasingly non-linear as the photon intensity increases. As expected the curvature of the fit increases with over-bias as the PDE and crosstalk of the device increases. The modified expression appears to fit to the shape of the data with high accuracy, however, fitted parameters have large errors. Addition of more data points at very high saturation would help reduce these errors and allow better parameter prediction.

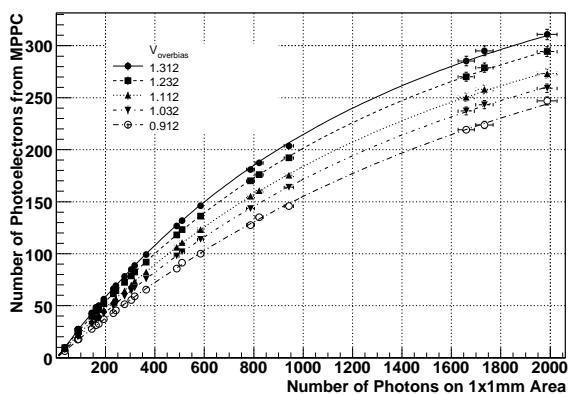


Figure 3: Linearity curves of a 1 x 1 mm MPPC for increasing over-bias fitted using equation 5. The PDE parameter  $\epsilon$  has been fixed based on intrinsic PDE as shown figure 2

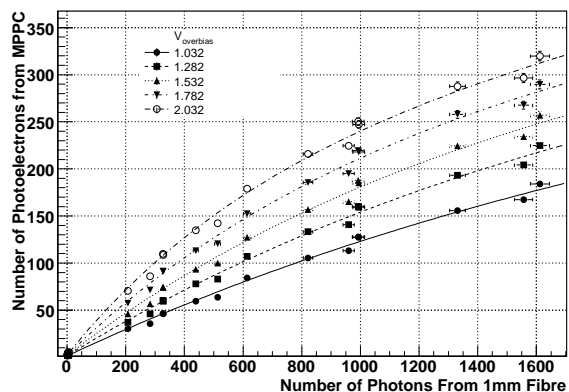


Figure 4: Linearity curves of a 1.3 x 1.3 mm MPPC for increasing over-bias fitted using equation 5. The PDE parameter  $\epsilon$  has been fixed based on intrinsic PDE as shown figure 2 and  $P_{AP}$  fixed based on waveform analysis

### 7.3. MPPC response with Y11 WLS fibre

The response of a 1.3 x 1.3mm MPPC to signals from WLS fibre has been studied. The coupling between the fibre and MPPC has been achieved using a connector designed for use in the ND280 detector. It uses a push fit mechanism and provides a dry connection between the MPPC and WLS fibre with a mean light yield reproducibility of 2%.

The response linearity of the MPPC coupled to Y11 fibre is shown figure 4. As observed in figure 3 the response of the MPPC to Y11 fibre becomes increasingly non-linear as the gain increases. Fixing both PDE and after-pulse probability, the fit expression is able to predict the probability of crosstalk within acceptable accuracy. A feature of the fitted parameters is a decrease in the total number of pixels with increasing gain. This behaviour is unexpected and likely the result of the fit expression being over simplified for our experiment. An integration gate of 200 ns is used, thus the probability of after-pulse should be using an integration of the probability distribution within this

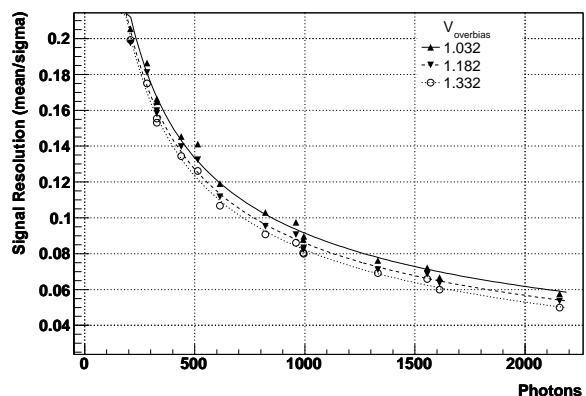


Figure 5: Peak resolution of an MPPC coupled to WLS fibre

window. The WLS fibre has a typical decay time of  $\sim 9$  ns leading to the possibility of a single pixel being fired several times during the integration window and thus not triggering a full gain response from the MPPC. The intensity profile emanating from the fibre tip is currently under study and the distribution of photons over the pixels array is expected to be non-uniform and probably following a 2D Gaussian density. Currently the fit expression does not account for any of these complexities. A Monte Carlo simulation is being implemented to describe LED and fibre data. This simulation will allow further development of the empirical fit expression by simulating data with processes turned on and off to determine aspects of the fit that need modification.

Figure 5 shows the peak resolution of the data of figure 4. The resolution doesn't show significant degradation with increased over-voltage. This could be interpreted as a compensation by increasing PDE and crosstalk to the degradation caused by increasing after-pulse with overvoltage.

## 8. Conclusion

The intrinsic photon detection efficiency of MPPCs produced by Hamamatsu Photonics has been investigated under conditions expected inside ND280 and is found to be 21.5% at 470 nm and 12.3% for Y11 fibre attached to ND280 connector. MPPC response to increasing light exposure has been studied and a simple empirical model proposed to describe experimental data. At present the model is under development with the aid of detailed MPPC simulation. When considering the operation of MPPCs crosstalk and after-pulse effects are of vital importance and must be modelled or simulated accurately in order to fully understand real experimental data.

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