Measuring and Modelling the Light Response of Pixelized Photon Detectors with Significant Photon-Induced Correlated Noise

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Introduction

Solid-state photon detectors such as those in use by CALICE and T2K are considered attractive candidates for light detection in a future linear collider detector when compared with the traditional PMT.

Some advantages

- B-field tolerance
- Cheap
- Apparent photon resolving capability
- Low voltage/size/integrability

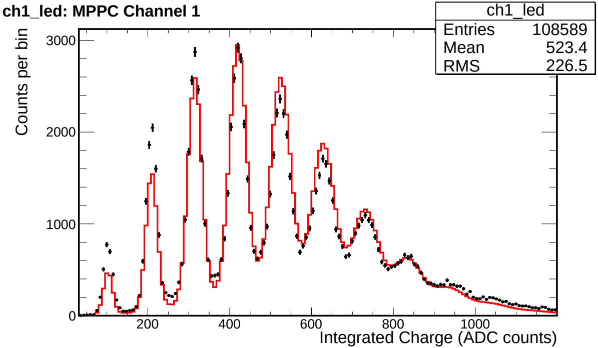
Some disadvantages

- Dark noise rate per mm^2 (can be 500 kHz cf 0.5 Hz).
- Correlated noise: cross-talk and after-pulsing
- Dynamic range

Photo-detector response modelling

Question

Does LED calibration data (points) follow Poisson model (red)?



Individual photons often lead to not just 1 fired pixel, but 2, 3, 4 etc. due to cross-talk and after-pulsing. Technology and device dependent.

Noise and Time Structure: Important or Not ?

ILC/CLIC

At ILC with a large inter-bunch spacing (337 ns), a relevant issue is noise within a time interval consistent with the BX under consideration. For CLIC, much tighter specs.
Various types of potential detectors: AHCAL, Scint. ECAL, Muon-detector, scint. fiber tracking have different requirements.

Why this study?

These studies use the 100-pixel Hamamatsu MPPC aimed at high efficiency low light-level detection. I work on the D0 fiber tracker and its light calibration and have explored instrumenting parts of a LC detector with similar instrumentation for time-stamping/TOF. At D0 using VLPCs we have an average threshold per fiber of 1.0 photo-electrons corresponding to 1% dark probability and Poisson distributed LED distributions....

Literature and this work

Literature

There is a substantial literature from many groups about characterization measurements related to pixelized solid-state photo-multiplier response (see references).

Short-comings

In practice many adopted methods are either approximate, or require dedicated measurements unlikely to be available en masse in situ for LC detector channel counts, or potentially lose substantial predictive power / precision by using more parameters than warranted by the underlying effects.

This work

Hopefully helps to put some of the issues better in focus and provides a coherent yet relatively simple integrated experimental method to test the response modelling and the measurement of associated parameters.

Experimental Goal and Design

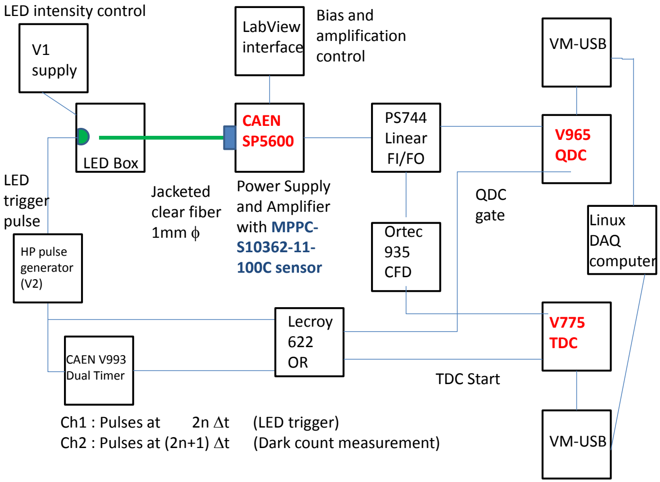
Goal

Measure the photo-detector response under essentially identical conditions using identical time intervals for both non-illuminated (dark) data and illuminated (LED) data. Currently using MPPC-S10362-11-100C sensor with 100 pixels.

Design

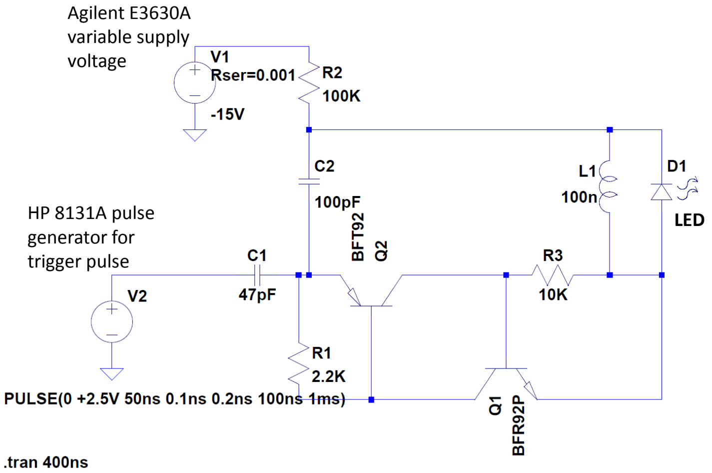
Use 100-1000 Hz clock to fire LED on every other cycle.
Measure total charge integrated within a 240-300 ns time window using dual-range QDC (FSR 800 pC).
Use single-hit TDC in common start mode to check timing characteristics.
Bias will be varied from run-to-run, but use 70.65 V corresponding to $\approx$ 0.72V over-voltage as default setting.

Experimental Setup

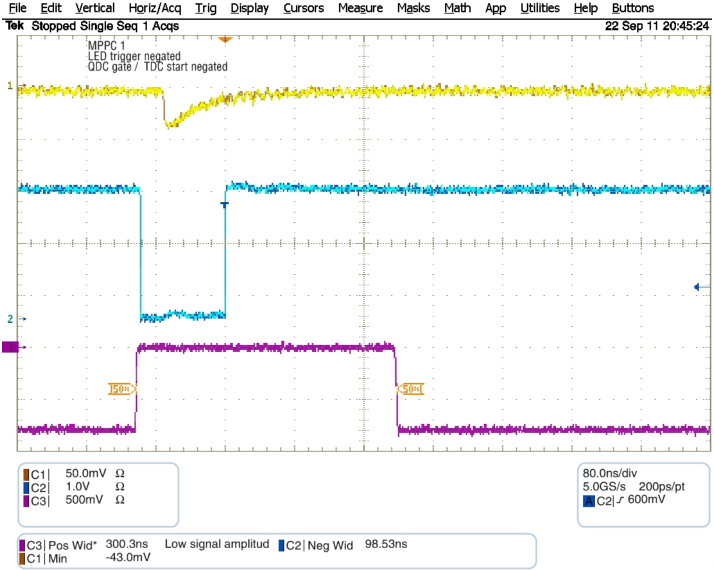


LED Circuit

Use Kapustinsky [1] type driver circuit to obtain fast time response.
Currently using off-the-shelf green LED ($\lambda = 565$nm).

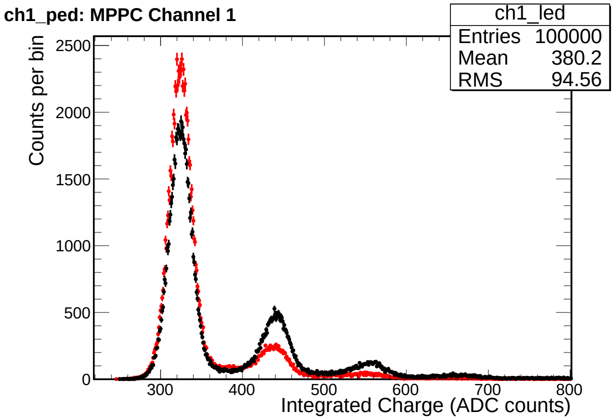


Typical LED Event 1: prompt 1 pixel event ($\tau \approx 40$ ns)



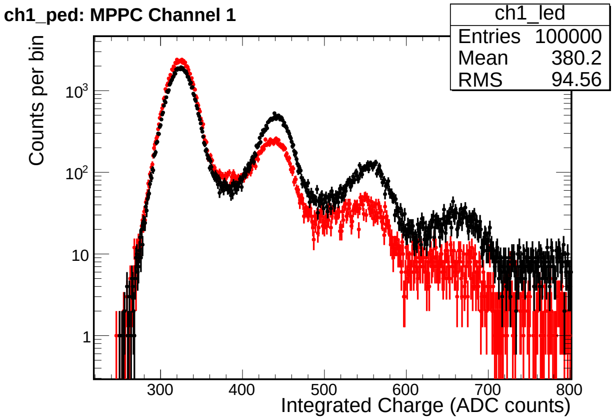
LED Charge Distribution (gate width = 300 ns)

Measure charge response to LED (black) and dark counts (red). Photon intensity = 0.22 detected photons/pulse.



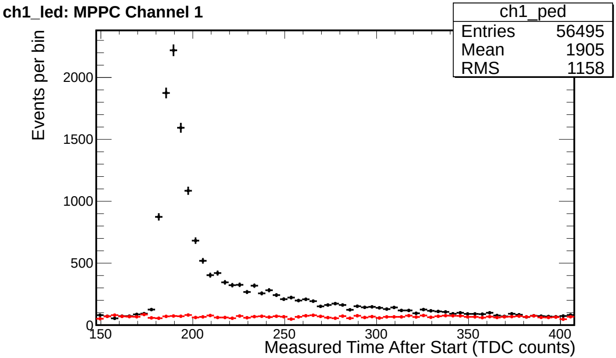
LED Charge Distribution - Log

Measure charge response to LED (black) and dark counts (red). Photon intensity = 0.22 detected photons/pulse.



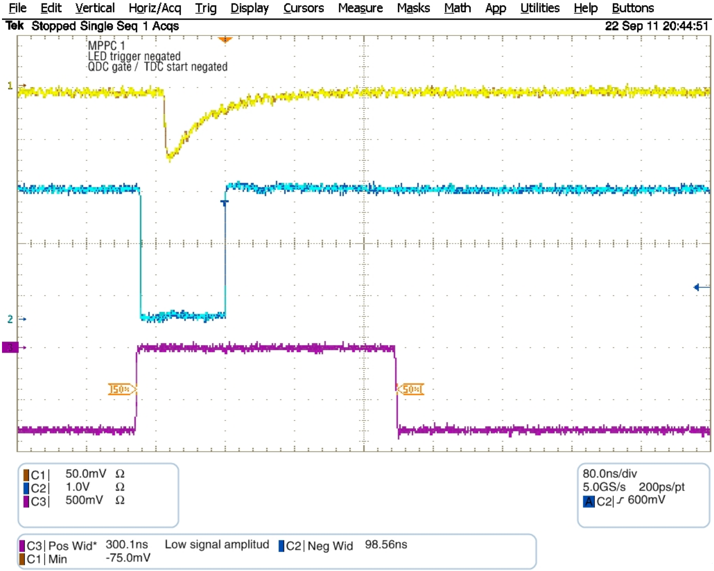
LED Time Distribution

Measure time response to LED (black) and dark counts (red). Photon intensity = 0.22 detected photons/pulse.

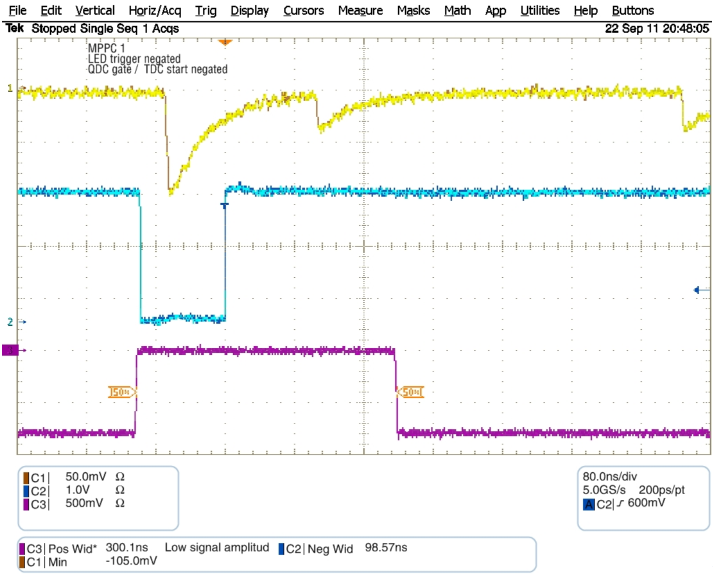


Find FWHM for this green LED of 5ns. (1 TDC count = 0.3 ns)

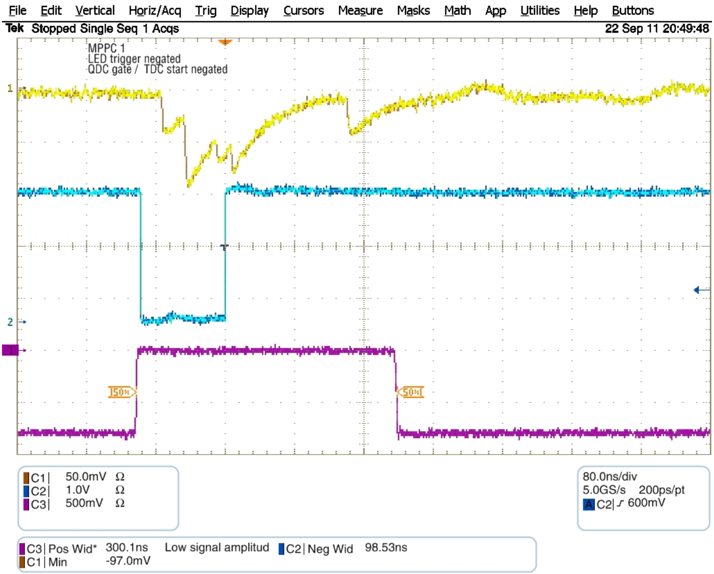
Typical LED Event 2: prompt 2 pixel event



Typical LED Event 3: prompt 3 pixel event + delayed pulse



Typical LED Event 4: multiple pixels + likely afterpulses



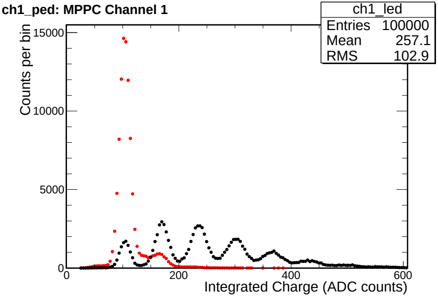
Charge Distribution Studies

Standard conditions mostly:

- Room temperature (Kansas summer day ....)
- Integration time: 270 ns
- LED supply voltage: 18.25 V. Leading to 4.5 detected photons at 1 V over-voltage and nominal intrinsic gain of 2.4e6.
- Amplifier gain: 38 dB

Fitting Method

Assume that the measured LED distribution, T(Q), arises from the convolution of N(q_{dark}) and L(q_{light}), where $Q = q_{dark} + q_{light}$.



Use measured non-illuminated data (red) for N(q_{dark}) and adjust the parameters of the L(q_{light}) model to give the best fit to the LED data (black) for the additional charge arising from LED photons.

Light Model: Essentially 2 parameters.

Pixel distribution

Use the simple probability distribution model discussed in Vinogradov et al [2] based on a Poisson distributed random variable for the number of photons, μ_γ, which result in a detected primary avalanche. Each primary avalanche may then create a secondary avalanche with a duplication probability, p_D, and likewise a secondary avalanche may create a tertiary avalanche with the same probability etc, etc ... p_D includes both cross-talk and after-pulsing assuming for simplicity equal charge response to both sources.

Charge Measurement Model Parameters

- 1 pixel gain, g (ADC counts per pixel)
- 1 pixel intrinsic fractional gain resolution, $\sigma_1 = \sigma_g/g$
- N-pixel non-linearity, β, where $q_{light} = Ng(1 + N\beta)/(1 + \beta)$
- N-pixel variance non-linearity, γ, where $\sigma_N^2 = N(1 + N\gamma)\sigma_g^2)/(1 + \gamma)$

Light Model Continued

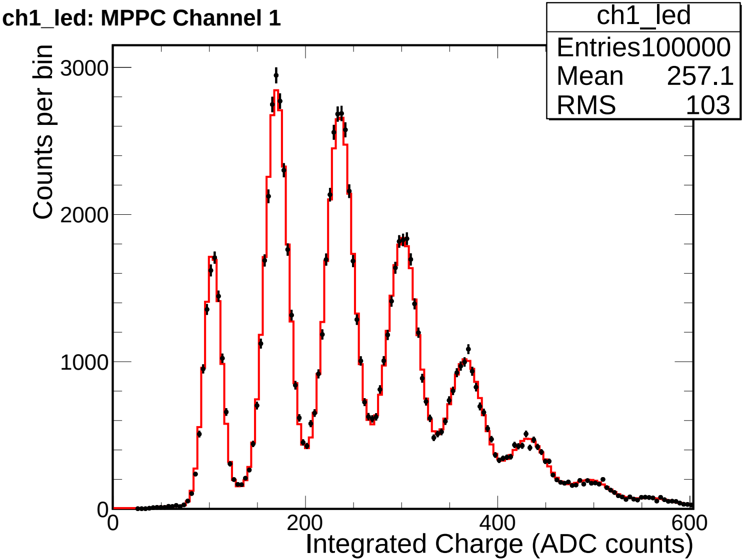
Example

- $p(n_A = 0) = \exp\{-\mu_\gamma\}$
- $p(n_A = 1) = \exp\{-\mu_\gamma\}\mu_\gamma(1 - p_D)$
- $p(n_A = 2) = \exp\{-\mu_\gamma\}\{\mu_\gamma p_D(1 - p_D) + \frac{1}{2}{\mu_\gamma}^2(1 - p_D)^2\}$
- $p(n_A = 3) =$ $\exp\{-\mu_\gamma\}\{\mu_\gamma p_D^2(1 - p_D) + {\mu_\gamma}^2 p_D(1 - p_D)^2 + \frac{1}{6}{\mu_\gamma}^3(1 - p_D)^3\}$
- etc ..
- Needless to say - currently neglect finite pixel number

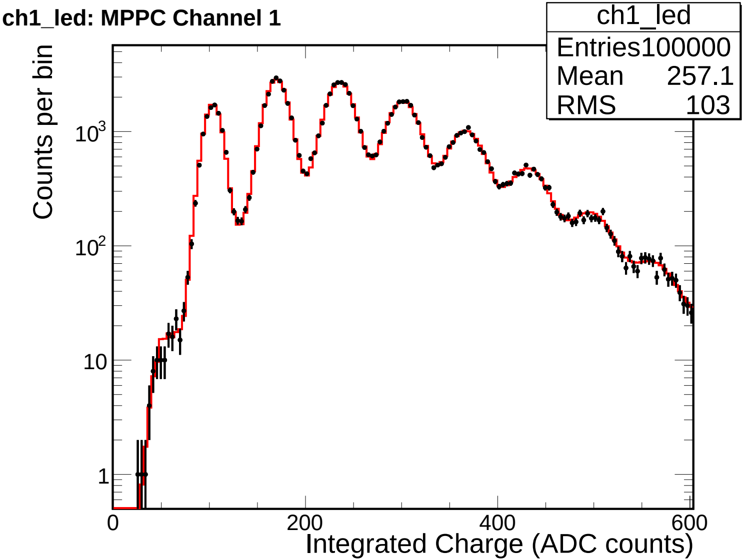
Characteristics

- Mean pixel count: $\mu_\gamma/(1 - p_D)$
- Variance of pixel count: $(\mu_\gamma/(1 - p_D))(1 + p_D)/(1 - p_D)$

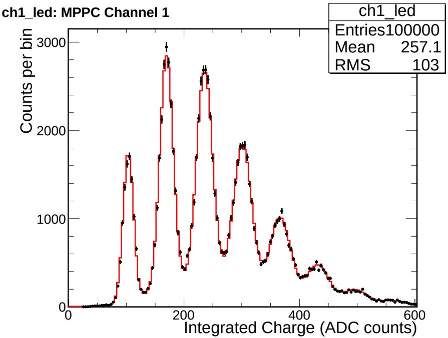
Example Fit (Run6 70.35V 38dB L)



Example Fit (Run6 70.35V 38dB L)

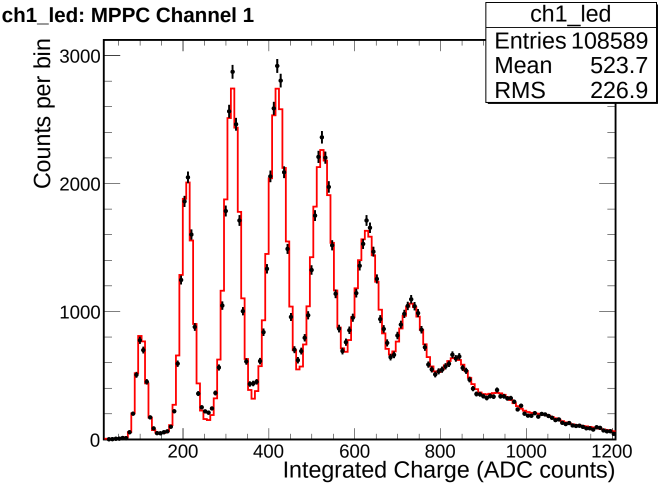


Example Fit (Run6 70.35V 38dB L)



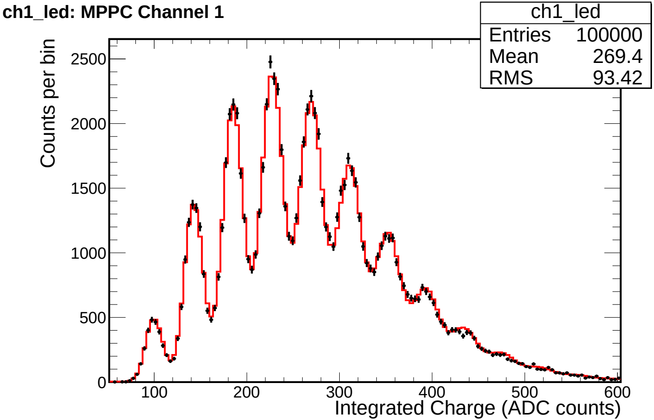
μ_γ	2.150(7)
$p_D(\%)$	5.00(25)
g	66.35(6)
σ_1	0.113(1)
β	-0.0022(4)
γ	0.007(10)
χ^2/dof	936 / 794

Example Fit (Run1 70.65V 38dB L)



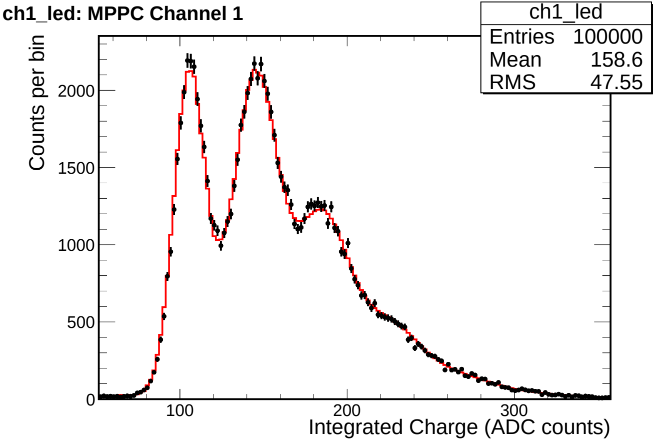
Fit: $\mu_\gamma = 3.36 \pm 0.01$, $p_D = 14.0 \pm 0.2\%$, $\chi^2/\text{dof}{=}1921/1594$.

Example Fit (Run10 70.65V 30dB L)



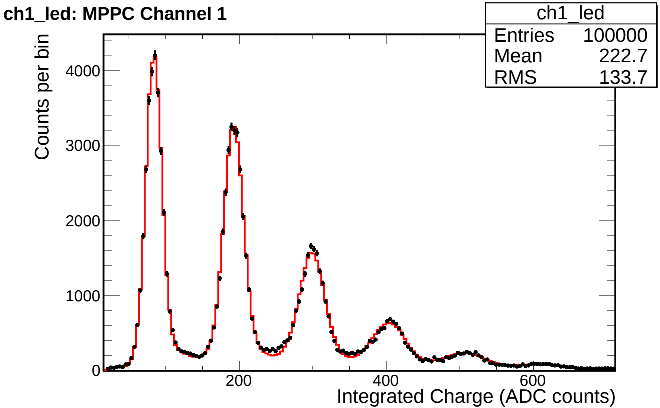
Fit: $\mu_\gamma = 3.36 \pm 0.01$, $p_D = 13.0 \pm 0.3\%$, $\chi^2/\text{dof}=774/794$.

Example Fit (Run8 70.20V 38dB L)



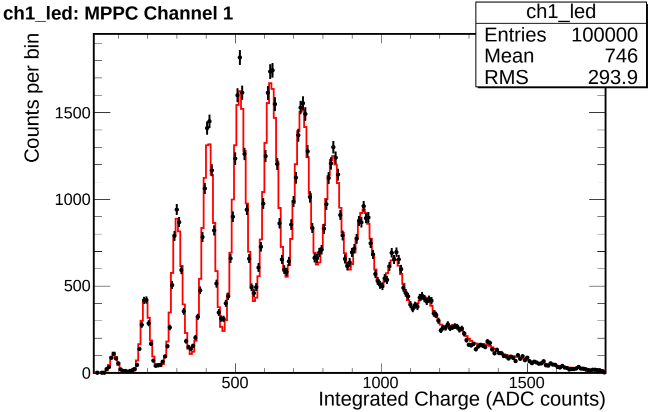
Fit: $\mu_\gamma = 1.268 \pm 0.006$, $p_D = 0$, $\chi^2/\text{dof}=510/394$.

Example Fit (Run11 70.65V 38dB 0.3L)



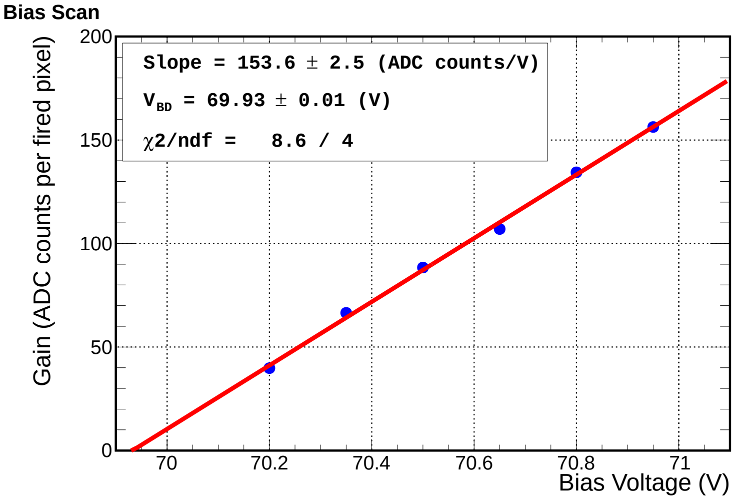
Fit: $\mu_\gamma = 0.961 \pm 0.004$, $p_D = 15.0 \pm 0.3\%$, $\chi^2/\mathrm{dof}=1424/1194$.

Example Fit (Run12 70.65V 38dB 1.6L)



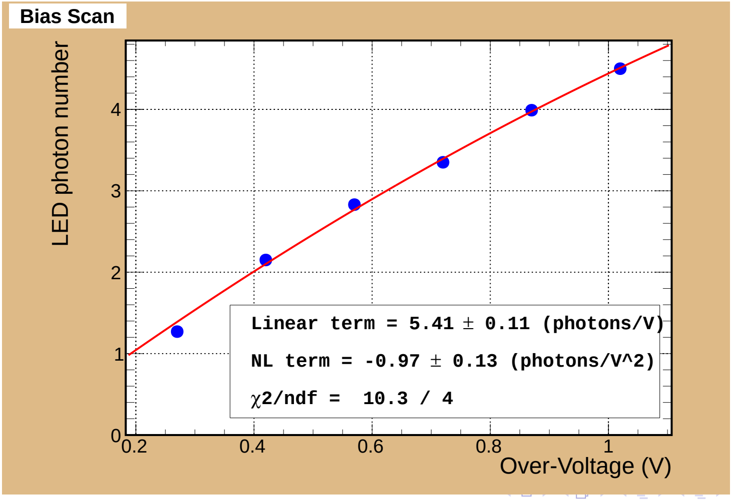
Fit: $\mu_\gamma = 5.22 \pm 0.02$, $p_D = 13.4 \pm 0.2\%$, $\chi^2/\text{dof}=2327/1994$.

Bias Scan

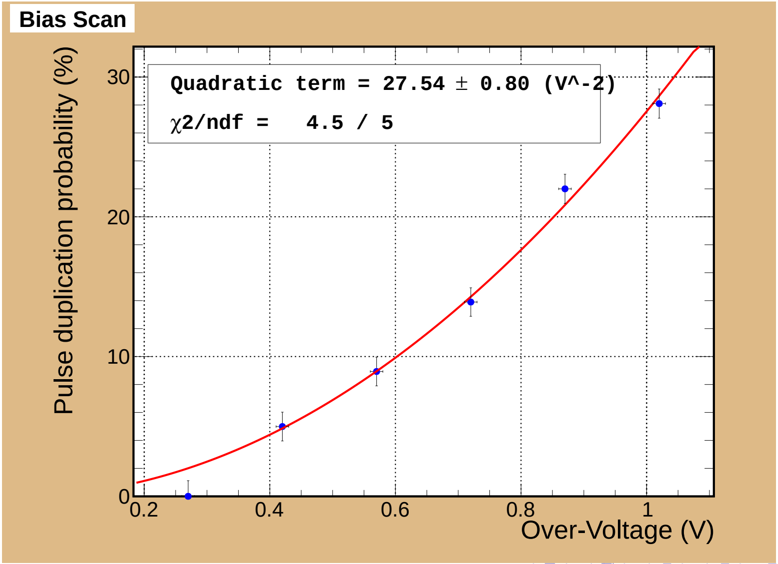

Bias Scan
Slope = 153.6 ± 2.5 (ADC counts/V)
V_BD = 69.93 ± 0.01 (V)
χ2/ndf = 8.6 / 4
Gain (ADC counts per fired pixel)
200
150
100
50
0
70
70.2
70.4
70.6
70.8
71
Bias Voltage (V)

Measured Photon Number

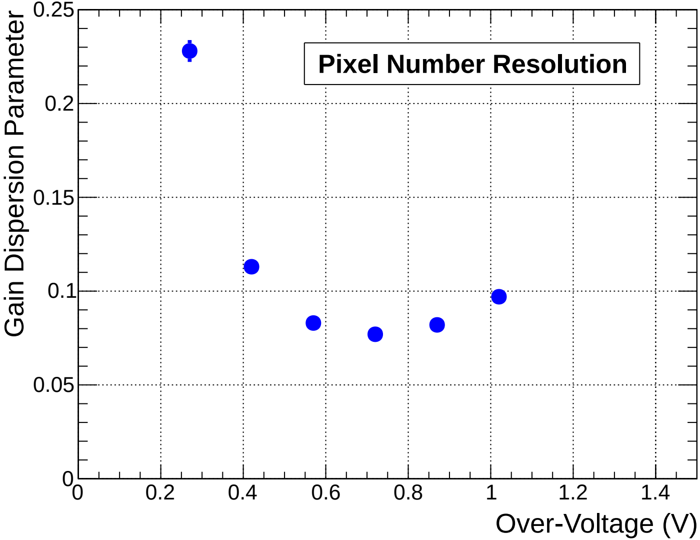
Measure the Poisson parameter of the detected primary LED photons, μ_γ. (gives relative photon detection efficiency vs ΔV).



Duplicate Probability



Photon Resolving Quality



Dark Count Probability

Can measure charge exceeding arbitrary threshold in charge integration window (has not been the focus of this work so far) using measured non-illuminated ADC spectrum.

Future Refinements

- Adjust LED intensity at each bias voltage to keep number of detected photons approximately constant. Should be a better method for measuring the photon-induced noise dependence on over-voltage.
- Incorporate after-pulsing time structure together with pulse shape time constant and resolve cross-talk and after-pulsing importance.
- Improve/better characterize charge measurement systematics - amplifier/ADC linearity.
- Improvements in the fitting, statistical method and convolution.

Conclusions

Summary

- Find that measured pixel number distributions can be well modelled using a simple light-detection model including duplicate avalanches. Important for understanding particle detection efficiency close to threshold.
- Experimental technique allows simultaneous determination of gain, duplicate probability, relative PDE, dark rate and pixel resolving capability for this particular sensor.

Conclusions

- New PPDs have significant noise which is sometimes correlated and needs to be taken into account when evaluating detector/sensor options, predicting performance and measuring performance.
- Correlated noise makes the standard procedure of setting a threshold at 1.5 "photo-electrons" not as useful as might be expected.

J.S. Kapustinsky et al.
A Fast Timing Light Pulser for Scintillation Detectors
NIM A, 241 (1985) 612.

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Probability Distribution and Noise Factor of Solid State Photomultiplier Signals with Cross-Talk and Afterpulsing
2009 IEEE Nuclear Science Symposium, N25-111.

Y. Du and F. Retière,
After-pulsing and cross-talk in multi-pixel photon counters
NIM A, 596 (2008) 396.

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NIM A, 656 (2011) 69.

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NIM A, 613 (2010) 23.

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