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Challenges of arbitrary waveform signal detection by SiPM in beam loss monitoring systems with Cherenkov fibre readout

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Silicon Photomultipliers (SiPMs) are well recognised as very competitive photodetectors due to their exceptional photon number and time resolution, room-temperature low-voltage operation, insensitivity to magnetic fields, compactness, and robustness. Detection of weak light pulses of nanosecond time scale appears to be the best area for SiPM applications because in this case most of the SiPM drawbacks have a rather limited effect on its performance. In contrast to the more typical scintillation and Cherenkov detection applications, which demand information on the number of photons and/or the arrival time of the light pulse only, beam loss monitoring (BLM) systems utilising Cherenkov fibres with photodetector readout have to precisely reconstruct the temporal profile of the light pulse. This is a rather challenging task for any photon detector especially taking into account the high dynamic range of incident signals (100K – 1M) from a few photons to a few percents of destructive losses in a beam line and presumably an arbitrary temporal distribution of photons (localisation of losses).

Nevertheless, a number of advantages and ongoing improvements of SiPM technology are considered to be a reasonable ground for this feasibility study of SiPM application in BLM systems. Transient SiPM responses to light pulses over a wide range of intensities have been measured and an analytical model has been applied to describe the results. Non-linearity of SiPMs due to the limited number of pixels and non-instant pixel recovery time is found to be a source of transient and history-dependent distortions of output signals.

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1. Introduction

Silicon Photomultipliers (SiPMs) are well recognized for their exceptional photon number and timing resolution. However, due to specific SiPM drawbacks such as high dark count rates, sources of correlated noise (crosstalk, afterpulsing), and limited dynamic range (limited number of pixels, relatively slow pixel recovery time) their applications are mostly associated with the detection of faint light flashes of nanosecond time scale [1], [2].

In contrast to the typical scintillation and Cherenkov detection - photon number and time resolving applications - accelerator Beam Loss Monitoring (BLM) systems with Cherenkov fibre readout have to precisely reconstruct the temporal profile of the light pulse. This is a rather challenging task for any photon detector because of the high dynamic range (~10^6) from a few photons to a few percent of destructive losses and presumably an arbitrary signal waveforms i.e. localization of losses (Fig. 1) [3], [4].

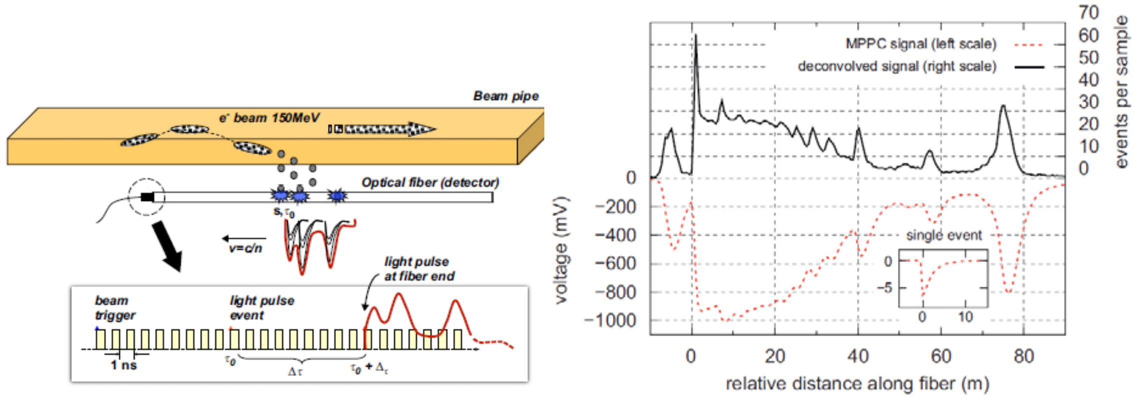

Fig. 1 a) Beam Loss Monitoring (BLM): 150 MeV electrons in a beam line; an optical fibre as Cherenkov radiator and light guide; SiPM (MPPC) as an upstream photon detector [3]; b) SiPM (MPPC) readout of typical BLM signal: raw output (red, left scale) and a result of deconvolution (black, right scale) with single electron pulse response function (red, inset)

This study is an attempt to advance an initial consideration of transient SiPM response to long and intense light pulses [5] based on a dynamical combination of earlier analytical approaches utilizing binomial nonlinearity and nonparalizible dead time models [2]. This attempt is a more comprehensive consideration of a transient SiPM response by modeling it as a reward-renewal Markov process formed by a non-homogeneous Poisson process of photon (and photoelectron) arrivals and the exponential pixel recovery process that is conditional on previous firing of the pixel.

2. Challenges of intense light signal detection due to SiPM nonlinearity

The nonlinearity of a photodetector response inevitably degrades its resolution. SiPM nonlinearities are associated with losses of photons due to the limited number of pixels and a non-instant pixel recovery (dead time). Applying the more realistic model of an exponential RC pixel recovery after avalanche breakdown instead of a nonparalizible dead time model, it was shown that the incomplete recovery of pixels during the detection of long intense light pulses results in a distortion of the probability distribution of SiPM gain towards lower mean values of gain, higher variance, and higher excess noise of gain, and therefore to a worse photon number resolution (PNR) defined as a standard deviation to mean ratio of an output signal calibrated in photons (Fig. 2).

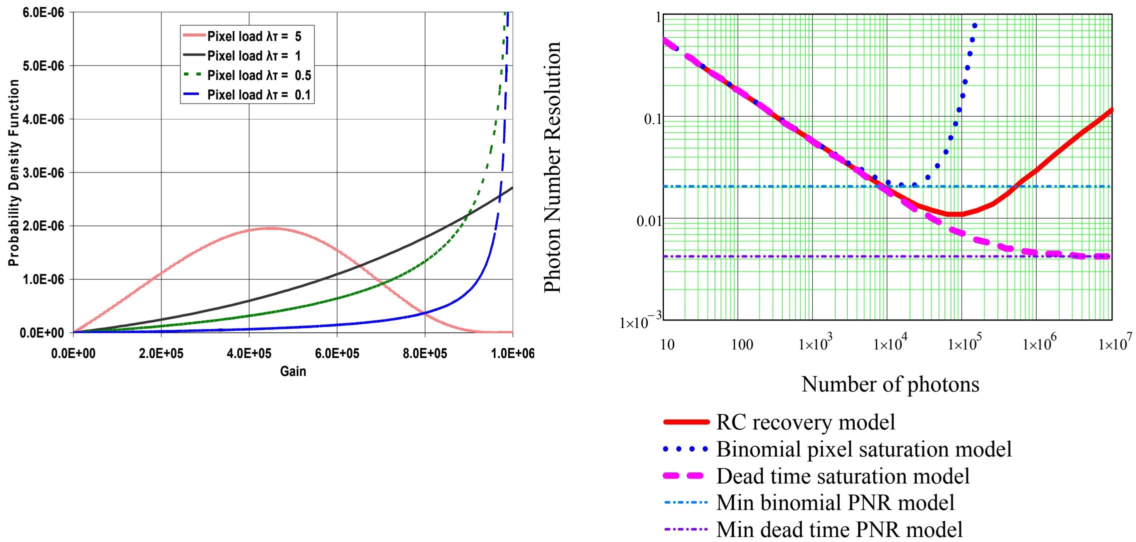

Fig. 2. Degradation of SiPM response and performance due to nonlinearity [6] a) Probability density function of SiPM *Gain*: degradation from delta-function at *Gain* =1M due to incomplete recovering of pixels at a high pixel load $\lambda{\cdot}\tau > 1$ (λ is a mean photon arrival rate per pixel and τ is a pixel recovery time); b) Photon number resolution models: binomial distribution, fixed dead time, exponential recovery.

The conclusion is that this kind of nonlinearity affects two main variables that determine the detector output: the number of detected photons and the gain of the detection. It also means that the detector signal is load-and-history-dependent. Therefore, known approaches to SiPM modeling based on fixed stationary parameters of SiPM response such as *PDE* and *Gain* should be made variable and dependent on the recovering state of the pixel.

3. Reward-renewal model of transient SiPM response

The renewal process can be considered as a Poisson process of photon arrivals with mean rate $\lambda(t)$ and exponential distribution of inter-arrival times. Each newly arrival photon passes through a Bernoulli detection process with a probability to detect the next photon $PDE(t)$ that depends on the time t lapsed since the previous avalanche because the breakdown probability depends on the recovery state of the pixel. The probability density function (PDF) of the photon inter-arrival time is $\rho_{ph}(t)$ and the PDF of single photon detection time is $\rho_{spd}(t)$, which is a product of $PDE(t)$ and the single photon time resolution PDF $\rho_{sptr}(t)$.

The reward process assumes that the $Gain(t)$ asymptotically approaches to the stationary value $Gain(\infty)$ from the previous firing with a characteristic recovery time τ_{rec}. The full set of equations (3.1) represents the reward-renewal model of the single SiPM pixel response to an arbitrary waveform signal with a photon arrival rate $\lambda(t)$.

$$Gain(t) = Gain(\infty)\cdot\left[1-\exp\left(-t/\tau_{rec}\right)\right]$$
$$PDE(t) = f[Gain(t)] \sim Gain(t)^{\alpha} \quad \alpha \sim 0.5 \quad \text{(typical experimental fit)}$$
$$\rho_{ph}(t) = \lambda(t)\cdot\exp\left(-\int_0^t \lambda(t')dt'\right) \tag{3.1}$$
$$\rho_{spd}(t) = PDE(t)\cdot\rho_{sptr}(t)$$
$$\rho_{\det}(t) = \rho_{ph}(t) * \rho_{spd}(t) \qquad P_{\det}(t) = \int_0^t \rho_{\det}(t')dt'$$

The renewal equation and the mean reward rate are evaluated according to the known reward-renewal theory and its applications [7]. The mean number of detected events $E[N_{det}(t)]$ is defined by the renewal equation:

$$E[N_{\det}(t)] = P_{\det}(t) + \int_0^{\infty} E[N_{\det}(t'-t)]\rho_{\det}(t')dt' \tag{3.2}$$

The solution to equation (3.2) is found by doing a Laplace transform $L\{\}$:

$$L\{E[N_{\det}(t)]\}(s) = \frac{L\{P_{\det}(t)\}(s)}{1-L\{P_{\det}(t)\}(s)} \tag{3.3}$$

Finally, the inverse Laplace transform $L^{-1}\{\}$ applied to (3.3) allows to determine the mean number of detected events, and the variable we are most interested in – the mean output response $I_{out}(t)$ – is to be found as follows:

$$I_{out}(t) = \frac{dE[N_{\det}(t)]}{dt}\cdot E[Gain(t)] \tag{3.4}$$

Particularly, in case if the temporal profile of an incident light pulse is described by a Heaviside step function (the light is turned on at time t=0), modeling of the SiPM response with (3.1)-(3.4) provides reasonable results (Fig. 3).

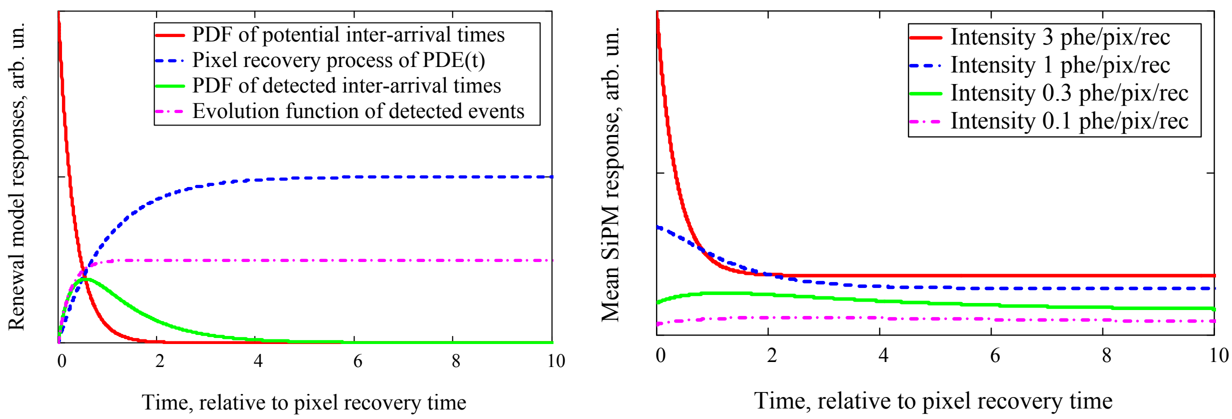

Fig. 3. Reward-renewal Markov process model of the SiPM response to a high-intensity step-function light pulse: a) Response components and contributions: probability density function (PDF) of inter-arrival times of potential events, transient pixel recovery process recovering its PDE during "dead time", PDF of actual detected event times; evolution function (mean detection rate) of events after the first detection (plots are given for intensity of 3 phe/pixel/recovery); b) Mean SiPM response as a result of renewal process with a mean detection rate and reward process with a mean gain affected by incomplete recovering of pixels to be compared with experimental results [5].

4.Experimental studies of transient SiPM response

Experiments have been carried out with rectangular pulses (8 ns rise & fall times) of a 440 nm LED with variable intensity [5]. The SiPM signal has been read out without a preamplifier at a 50 Ohm termination to avoid any possible saturation of high amplitude signals in analog bandwidth from DC to 1 GHz. The single electron response was measured with a 20 dB, 4 GHz external amplifier Mini-Circuits ZX60-4016E+. Hamamatsu MPPC S10362-33-050C with 50 µm cell size and 3x3 mm^2 area was used as a well known reference and representative SiPM sample. A set of MPPC transient responses similar to that shown on Fig. 3 have been measured and analyzed.

5.Conclusion

The transient SiPM response reveals a rather complex dynamic behavior with a strong dependence on the mean number of detected photons per pixel per recovery time. A reward-renewal Markov process model has been applied to the SiPM response analysis for the first time and promising analytical results have been obtained. In the case of rectangular light pulse detection, the model allows to get an analytical expression for the mean SiPM response as a result of renewal process with a mean detection rate and reward process with a mean gain that is affected by incomplete recovering of pixels, which are in a qualitative agreement with previous analytical and experimental results.

Acknowledgments

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References

[1] P. Buzhan et al., *Silicon photomultiplier and its possible applications, Nucl. Instr. Methods A* (2003) **504**, p. 48 [http://dx.doi.org/10.1016/S0168-9002(03)00749-6].

[2] S. Vinogradov et al., *Efficiency of Solid State Photomultipliers in Photon Number Resolution, IEEE Trans. Nucl. Sci.* (2011) **58**, p. 9 [http://dx.doi.org/10.1109/TNS.2010.2096474].

[3] D. Di Giovenale, L. Catani, and L. Frohlich, *A read-out system for online monitoring of intensity and position of beam losses in electron linacs, Nucl. Instr. Methods A* (2011) **665**, p. 33 [http://dx.doi.org/10.1016/j.nima.2011.11.038].

[4] L.J. Devlin, C.P. Welsch, E.N. del Busto, *Update on Beam Loss Monitoring at CTF3 for CLIC, in proceedings of IBIC 2013*, p.787, Oxford, UK, 2013 [http://accelconf.web.cern.ch/AccelConf/ibic2013/papers/wepc43.pdf].

[5] S. Vinogradov, A. Arodzero, R.C. Lanza, and C.P. Welsch, *SiPM response to long and intense light pulses, Nucl. Instr. Methods A* (2015) **787**, p. 148 [http://dx.doi.org/10.1016/j.nima.2014.11.079].

[6] S. Vinogradov, *Probabilistic analysis of Solid State Photomultiplier performance, in proceedings of Advanced Photon Counting Techniques VI, SPIE 2012* **8375**, p. 83750S, Baltimor, USA, 2012 [http://dx.doi.org/10.1117/12.919971].

[7] W. Feller, *An introduction to probability theory and its applications*, Vol. II, Ch. XI-XIV, Second edition, John Wiley & Sons Inc., New York, 1971.