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SiPM response to long and intense light pulses

S. Vinogradov [a,b,*], A. Arodzero [c,d], R.C. Lanza [c], C.P. Welsch [a]

[a] University of Liverpool and Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Warrington WA4 4AD, UK
[b] P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 119991 Leninskiy prospekt 53, Moscow, Russia
[c] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA
[d] RadiaBeam Technologies Inc., 1717 Stewart St., Santa Monica, CA 90404, USA

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ABSTRACT

Recently Silicon Photomultipliers (SiPMs) have become well recognized as the detector of choice for various applications which demand good photon number resolution and time resolution of short weak light pulses in the nanosecond time scale. In the case of longer and more intensive light pulses, SiPM performance gradually degrades due to dark noise, afterpulsing, and non-instant cell recovering. Nevertheless, SiPM benefits are expected to overbalance their drawbacks in applications such as X-ray cargo inspection using Scintillation-Cherenkov detectors and accelerator beam loss monitoring with Cherenkov fibres, where light pulses of a microsecond time scale have to be detected with good amplitude and timing resolution in a wide dynamic range of 10^5–10^6.

This report is focused on transient characteristics of a SiPM response on a long rectangular light pulse with special attention to moderate and high light intensities above the linear dynamic range. An analytical model of the transient response and an initial consideration of experimental results in comparison with the model are presented.

1. Introduction

In the last decade Silicon Photomultipliers (SiPMs) have become well recognized as very competitive photodetectors due to their unique photon number resolution at room temperature, exceptional single photon time resolution, low operating voltages, compactness, and insensitivity to magnetic fields. Detection of short weak light pulses of nanosecond time scale appears to be the best suited for SiPM applications because for these signals most of the SiPM drawbacks have rather limited effect on the amplitude and time resolution of the signal. For these reasons, the most popular applications of SiPM technology are short-decay scintillation and Cherenkov light detection in high energy physics (particle calorimeters, Cherenkov telescopes, and imaging arrays) and in nuclear medicine (gamma cameras, positron emission tomography systems, namely PET/MRI, TOF-PET scanners) [1,2]. These applications require only very limited information to be extracted from a photodetector output signal: the number of photons and/or arrival time of the light pulse, and nothing else, because the pulse shape is not a subject of measurement.

In the case of detecting relatively long pulses starting from the microsecond time scale, the SiPM performance in photon number resolution is considerably affected by noise contributions from afterpulsing and dark counts as well as by losses of the detected photons due to non-instant cell recovery and a limited number of cells. Detection of arbitrary waveform light signals in order to reconstruct an input signal temporal structure from an output seems to be an especially challenging application for SiPM. At very low light intensity SiPM should be competitive with mature photon counters of much higher photon detection efficiency and much lower dark count rate (e.g. PMT and Geiger mode APD). At high light intensity SiPM should be competitive with a variety of conventional photodetectors (e.g. linear mode APD and PIN) of much higher photon detection efficiency, much wider dynamic range, and higher bandwidth. Nevertheless, there are some mixed applications which demand arbitrary signal waveform detection with photon number resolution where SiPM is expected to be more beneficial than other photodetectors.

X-ray cargo inspection with Scintillation-Cherenkov detectors is one such challenging application because good amplitude and timing resolution of a temporal structure of a light signal is required to reconstruct an absorption profile inside a cargo under test [3–5]. In such inspection systems, the intensities of scintillation and Cherenkov signals in detectors can vary by as much as 1:100,000 due to highly variable X-ray absorption inside the cargo (Figs. 1, 2).

* Corresponding author at: University of Liverpool and Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Warrington WA4 4AD, UK.
Tel.: +44 19 25 60 31 97; fax: +44 19 25 86 42.
E-mail address: Sergey.Vinogradov@liverpool.ac.uk (S. Vinogradov).

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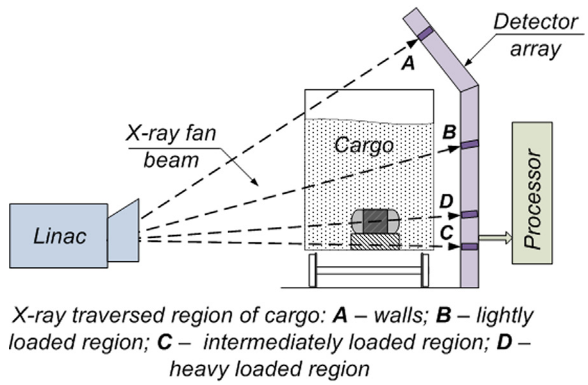

Fig. 1. Scheme of an X-ray accelerator-based cargo inspection system. As a result of a wide range of attenuation paths, the detector output signal intensities can vary by as much as 100,000 to one (reproduced from [5]).

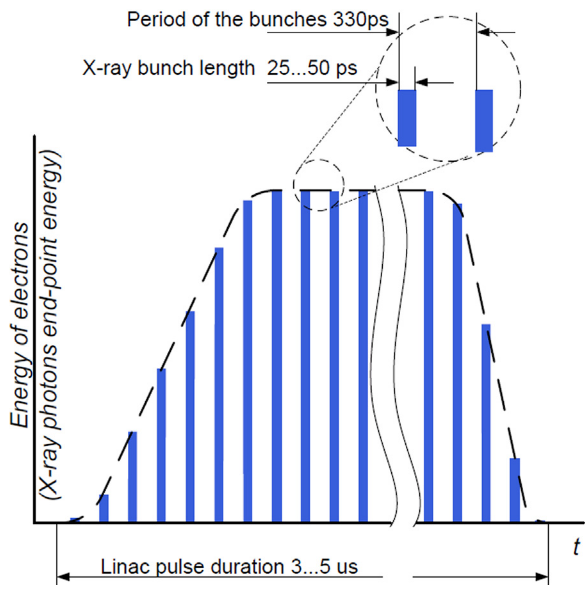

Fig. 2. X-ray pulse produced by typical Linac-based source. Several microseconds duration pulse consists of bunches of X-ray micro-pulses, about 25…50 ps duration each with period about 330 ps (reproduced from [5]).

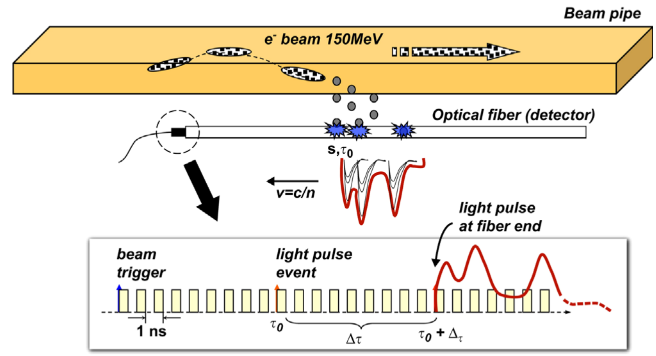

Fig. 3. Beam Loss Monitoring schematic: a beam line with relativistic electrons, Cherenkov optical fibre with Cherenkov photon detector (MPPC) at the upstream fibre end, and input/output pulse timing profiles (reproduced from [6]).

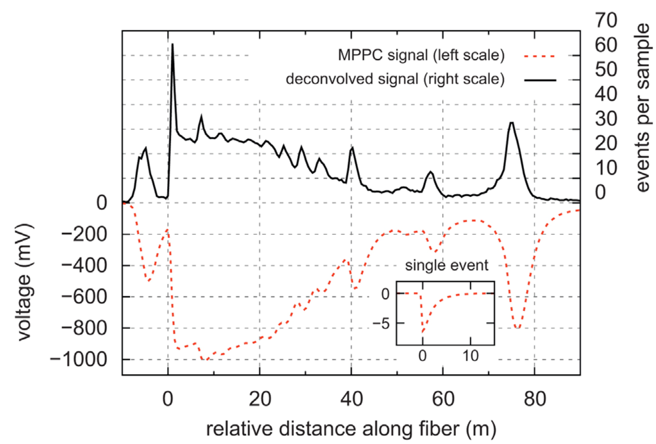

Fig. 4. MPPC output response at the BLM: raw MPPC signal (dashed line, left scale) and after deconvolution with single electron pulse shape (solid line, right scale) (reproduced from [6]).

An initial analysis for the possible application of SiPM (MPPC) in a cargo accelerator-based inspection system has been presented in our earlier report [5]. This report was focused on energy resolution with a special attention to SiPM nonlinearity and saturation effects.

Accelerator beam loss monitoring (BLM) using a Cherenkov fibre and SiPM readout (Fig. 3) is another application with arbitrary waveform light signals of very wide dynamic range ($\sim 10^6$) from a few Cherenkov photons up to a few percent fraction of destructive losses in an accelerator [6,7]. Light pulse shape at the fibre output is in general unpredictable as it reflects the location of beam losses in about 100 m long Cherenkov fibre placed in parallel with the beam line. The main goal of the detection is to reconstruct initial light intensity profile to identify beam loss location profile alongside the beam line resolving the number of lost particles per location (Fig. 4).

This report is focused on the SiPM response dynamics and transient characteristics for the long light pulse detection ($T_{pulse} > T_{rec}$, where T_{pulse} is a light pulse duration, and T_{rec} is a cell recovery time). Special attention has been paid to high light intensities approaching to SiPM saturation level. It would be worth to note that such a case has been out of scope for most SiPM studies up to now except just a few examples [8].

2. Method

2.1. Experiment

Experiments have been carried out with rectangular pulses (8 ns rise & fall times) of 440 nm from an LED with variable intensity, repetition rate, and pulse width (nanosecond to microsecond time scale range). The light illuminated over the MPPC was uniformly distributed. The SiPM light response was read out without a preamplifier to avoid any possible nonlinearities and saturation at high output signal level. The SiPM anode was directly connected to a 50 Ω oscilloscope input of DC to 1 GHz analogue bandwidth and grounded through 50 Ω inside an acquisition box for an appropriate coupling.

For calibration of an output signal in single electron response (SER) units, the SER amplitudes have been measured with 20 dB, 4 GHz external amplifier Mini-Circuits ZX60-4016E+.

Hamamatsu MPPC S10362-33-050 C 3×3 mm^2 of 50 μm cell size has been used as a well-known and very popular representative of SiPM technology.

2.2. Model

To the best of our knowledge, there are no models for arbitrary waveform detection by SiPMs except some Monte Carlo simulations and electrical circuit models [9,10]. However, SiPM performance in photon number and time resolution in the case of short pulse detection is comprehensively modelled due to its high practical importance [11,12], but results have rather limited applicability to