PDE Measurement for Digital SiPMs: Comparison Between Pulsed And Continuous Light Methods

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University of Sherbrooke

ICASiPM, June 12th 2018

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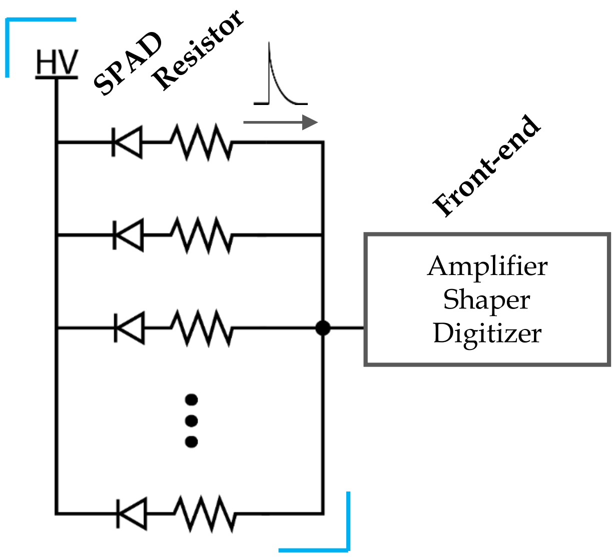
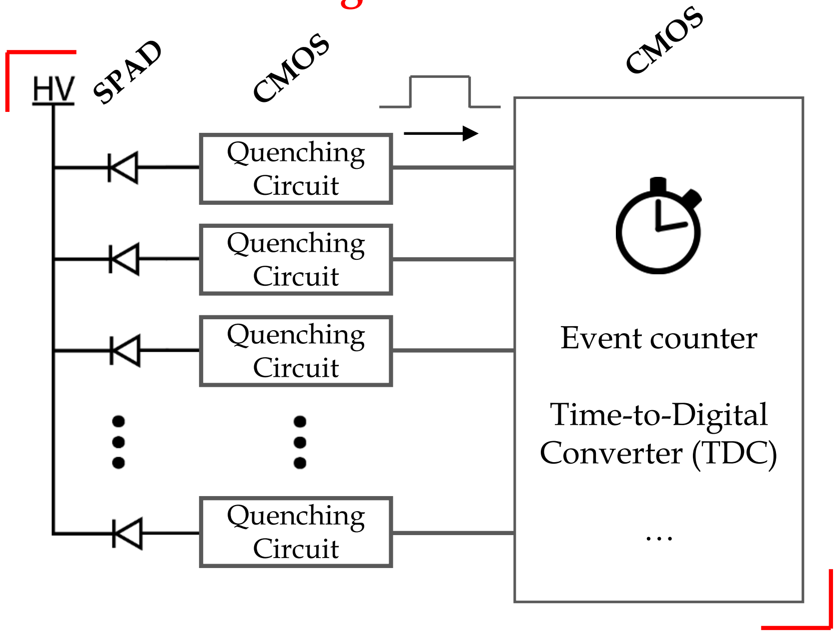
GRAMS

Terminology

Analog SiPM



Digital SiPM



Analog SiPM :

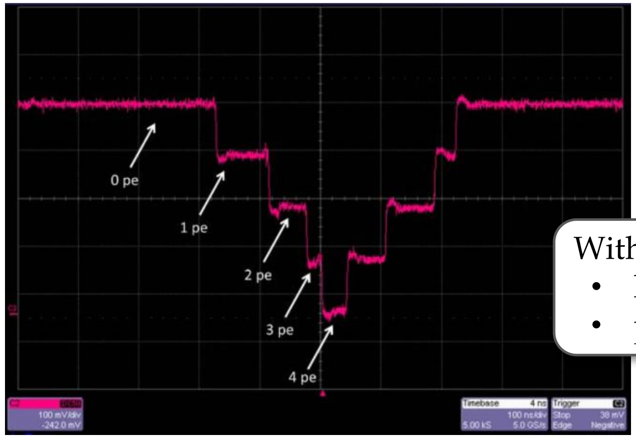
- each SPAD is coupled 1 to 1 to a passive quenching resistor
- SPAD signals are summed up to a common reading node before amplification, shaping and digitization

Digital SiPM :

- each SPAD is coupled 1 to 1 to a CMOS quenching circuit (QC)
- each QC ouput is read and digitalized (event counter, TDC, SPAD address, etc.)

Typical data outputs in a digital SiPM

Analog monitor (current sum)



With control over :
- hold-off time
- pulse amplitude

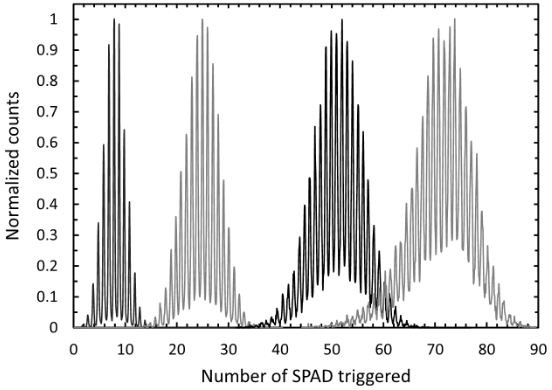
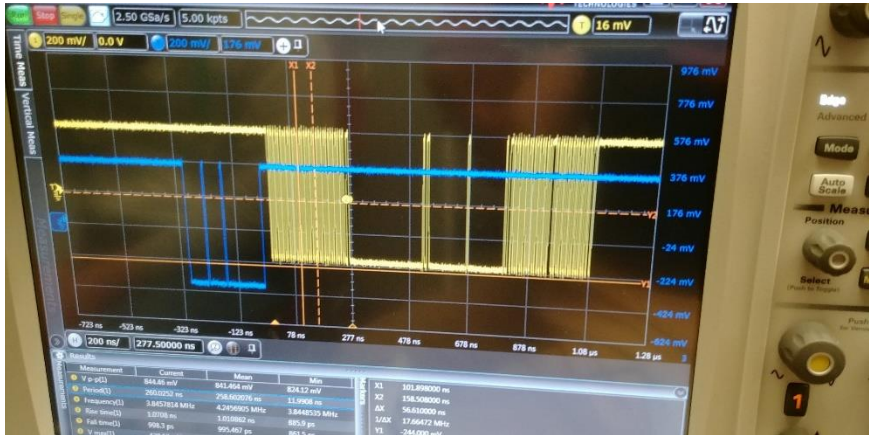


Fig. 11. Charge histogram for four different light intensities with clear steps of 0 to 90 SPADs triggered at the same time showing the single photon resolution capability of the digital SiPM. **[Nolet 2016] doi:** 10.1109/TNS.2016.2582686

Fully digital communication : 4 x 64-bit data frame




```
AAAAAAAAAAAAAAAA
0000000000000000
0009073DF45802FF
AAAAAAABAAAAAAAB
```

- Start frame
- SiPM address
- Event counter
- Timestamps
- SPAD address
- Stop frame

Custom communication protocol for PET scanner

Typical data outputs in a digital SiPM

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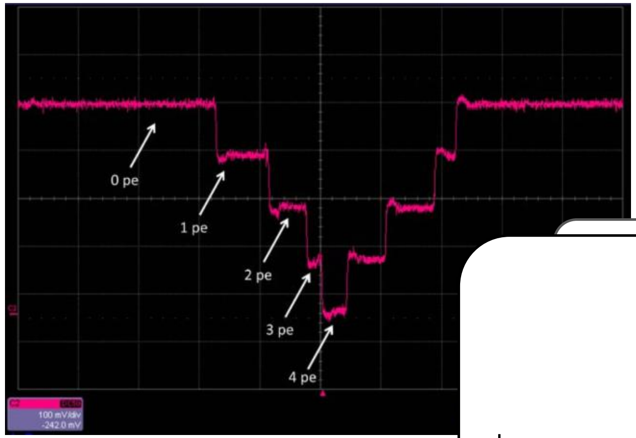

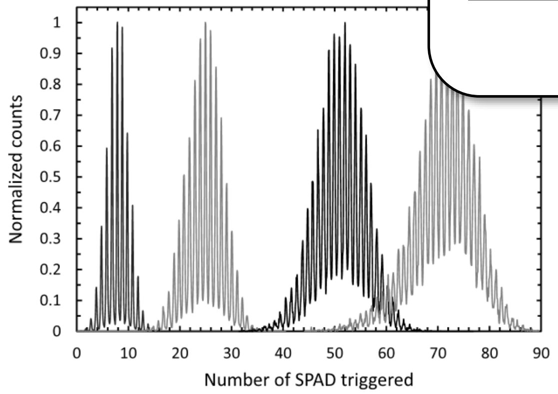

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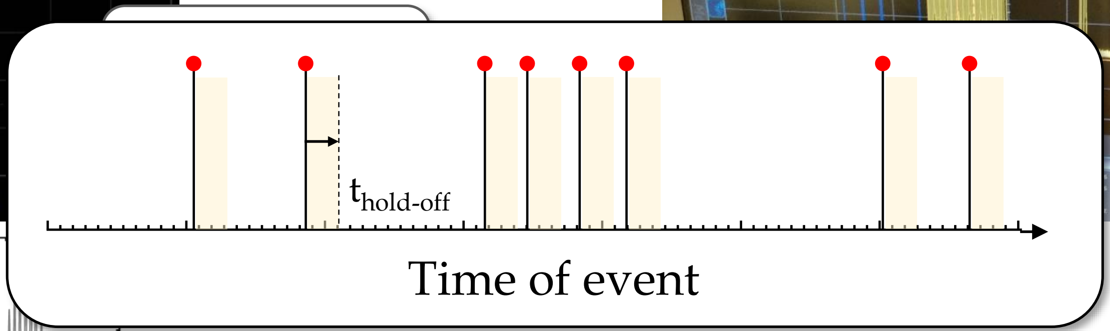

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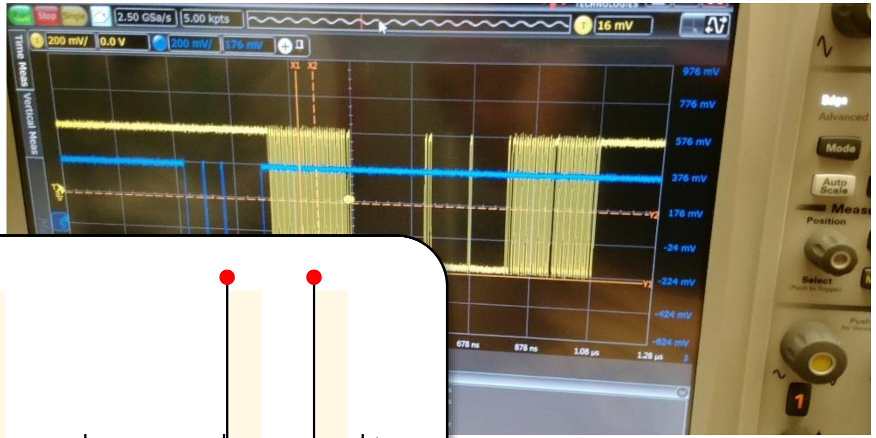


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Custom communication protocol for PET scanner

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SiPM Photon Detection Efficiency

Definition of PDE :

$$\mathrm{PDE} = \mathrm{QE}(\lambda) \cdot \mathcal{P}_{\mathrm{BD}}\left(\vec{\mathrm{E}}\right) \cdot \mathrm{FF}$$

where
- QE : quantum efficiency
- $\mathcal{P}_{\mathrm{BD}}$: breakdown initiation probability
- FF : filling factor

Very basics of the PDE measurement :

Ratio between detected photons (N_{ph}) and photons really impinging on the detector (N_{ref}).

$$\mathrm{PDE} = \frac{\mathrm{N}_{\mathrm{photon+dark\ noise}} - \mathrm{N}_{\mathrm{dark\ noise}}}{\mathrm{N}_{\mathrm{ref}}}$$

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Challenge : distinguishing correlated events (afterpulsing, optical crosstalk) from uncorrelated events (thermal noise, photons) otherwise → PDE overestimation

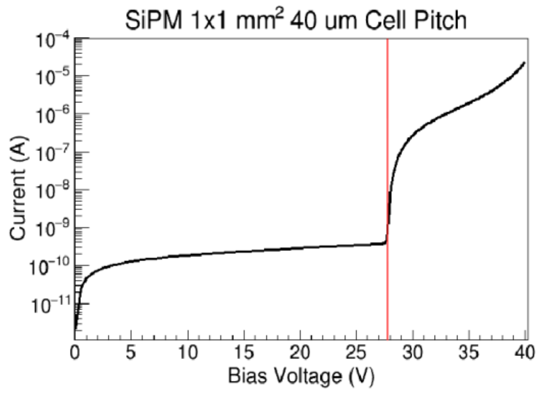
PDE measurement methods

Methods commonly used in the literature :

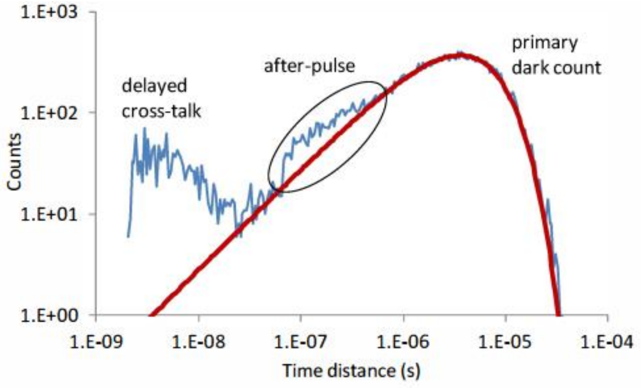
- Photocurrent method : IV characteristics [Zappalà 2016]

- Continuous-light counting method : Time delays distribution [Piemonte 2012]

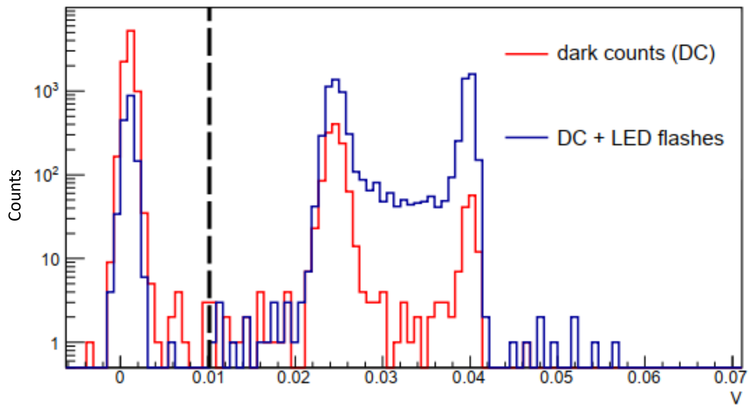
- Pulsed-light counting method : Pedestal peak of charge spectrum [Otte 2017, 2006]



[Zappalà 2016] doi: 10.1088/1748-0221/11/08/P08014



[Piemonte 2012] doi: 10.1109/NSSMIC.2012.6551141



[Otte 2017] doi: 10.1016/j.nima.2016.09.053

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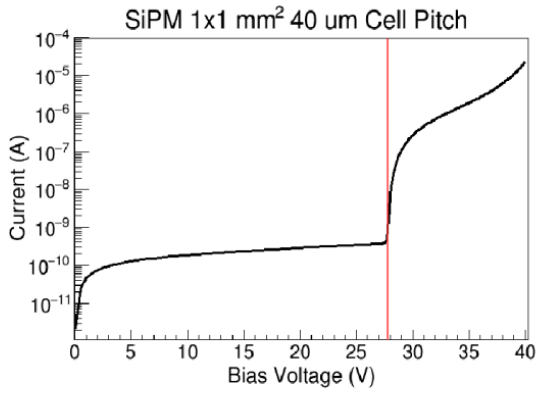

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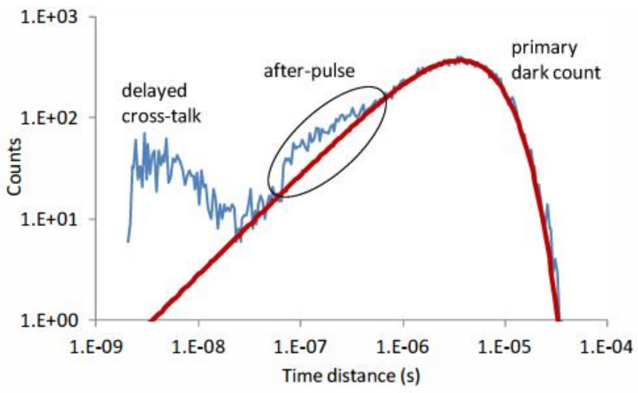

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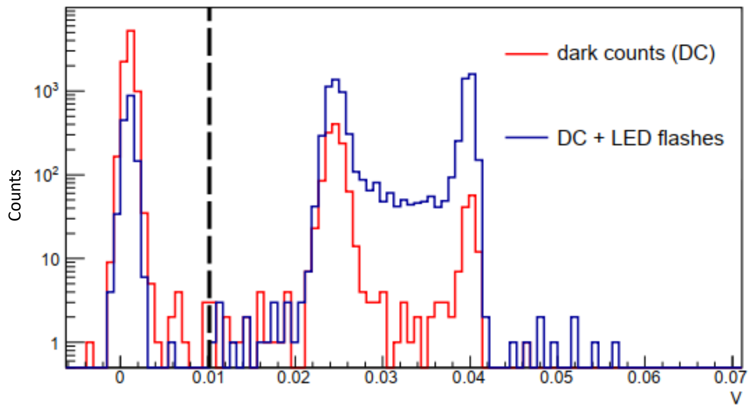

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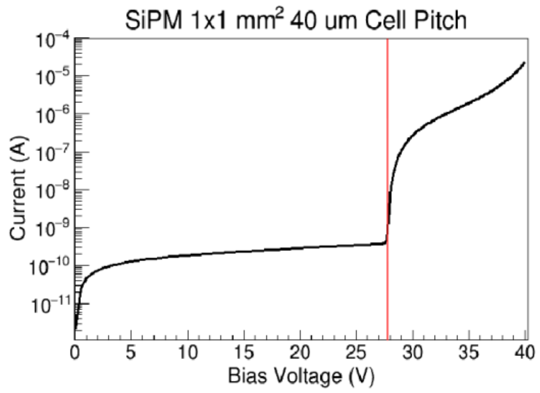
} Compare their applicability to digital SiPM



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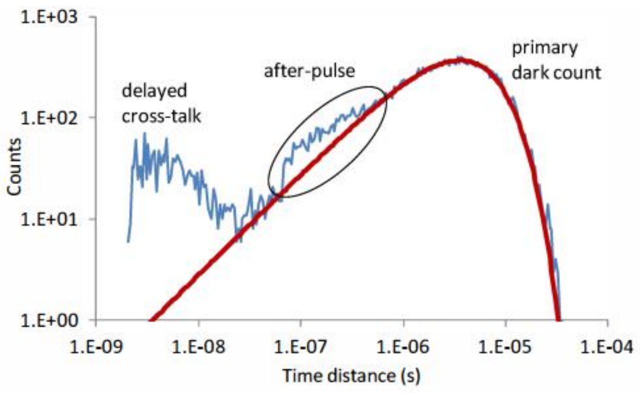

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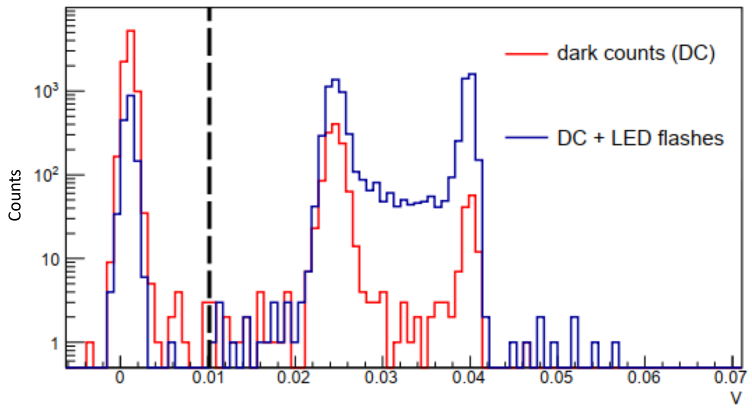

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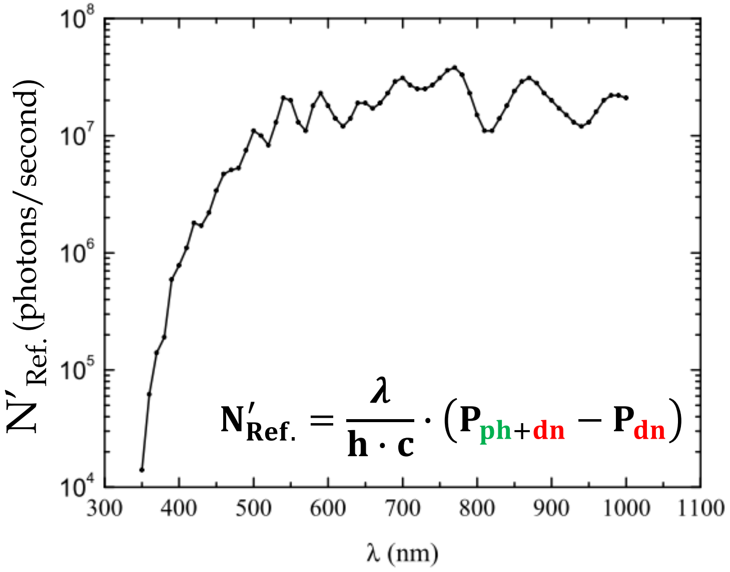
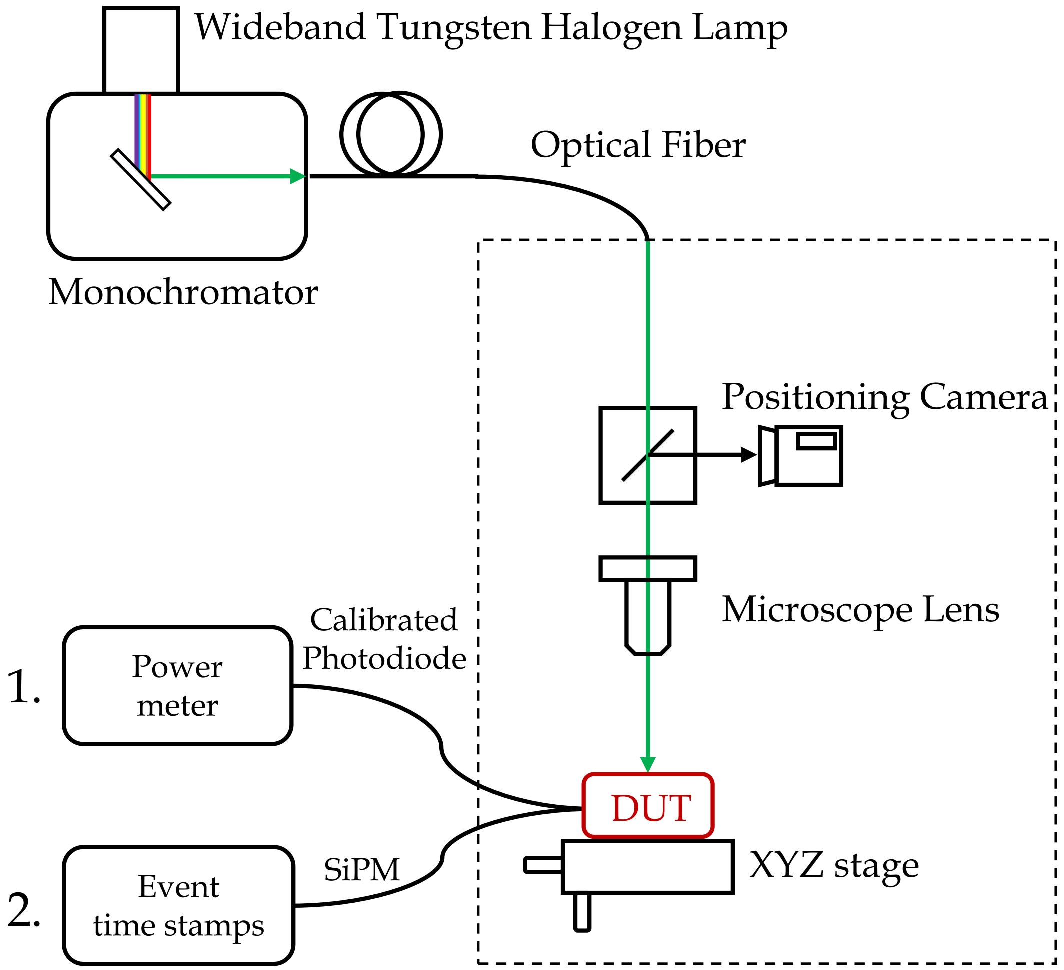
Setup

Two steps measurement using continuous light

1. Measure light intensity with a calibrated photodiode



2. Record SiPM event time stamps and calculate the rate of uncorrelated events using either methods



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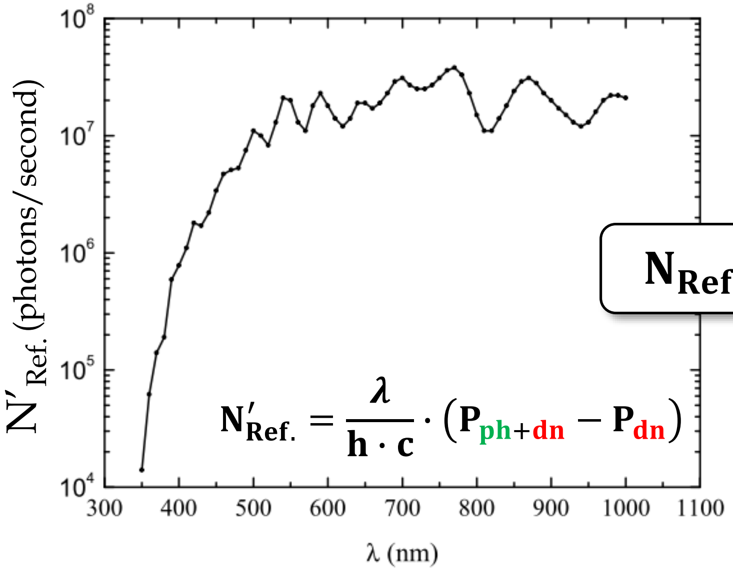
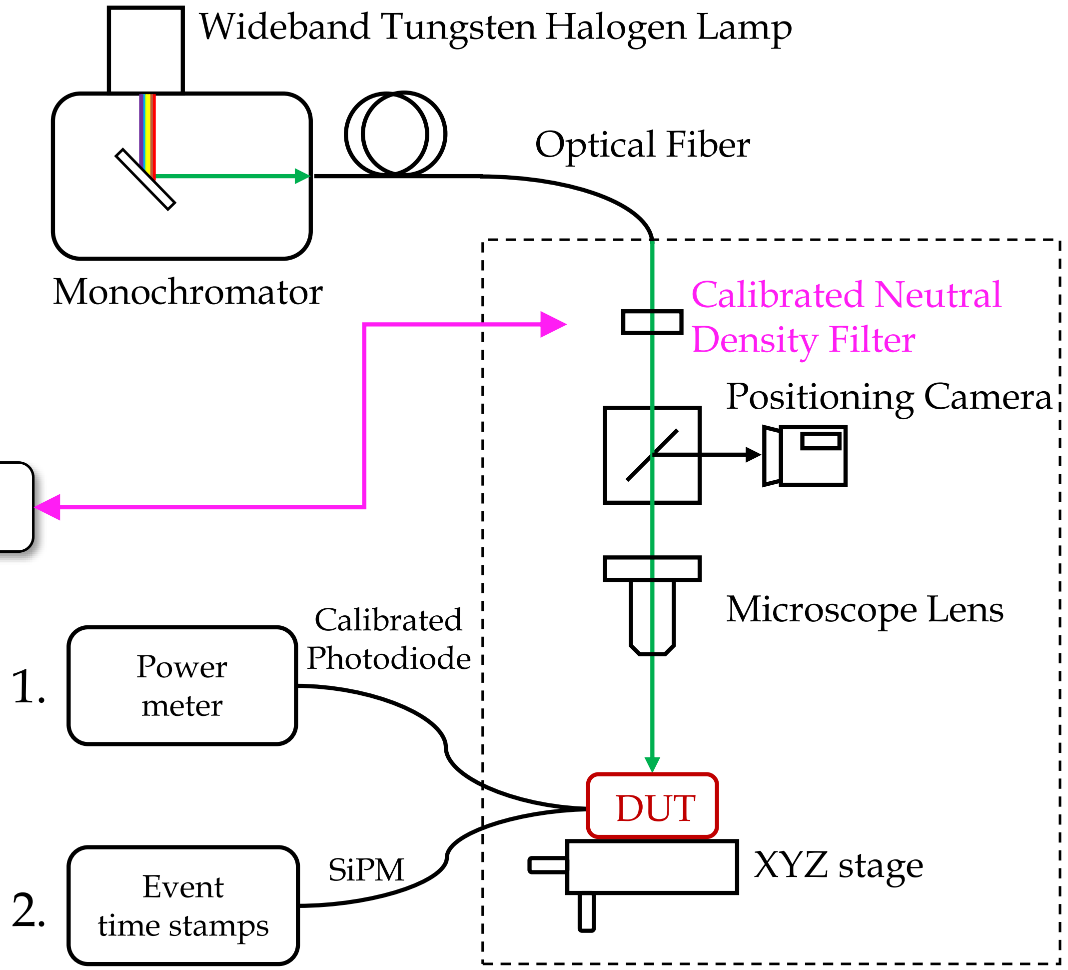


$$N'_{Ref.} = \frac{\lambda}{h \cdot c} \cdot \left(P_{ph+dn} - P_{dn}\right)$$

$$N_{Ref.} = N'_{Ref.} \cdot \left(1 - T_{NDF}(\lambda)\right)$$



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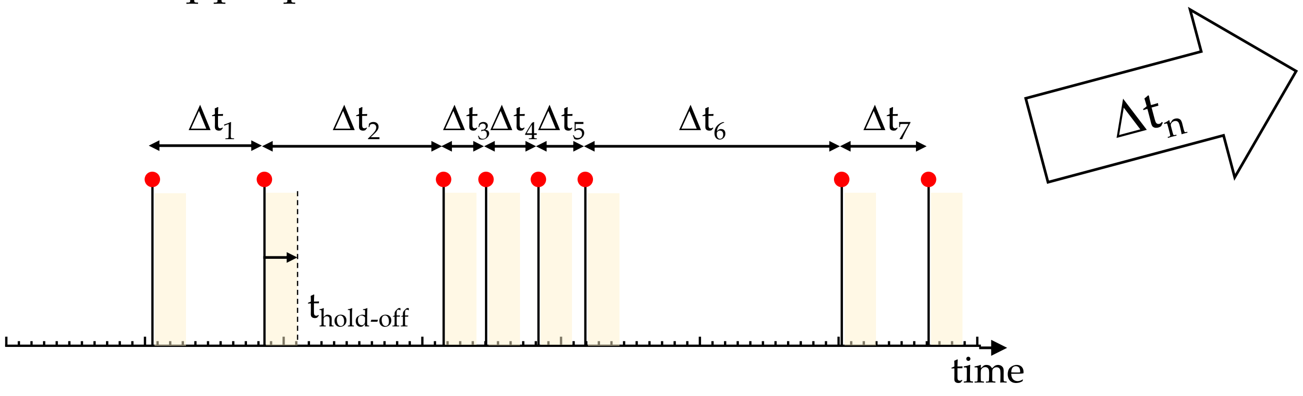
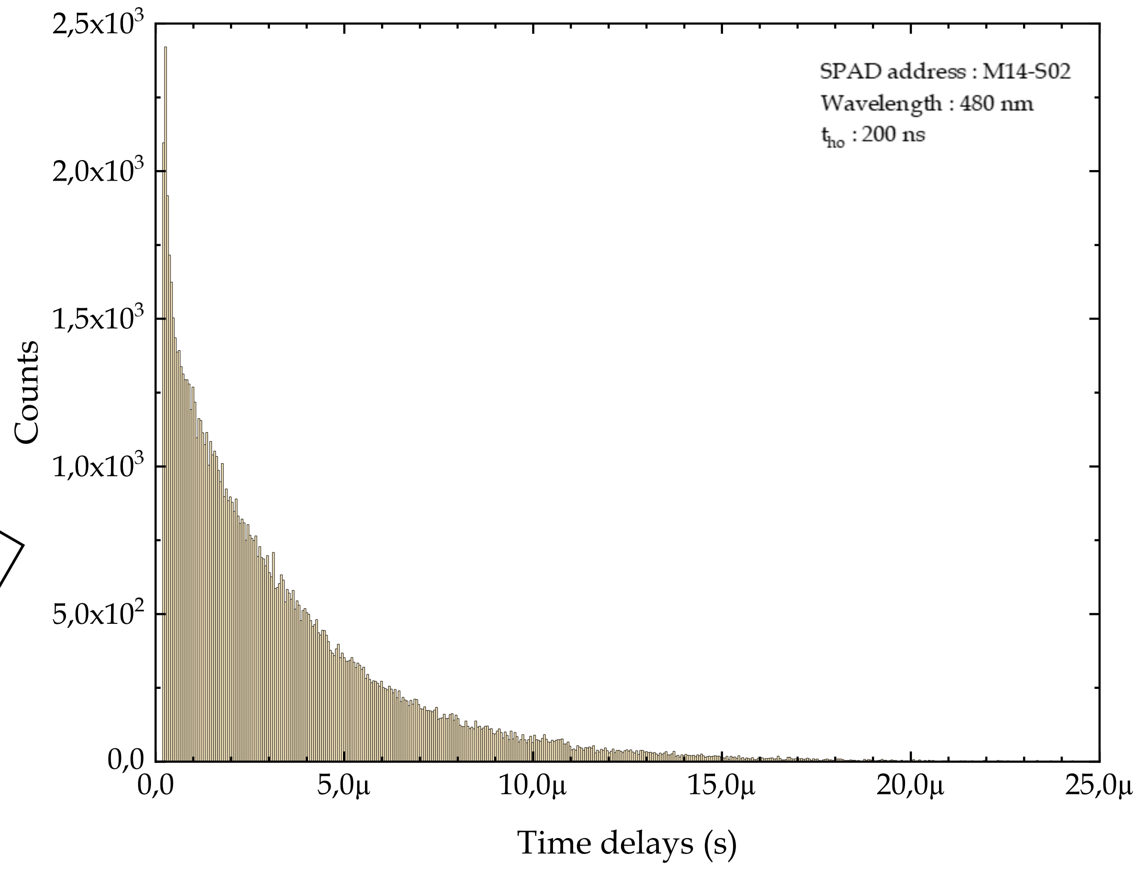
Continuous-light counting method

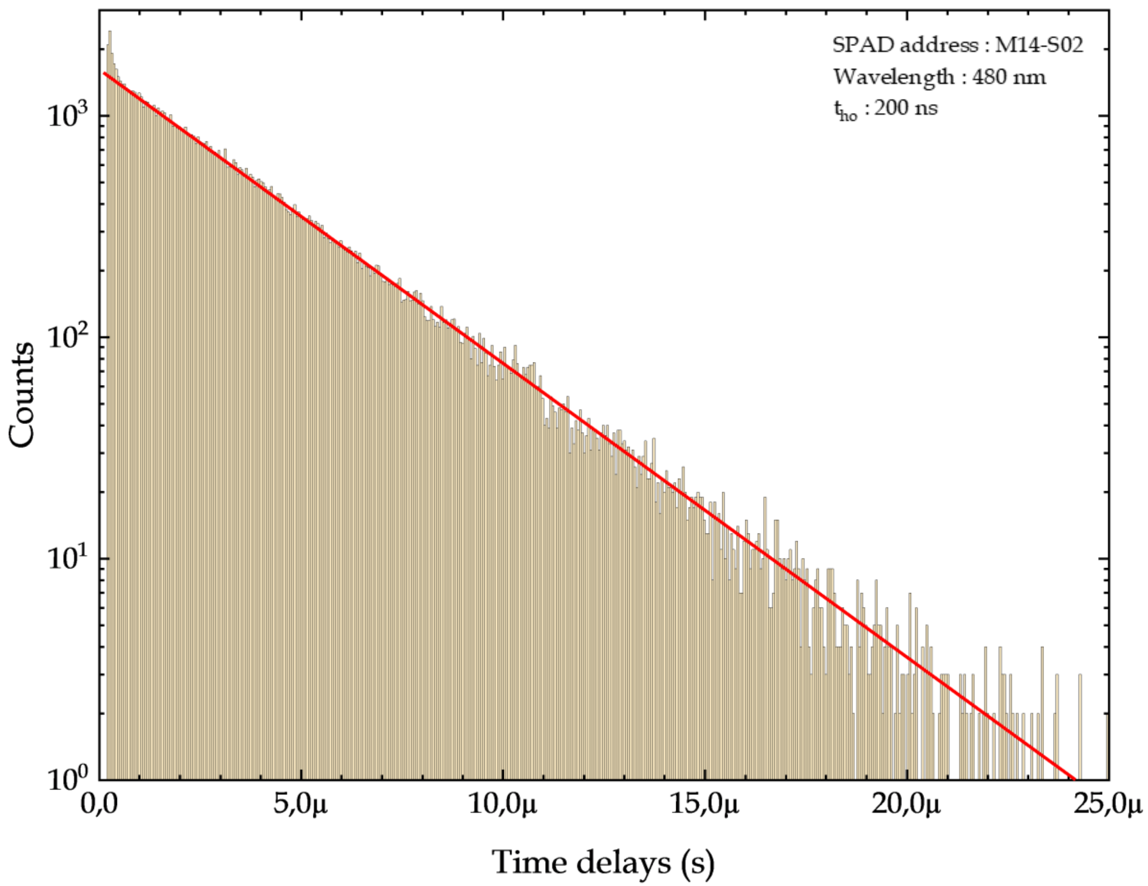
- Measure time delays between consecutive events
- Build a Δt histogram : according to Poisson statistic, time delays of uncorrelated events (thermal noise or photons) will follow an exponentially decreasing distribution
- Extract uncorrelated events from correlated events with the appropriate fit.



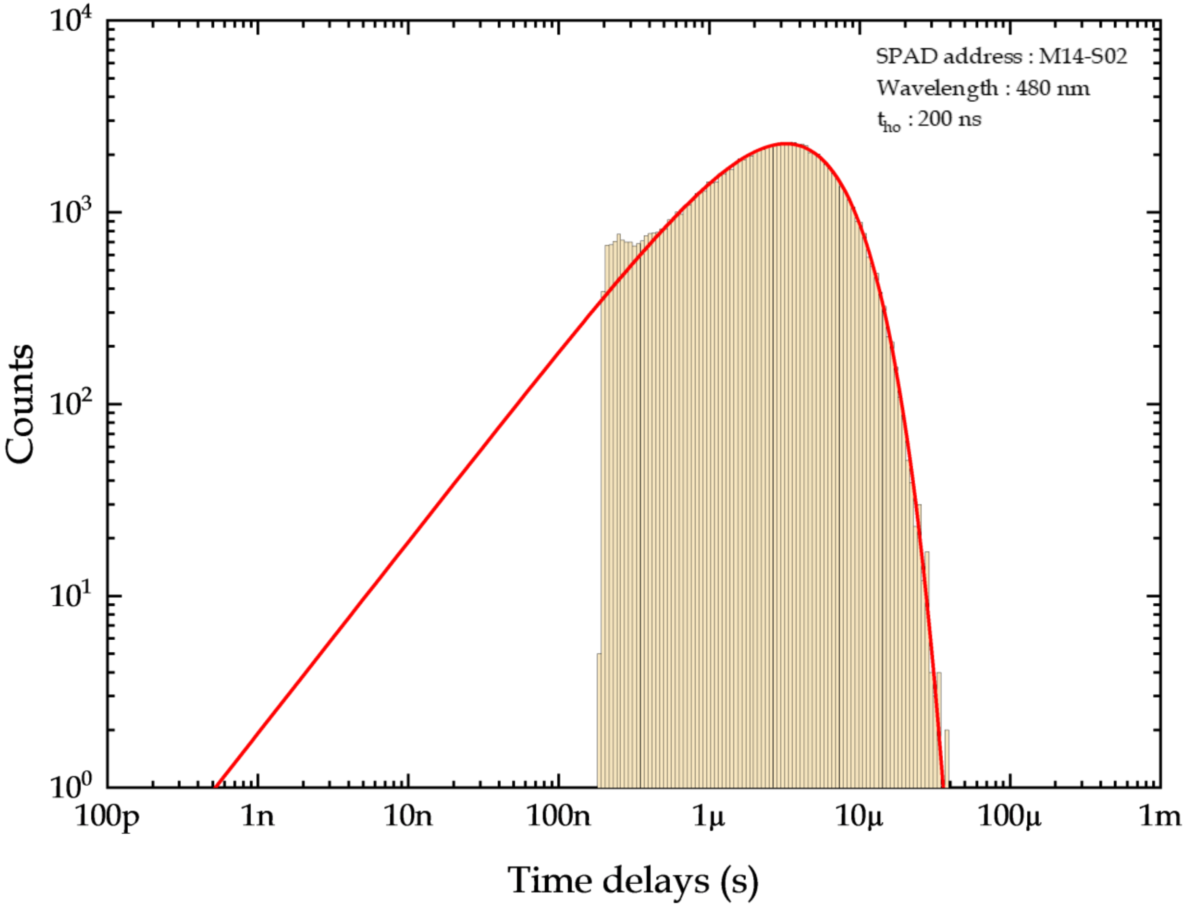


Continuous-light counting method

Log Y-axis and Linear X-axis



Log Y-axis and Log X-axis



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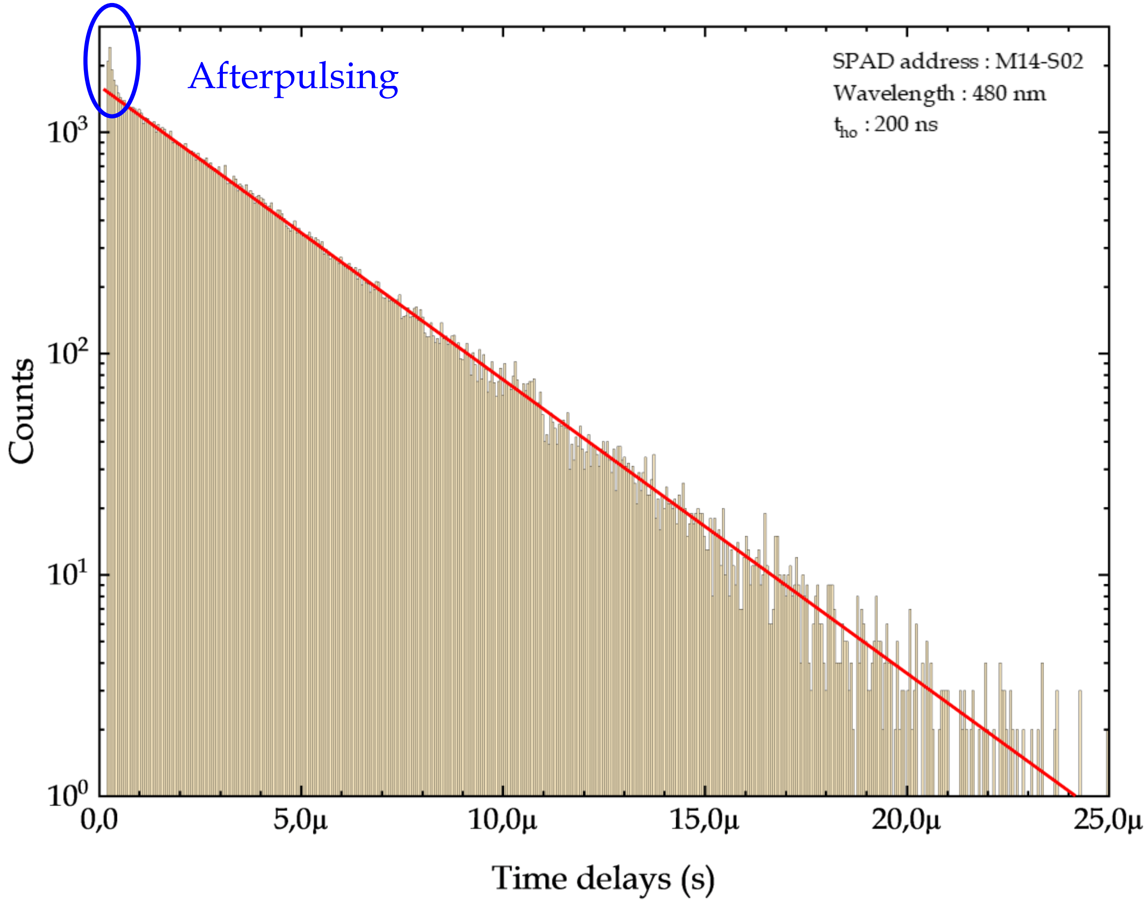

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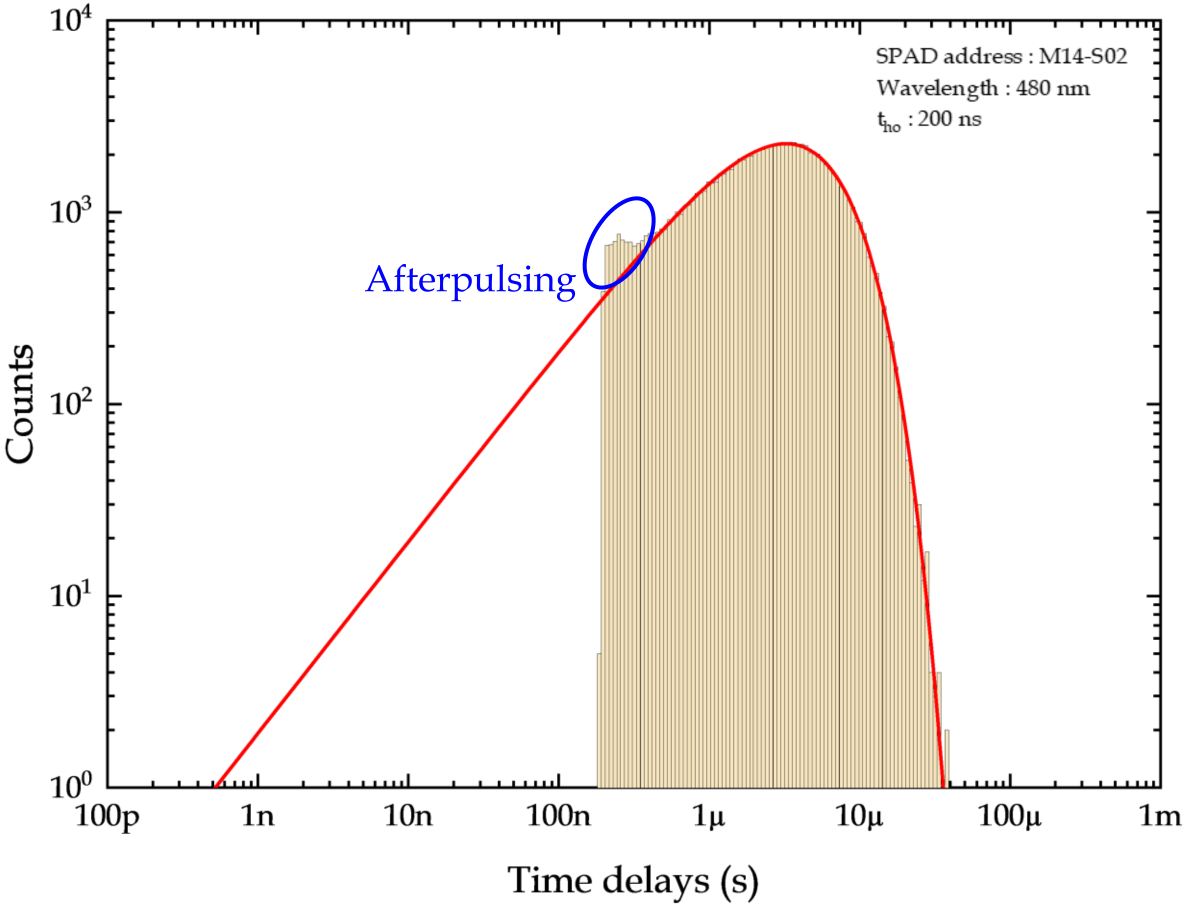

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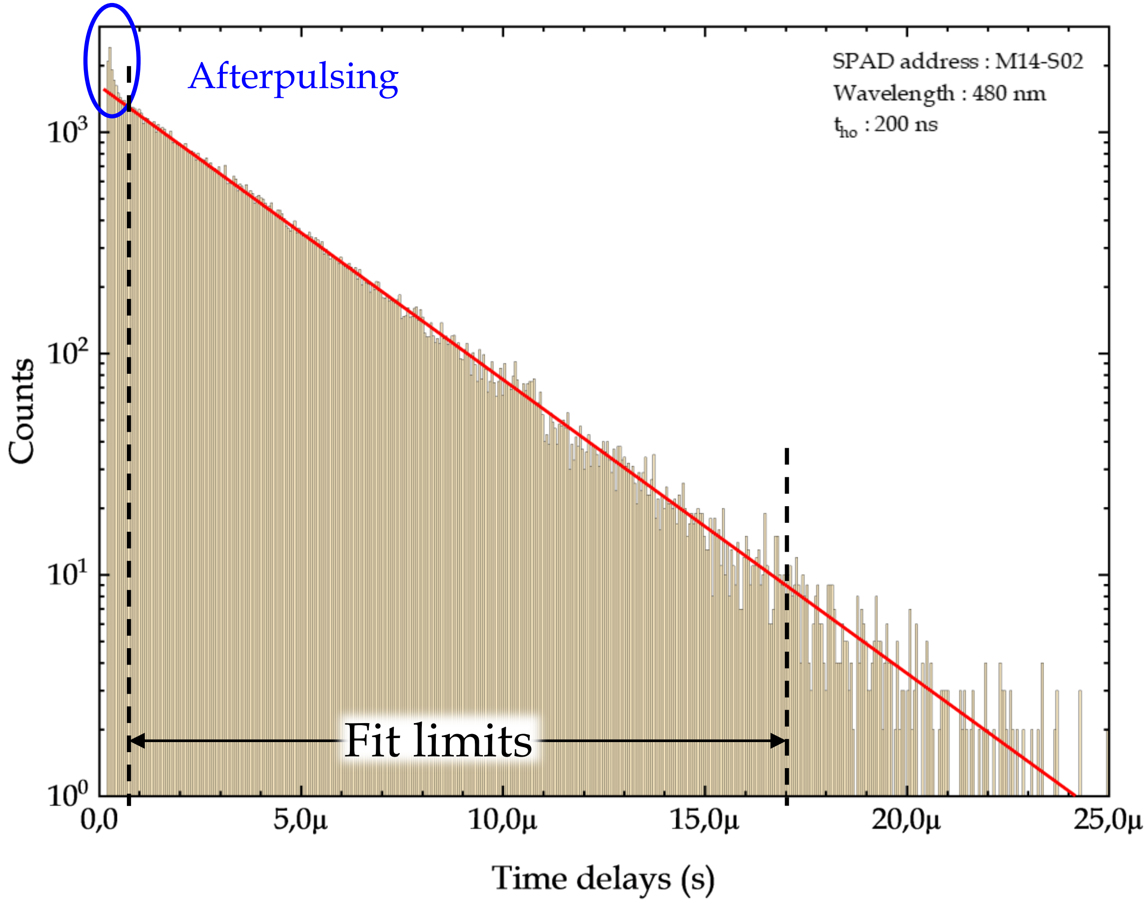

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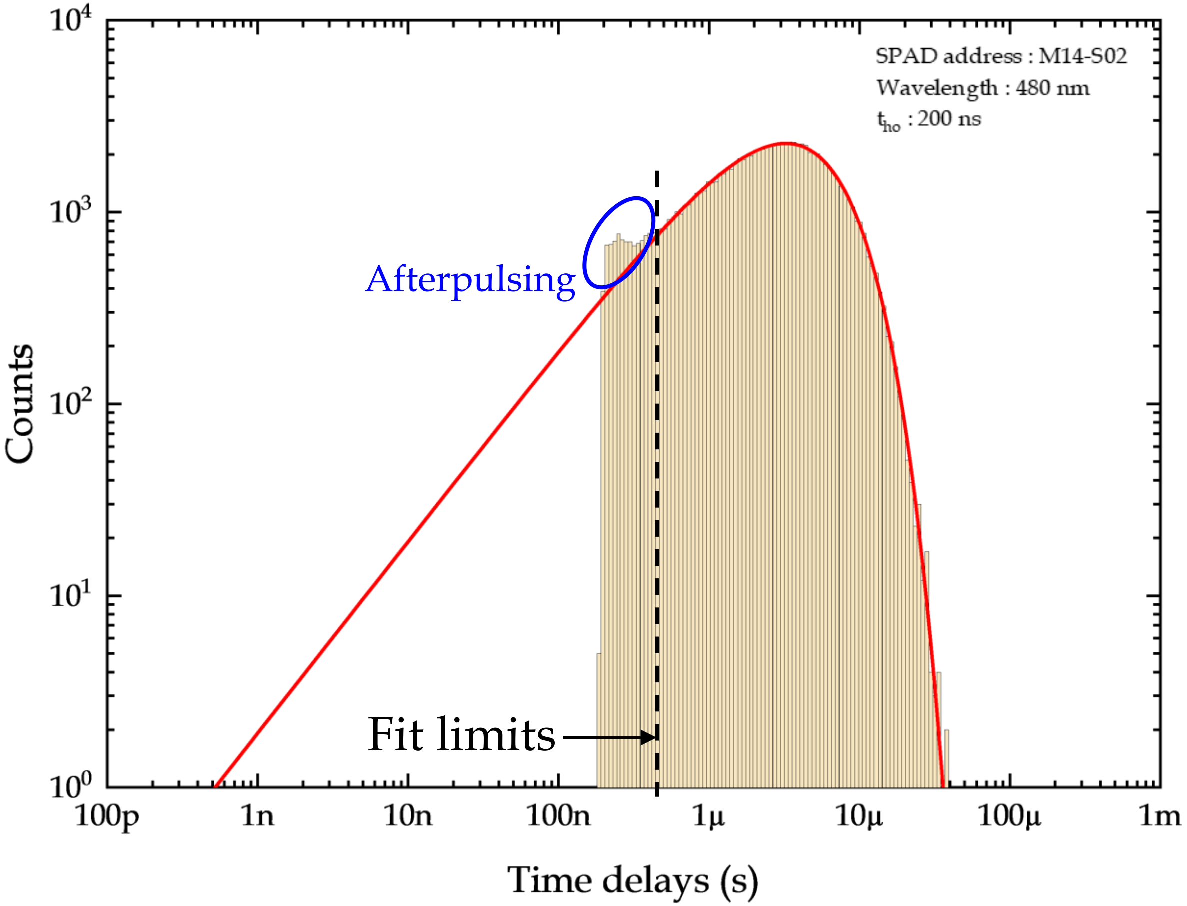
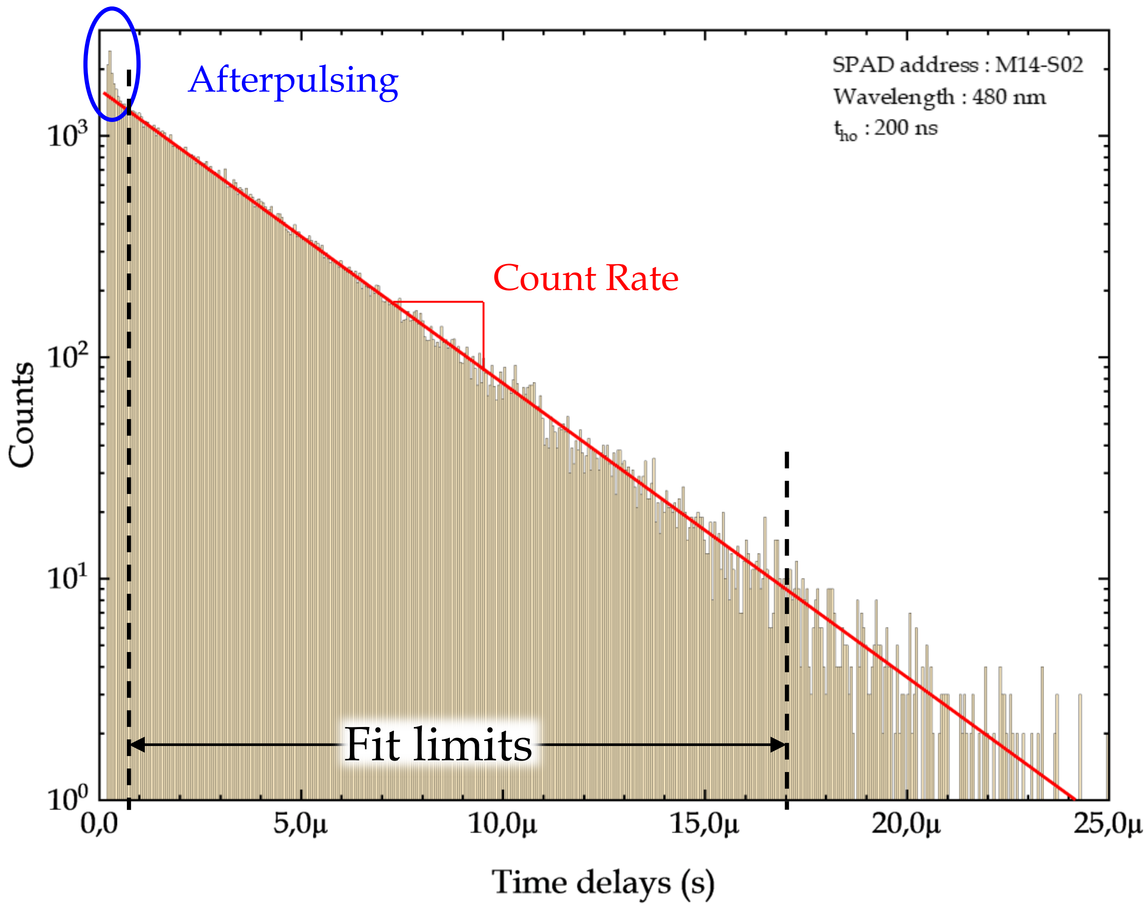
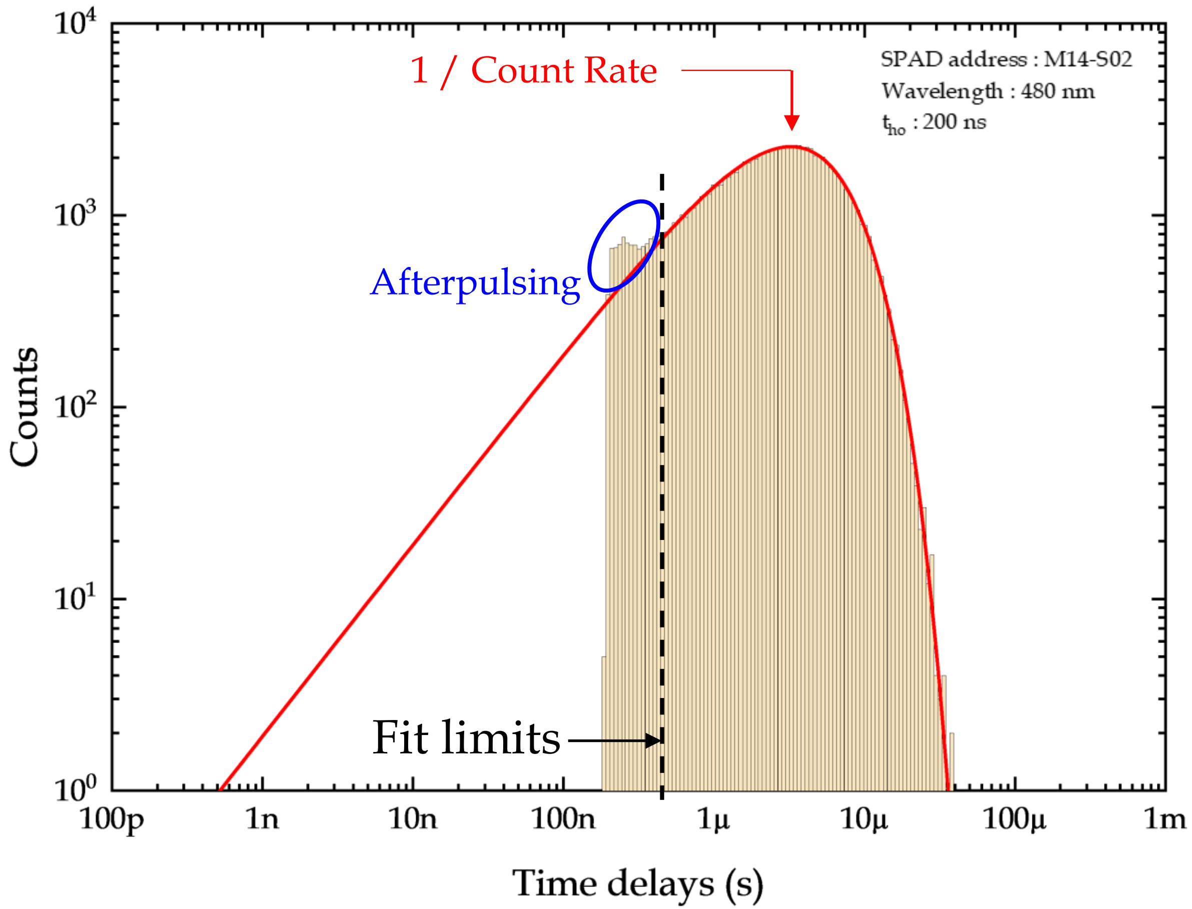


Continuous-light counting method

Log Y-axis and Linear X-axis $y = -CR \cdot t$



Log Y-axis and Log X-axis $y = A \cdot t \cdot \exp(-CR \cdot t)$



Pulsed-light counting method

- Count the number of times where no events were detected during a given interval

- Assuming that uncorrelated events (thermal noise and photons) follow a Poisson distribution, the probability of events is :

$$\mathcal{P}(\text{k events in interval}) = e^{-\mu}\frac{\mu^k}{k!}$$

where
- μ is the average number of events per interval
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The average number of uncorrelated events in a given interval is then :

$$\mu_{ph} = \mu_{ph+dn} - \mu_{dn} = -\ln\left(\frac{N_0^{ph+dn}}{N_{total}}\right) + \ln\left(\frac{N_0^{dn}}{N_{total}}\right) = \ln\left(\frac{N_0^{dn}}{N_0^{ph+dn}}\right)$$

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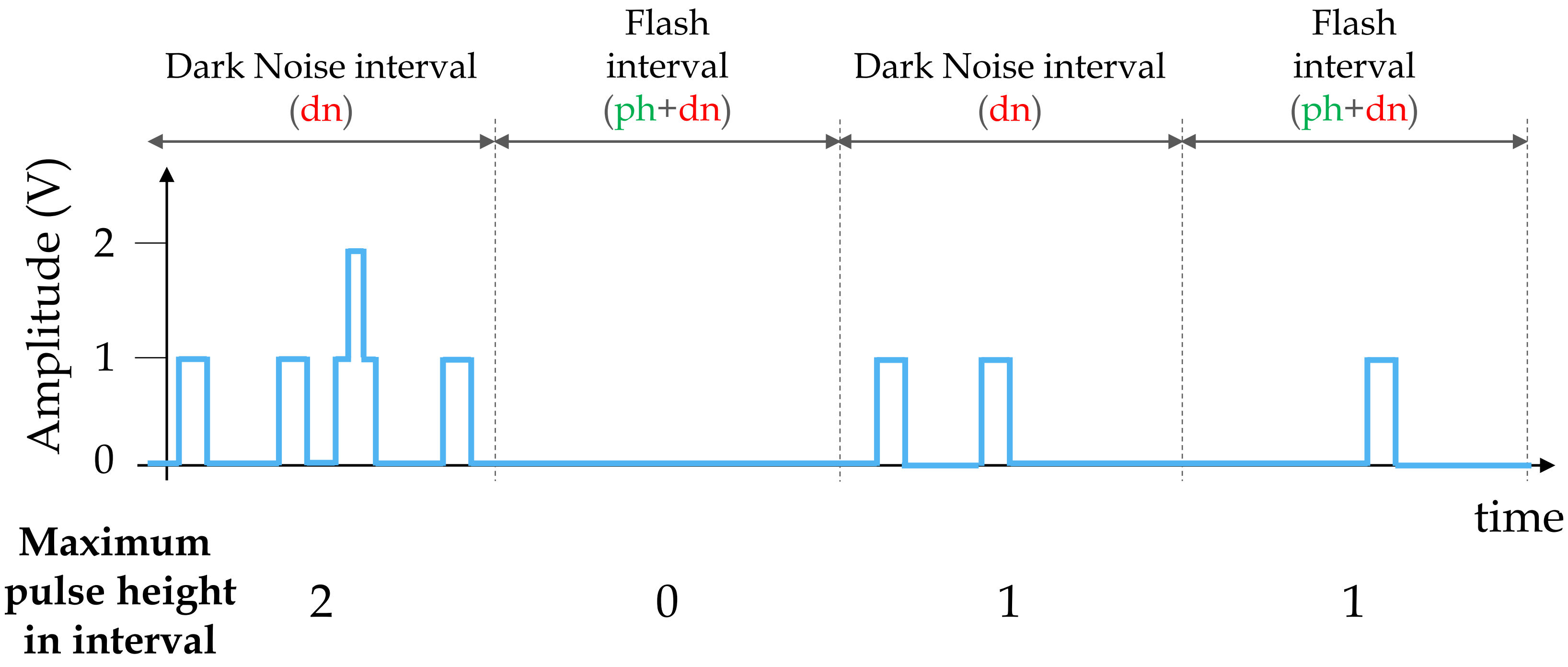
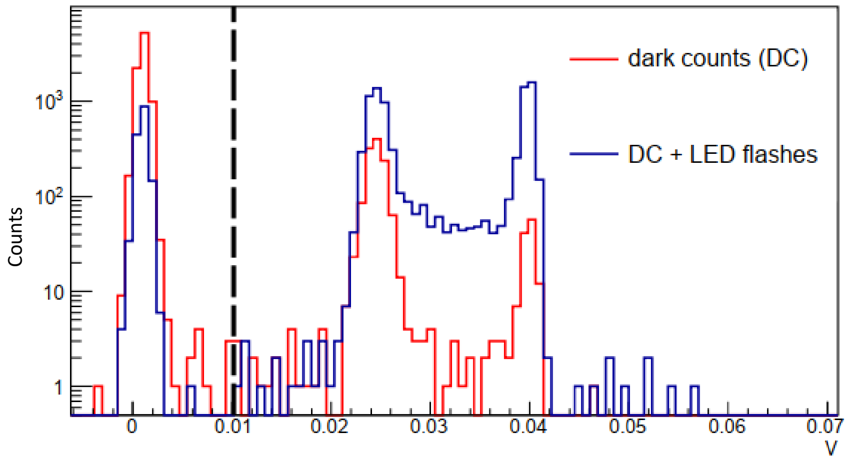
Pulsed-light counting method

- Common procedure for analog SiPM is by flashing a LED so that, in the same data set, some intervals at a known rate contain photon events (μ_{ph+dn}) and some, dark noise events (μ_{dn}).





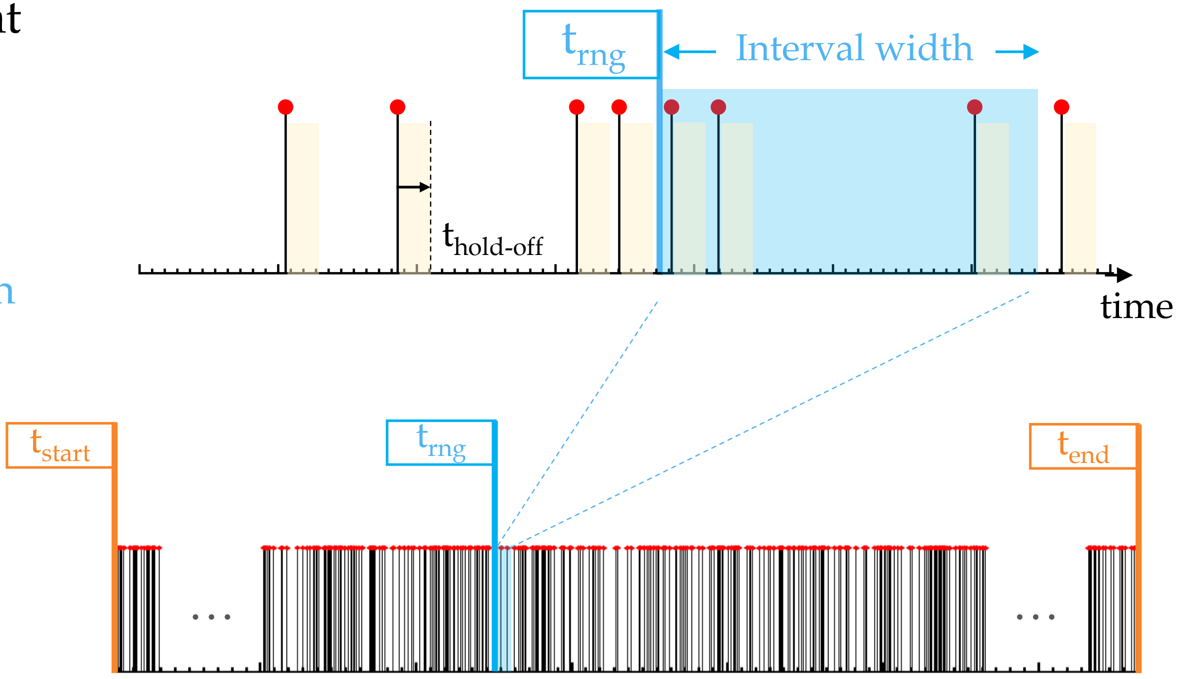
[Otte 2017] doi: 10.1016/j.nima.2016.09.053

Pulsed counting method using a continuous-light source

Different procedure using a <u>continuous-light</u> source with digital SiPM time stamps

1. Acquire 2 time stamps frame : with and without light
2. Sample frame to the event distribution
   a) Draw a random time between given boundaries
   b) Count number of events in a time interval of fixed width
   c) Acquire a large number of intervals
   d) Build a histogram of 0, 1 ,2, …, k events
   e) Extract N_0^{dc}, N_0^{ph+dc} and N_{total}

$$\mu_{ph} = \ln\left(\frac{N_0^{dc}}{N_0^{ph+dc}}\right)$$

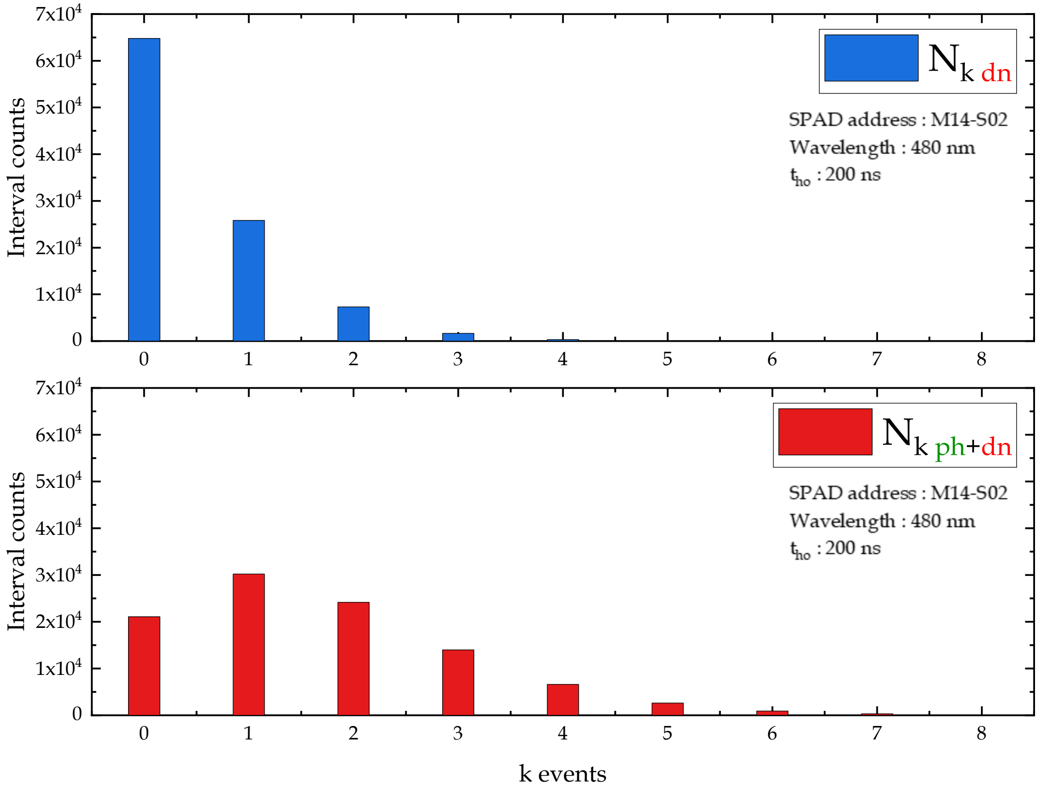


Time stamps frame

Pulsed counting method using a continuous-light source

Extracting N_0 and N_{total}

from time stamps (*Digital SiPM*)



from pulse amplitudes (*Analog SiPM*)

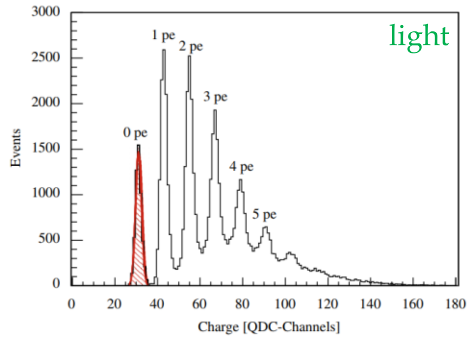


Fig. 3. Single photoelectron spectrum recorded for an MPPC with 1600 pixels. Each peak corresponds to a certain number of photoelectrons (pe).

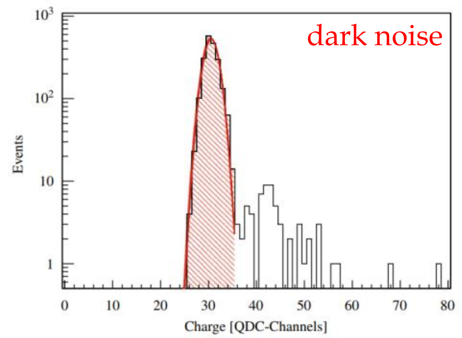


Fig. 4. Thermal noise spectrum, recorded for an MPPC with 1600 pixels. The shaded area corresponds to the number of pedestal events.

[Eckert 2010] doi: 10.1016/j.nima.2010.03.169

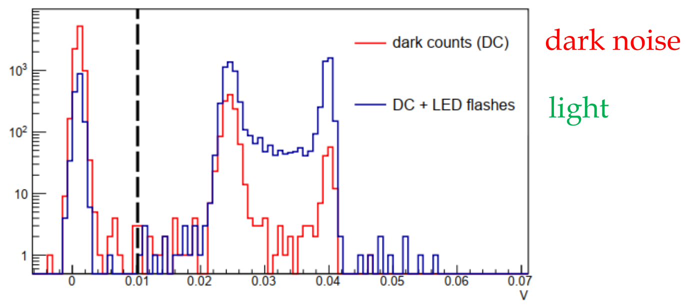


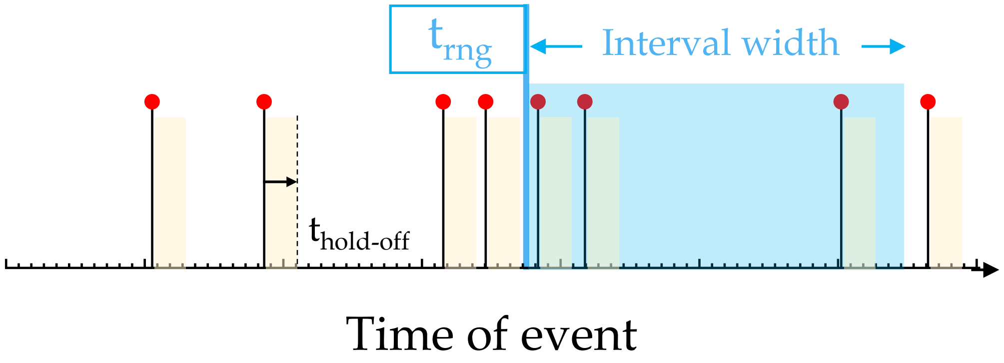
Figure 5: Pulse-height distributions of Hamamatsu SiPM signals recorded in a PDE measurement. See text for details on the signal extraction. A total of 10,000 flashes contribute to each distribution.

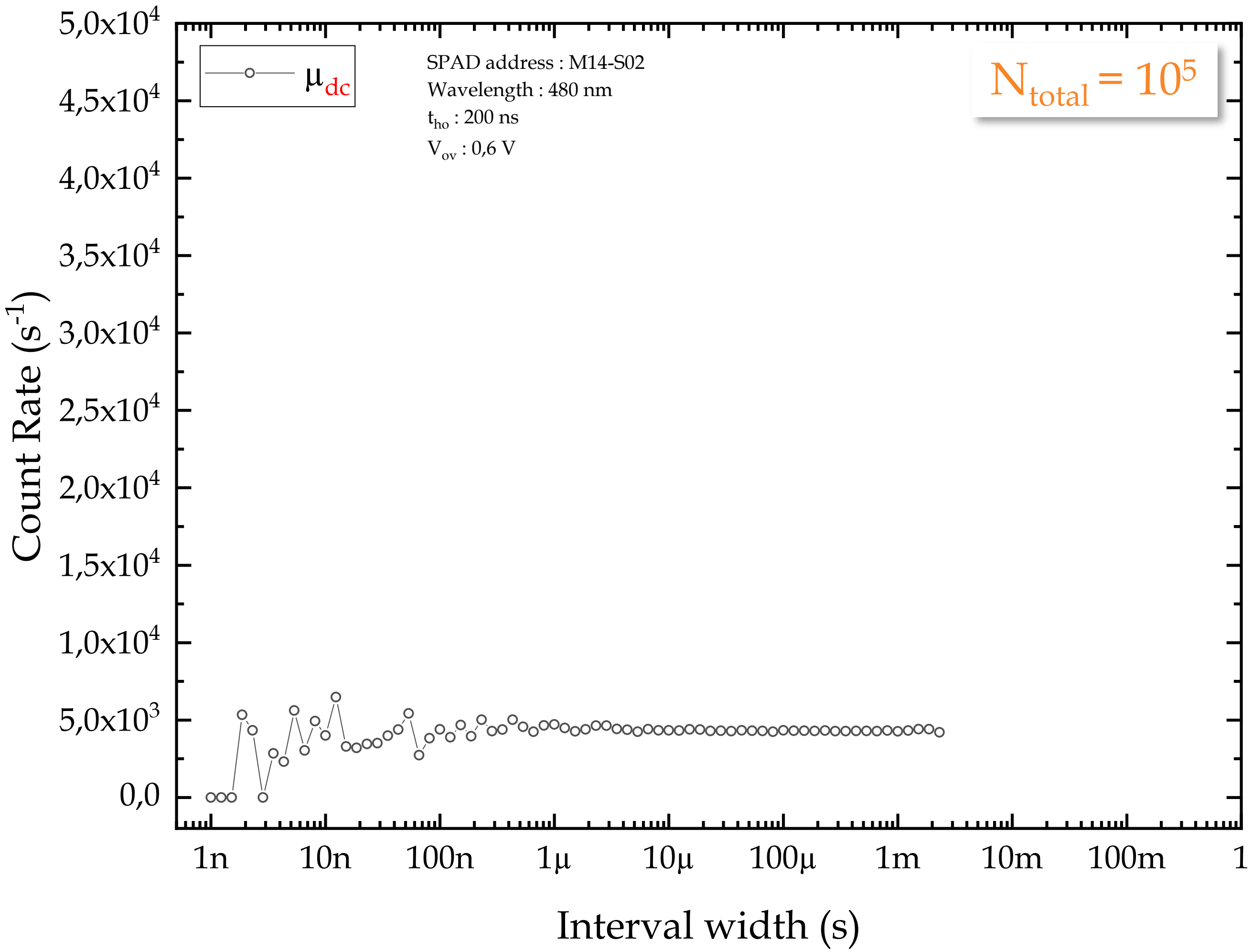
[Otte 2017] doi: 10.1016/j.nima.2016.09.053

Pulsed counting method using a continuous-light source

Dependence on interval width

- Interval width is chosen where the count rate plateaus
- Number of total intervals taken gives an upper limit





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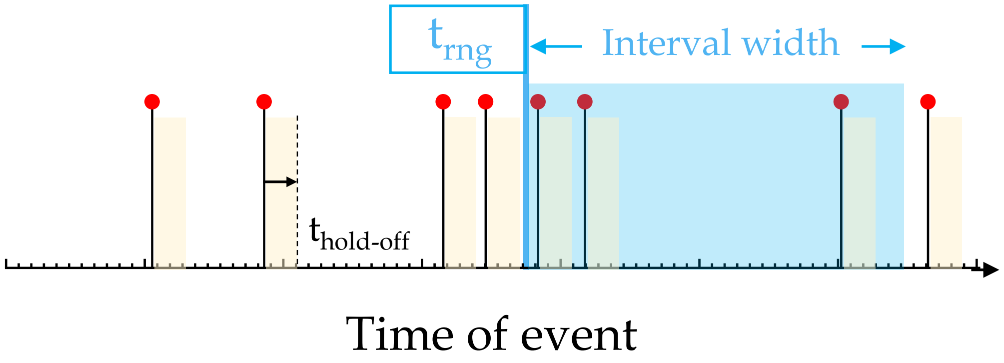

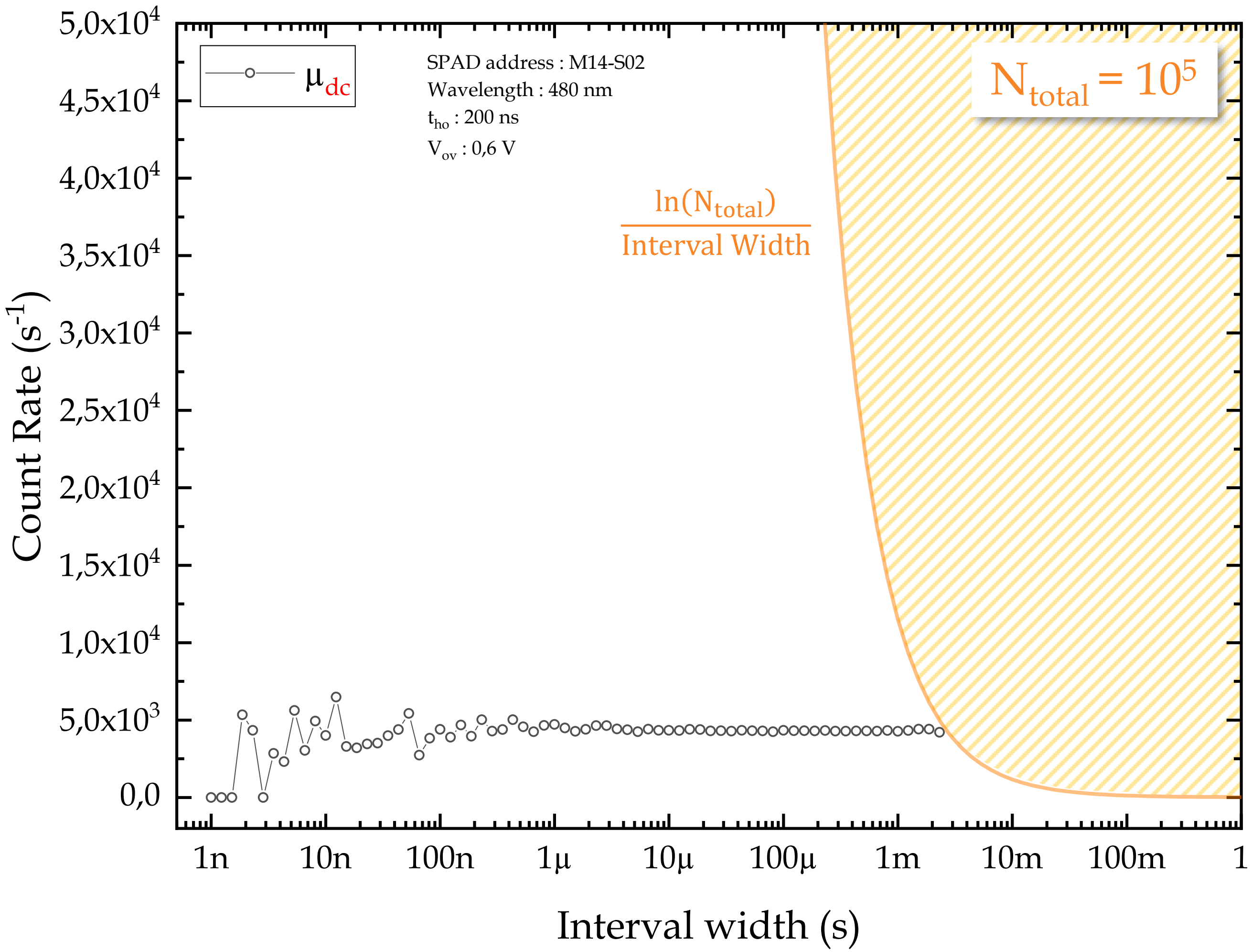

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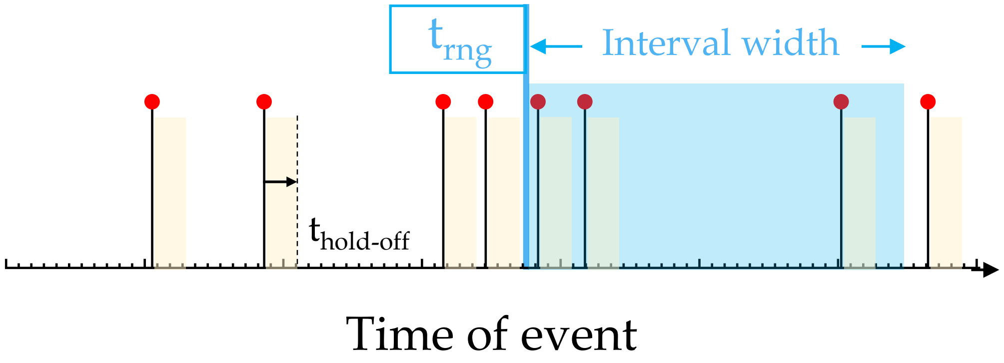

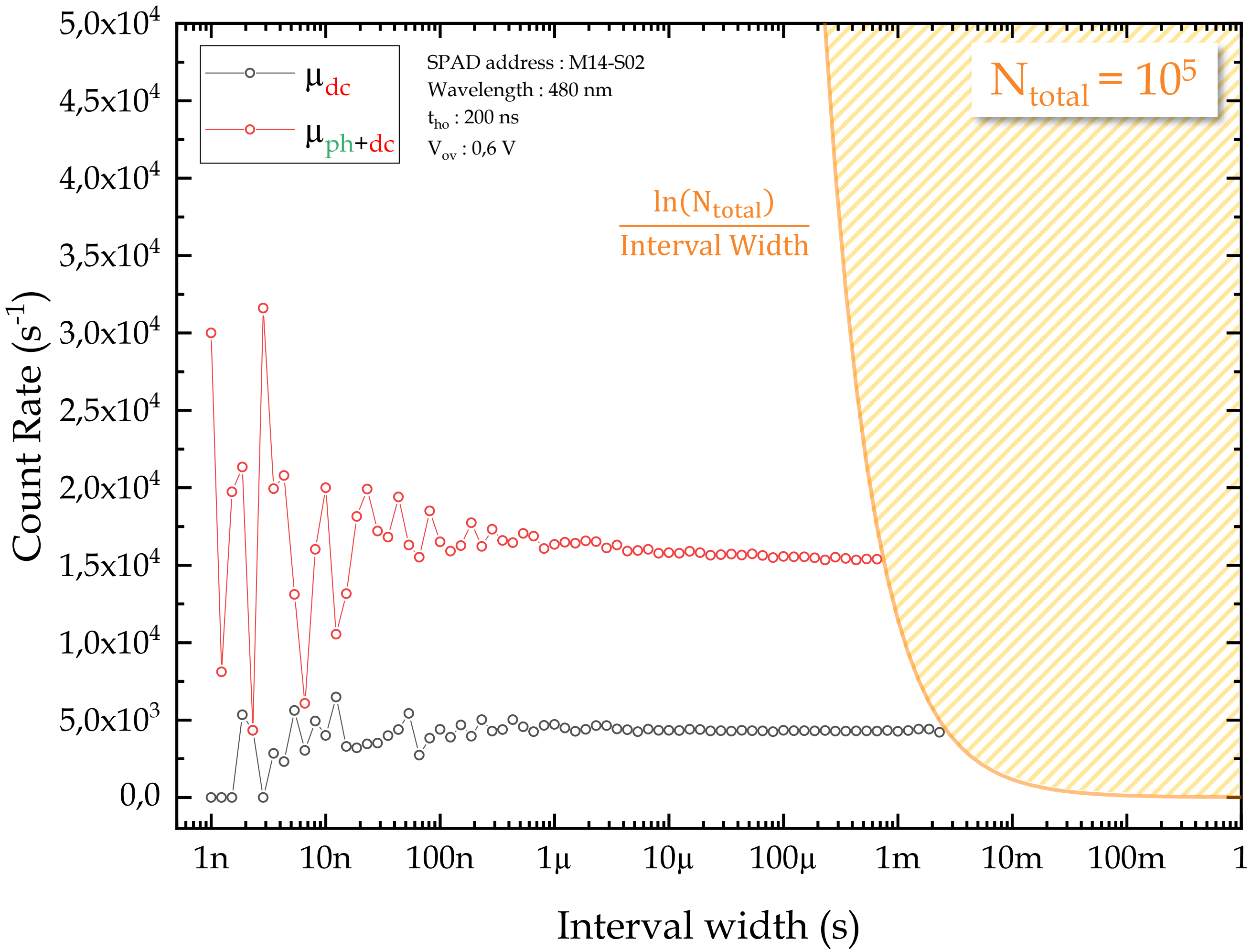

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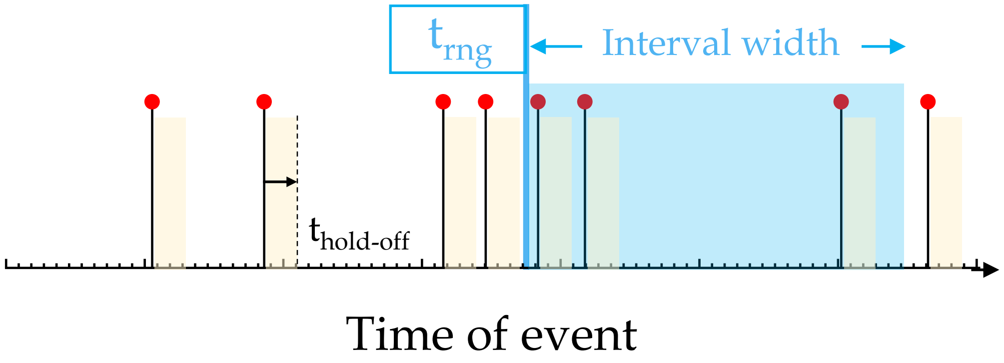
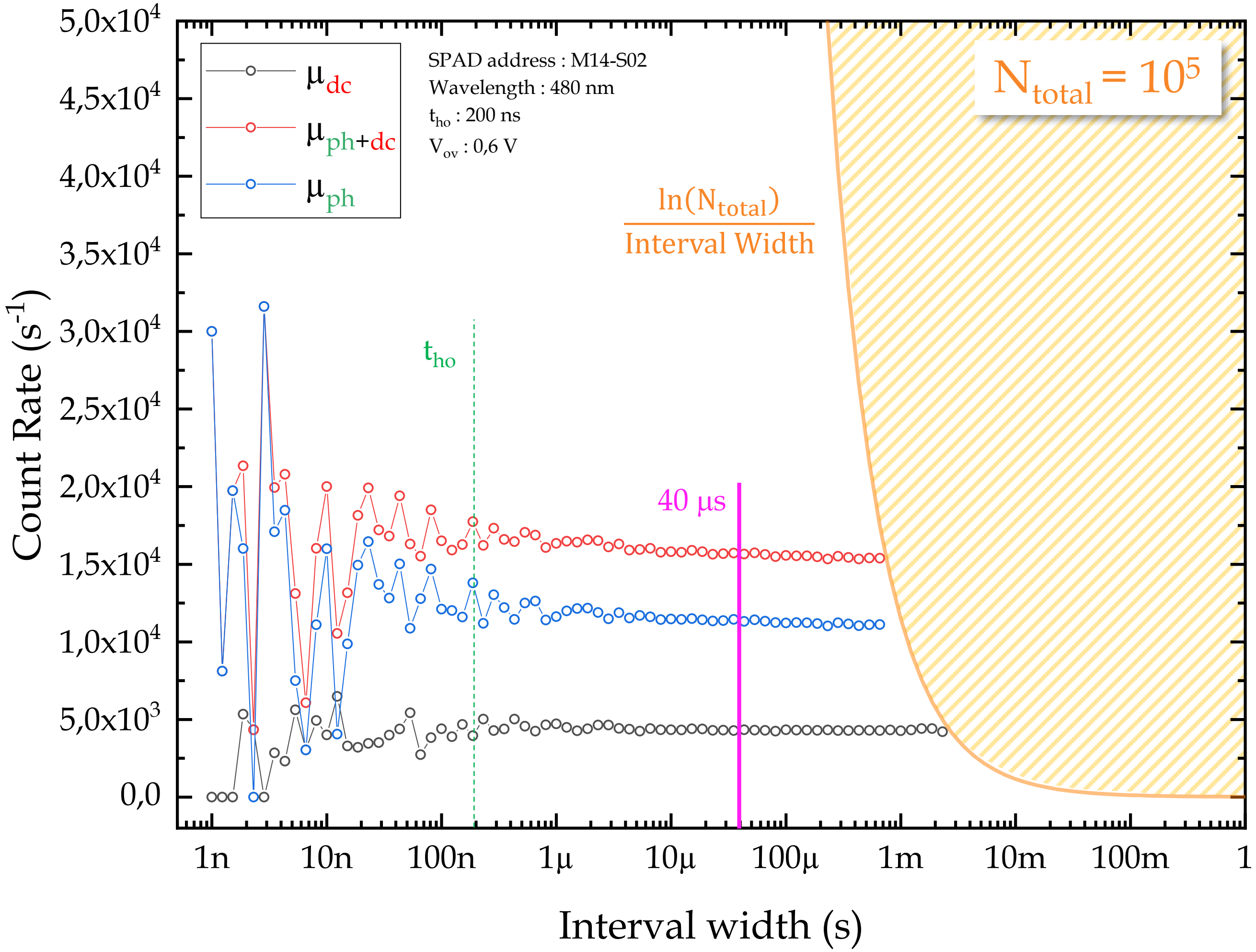
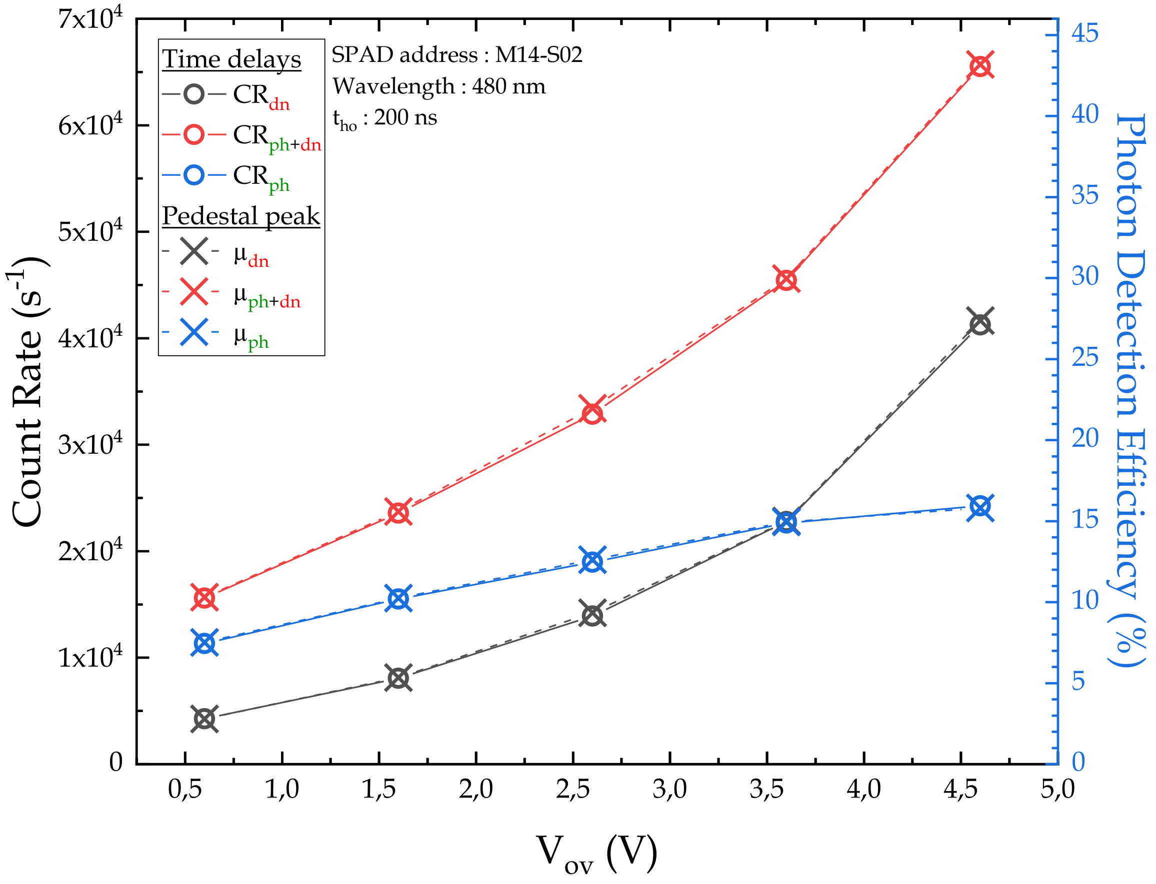




Comparison between methods

Time delays and pedestal peak using a continuous-light source



$$\mathbf{PDE(\lambda)} = \frac{\mathbf{N_{ph+dn} - N_{dn}}}{\left[\mathbf{N'_{Ref.} \cdot (1 - T_{NDF})}\right]}$$

Conclusion

- Both methods do apply to digital SiPM time stamps : time delays and pedestal peak
- Both methods were done only using a continuous-light source (instead of flash LED)
  - Gives access to any wavelengths
- Digital SiPM are built most of the time following an application-specific architecture.
  - For characterization purposes having access to time stamps of event is sufficient
  - … or a time-driven event counter with a configurable interval width

Acknowledgements

Thank you !

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