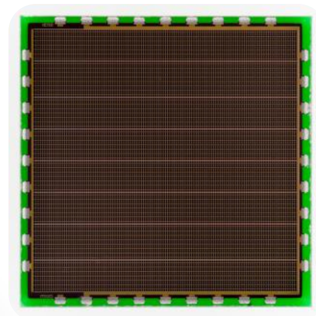
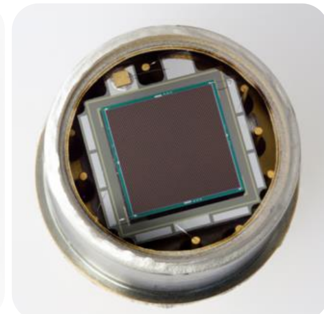
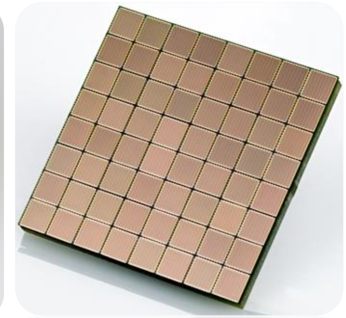
KETEK
SiPM







SiPM Noise Measurement with Waveform Analysis

E. Engelmann on behalf of the ICASIPM nuisance parameters group

Outline

I. Introduction of technique for waveform analysis

II. Methods for extraction of nuisance parameters
   i. Optical crosstalk
   ii. Dark count rate (comparison of two methods)
   iii. Correlated noise (afterpulsing and delayed crosstalk)

III. Application of presented methods to simulated SiPM pulses

IV. Discussion

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Waveform analysis

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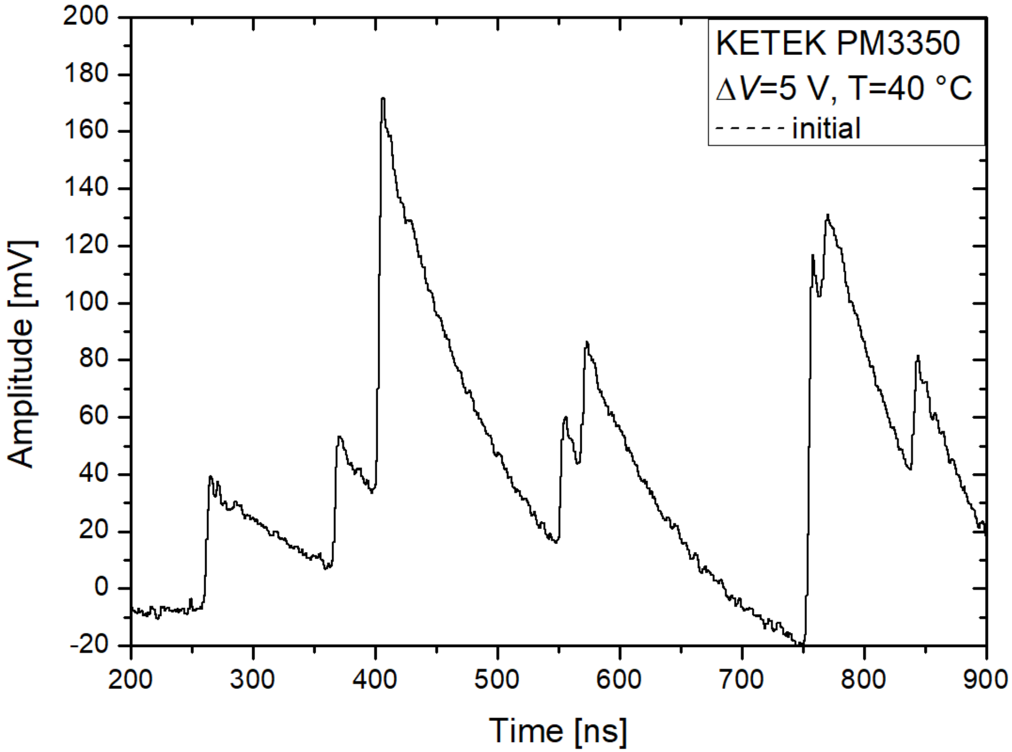
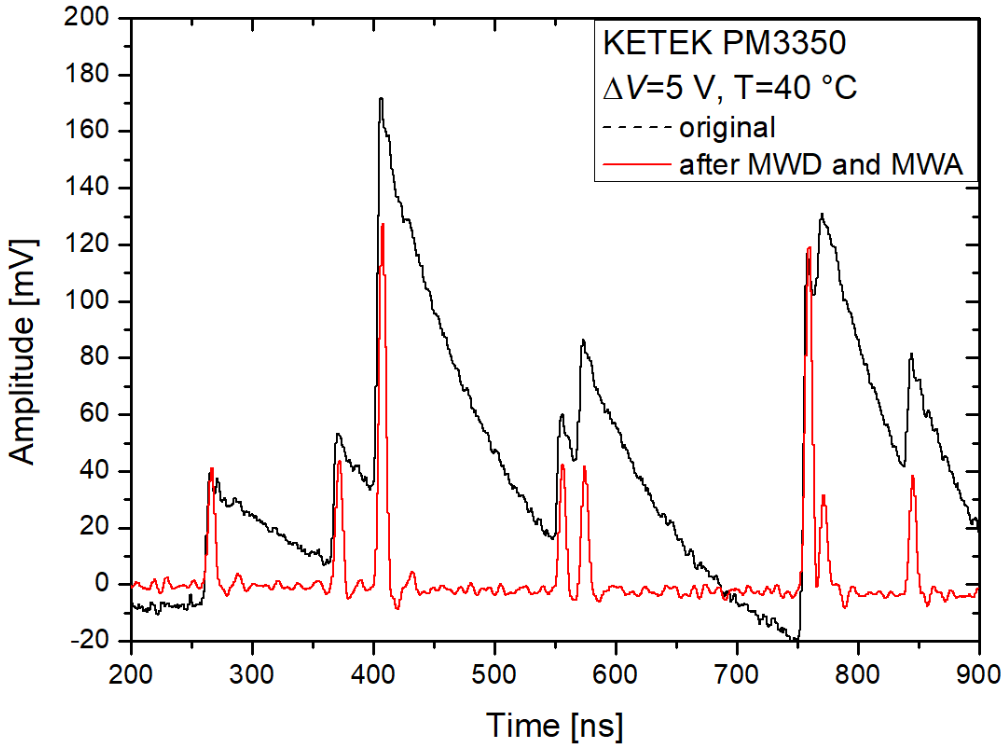


- pile-ups due to high DCR (e.g. at high T)
- difficult to analyze single pulses
- LE-threshold not applicable

Waveform analysis



- pile-ups due to high DCR (e.g. at high T)
- difficult to analyze single pulses
- LE-threshold not applicable

⇩

- two simple filters help to solve the problem
- pulses are shifted in time
- absolute amplitudes are reduced
- first k samples of WF are lost (typ. k=12)

Moving Window Difference

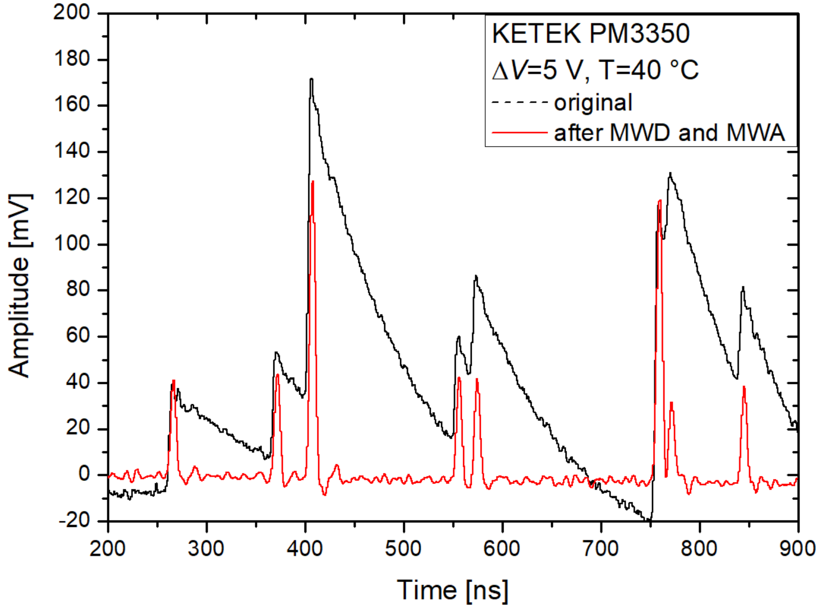
$$F^k_{MWD}(A_n) = A_n - A_{n-k}$$

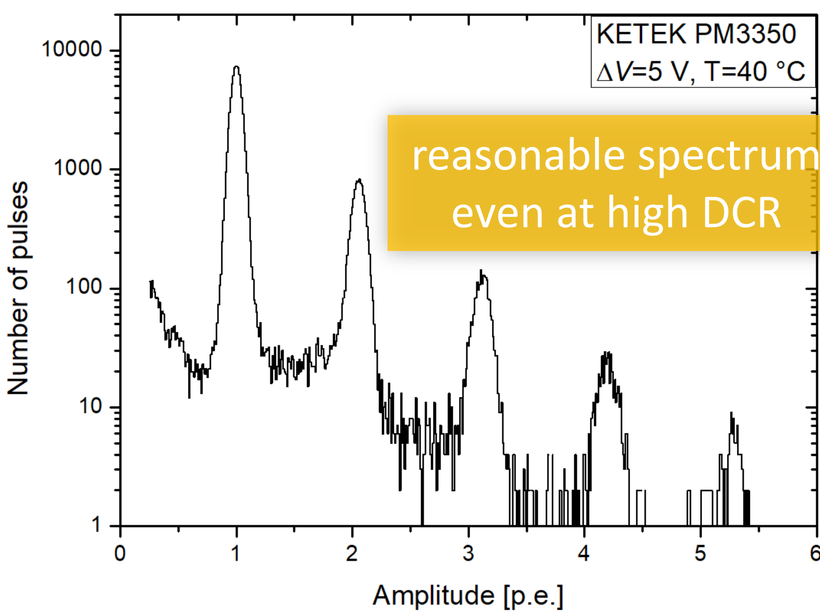
(J. Stein et al., doi: 10.1016/0168-583X(95)01417-9)

Moving Window Average

$$F^m_{MWA}(A_n) = \frac{1}{m}\sum_{i=0}^{m-1} A_{n-i}$$

Waveform analysis



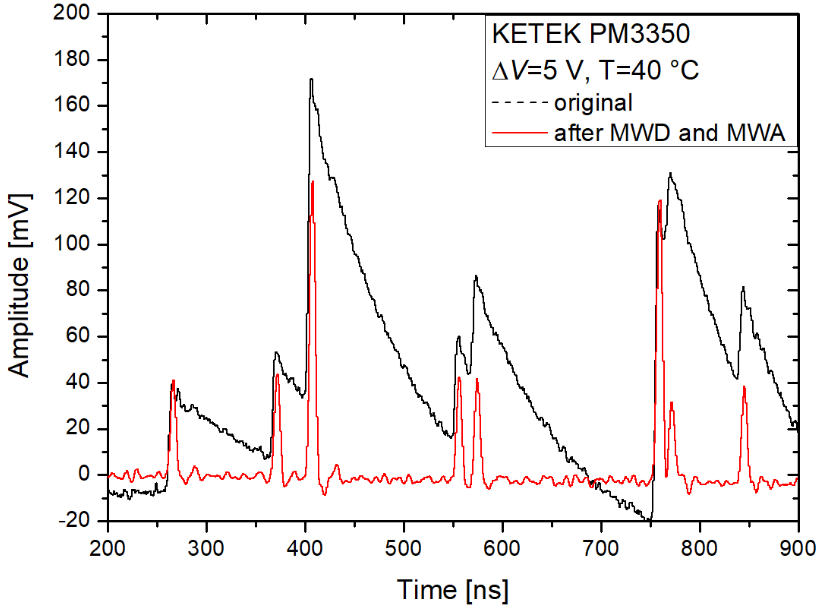


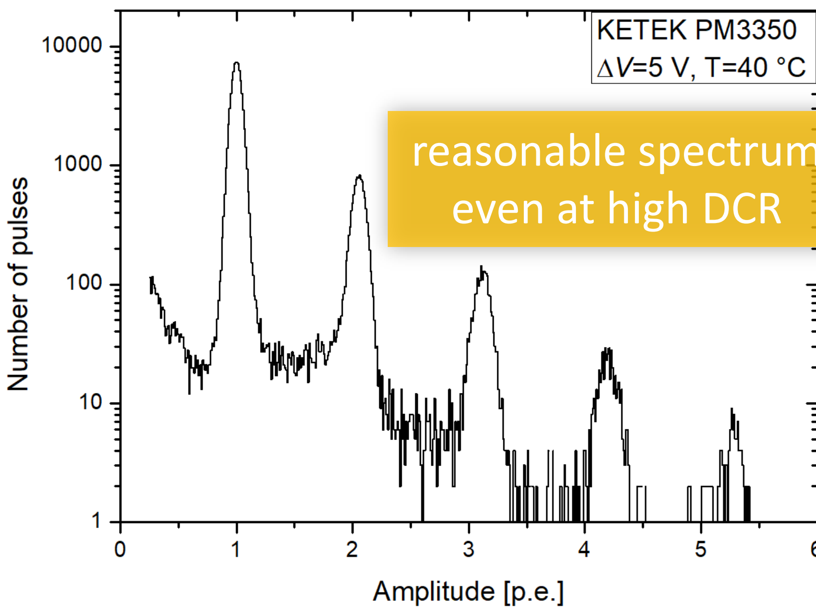
reasonable spectrum even at high DCR

accessible information:

- number of pulses in WF
- arrival time
- amplitudes (prop. to gain)
- integral (prop. to gain)

Waveform analysis





reasonable spectrum even at high DCR

accessible information:

- number of pulses in WF
- arrival time
- amplitudes (prop. to gain)
- integral (prop. to gain)

accessible SiPM parameters:

- dark count rate
- optical crosstalk prob.
- afterpulsing + delayed crosstalk
- breakdown voltage
  via ampl. or integral

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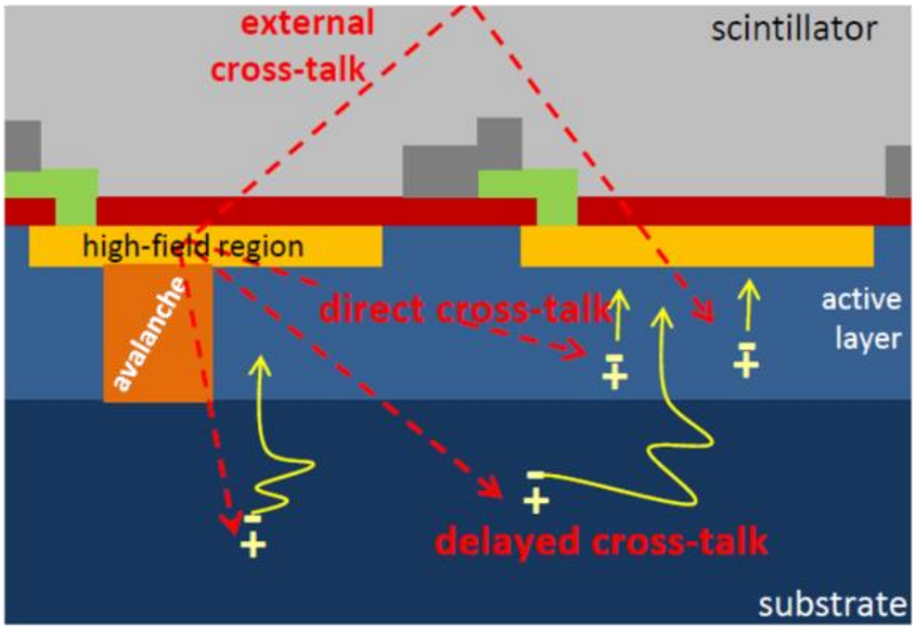
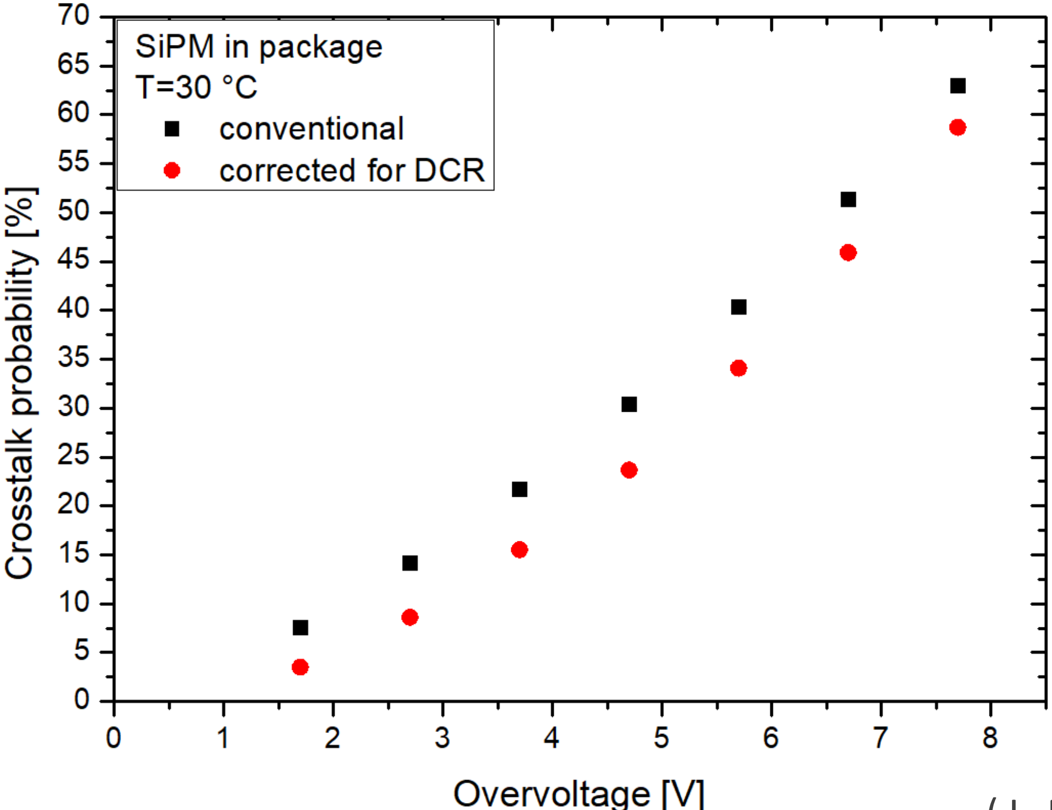
Optical crosstalk probability



Fabio Acerbi, PhotoDet 2015

- propagation of photons by several paths
  - prompt opt. crosstalk (CT)
  - delayed opt. crosstalk (DCT)
- “delayed self-crosstalk” is also possible
- CT is significantly affected by:
  - package/coupled scintillator
  - substrate material and thickness
  - gain (overvoltage)
  - cell geometry
  - Geiger discharge prob. (overvoltage)

Optical crosstalk probability



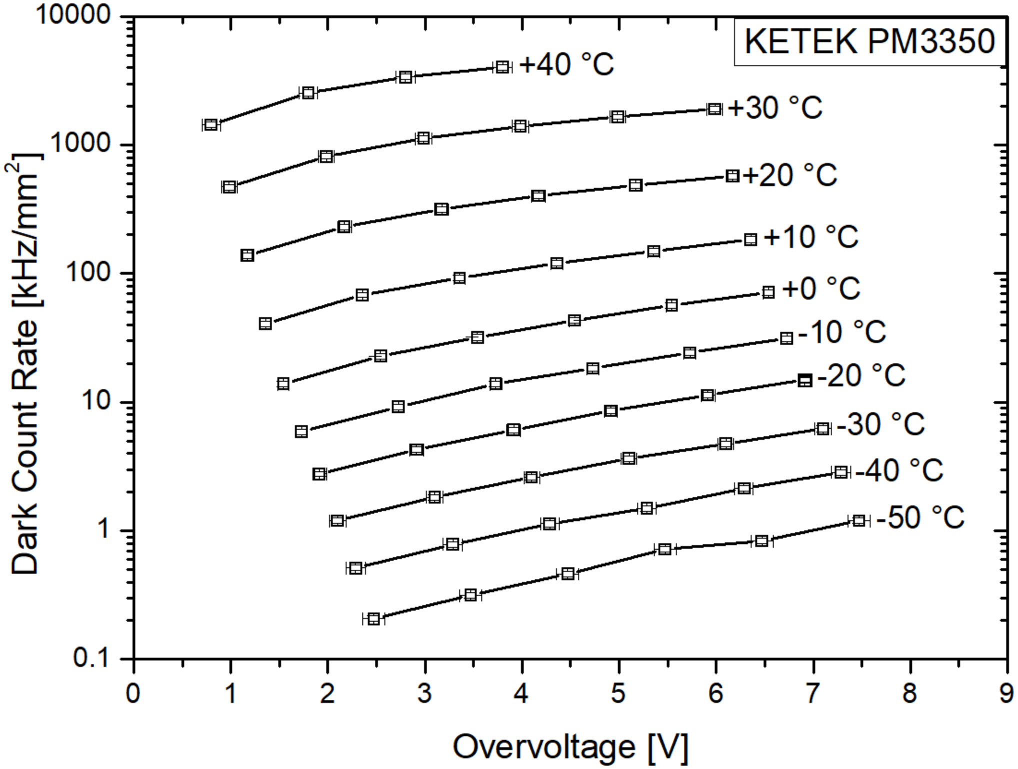
(L. Futlik et al., doi: 10.3103/S1068335611100058)

$$P_{CT} = 1 - \left[1 - \frac{DCR_{1.5}}{DCR_{0.5}}\right] \cdot \exp\left(DCR_{0.5} \cdot \Delta t_{crit}\right)$$

conventional term

correction for coinciding dark pulses

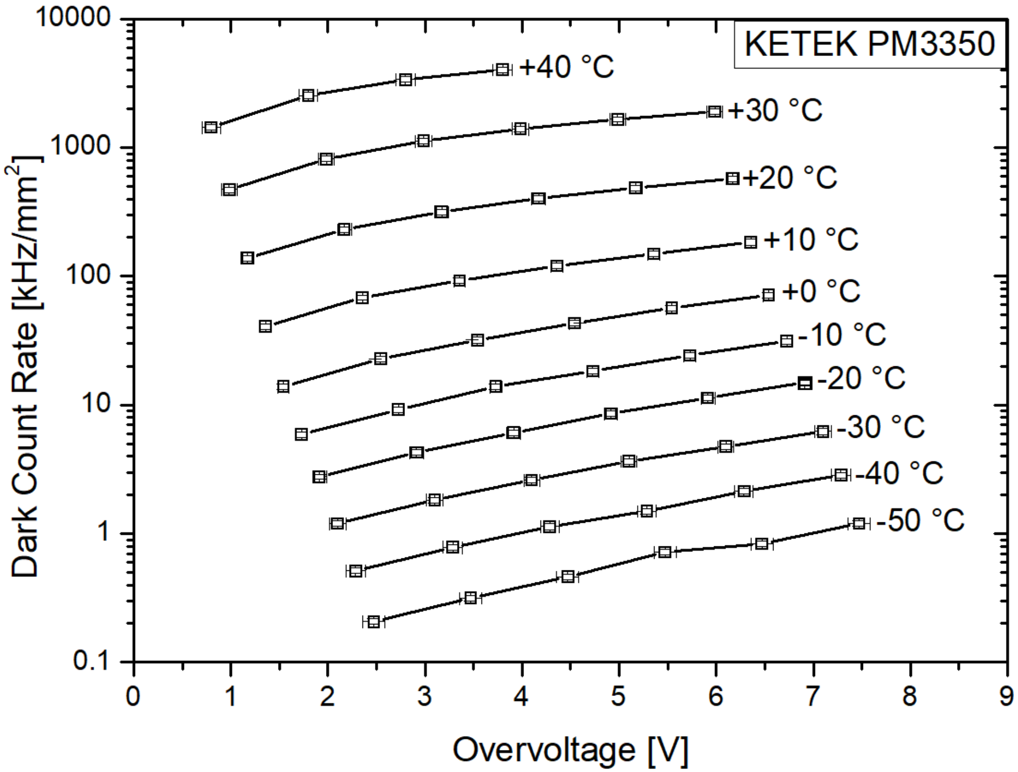
Dark count rate via pulse counting



Procedure:

- acquisition of randomly triggered WFs
- set LE-threshold at 0.5 p.e.
  (is this really the best choice?)
- DCR determined by avg. number of pulses per WF, divided by length of WF

Dark count rate via pulse counting



Procedure:

- acquisition of randomly triggered WFs
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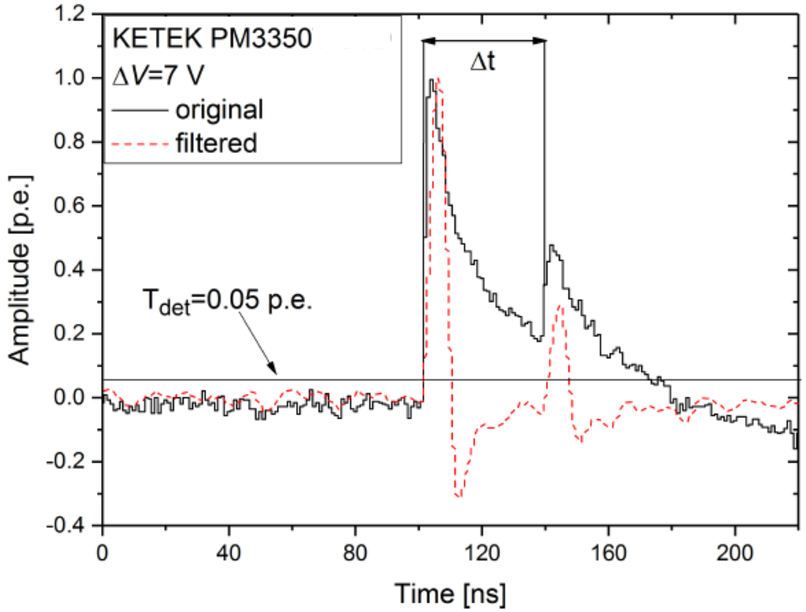
  (is this really the best choice?)
- DCR determined by avg. number of pulses per WF, divided by length of WF

Limitations:

- acq. time at low DCR
- speed of electronics at high DCR
- underestimation of DCR due to overlapping
- overestimation of DCR due to late afterpulses and DCT-pulses

Probability of correlated pulses (P_{CP})



Procedure:

- triggered acquisition of waveforms
- selection of valid WF
  - contains dark pulse with 1 p.e. ampl.
  - no preceding pulses within certain timegate
- determination of Δt between pulses
- build compl. cumulative distr. function P^{*}_{tot} (S. Vinogradov, doi:10.1109/NSSMIC.2016.8069965)

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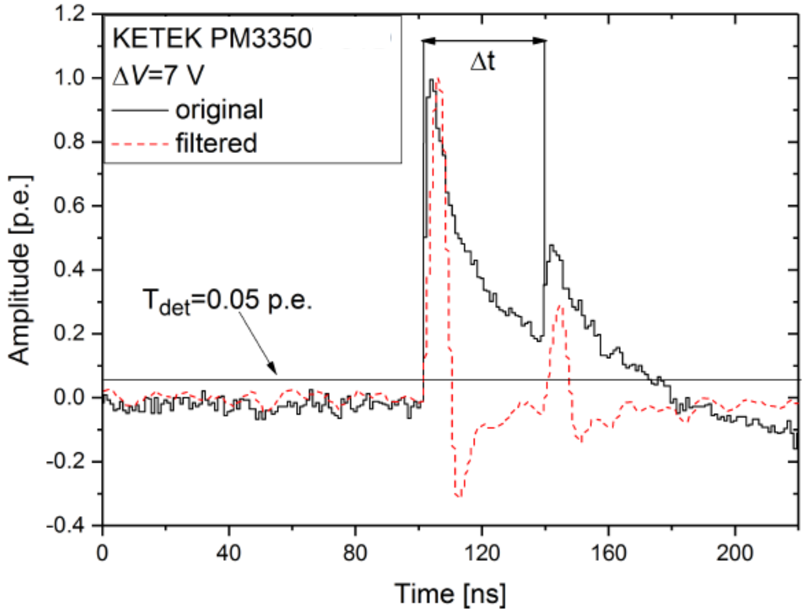

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$$P^*_{\text{tot}}(\Delta t) = \exp\left(-DCR \cdot \Delta t\right) \cdot P^*_{\text{corr}}(\Delta t)$$

(prob. that no event occurs at a delaytime < Δt)

$$\lim_{\Delta t \to \infty} P^*_{\text{corr}}(\Delta t) = 1 - P_{\text{CP}}$$

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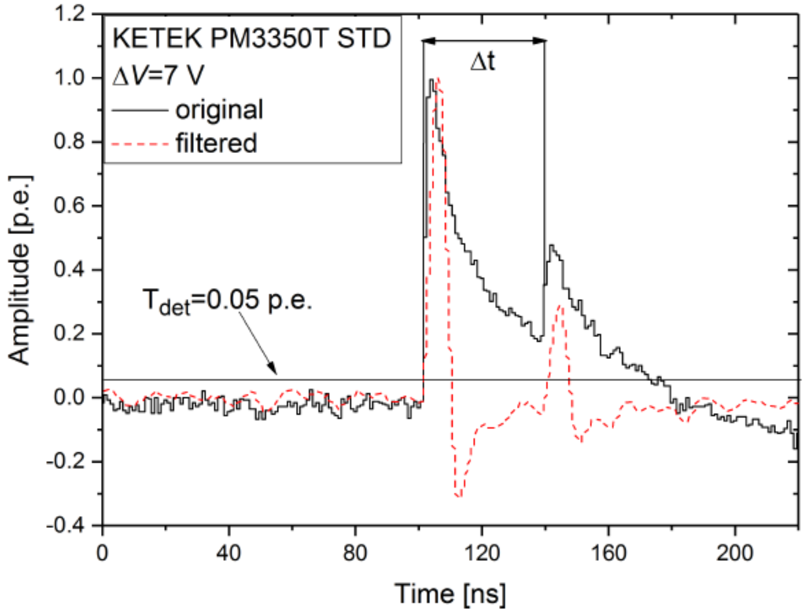

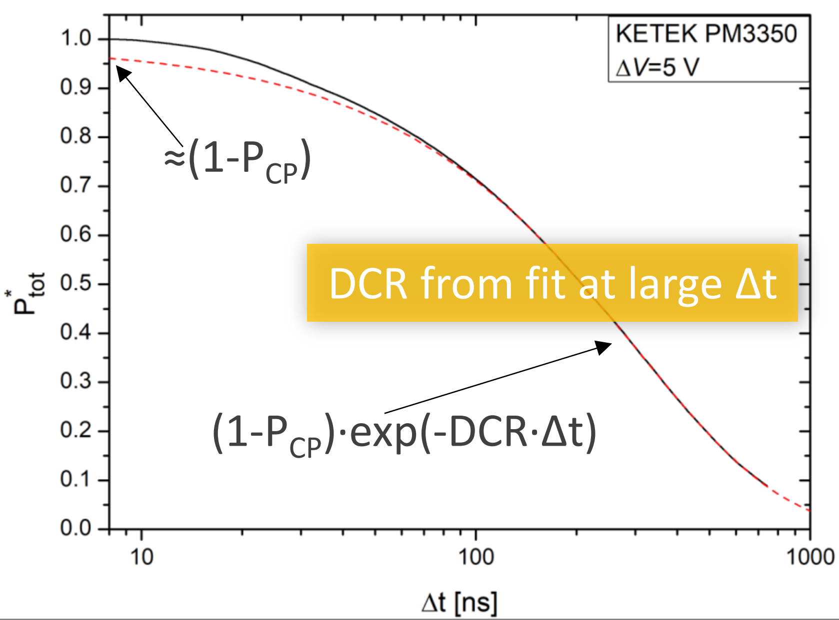

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  - no preceding pulses within certain timegate
- determination of Δt between pulses
- build compl. cumulative distr. function P^*_{tot} (S. Vinogradov, doi:10.1109/NSSMIC.2016.8069965)
- fit DCR as slowest component of P^*_{tot}

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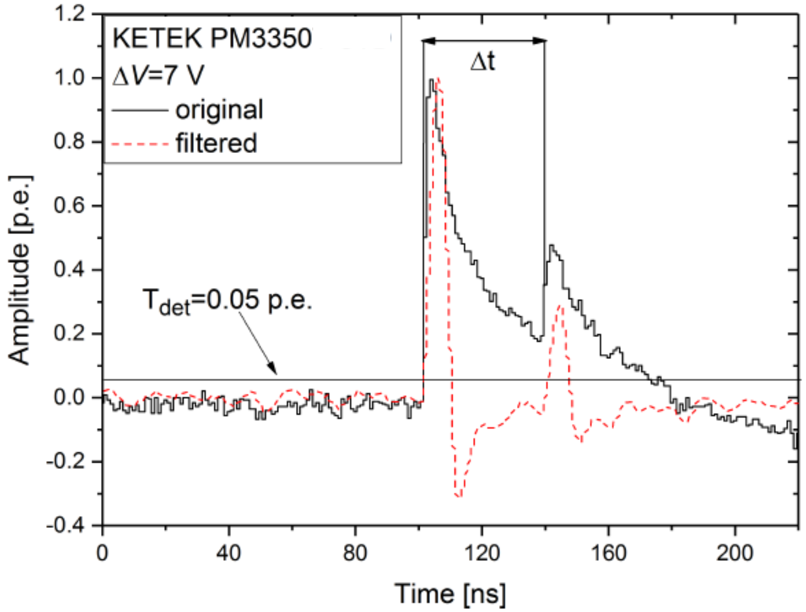
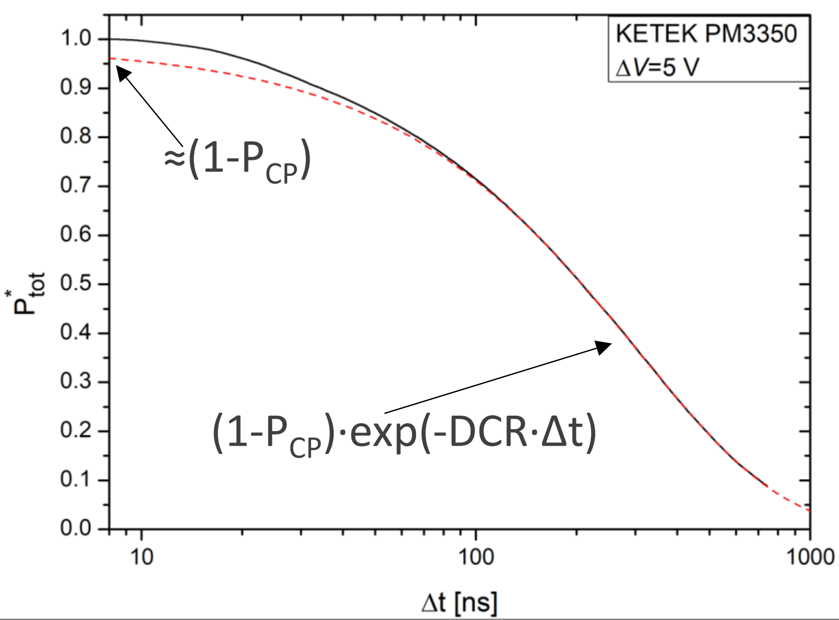
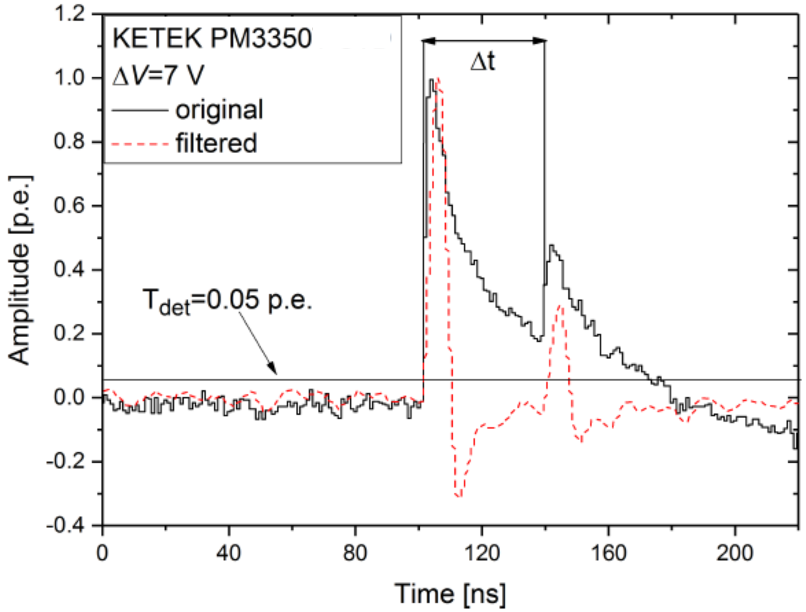


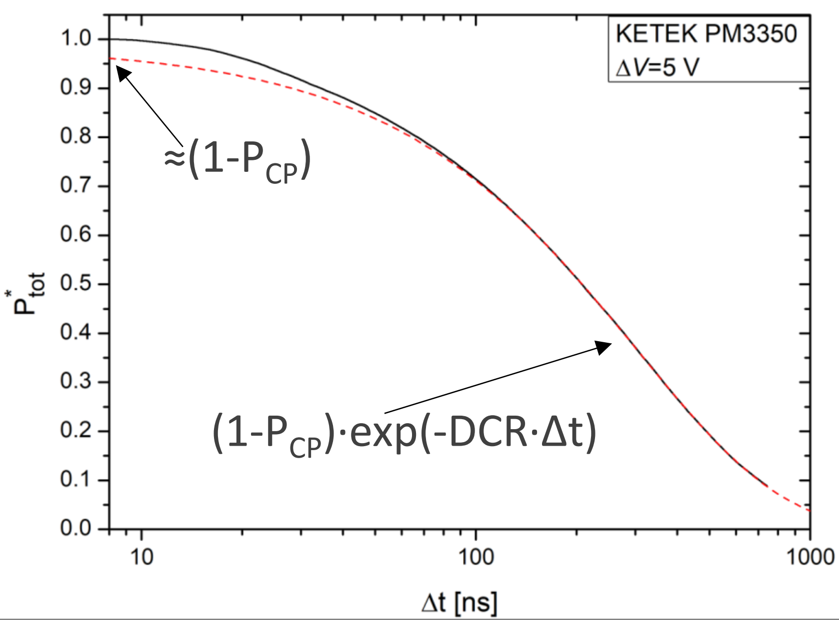


Advantages:

- acq. of one data-set is enough to measure DCR, CT, corr. noise and V_{BD}
- no need to decide for DCR threshold
- min. threshold determined by electronic noise
- full information about P_{corr} without making assumptions

Probability of correlated pulses (P_{CP})





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- full information about P_{corr} without making assumptions

Limitations:

- afterpulsing and delayed crosstalk are not distinguished
- fast afterpulses are lost due to small ampl.
- length of WF must be scaled with DCR

Probability of correlated pulses (P_{CP})

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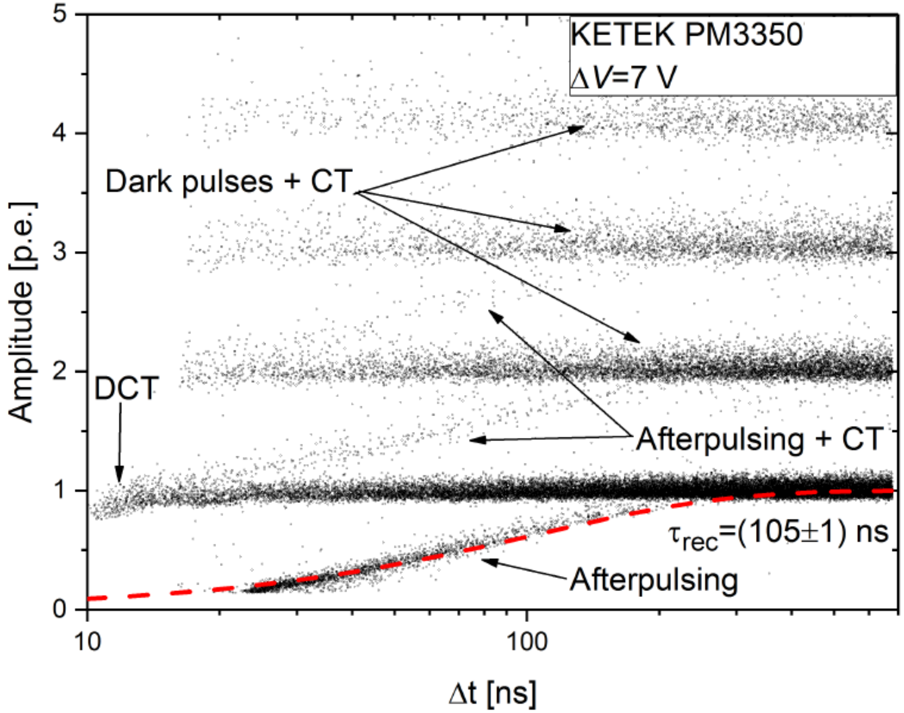
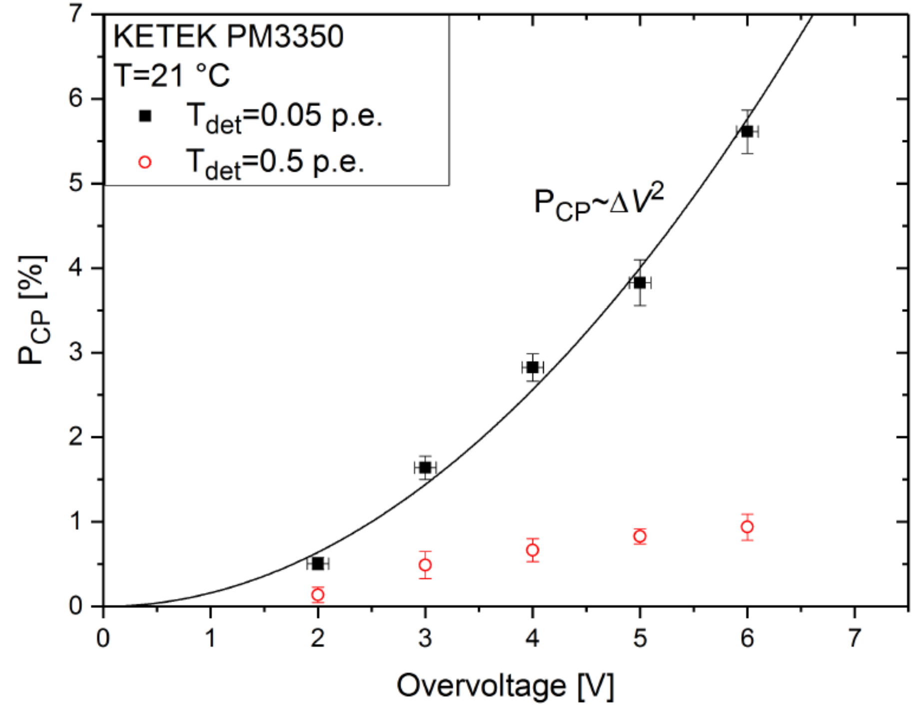
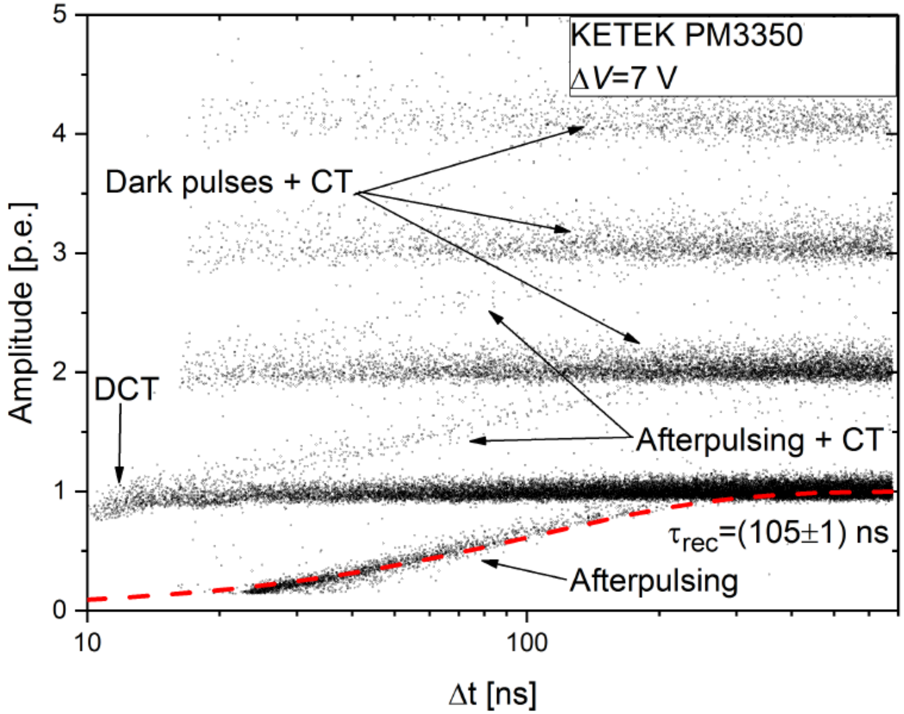


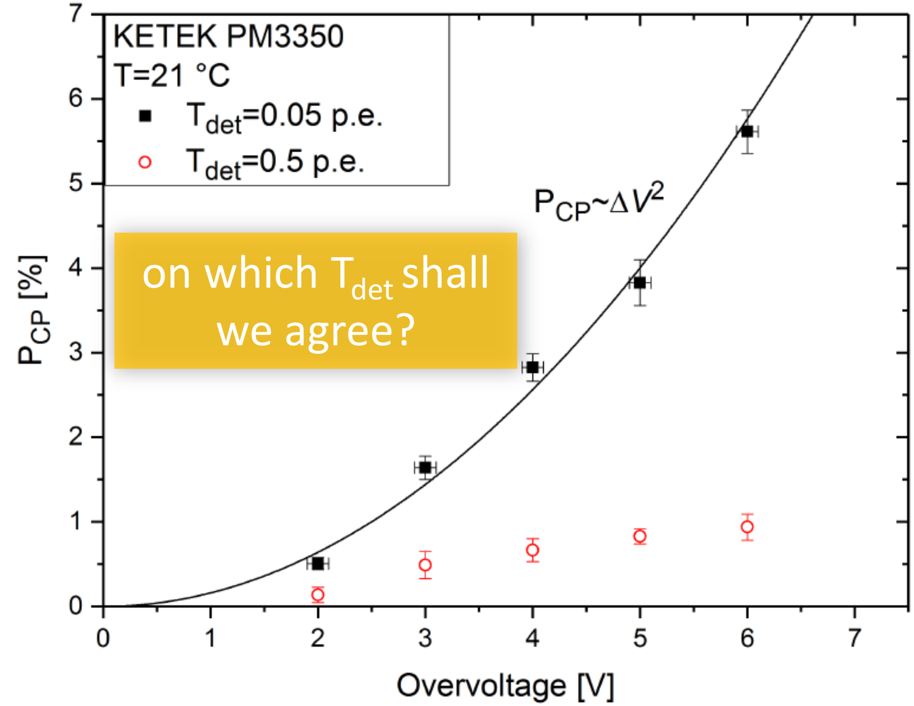


- P_{CP} strongly depends on chosen threshold (T_{det})
- standardization required for datasheets of producers
- evaluation of afterpulses according to their amplitude?

Probability of correlated pulses (P_{CP})

KETEK





- P_{CP} strongly depends on chosen threshold (T_{det})
- standardization required for datasheets of producers
- evaluation of afterpulses according to Δt and recovery time?

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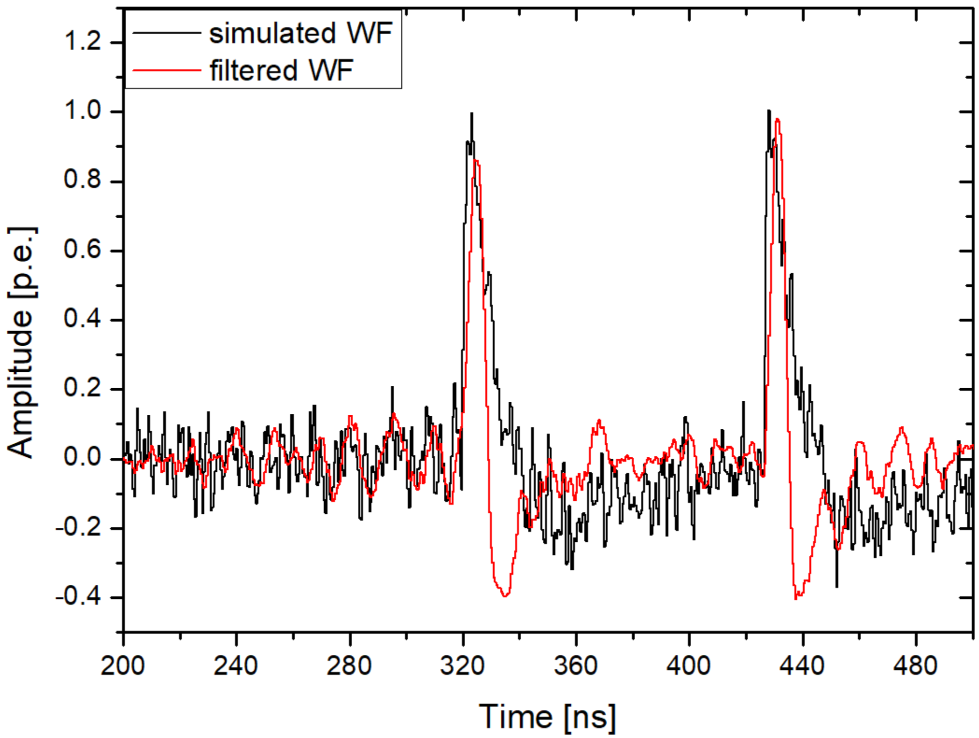
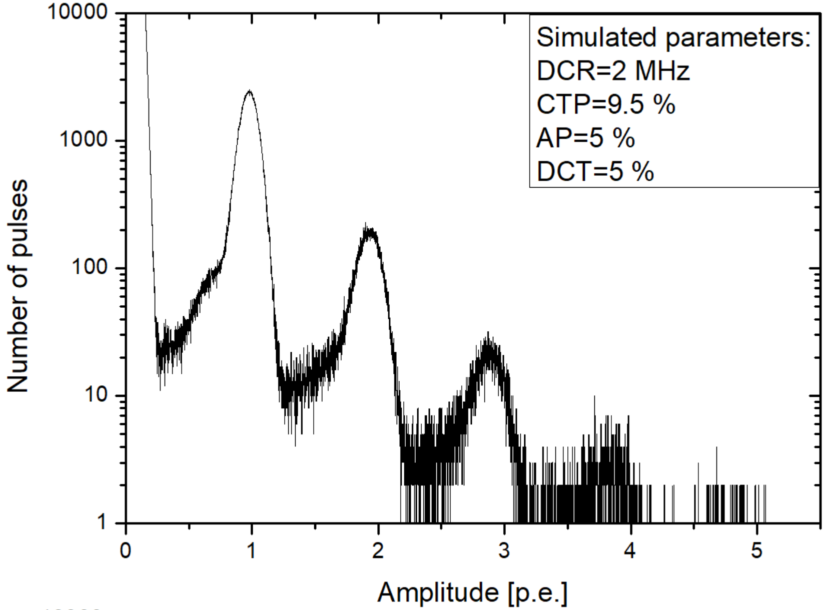
Waveform analysis of simul. SiPM output

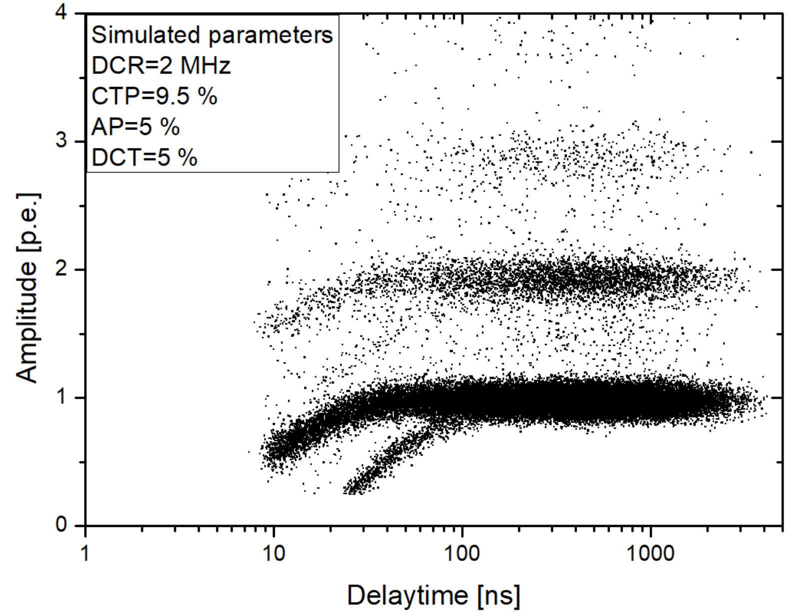


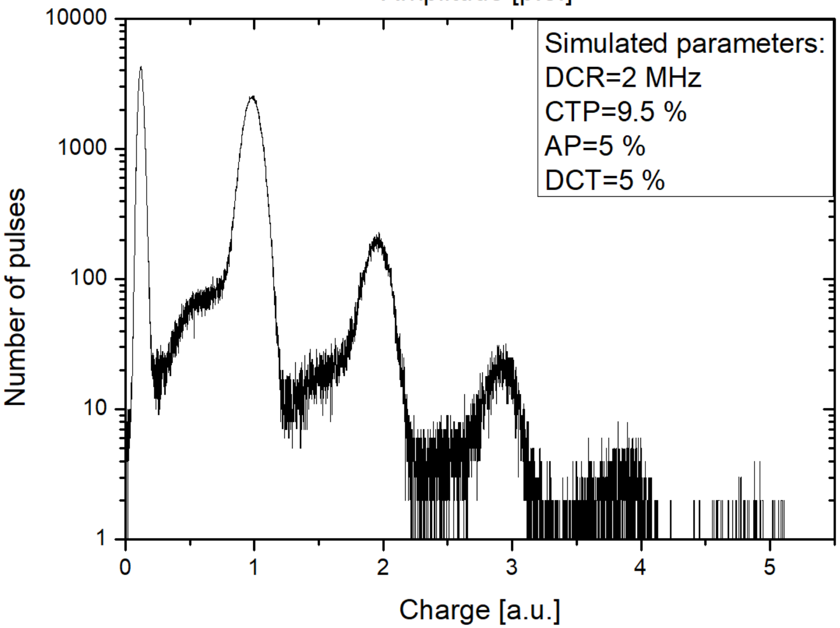
Parameter	Value
SiPM size [µ-cells]	100 x 100
Recovery time [ns]	50
CT range [µ-cells]	1
CT delaytime [ns]	0.5
DCT range [µ-cells]	3
DCT delaytime [ns]	10
AP delaytime [ns]	50

- waveform analysis is applied to simulated SiPM output
- simulation software is provided by Johannes Breuer (for more information visit his talk Wed. at 17:00)
- nuisance parameters are turned on successively
- 50k waveforms with a length of 5 µs are analyzed

Waveform analysis of simul. SiPM output

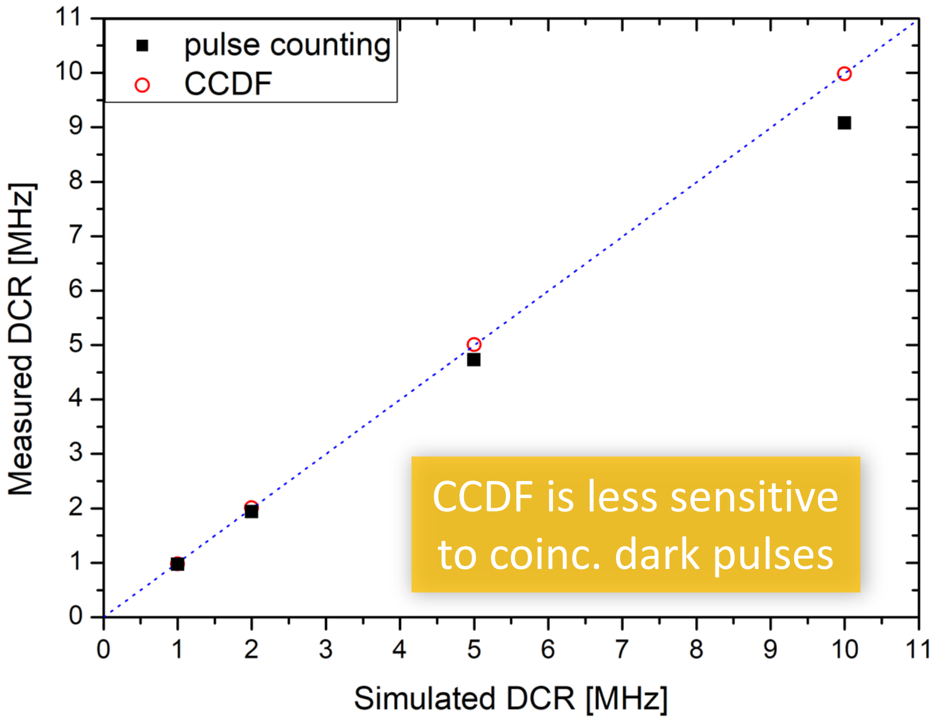






- the pulse-amplitudes are used for the analysis
- pulse counting and CCDF method are compared
- LE-threshold set at 0.5 p.e. for pulse counting method
- LE-threshold set to 0.25 p.e. for CCDF method

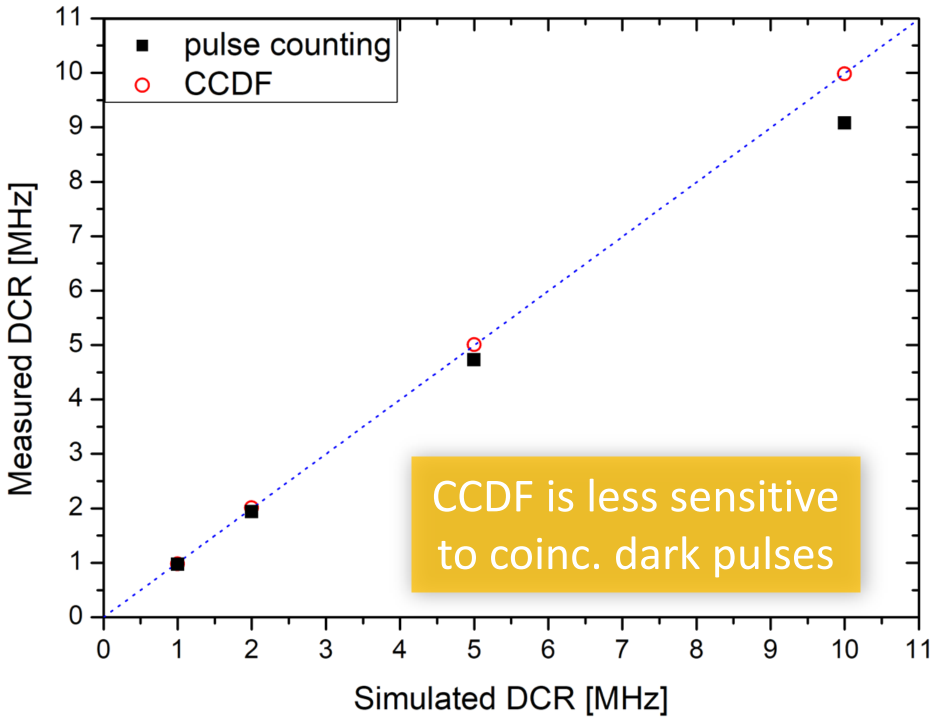
Variation of DCR



Parameter	Value
DCR [MHz]	variable
P_{CT} [%]	0
P_{AP} [%]	0
P_{DCT} [%]	0

- comparable results of both methods at lower DCR
- underestimation at high DCR by pulse counting
- reason: coincidential dark pulses

Variation of DCR



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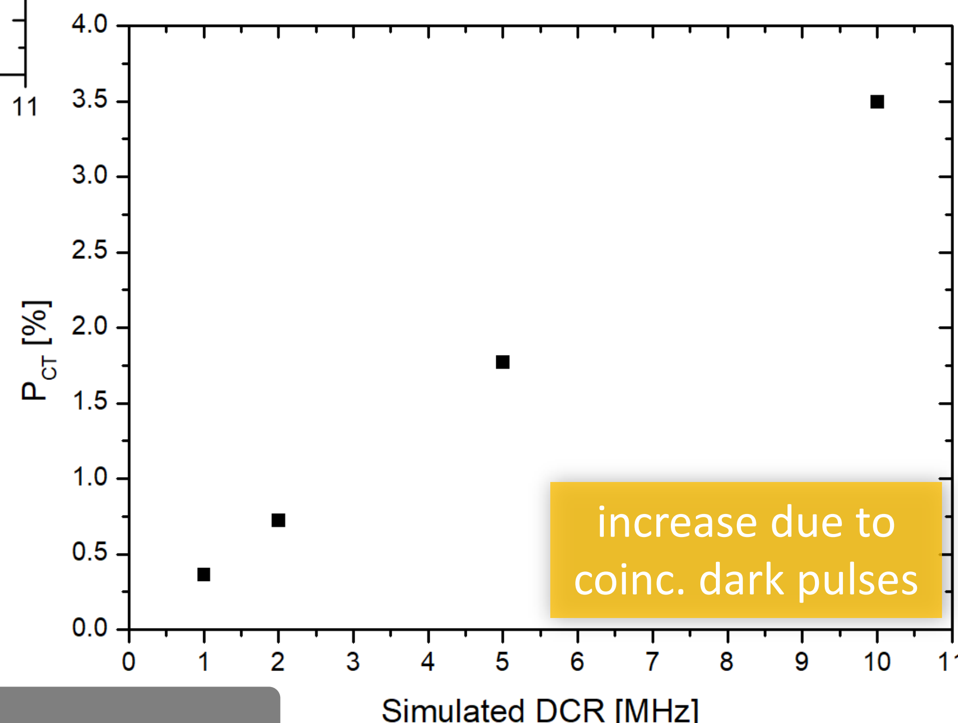
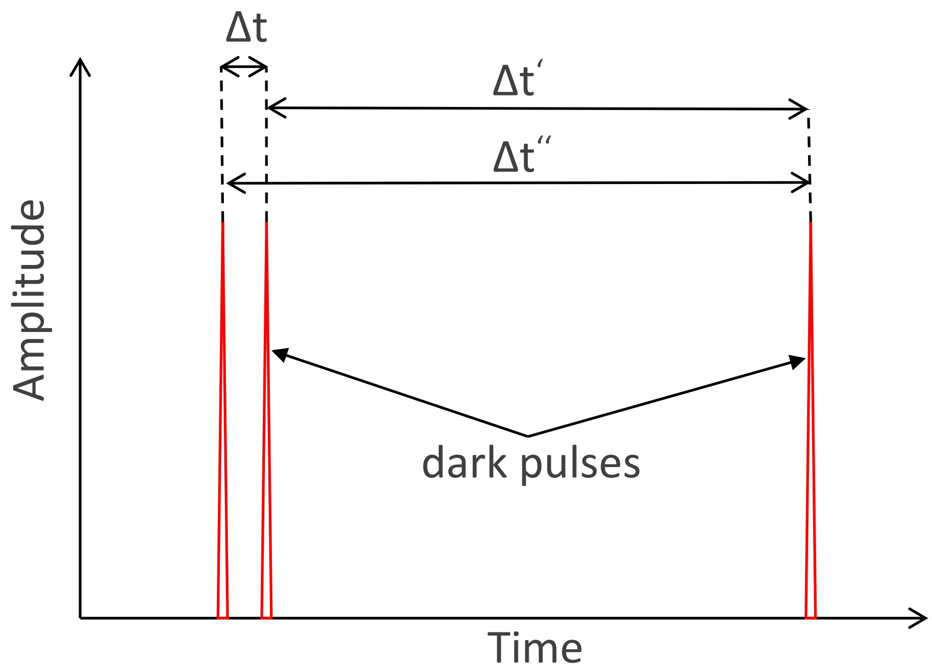
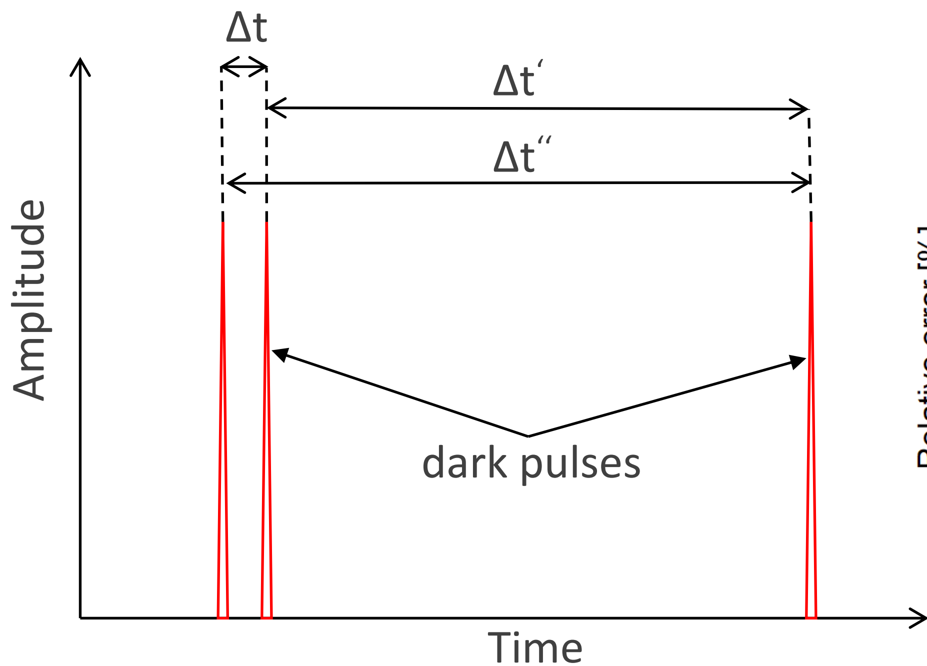


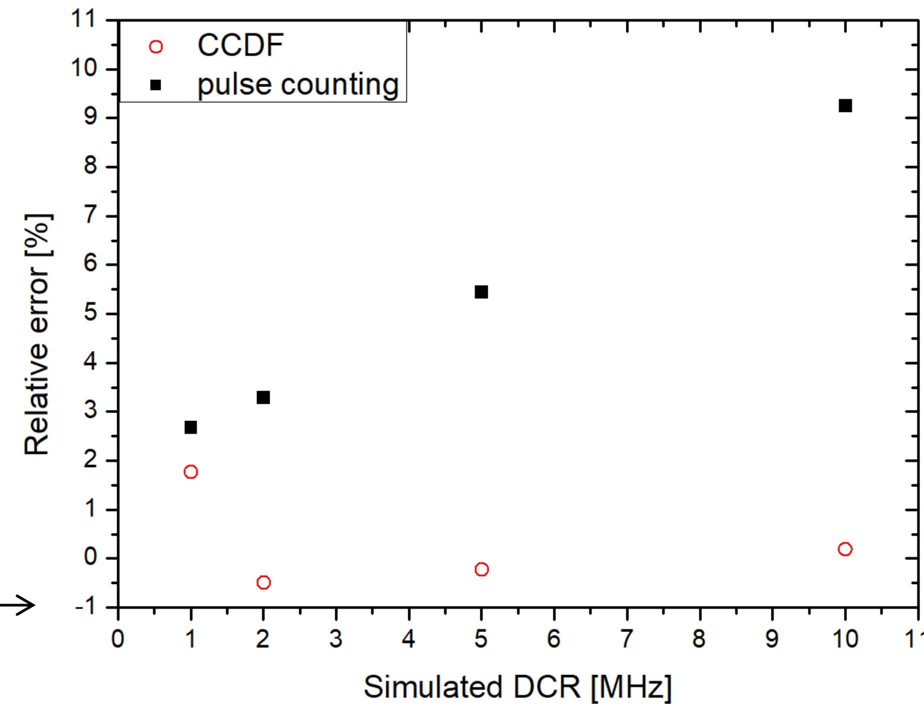
Variation of DCR



- if Δt is too small, pulses are not distinguished
- Δt and Δt' are not accessible
- instead Δt'' is measured
- but Δt''≈ Δt'

Variation of DCR



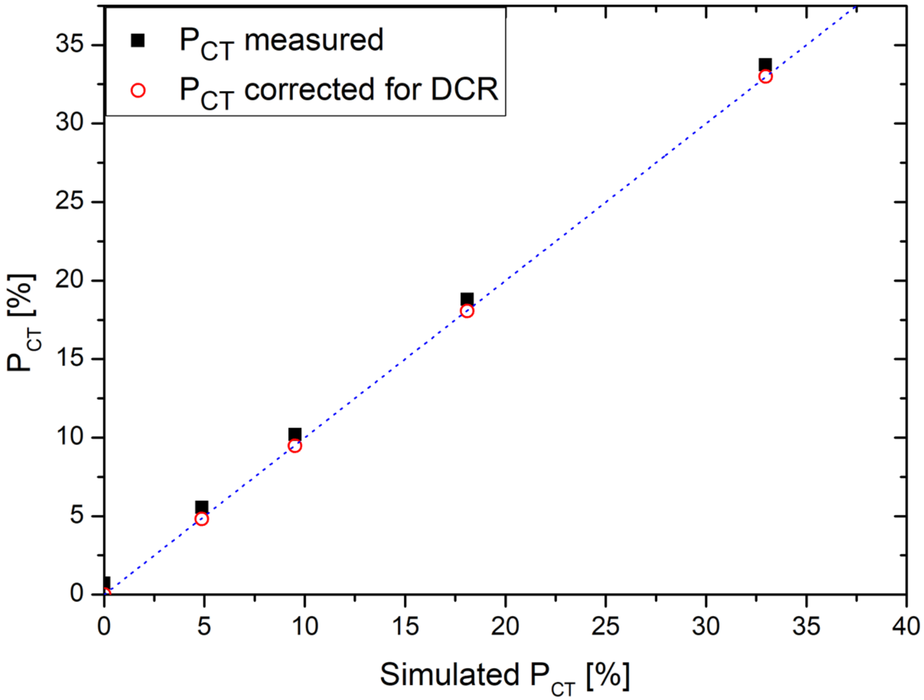


- if Δt is too small, pulses are not distinguished
- Δt and Δt' are not accessible
- instead Δt'' is measured
- but Δt''≈ Δt'

➢ **pulse counting significantly underestimates DCR**

➢ **CCDF is less sensitive to coincidential dark pulses**

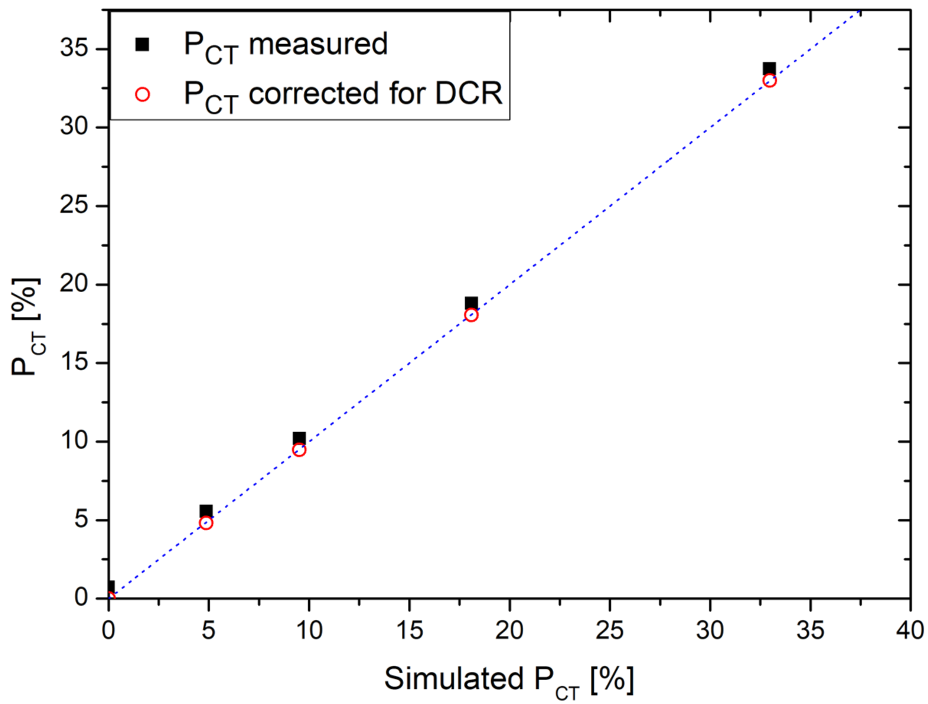
Variation of CT



Parameter	Value
DCR [MHz]	2
P_{CT} [%]	variable
P_{AP} [%]	0
P_{DCT} [%]	0

- overestimation of P_{CT} due to coinciding dark pulses
- relative error increases with decreasing P_{CT}
- correction from slide is recommeded at high DCR

Variation of CT



Parameter	Value
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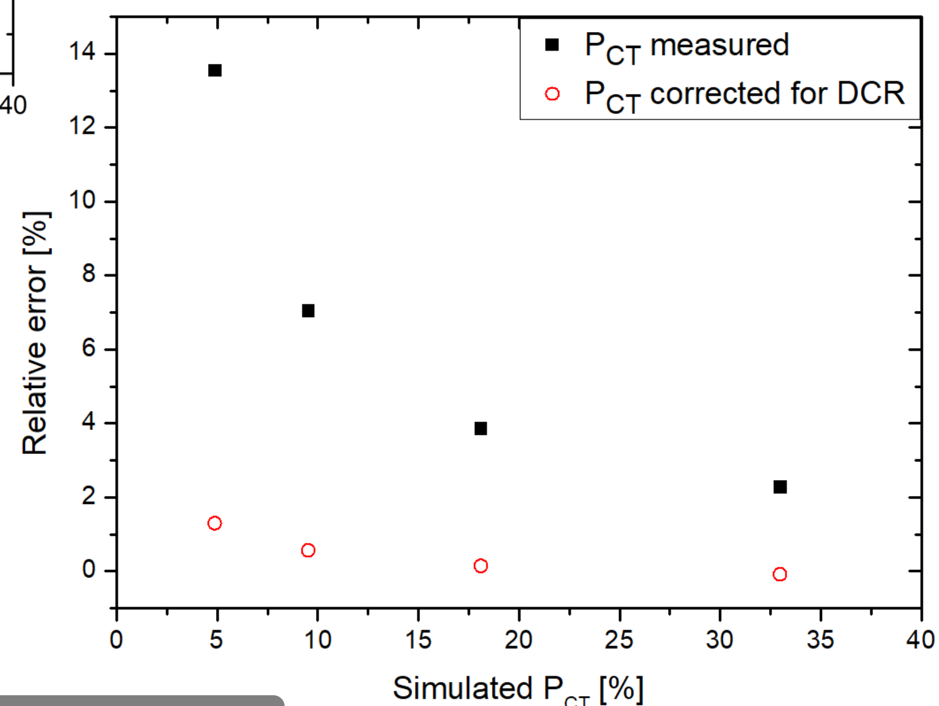

- overestimation of P_{CT} due to coinciding dark pulses
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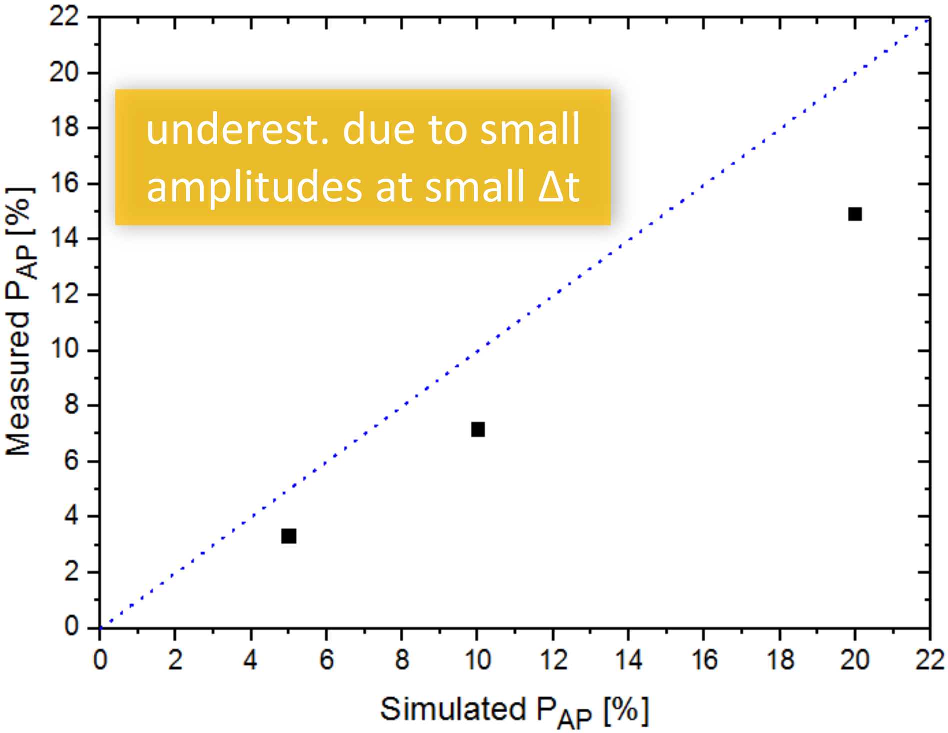
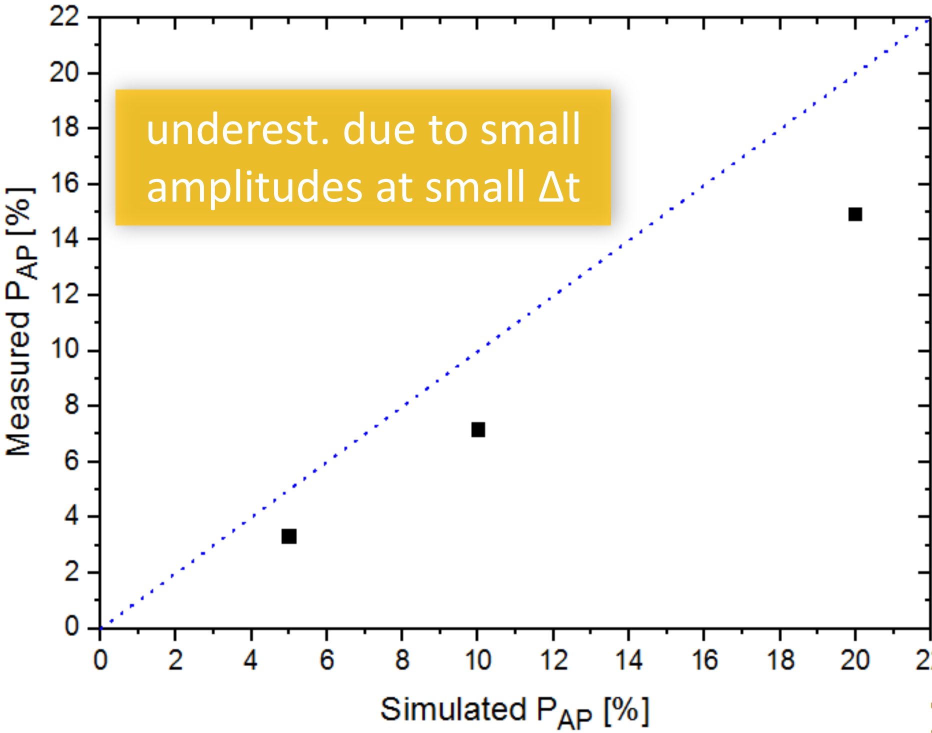
Variation of AP



Parameter	Value
DCR [MHz]	2
P_{CT} [%]	9.5
P_{AP} [%]	variable
P_{DCT} [%]	0

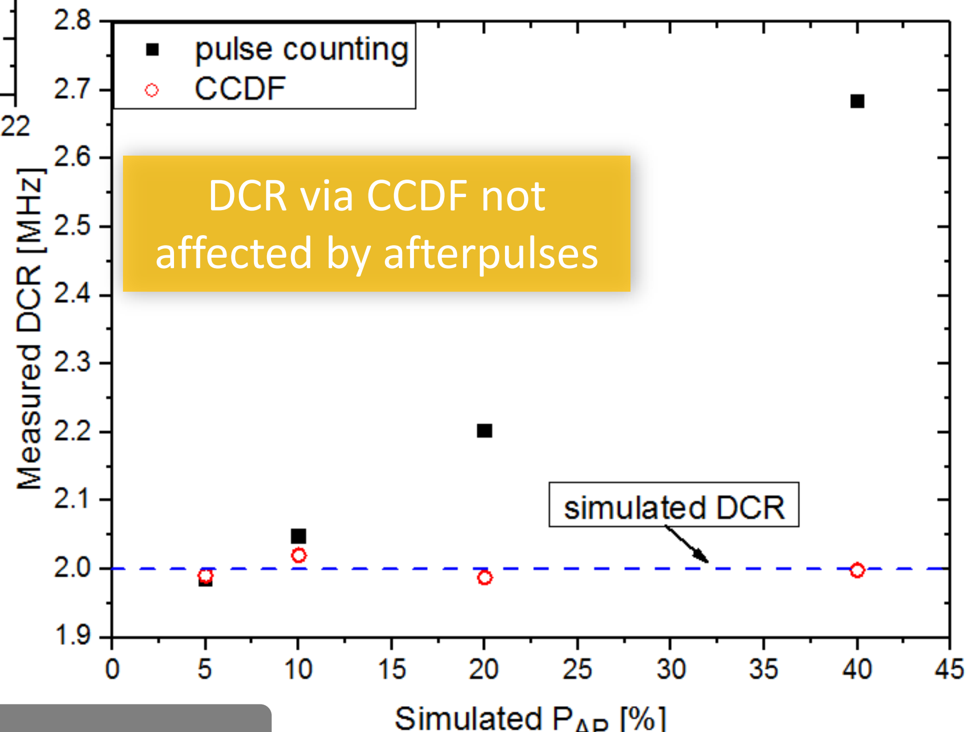
- underestimation of P_{AP} due to inefficient detection of fast afterpulses

Variation of AP



Parameter	Value
DCR [MHz]	2
P_{CT} [%]	9.5
P_{AP} [%]	variable
P_{DCT} [%]	0

- underestimation of P_{AP} due to inefficient detection of fast afterpulses
- overestimation of DCR with pulse counting method
- CCDF method is recommended in case of high P_{AP}



Variation of AP

$$P^*_{\mathrm{tot}}(\Delta t) = \exp\left(-DCR \cdot \Delta t\right) \cdot P^*_{\mathrm{corr}}(\Delta t)$$

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commonly used model

Variation of AP

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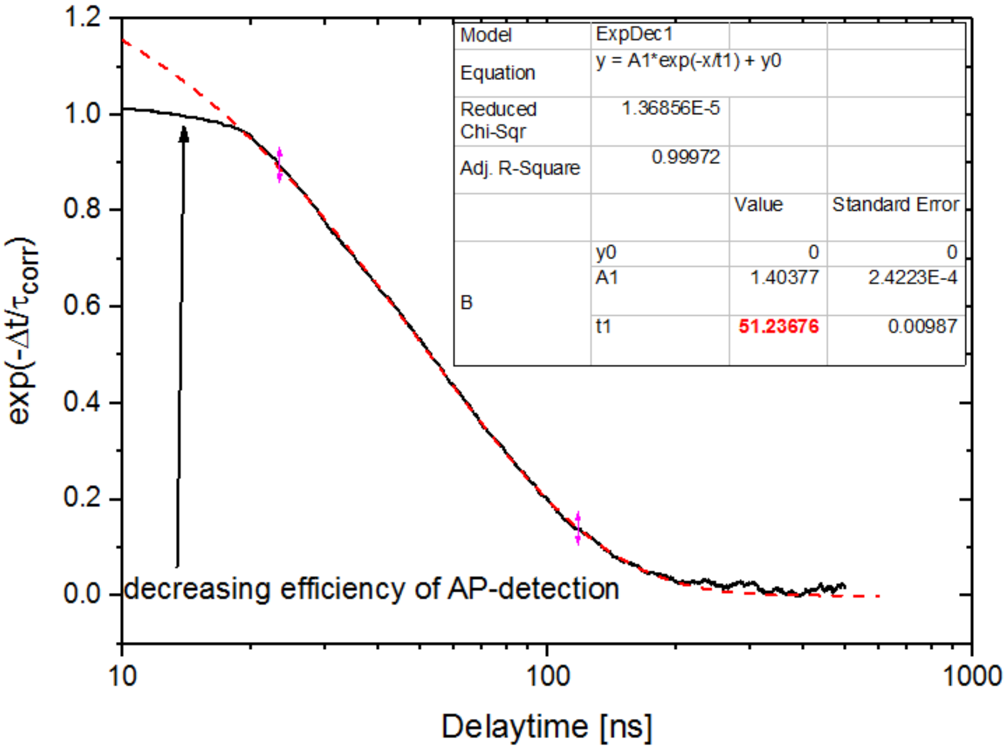
commonly used model

$$\exp\left[-\frac{\Delta t}{\tau_{corr}}\right] = 1 - \frac{\left(1 - \frac{P^*_{\mathrm{tot}}}{\exp[-DCR \cdot \Delta t]}\right)}{P_{\mathrm{C}}}$$

Variation of AP



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commonly used model

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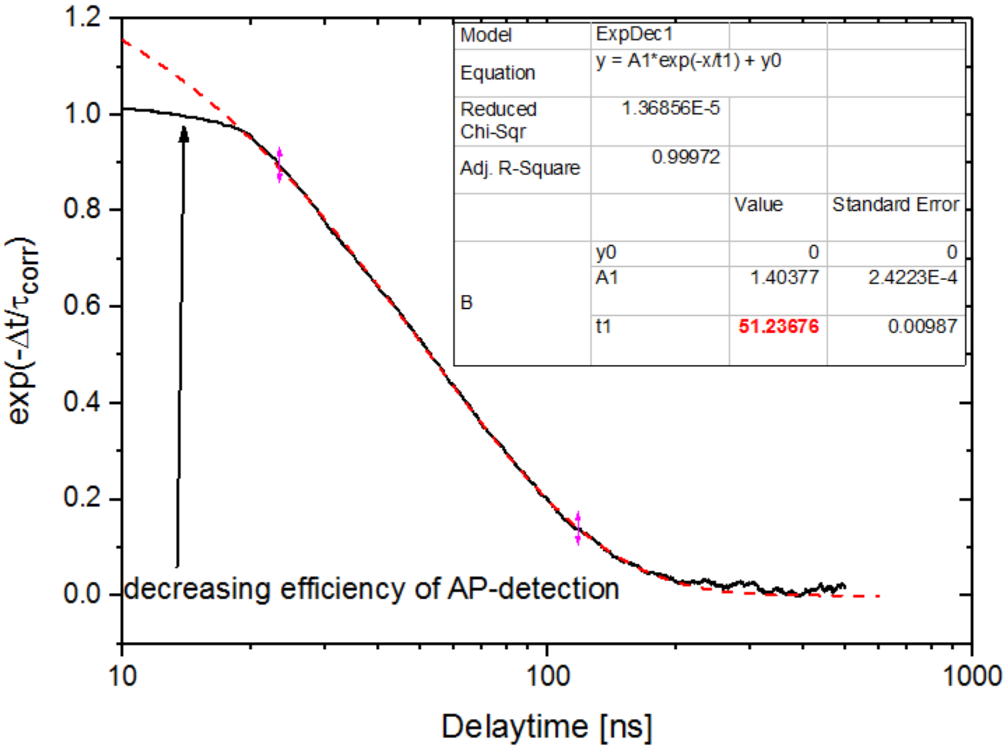
Variation of AP

KETEK



$\tau_{corr} \approx$ 51 ns is in good agreement with simulated 50ns!

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commonly used model

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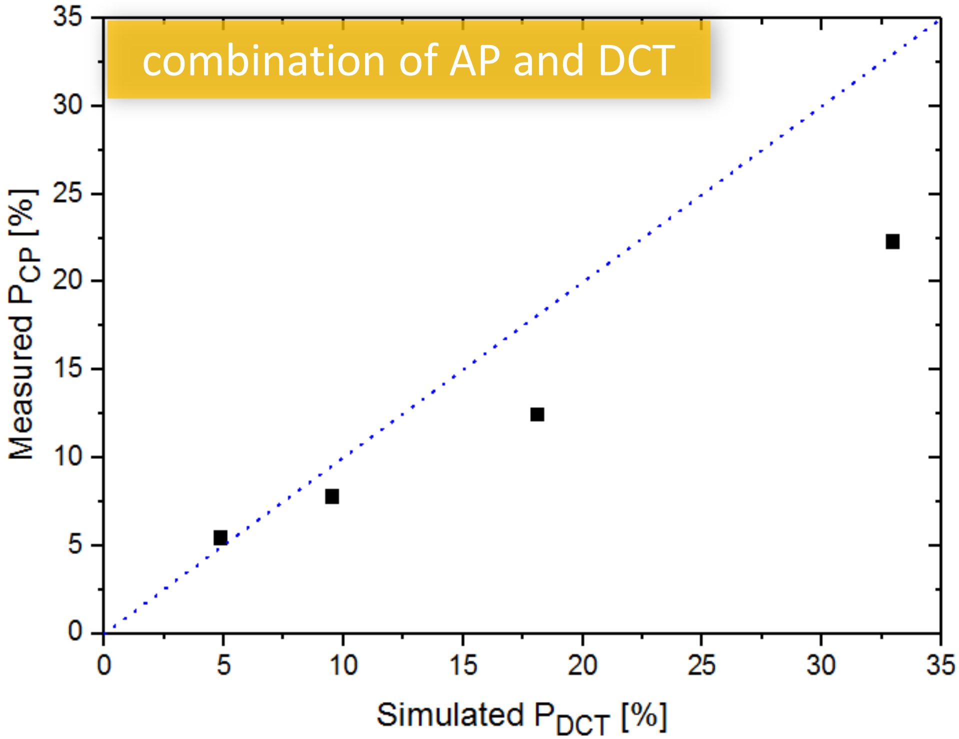
AP delaytime [ns]	50

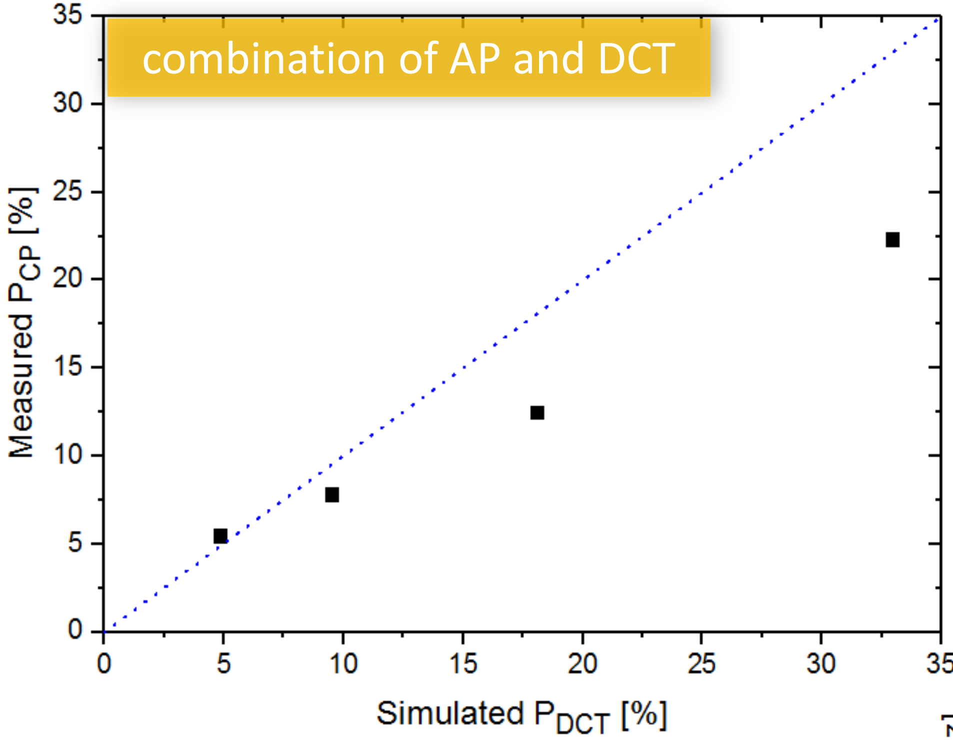
Variation of DCT



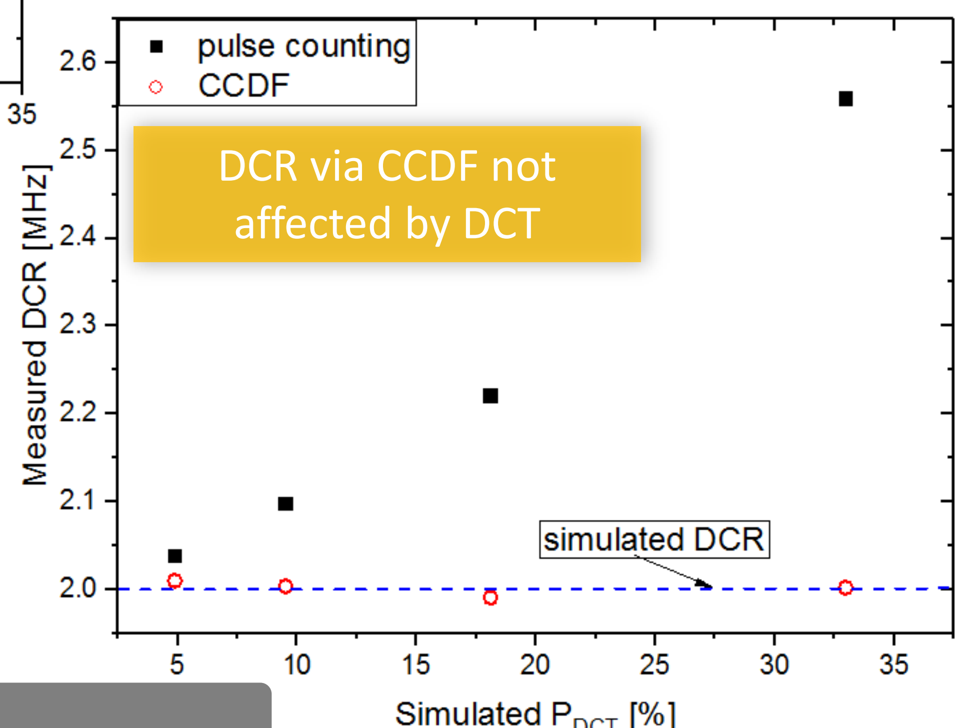
Parameter	Value
DCR [MHz]	2
P_{CT} [%]	9.5
P_{AP} [%]	5
P_{DCT} [%]	variable

- similar problems as for pure afterpulsing
- underestimation of P_{CP} due to inefficient detection of fast pulses

Variation of DCT

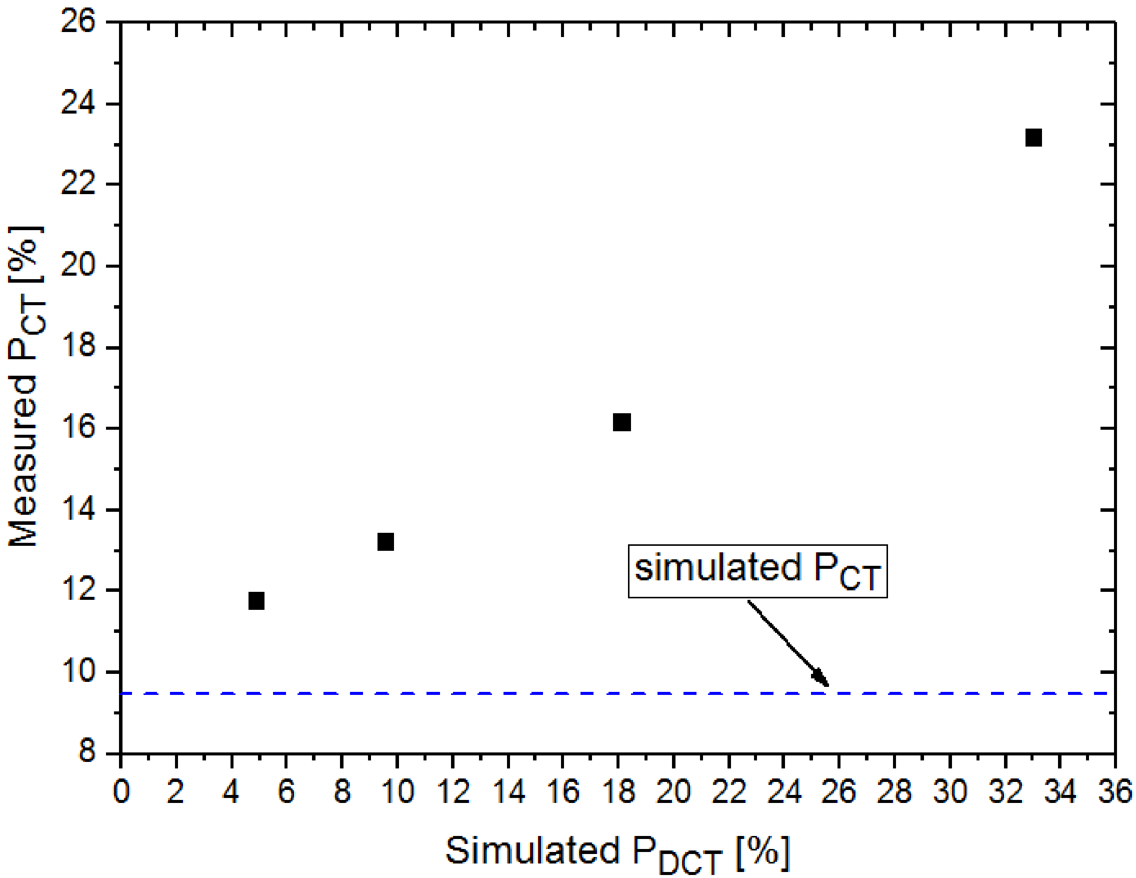


Parameter	Value
DCR [MHz]	2
P_{CT} [%]	9.5
P_{AP} [%]	5
P_{DCT} [%]	variable



- similar problems as for pure afterpulsing
- underestimation of P_{CP} due to inefficient detection of fast pulses
- overestimation of DCR by pulse counting method
- CCDF method is recommended in case of high P_{CP}

Variation of DCT



Parameter	Value
DCR [MHz]	2
P_{CT} [%]	9.5
P_{AP} [%]	5
P_{DCT} [%]	variable

- overestimation of P_{CT} increases with P_{DCT}
- not clear how to separate fast DCT and CT
- is a temperature sweep a possible solution?

I. Introduction of technique for waveform analysis

II. Methods for extraction of nuisance parameters
   i. Optical crosstalk
   ii. Dark count rate (comparison of two methods)
   iii. Correlated noise (afterpulsing and delayed crosstalk)

III. Application of presented methods to simulated SiPM pulses

IV. Discussion

Discussion

- Where to set threshold for detection of afterpulses?
  - datasheets are not comparable otherwise
- Shall afterpulses be weighted according to their amplitude?
- How to distinguish between DCT and AP?
  - amplitude is only a workaround, cannot be applied for fast recovery
  - use special structures with varying quenching resistors?
- How to distinguish between CT and fast DCT?
  - DCT is based on diffusion
  - time-constant of DCT should vary with T
  - CT shows no/weak T dependence