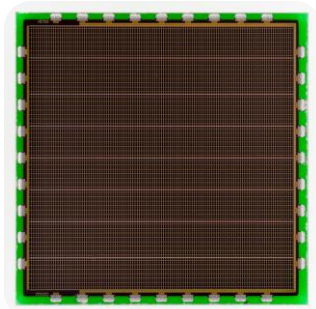
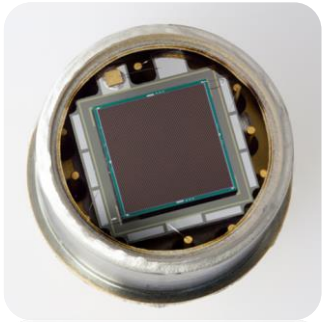
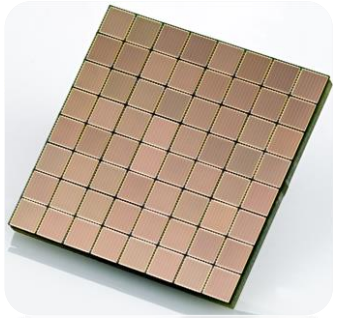
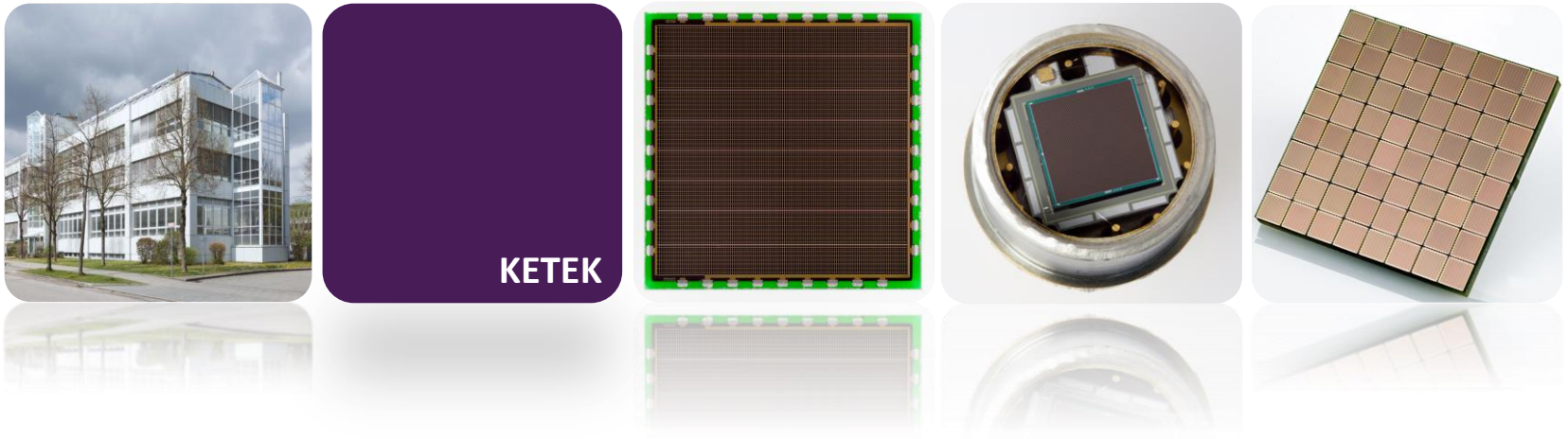




Characterization of SiPMs for Large Scale Applications

Eugen Engelmann
(eugen.engelmann@ketek.net)



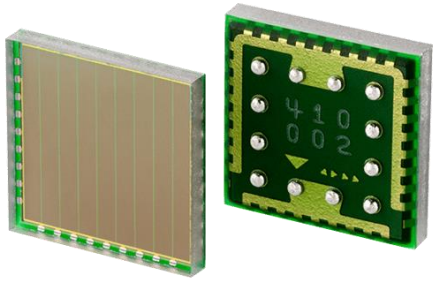
- Family-owned enterprise, founded in 1989 by Dr. Josef Kemmer
- Number of employees: 100
- Certified according to ISO9001:2015
- Major product lines:

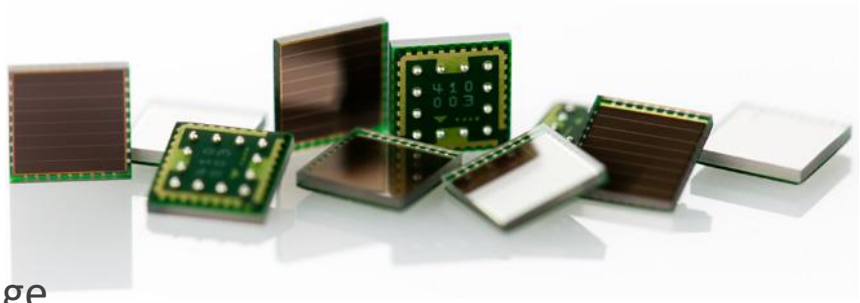
  - SDD modules, detector electronics and complete systems

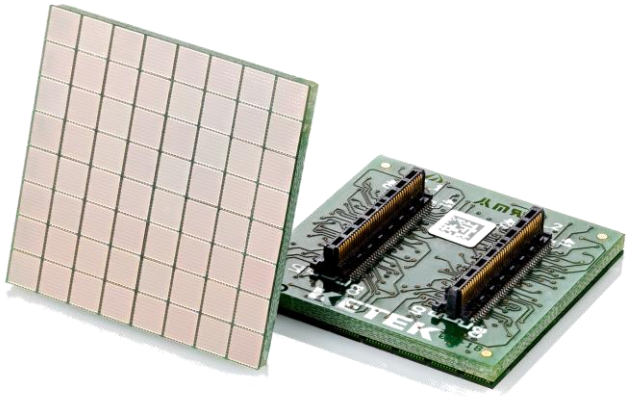
  - **Silicon Photo Multipliers (SiPMs) since 2007**

KETEK SiPM

- **Performance of new WB-Series**
  - superior ratio of PDE to micro-cell pitch
    (up to 50 % at 420 nm)
  - superior DQE
    (S. Vinogradov, talk given at LIGHT-2014)
  - low dark count rate
    (< 100 kHz/mm²)
  - state of the art SPTR
    (down to 150 ps FWHM)
  - highly robust and MSL1 approved package







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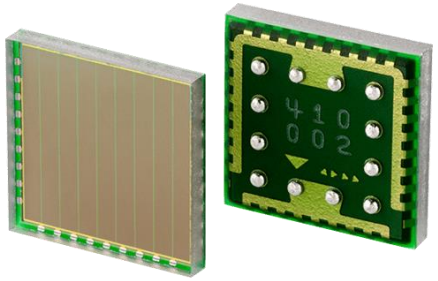
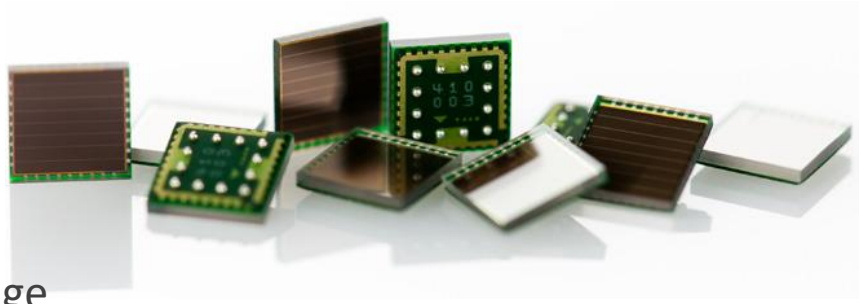
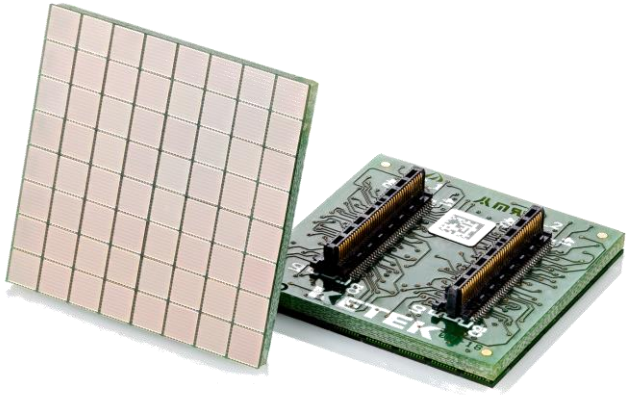




- **Objectives of current research**
  - further suppression of noise parameters
  - combination of high dynamic range and high PDE
  - improve PDE for NIR light



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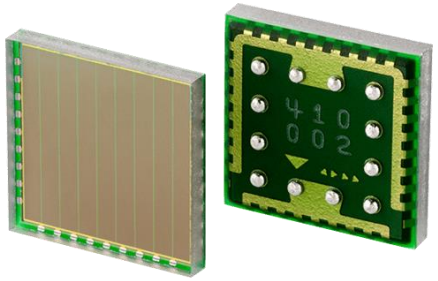

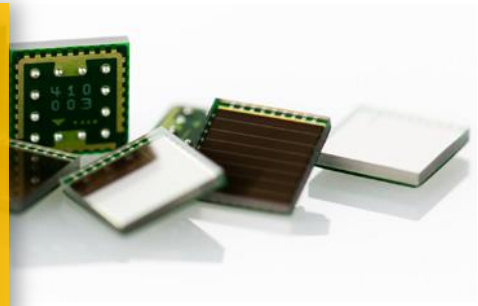

Visit
www.ketek.net/sipm
for more information

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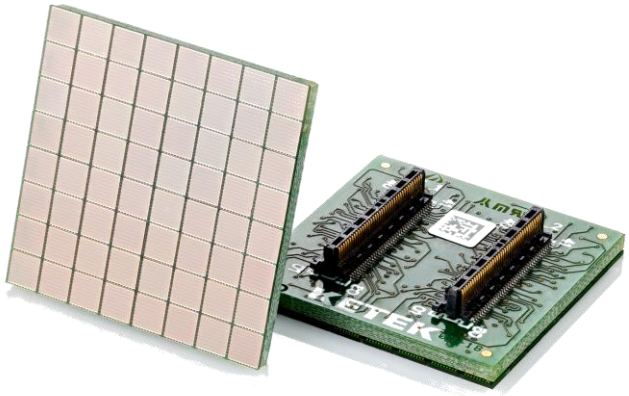

Production chain of the KETEK SiPM

SiPM Fabrication at CMOS Foundry

- ISO/TS 16949:2009 resp. IATF 16949:2016
  (Quality Systems for Automotive Suppliers)

Production chain of the KETEK SiPM

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IV screening of wafers

Wafer Level Scale Packaging

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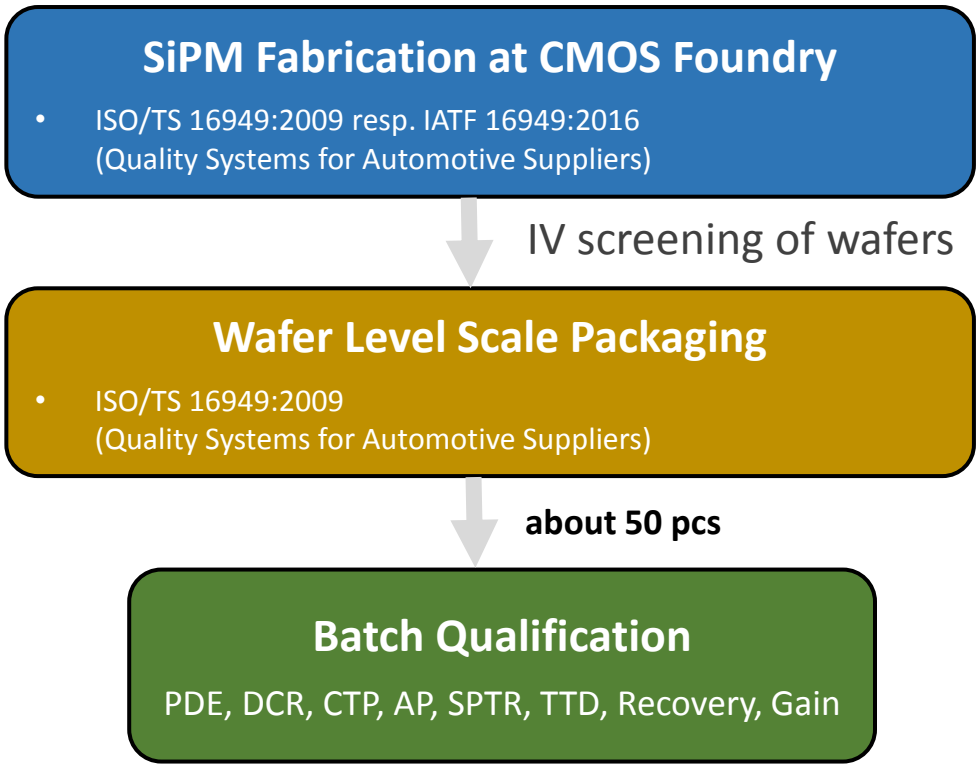

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Wafer Level Scale Packaging

- ISO/TS 16949:2009
  (Quality Systems for Automotive Suppliers)

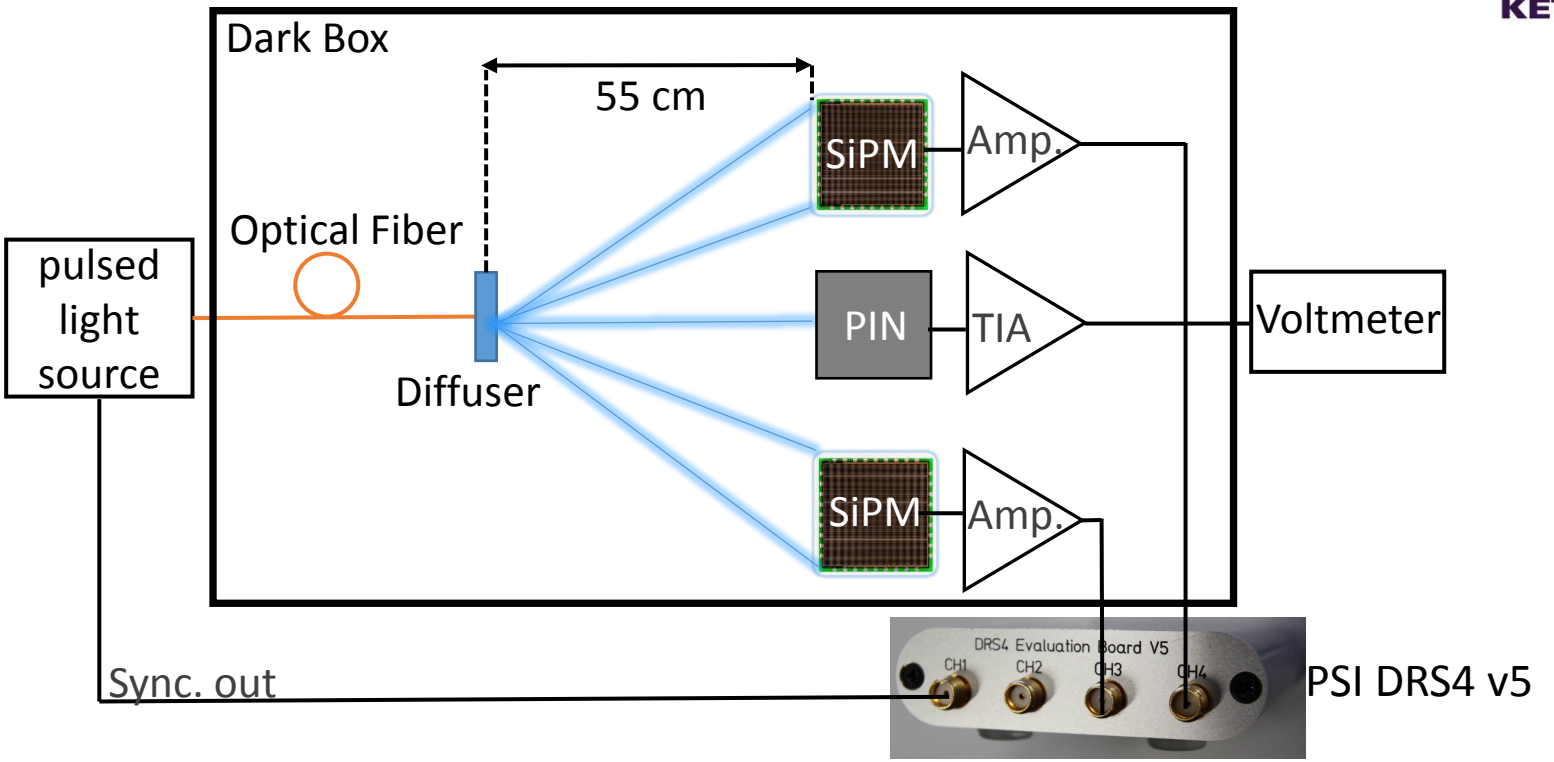
about 50 pcs

Batch Qualification

PDE, DCR, CTP, AP, SPTR, TTD, Recovery, Gain

- **Standard techniques:**
  - PDE (photo detection efficiency)
  - SPTR (single photon time resolution)
  - DCR (dark count rate)
  - Recovery time and gain
- **Advanced techniques:**
  - correlated noise
  - spatially resolved DCR

KETEK PDE-Setup



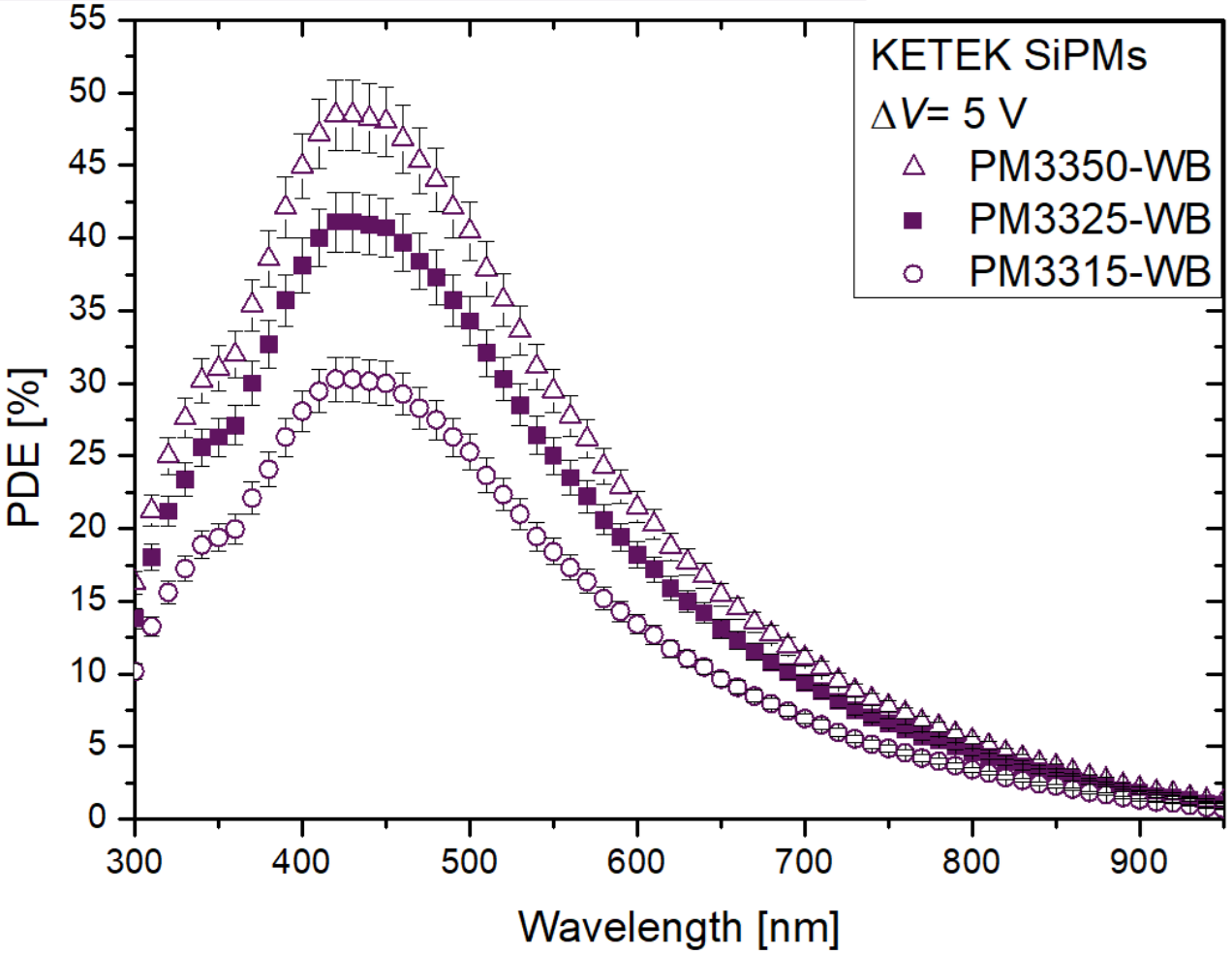
- simultaneous meas. of two SiPMs
- automatic DAQ and analysis
- PIN-diode as reference for incident light
- commonly used approach:
  - P. Eckert et al., doi: 10.1016/j.nima.2010.03.169
    A. Otte et al., doi: 10.1016/j.nima.2016.09.053

$$N_{detected} = -ln\left(\frac{N_0}{N_{flashes}}\right) + ln\left(\frac{N_0^{dark}}{N_{flashes}}\right)$$

$$PDE = \frac{N_{detected}}{N_{incident}}$$

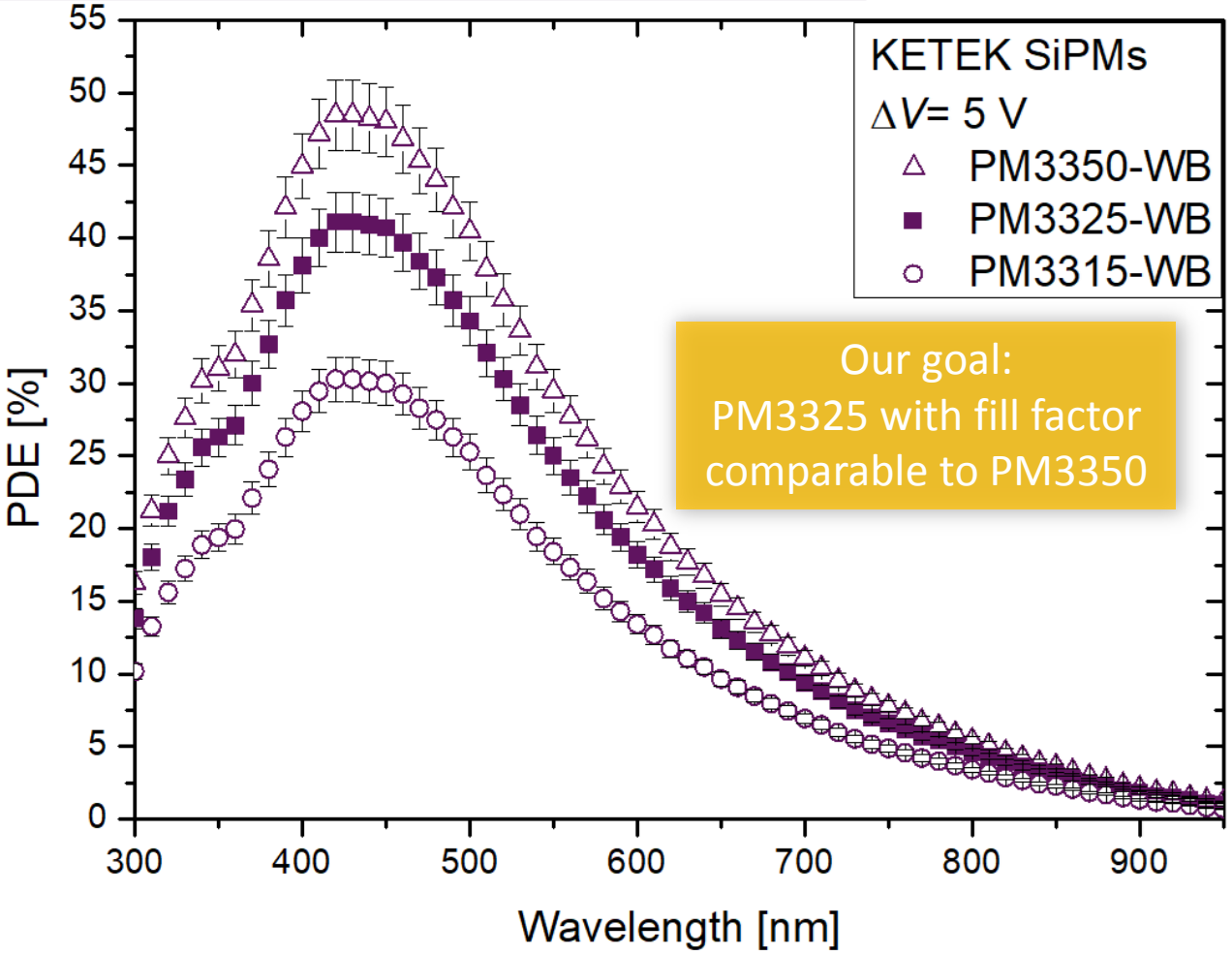
$N_{incident}$ via ref. SiPM or PIN-diode

PDE



- superior ratio of PDE to µ-cell pitch for blue light
- trade off: PDE vs. dynamic range

PDE



- superior ratio of PDE to µ-cell pitch for blue light
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KETEK SPTR Setup

Diode Laser
HPK PLP-10 C10196
with 406nm and 60ps pulse width (FWHM)

sync out

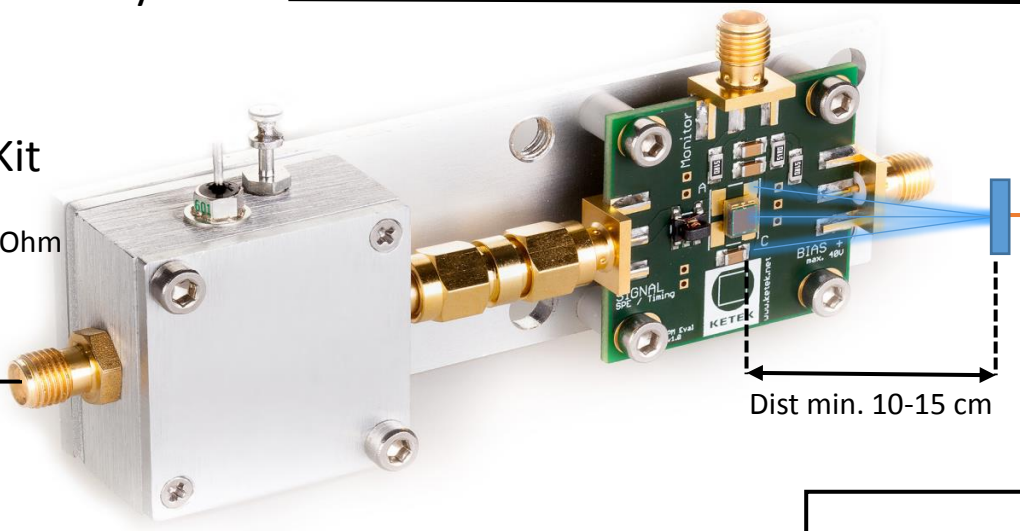
Free-space Attenuator

Optical Fiber
Thorlabs M31L01

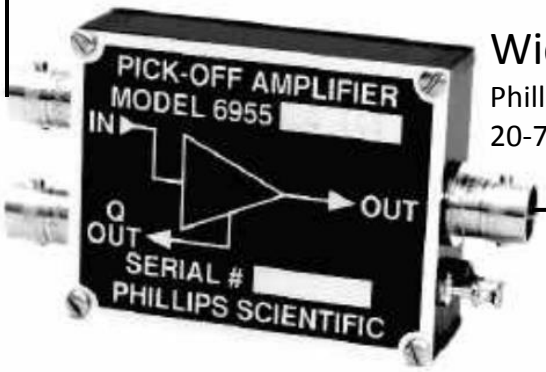
Optical Fiber
Thorlabs M31L01

KETEK Evaluation Kit

0.1-1000 MHz G=13
Impedance matching to 50 Ohm input with reference transformer



Dist min. 10-15 cm



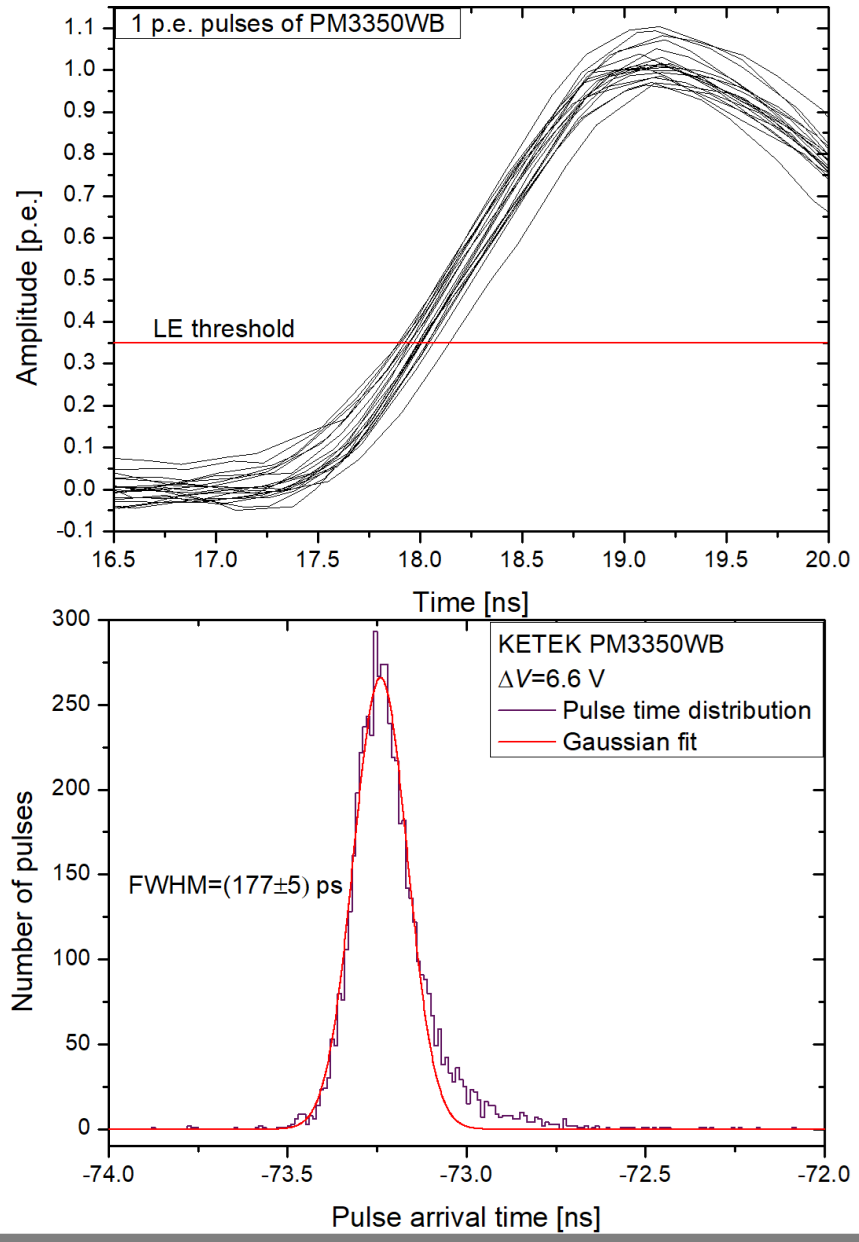
Wideband Amplifier

Phillips Scientific 6955
20-700 MHz G=10

PSI DRS4 v5

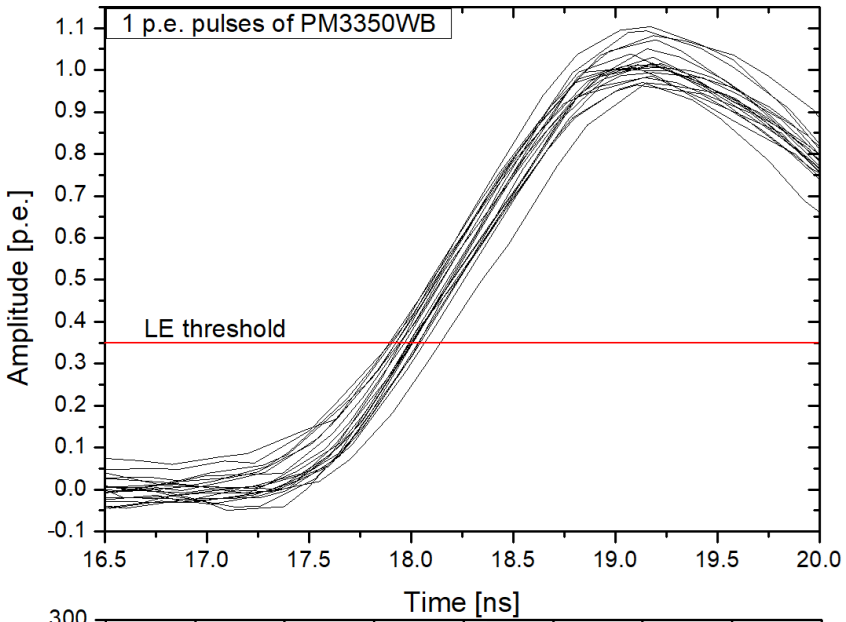
BW 700 MHz
14-bit ADC
5 GS/s

SPTR



- only 1 p.e. pulses are considered
- LE-threshold at ≈0.35 p.e.
- linear interpolation between samples to increase accuracy
- correction for baseline fluctuation

SPTR



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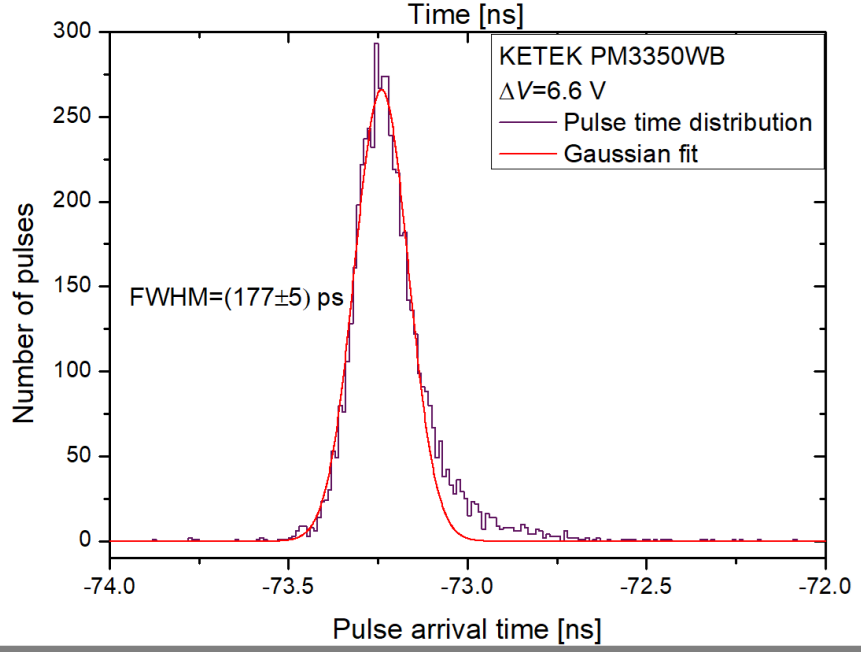
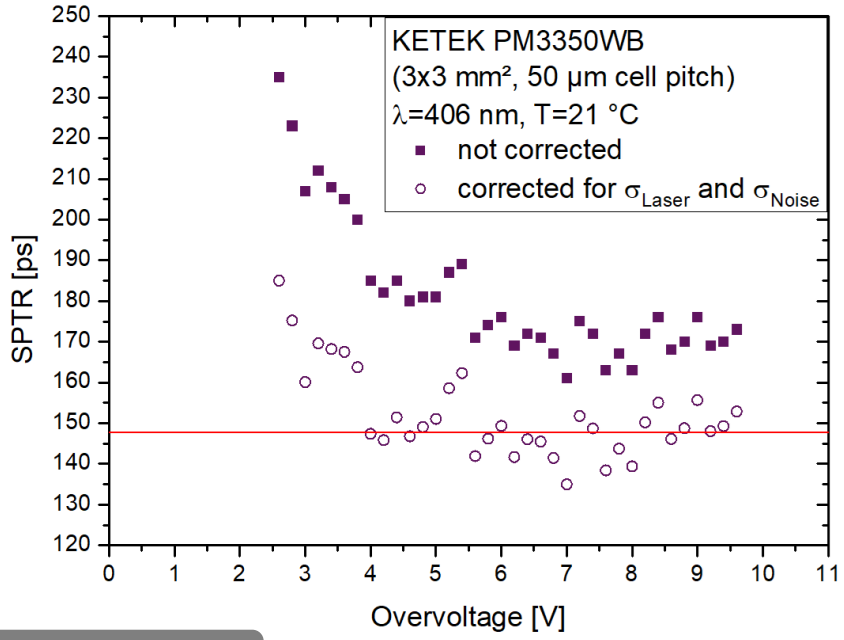
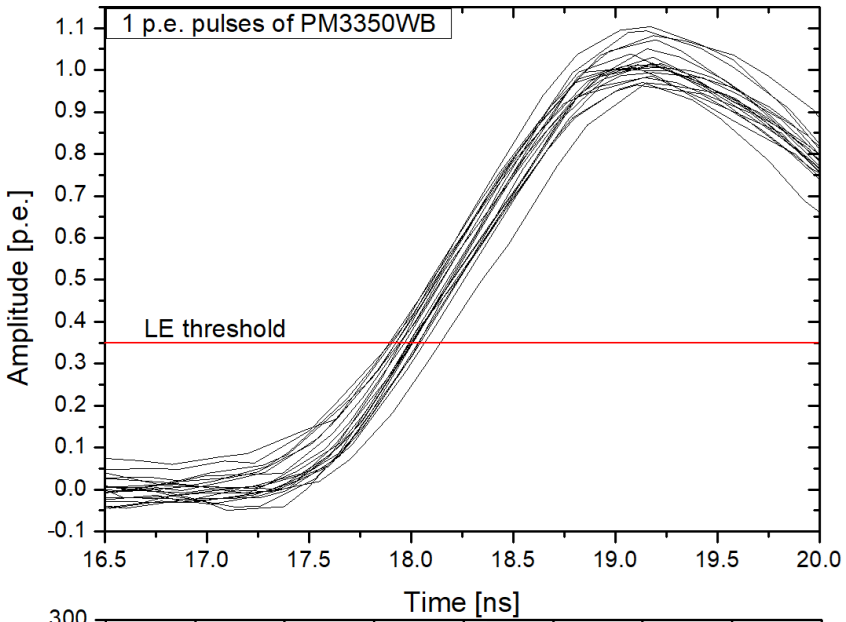
$$\sigma^2_{SPTR} \approx \sigma^2_{SiPM} + \sigma^2_{Laser} + \sigma^2_{Noise}$$





SPTR



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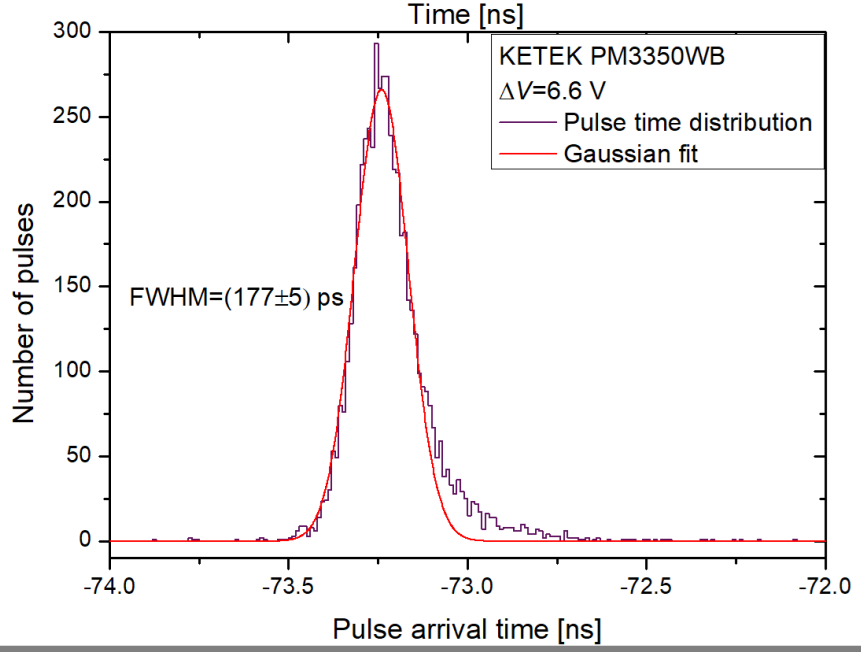
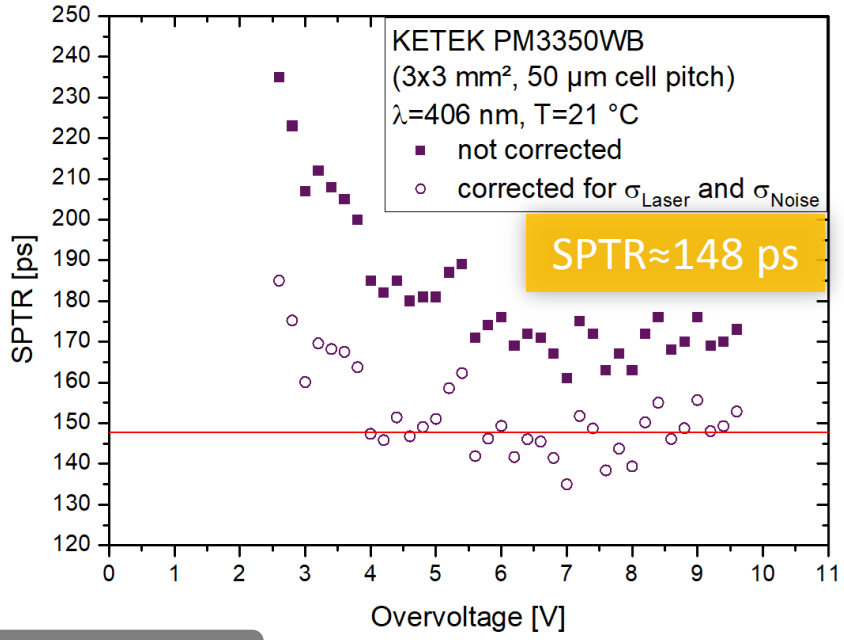
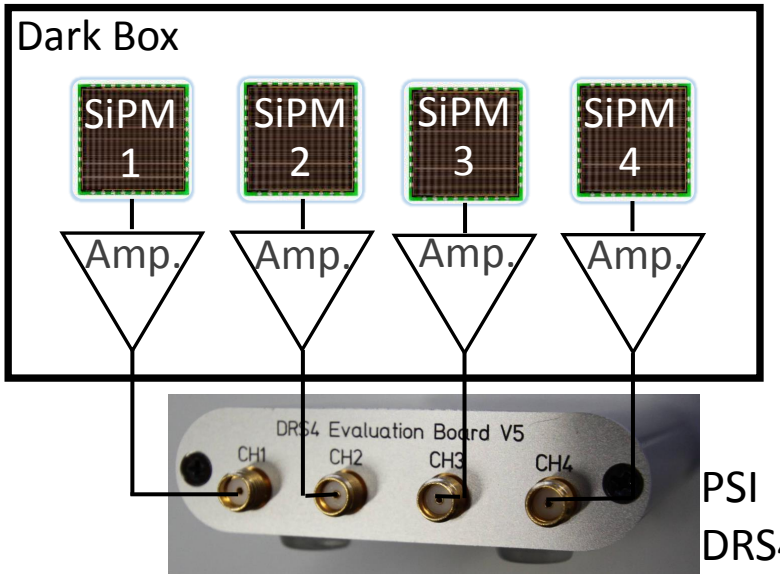


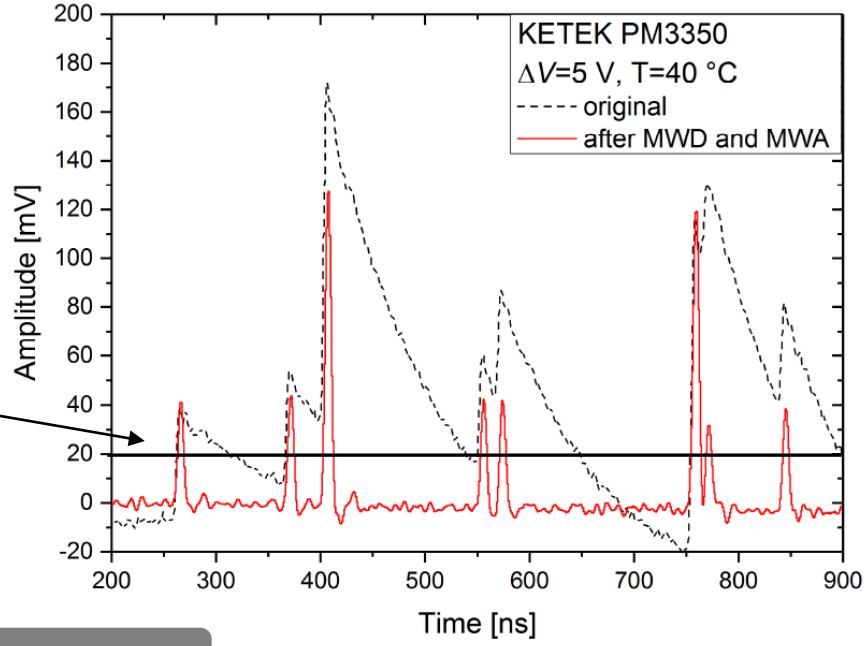


KETEK DCR-Setup



PSI
DRS4 v5

- automatic DAQ
  (4 samples simultaneously)
- acquisition of randomly triggered WFs
- pulse detection via WF-analysis
- LED with threshold set at 0.5 p.e.
- DCR is number of pulses per investigated signal time



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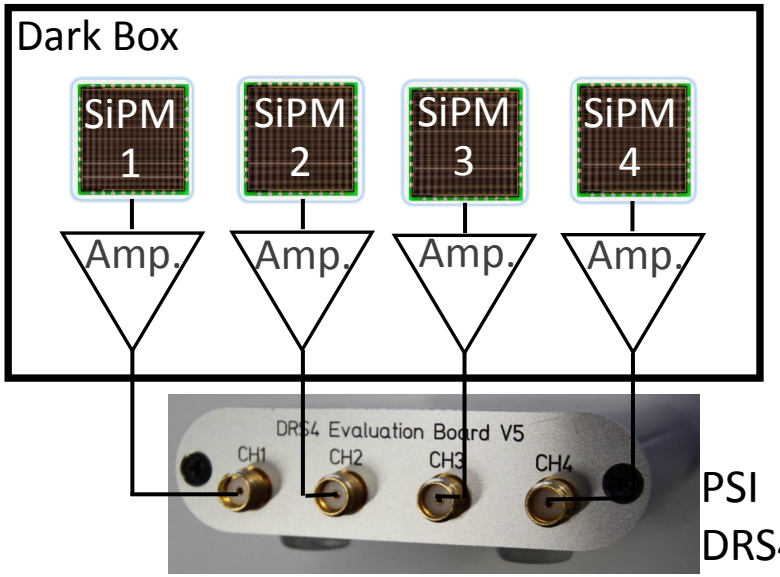

PSI
DRS4 v5

DCR via pulse counting is only applicable due to low afterpulsing and delayed X-talk

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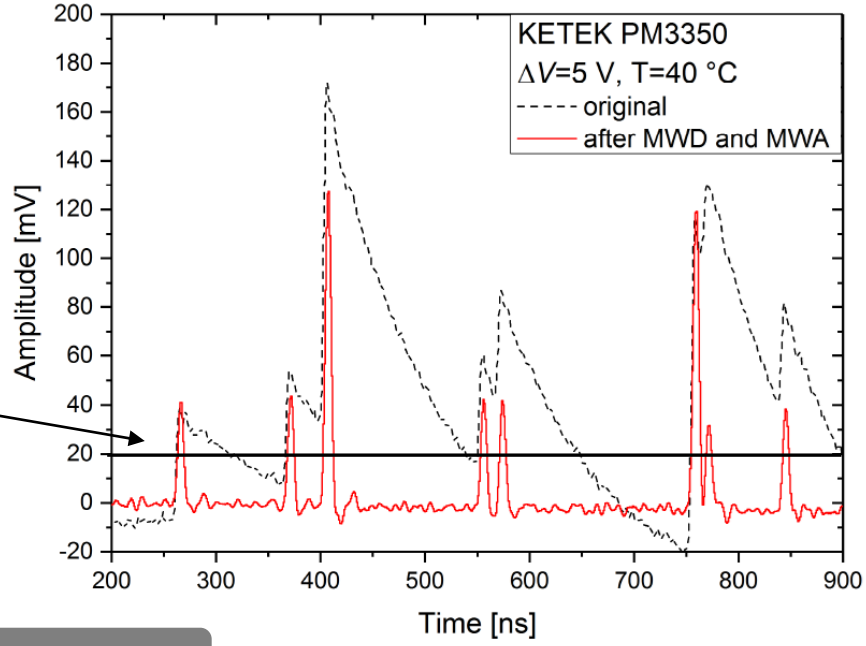

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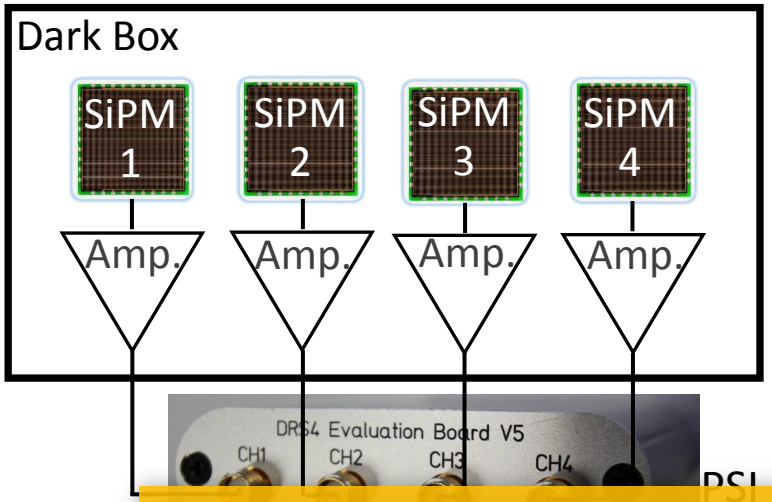

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Visit my talk on Wed at 14:40 for more details

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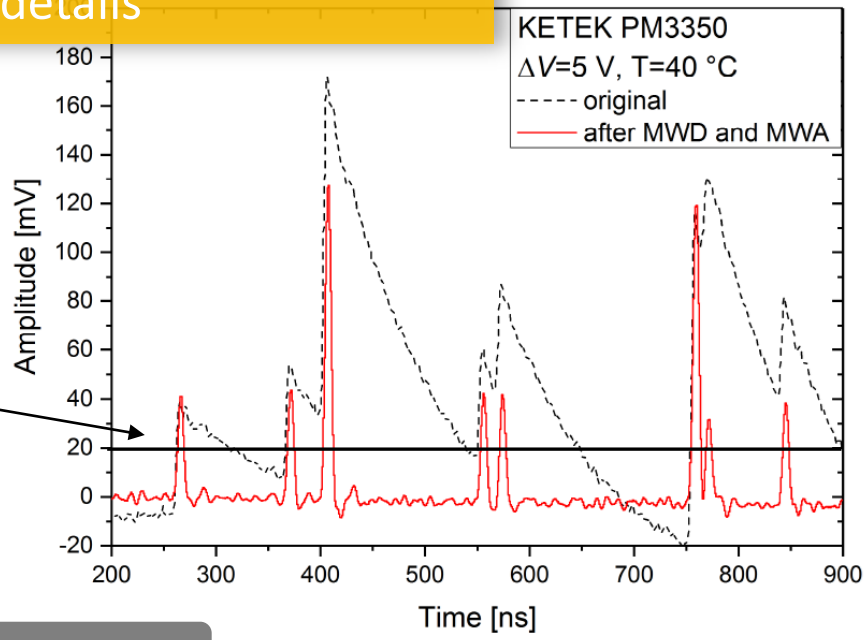
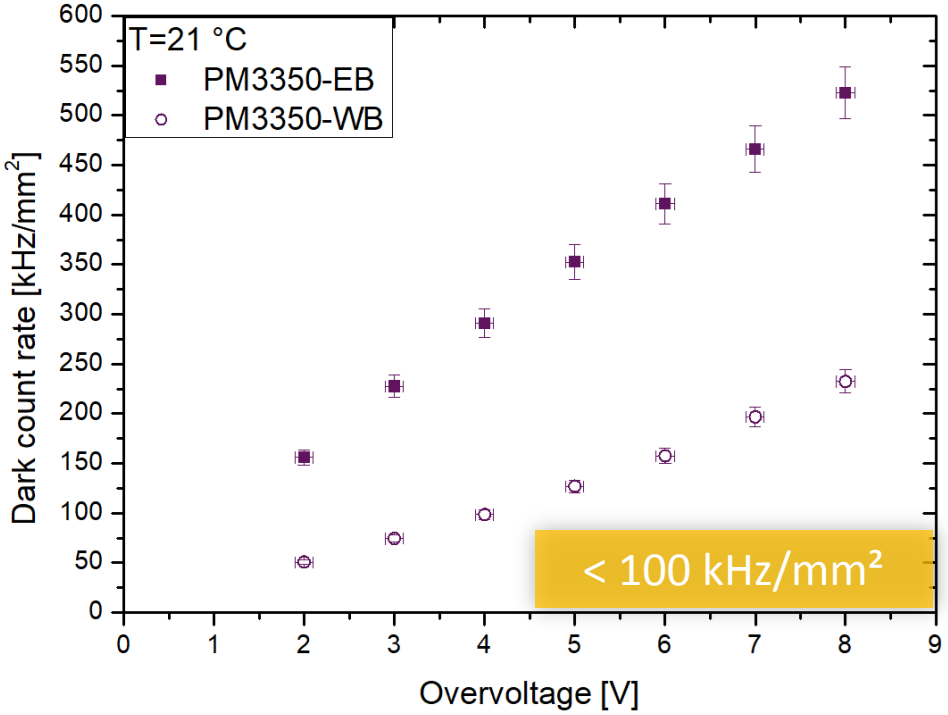
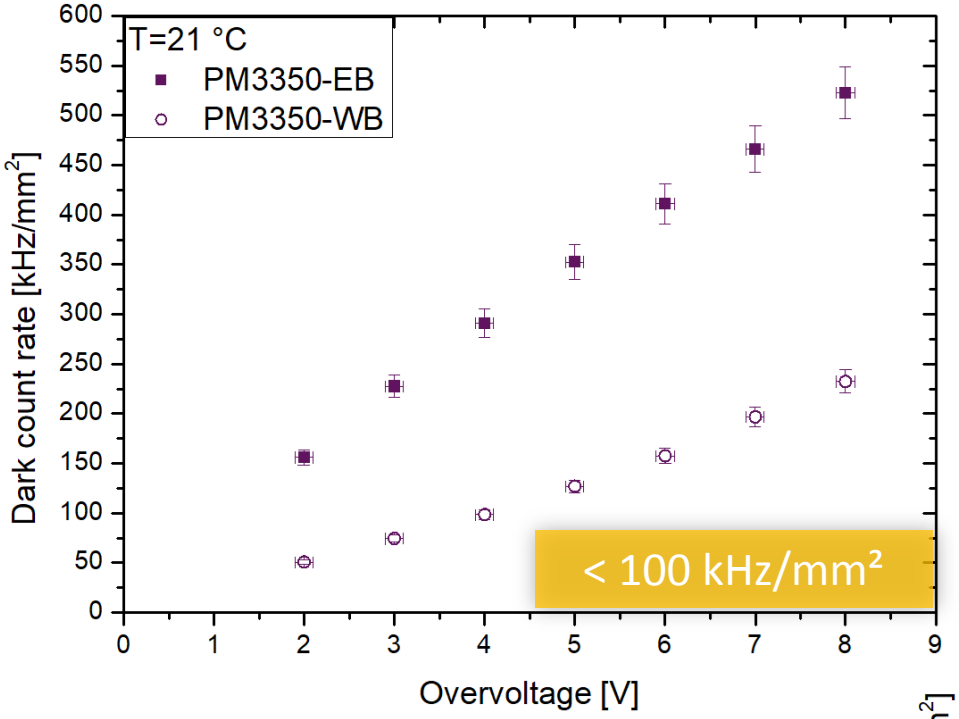


DCR



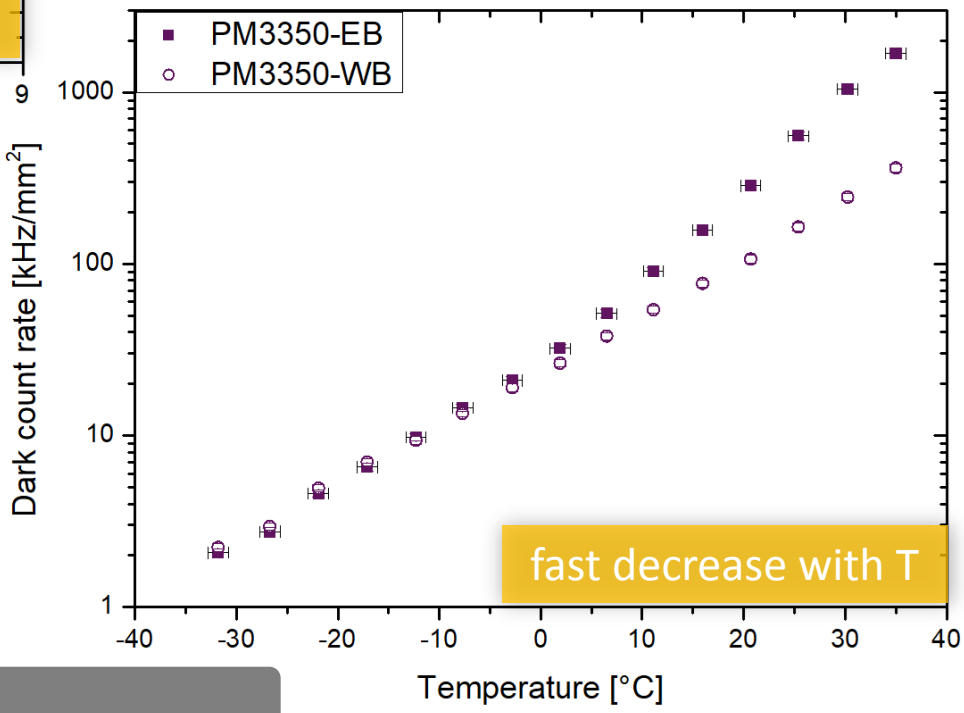
- modification of µ-cell for new WB-series
- suppression of diffusion current
- significant reduction of DCR below 100 kHz/mm² at T=21 °C and saturated PDE

DCR

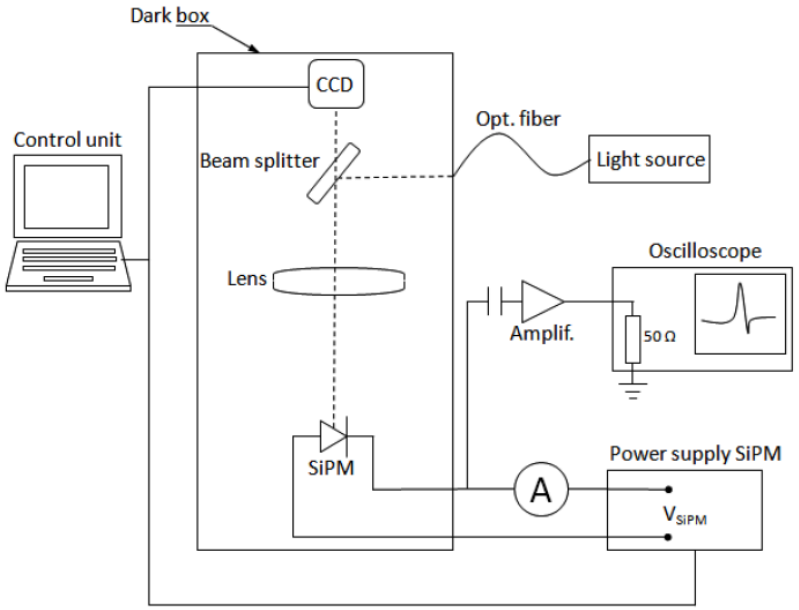


- modification of µ-cell for new WB-series
- suppression of diffusion current
- significant reduction of DCR below 100 kHz/mm² at T=21 °C and saturated PDE

- no impact on DCR at lower temperatures

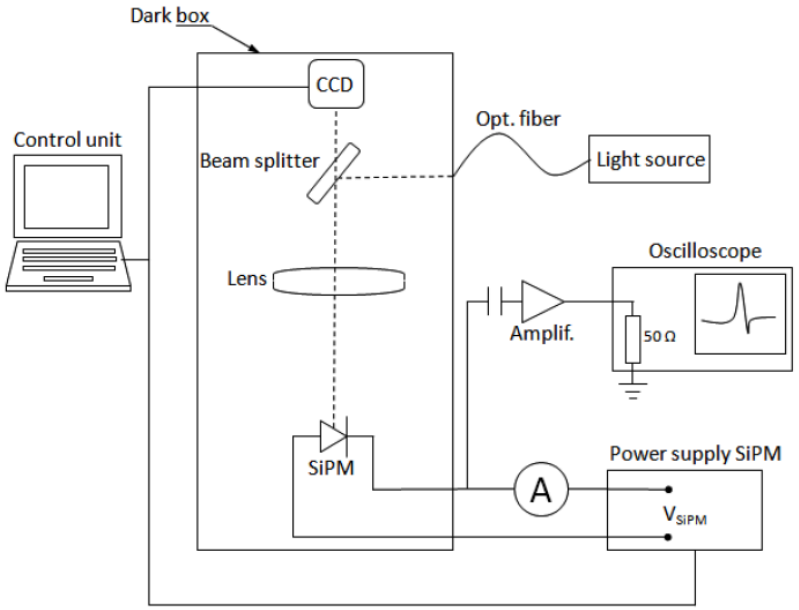


Spatially Resolved DCR



- µ-cells emit light during breakdown
- ~2.6 $\cdot 10^{-5}$ photons/electron in spectral range from 500 – 1600 nm
  (R. Mirzoyan et al., doi:10.1016/j.nima.2009.05.081)
- detection of emitted light with CCD camera
- light intensity is proportional to DCR

Spatially Resolved DCR



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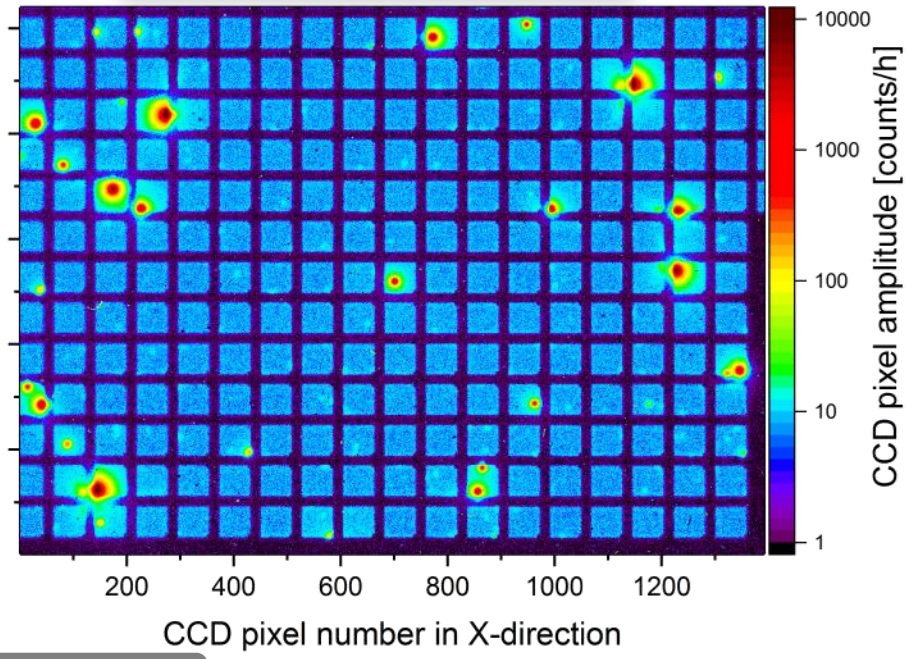
spatially resolved DCR



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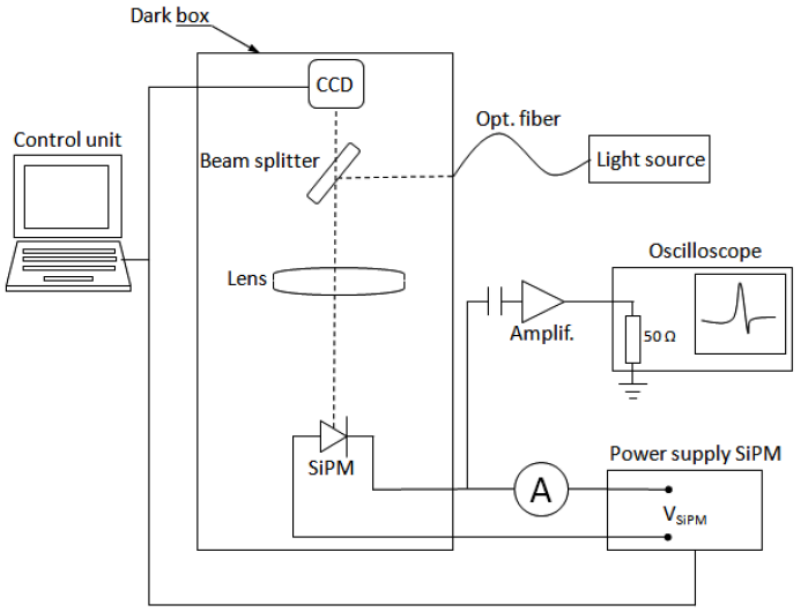

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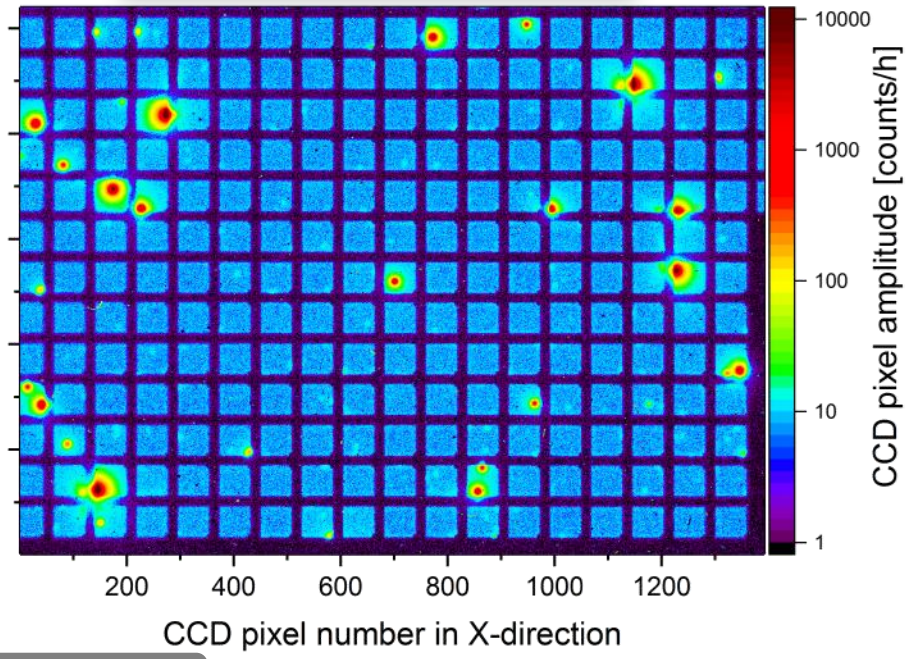
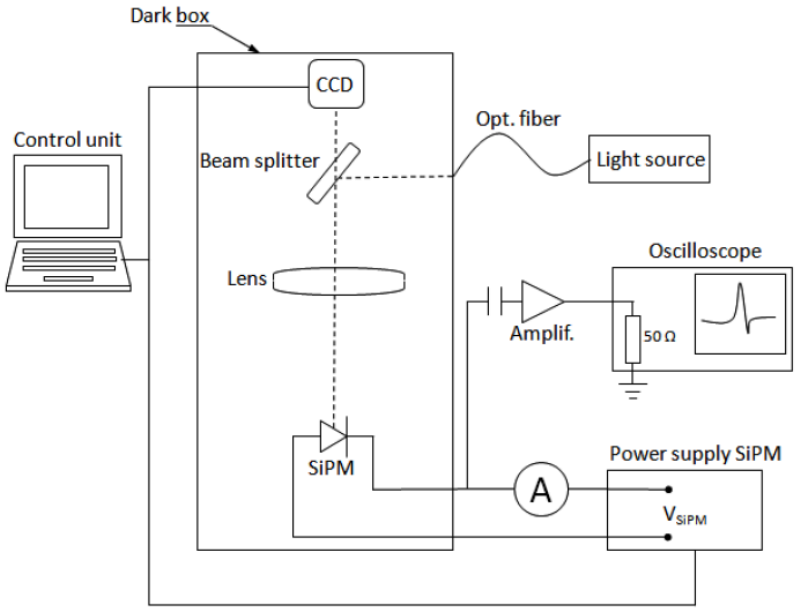


- non-destructive method for defect analysis
  (presented at IEEE NSS/MIC/RTSD 2016 and NDIP 2017)
- homogeneous emission from majority of µ-cells
- enhanced emission from hotspots in single µ-cells

Spatially Resolved DCR



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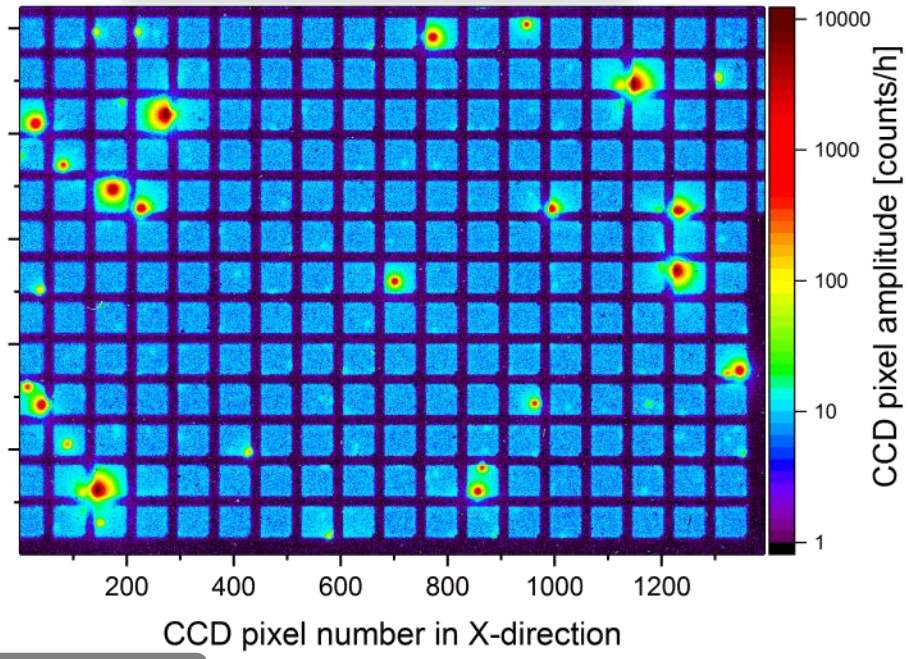
spatially resolved DCR



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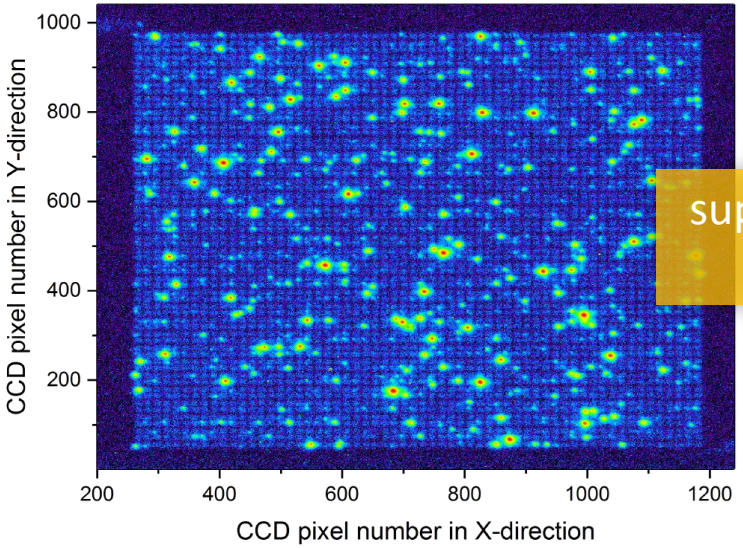
  (presented at IEEE NSS/MIC/RTSD 2016 and NDIP 2017)
- homogeneous emission from majority of µ-cells
- enhanced emission from hotspots in single µ-cells

hotspots are responsible for ≈55 % of the total DCR

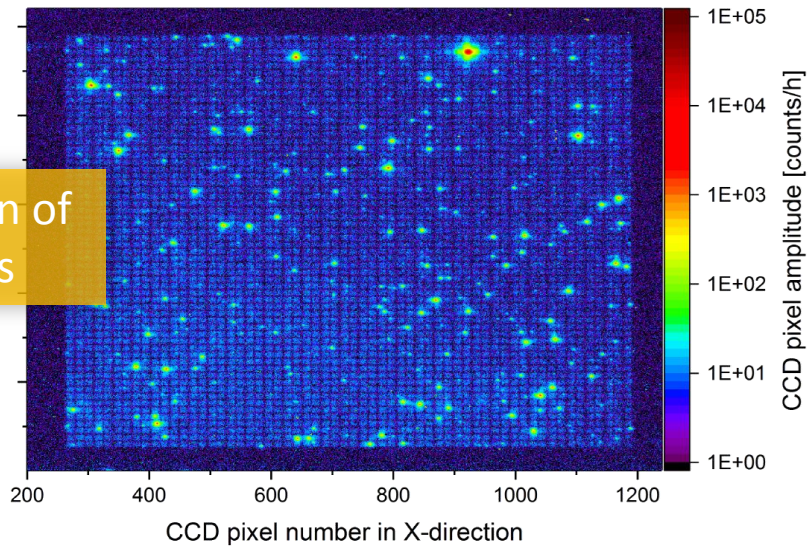
Spatially Resolved DCR

PM3350-WB



suppression of hotspots

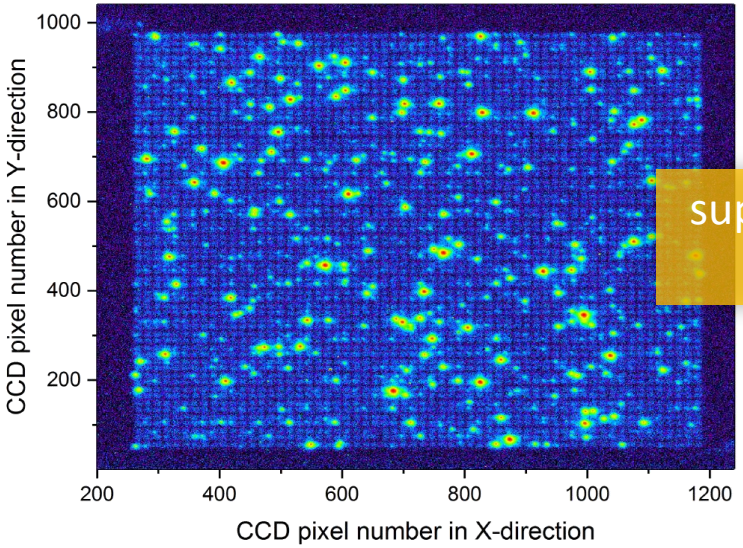
PM3350-Prototype



- variation of fabrication process
- reduction of crystal defects in aval. zone
- significant reduction of hotspots in prototype SiPMs

Spatially Resolved DCR

PM3350-WB



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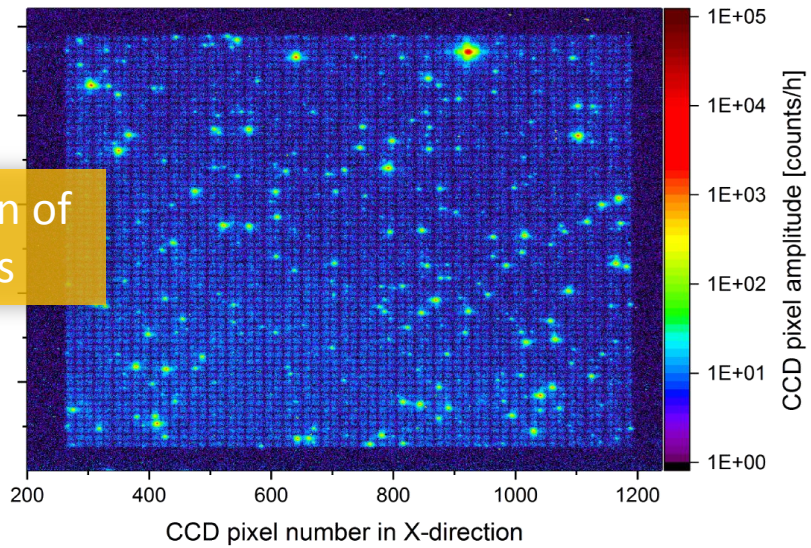
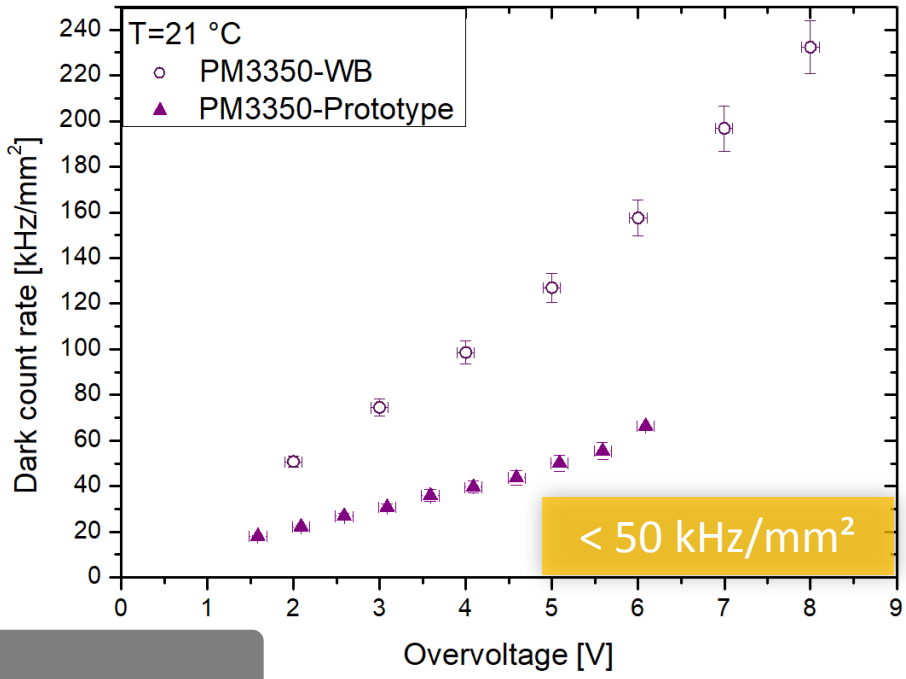


suppression of hotspots

- variation of fabrication process
- reduction of crystal defects in aval. zone
- significant reduction of hotspots in prototype SiPMs
- further suppression of DCR below 50 kHz/mm²
- goal in SiPM development: DCR< 10 kHz/mm²



Probability of Correlated Pulses (P_{CP})

- measure Δt between pulses
- use CCDF method to extract P_{CP} (S. Vinogradov, doi:10.1109/NSSMIC.2016.8069965)
- CCDF and pulse counting show same DCR
- reason is the low afterpulsing and delayed X-talk probability

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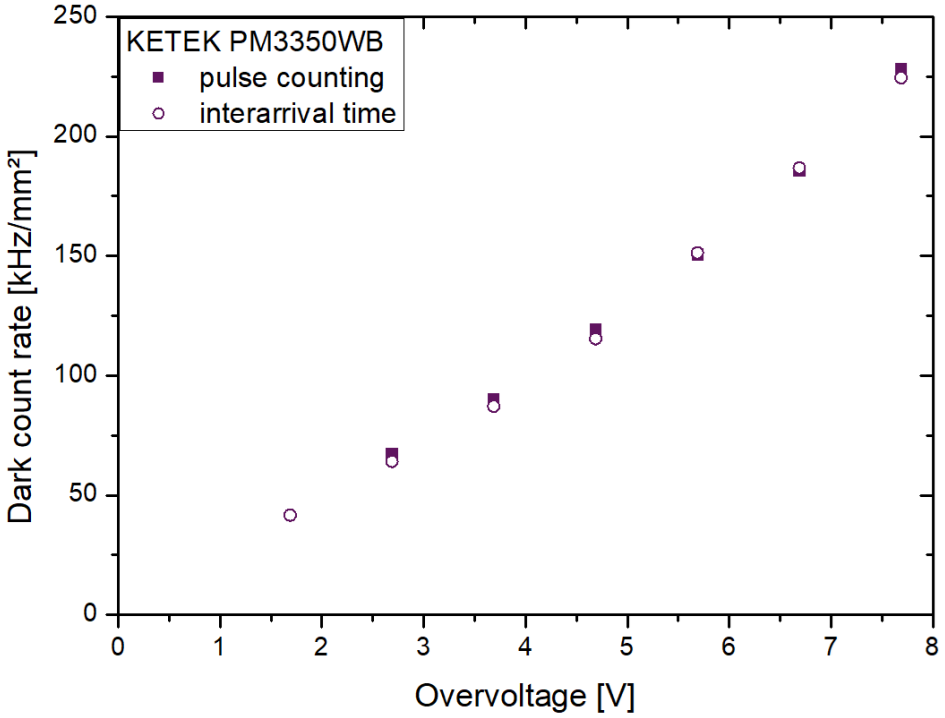

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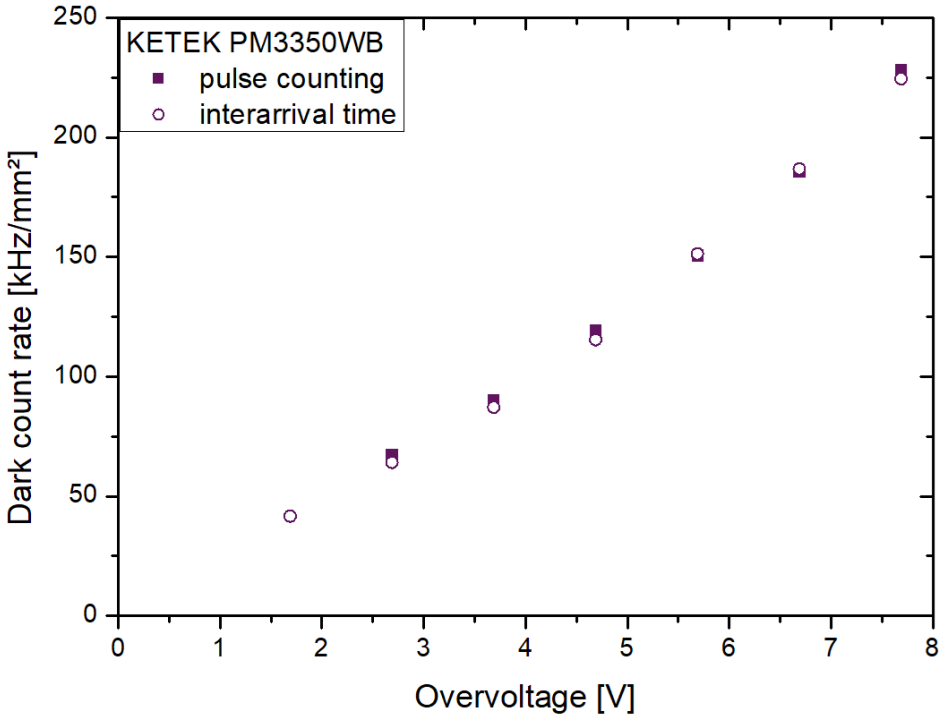

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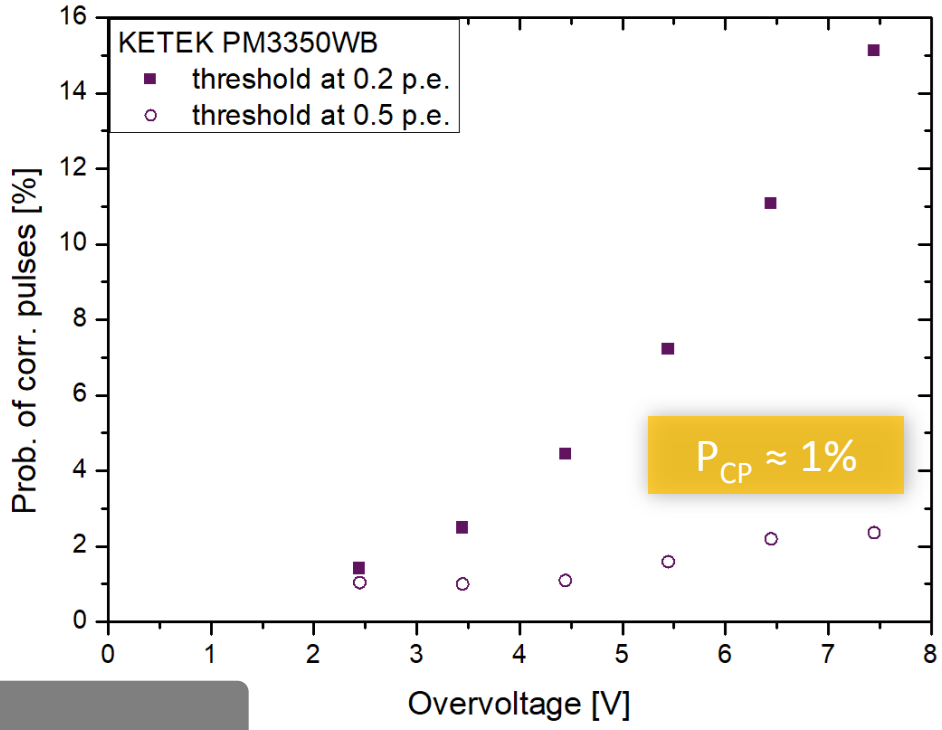
- P_{CP} increases with decreasing threshold
- afterpulsing and delayed X-talk are not distinguished



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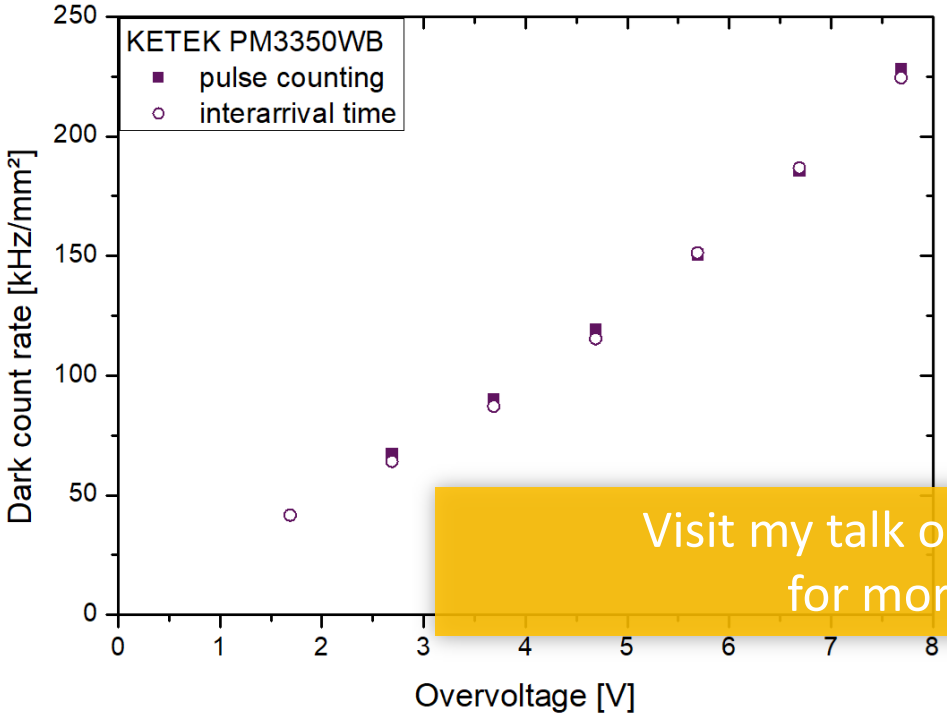

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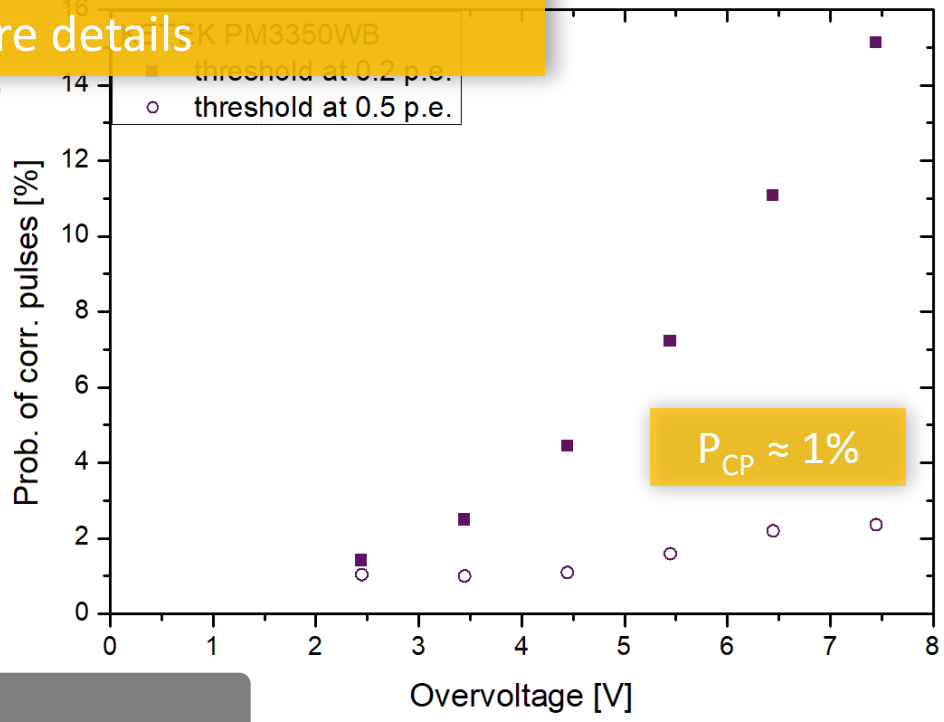
Visit my talk on Wed at 14:40 for more details

- P_{CP} increases with lower threshold
- afterpulsing and delayed X-talk are not distinguished



Production chain of the KETEK SiPM

SiPM Fabrication at CMOS Foundry

- ISO/TS 16949:2009 resp. IATF 16949:2016
  (Quality Systems for Automotive Suppliers)

IV screening of wafers

Wafer Level Scale Packaging

- ISO/TS 16949:2009
  (Quality Systems for Automotive Suppliers)

Batch Qualification

DCR, CTP, AP, PDE, TTDS, SPTR, Recovery, Gain

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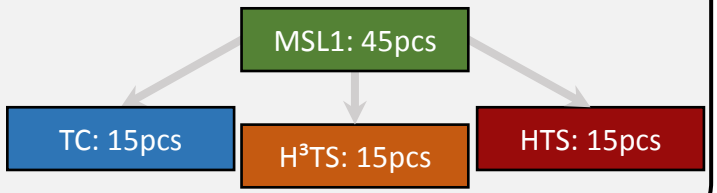
Reliability Testing



Production chain of the KETEK SiPM

KETEK

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Wafer Level Scale Packaging

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  (Quality Systems for Automotive Suppliers)

100% Final IV-Testing

- ISO 9001:2015
- ISO 17025:2005 (for test environment)

acceptance gate

Batch Qualification

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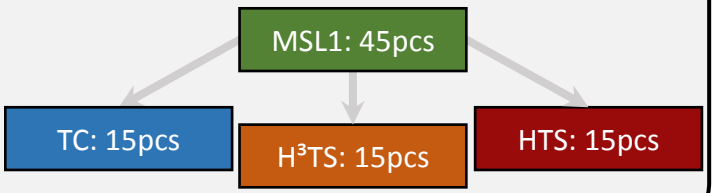
Reliability Testing



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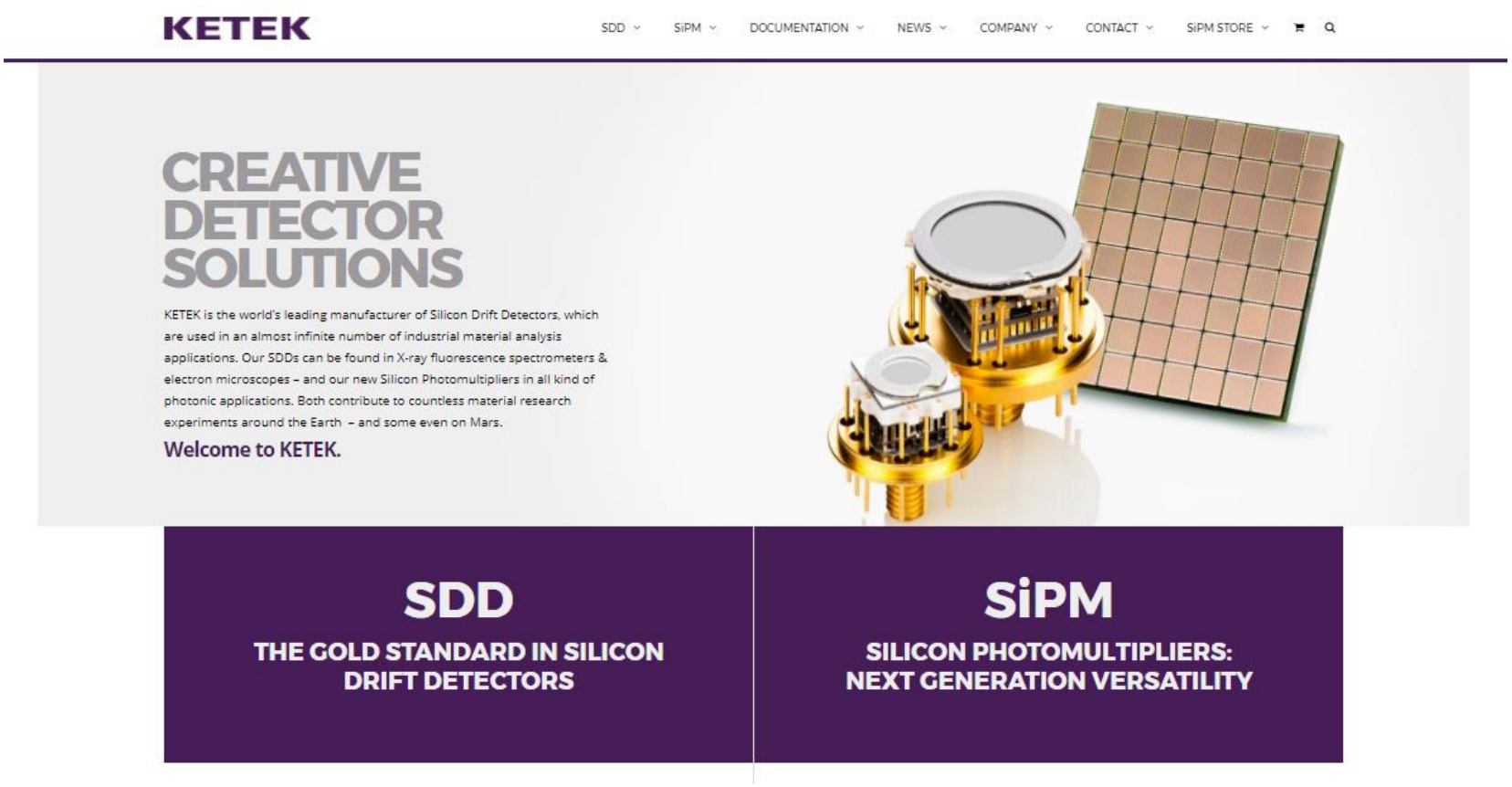
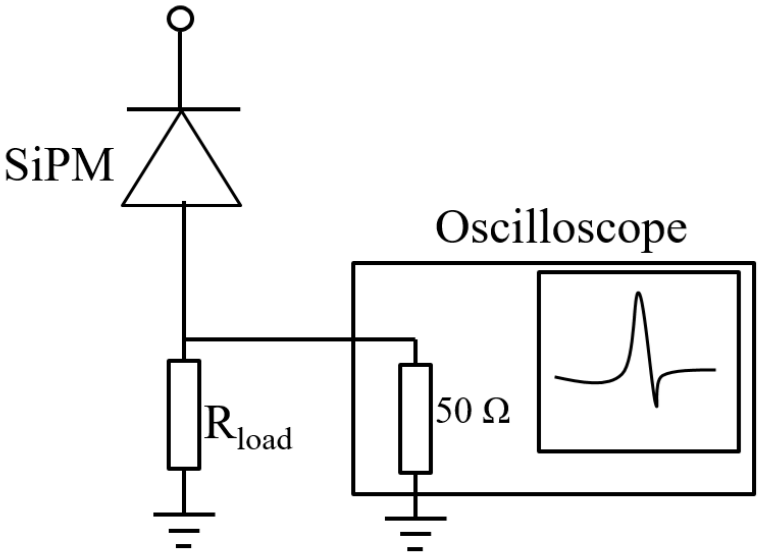
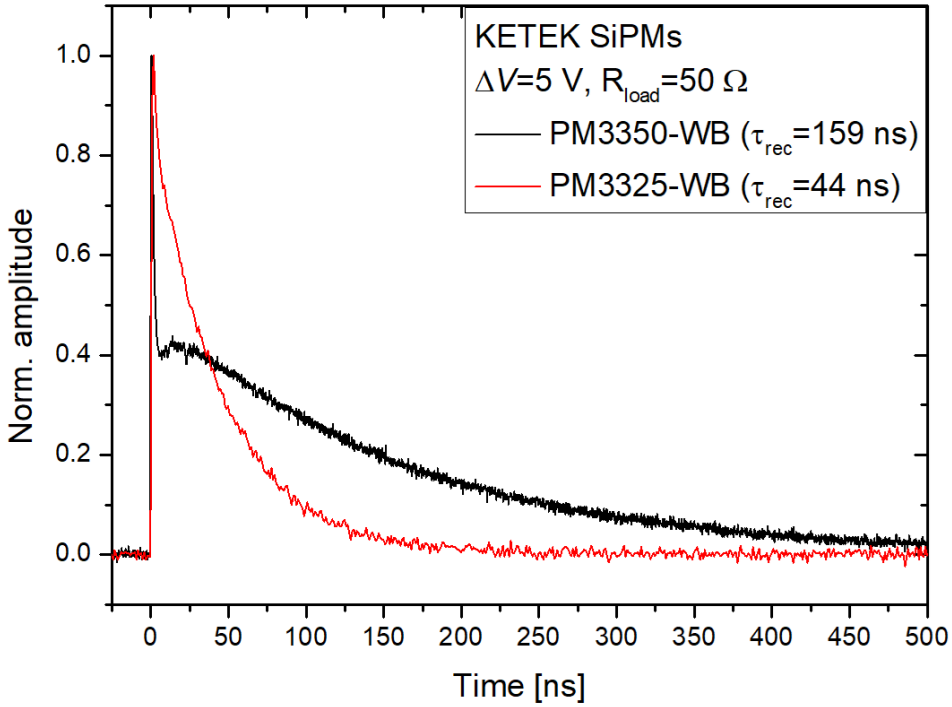


Additional Slides

Recovery Time and Gain

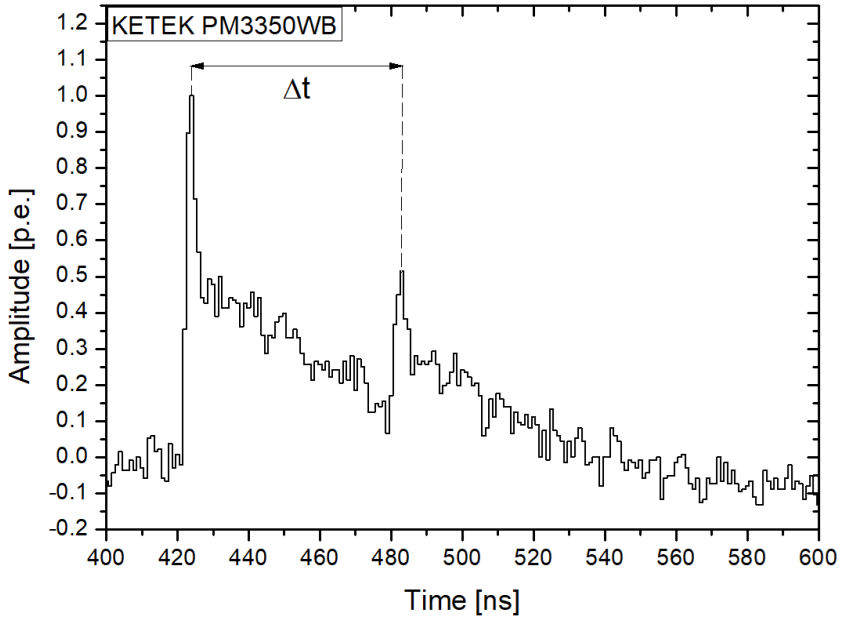




- illumination with a short laser pulse (70 ps pulse width)
- SiPM is driven into saturation ($N_{photons} >> N_{cells}$)
- measure signal without amplifier
- recovery time (τ_{rec}) via exponential fit
- gain (G) via integration of output charge

Probability of Correlated Pulses (P_{CP})

- DCR-setup is used
- triggered acquisition of waveforms
- determination of Δt between pulses
- build Compl. Cumulative Distr. Function (P^*_{tot})
  doi:10.1109/NSSMIC.2016.8069965
- fit DCR as slowest component of P^*_{tot}

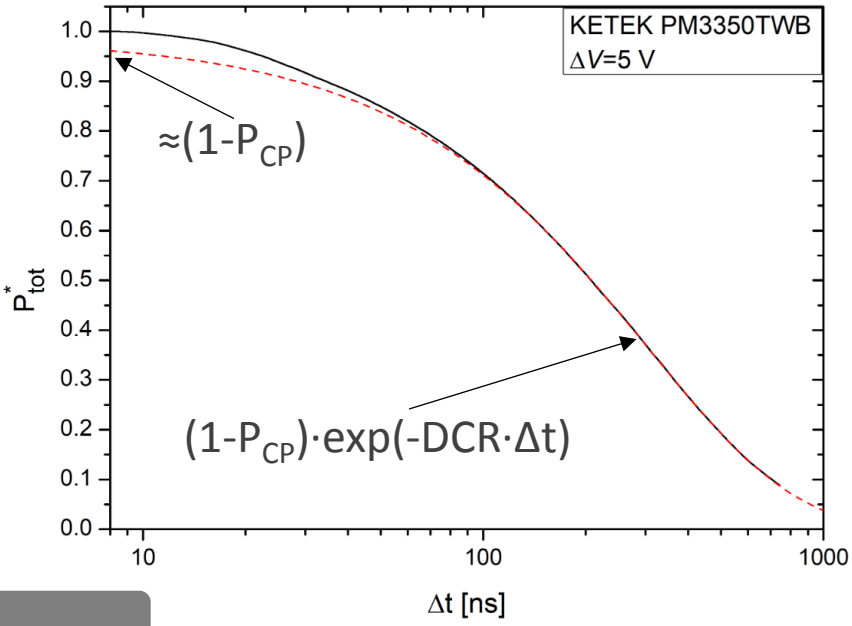


$$P^*_{\mathrm{tot}}(\Delta t) = \exp\left(-DCR \cdot \Delta t\right) \cdot P^*_{\mathrm{corr}}(\Delta t)$$

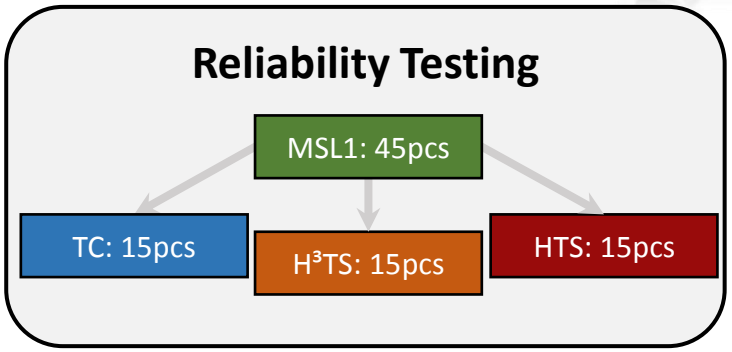
(prob. that no event occurs at a delaytime < Δt)

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

determined DCR is independent of P_{CP}



Reliability Testing



Test	Method	Conditions	Qty	Target
MSL	MSL classification (accord. to J-STD-020)	MSL1	45	0 failed
TC	Temperature Cycling (accord. to JESD22-A104)	1000x -55°C / 125 °C	15	0 failed
H³TS	High Humid. High Temp. Storage (accord. to JESD22-A101)	1000 h at 85 °C + 85 % RH	15	0 failed
HTS	High Temp. Storage (accord. to JESD22-A103)	1000 h at 125 °C	15	0 failed

all test are performed without bias voltage