Characterization of Silicon Photomultipliers

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Outline

- Applications
  - Calorimetry at the ILC
  - Positron Emission Tomography
- Silicon Photomultipliers (SiPM)
  - Basic Properties
  - SiPM Characterization
- Summary

Calorimetry at the ILC

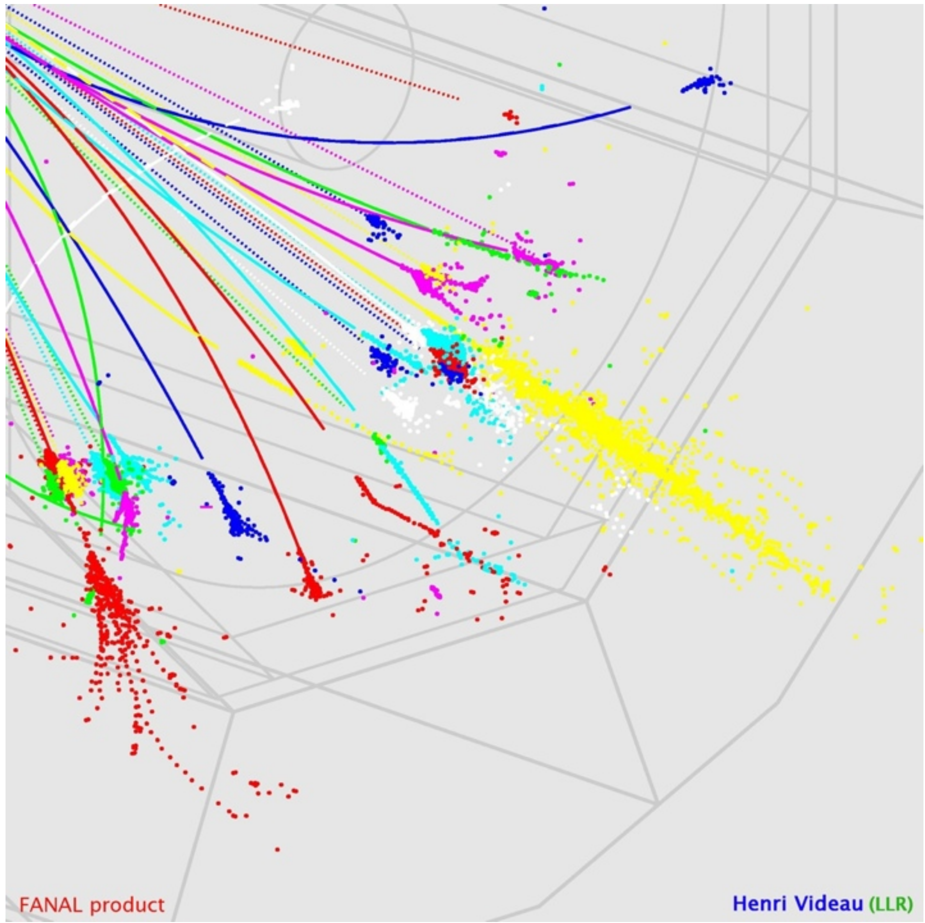
•ILC: future e+ e- collider for precision measurements of the LHC physics

•ILC physics require excellent jet-energy resolution

•Challenging goal:

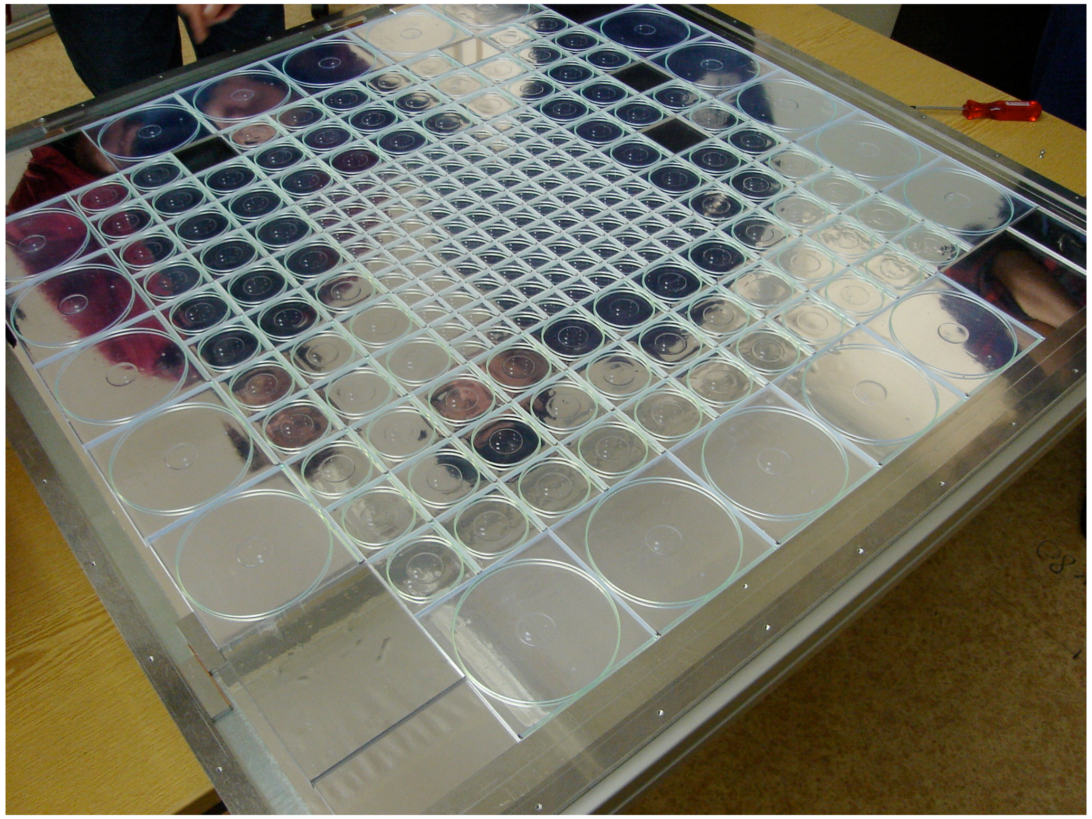
$$\sigma_{E_{jet}}/E_{jet} = 30\%/\sqrt{E_{jet}}$$

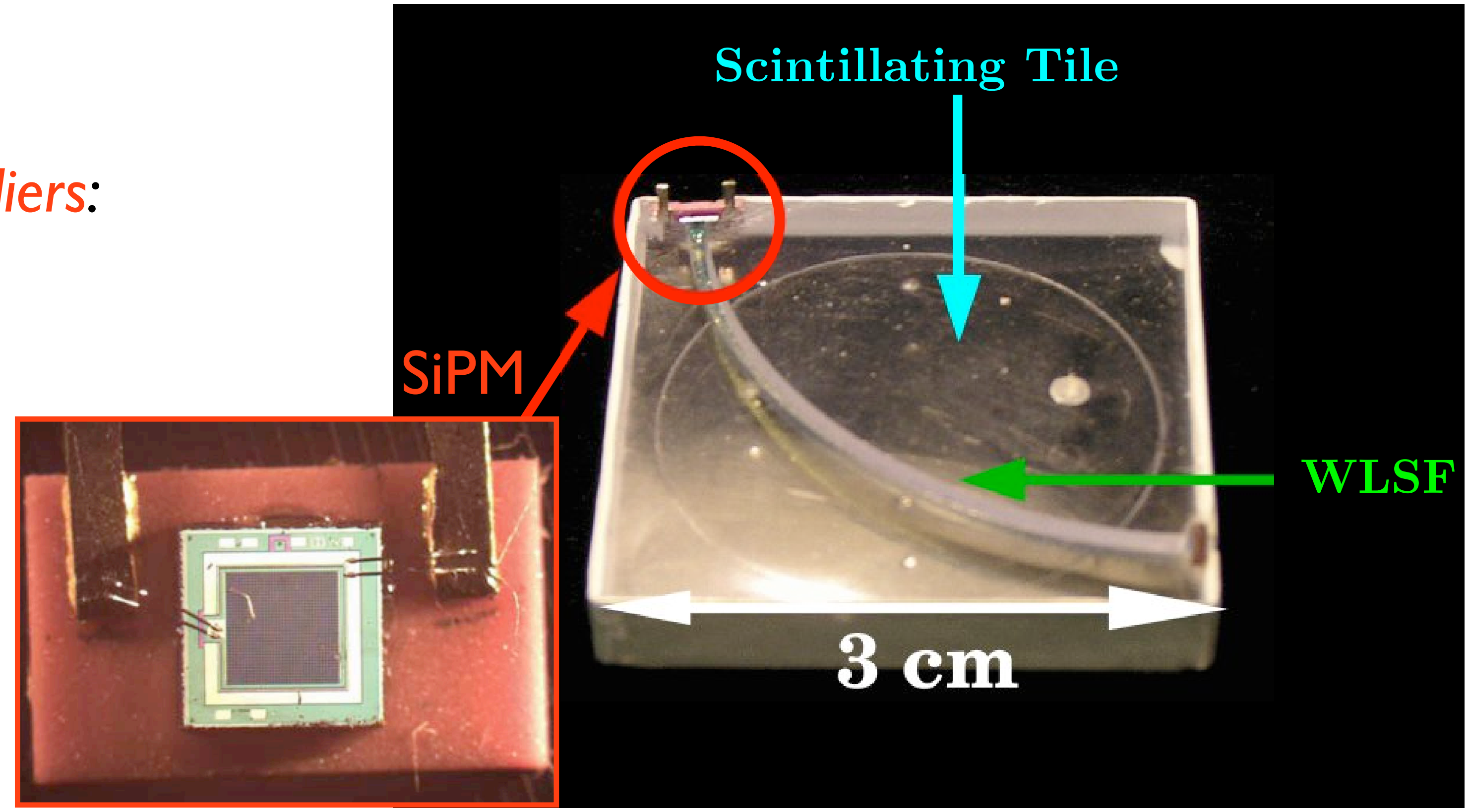
➡Highly granular „imaging“ calorimeters



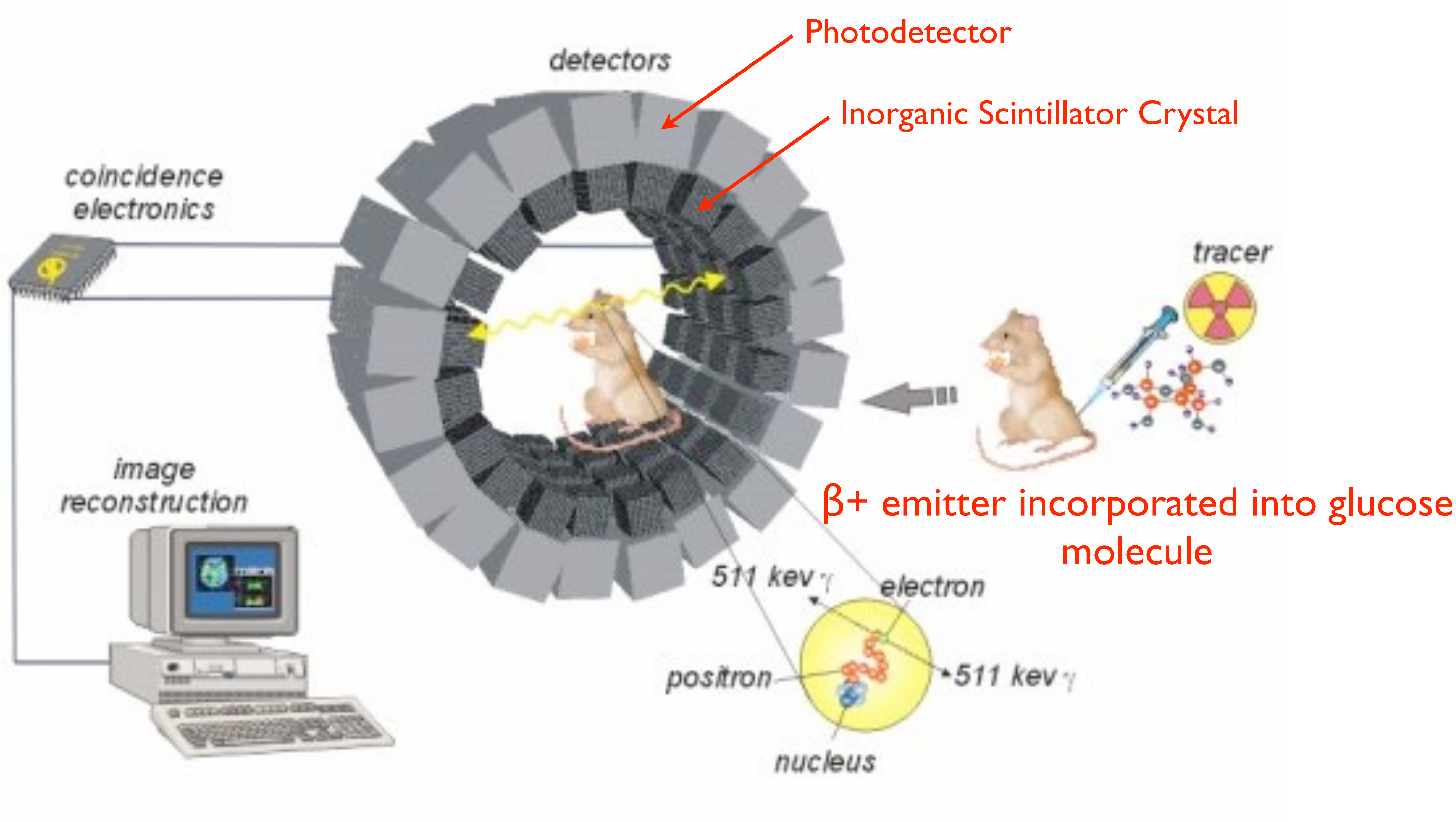
HCAL Prototype

- Sandwich calorimeter with plastic scintillator (blue scintillation light)
- 1 m^3 Prototype made of 38 Layers 216 Channels per Layer
- $3x3x0.5cm^3$ tiles
- Wavelength shifting fiber collects the scintillation light and converts it into green light
- Tiles are read out with *Silicon Photomultipliers*:
    - Very compact
    - Insensitive to magnetic fields



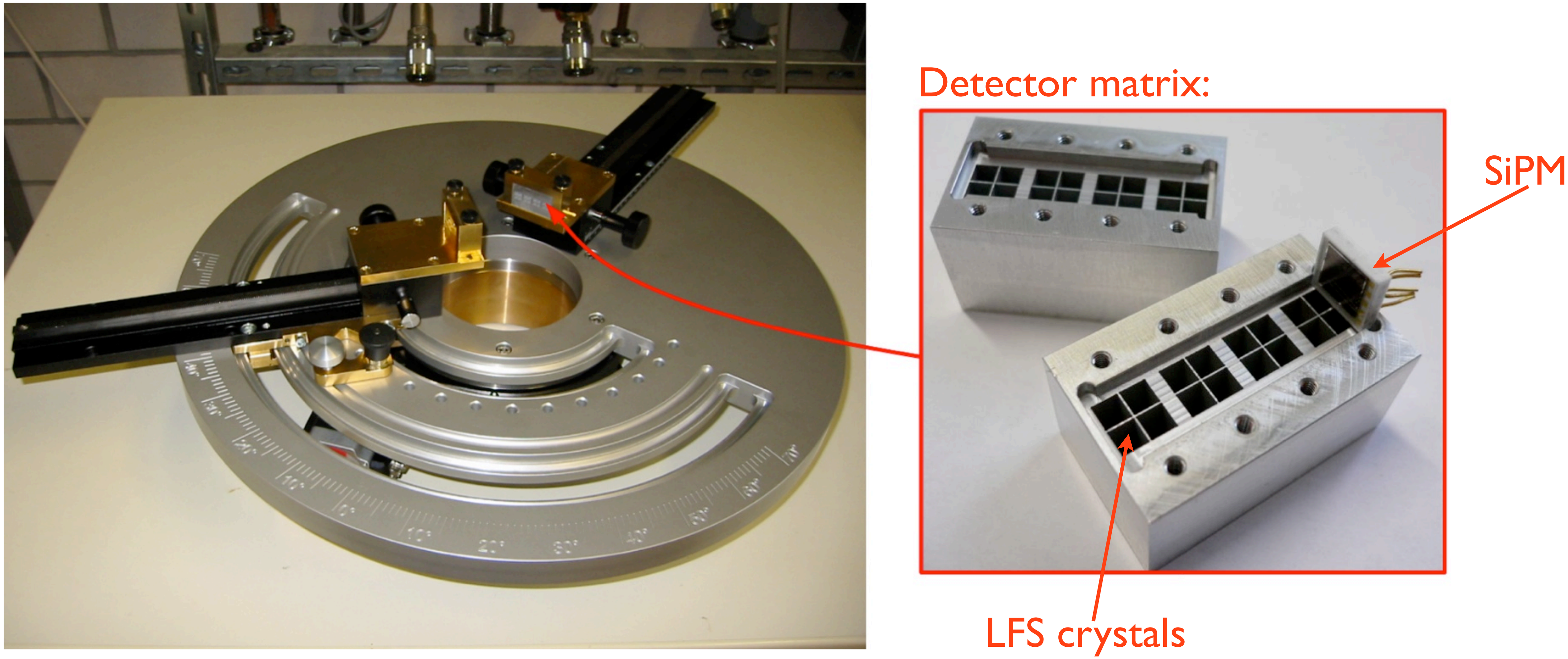


Positron Emission Tomography



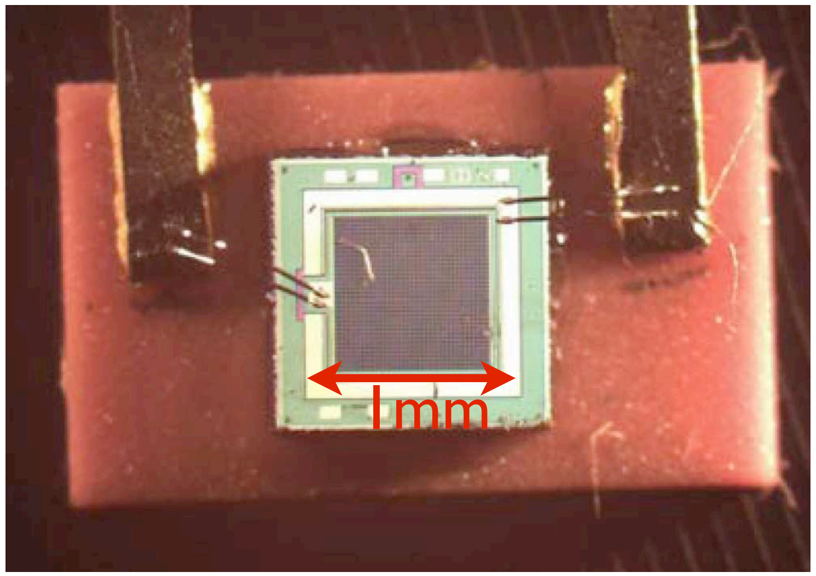
- Advantages of a PET with SiPM readout:
  - Small size ➟ allows high granularity
  - Insensitivity to B-fields ➟ allows combination with MRI
  - Good timing resolution ➟ Time of Flight PET

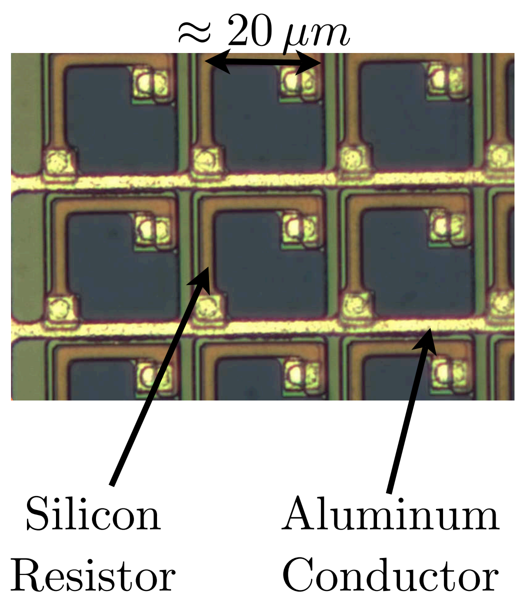
PET Prototype



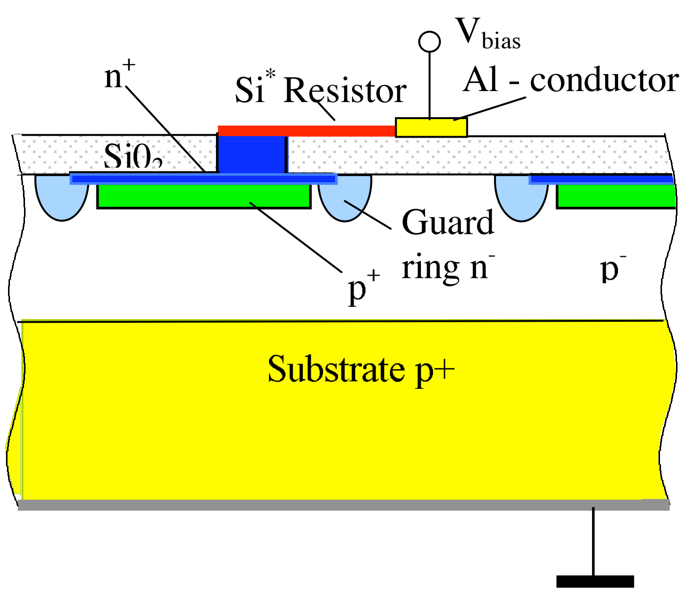
- PET prototype built in KIP workshop
- Two detector head with 4x4 channels (LFS crystals) read out by SiPMs
- Can be rotated to simulate 360° detector

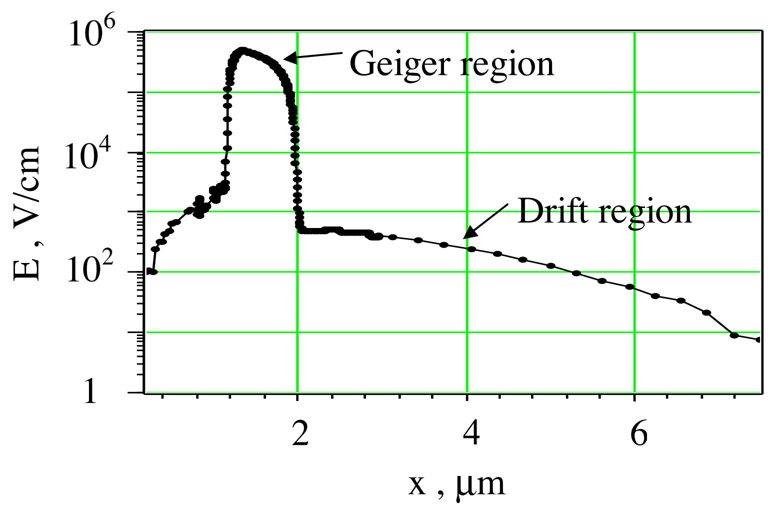
The Silicon Photomultiplier



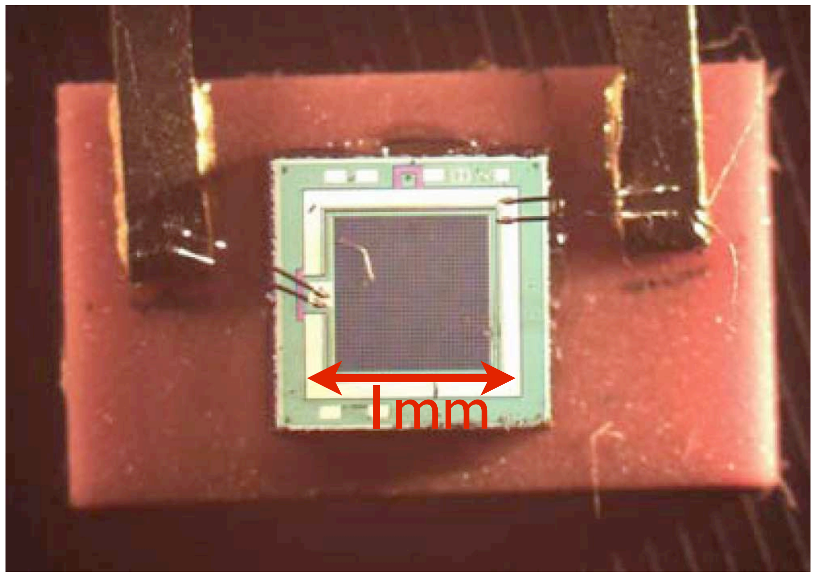


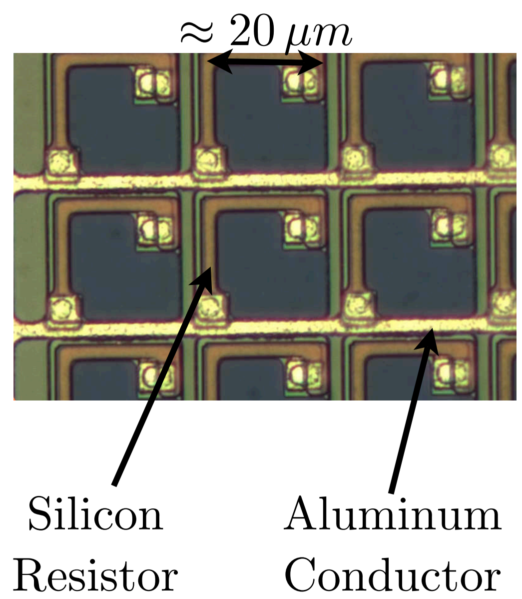
- Array of APDs (typ. 1000 per mm^2) connected to a common output
- APDs operated in „Geiger mode“ ($V_{bias} > V_{breakdown}$):
  - Free charge carrier can trigger „avalanche“ in the high field region
  - ➡Gain ~10^6
- Avalanche is self-sustaining and has to be stopped (quenched)
- APD signal independent from number of photons (only „yes/no“ information)
- Output signal = sum of all APD signals
- Dynamic range limited by number of pixels:
  - $N_\gamma << N_{pixels}$: linear response
  - $N_\gamma \approx N_{pixels}$: saturation





Quenching





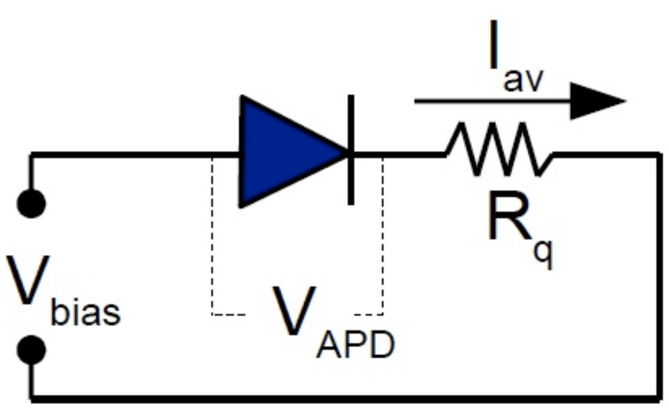
•Avalanche is self sustaining and has to be stopped (quenched)

<u>Passive quenching:</u>

•APD is connected to resistance in series

➡Voltage at APD drops below $V_{breakdown}$ during avalanche breakdown

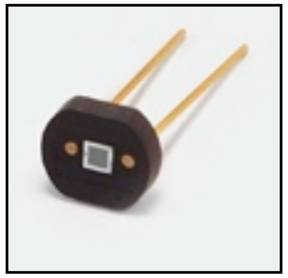
•Recovery time = R_qC

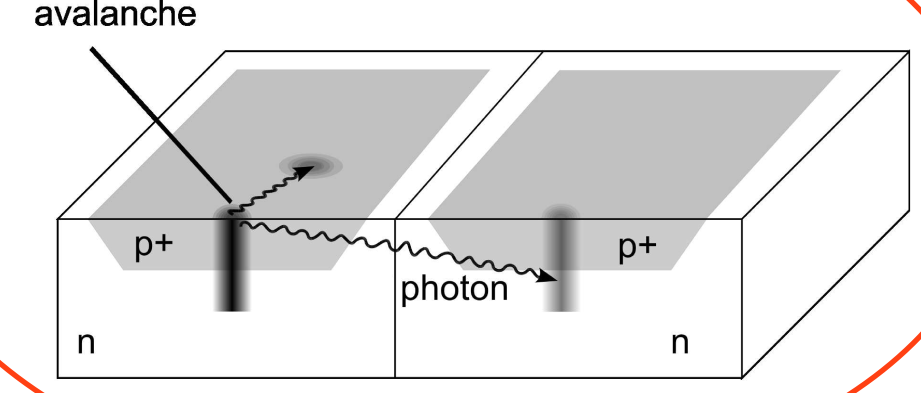


$$V_{APD} = V_{bias} - R_q I_{av}$$

Basic Properties

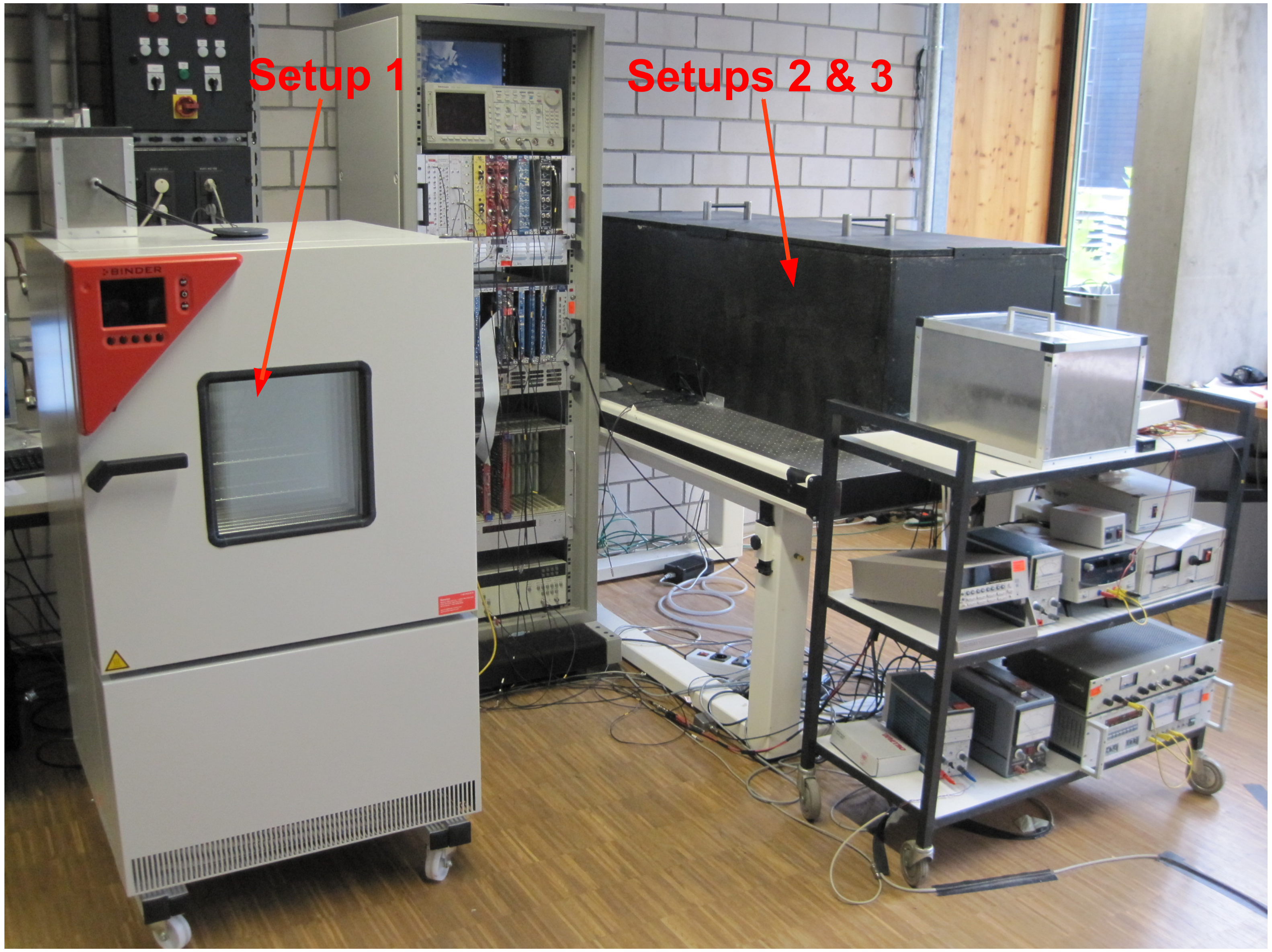
- Basic properties:
  - High gain 10^5 - 10^6
  - Low operating voltage (<100V)
  - Very compact
  - Insensitive to magnetic fields
  - Very small sensitivity to charged particles
  - Excellent single photon resolution
  - Limited dynamic range
  - Noise:
    - Dark-rate ~1MHz (thermal excitation)
    - Cross-talk
    - After-pulses (from trapped charge carriers)





SiPM Characterization

- Compare different sensors
- Find the best operating conditions



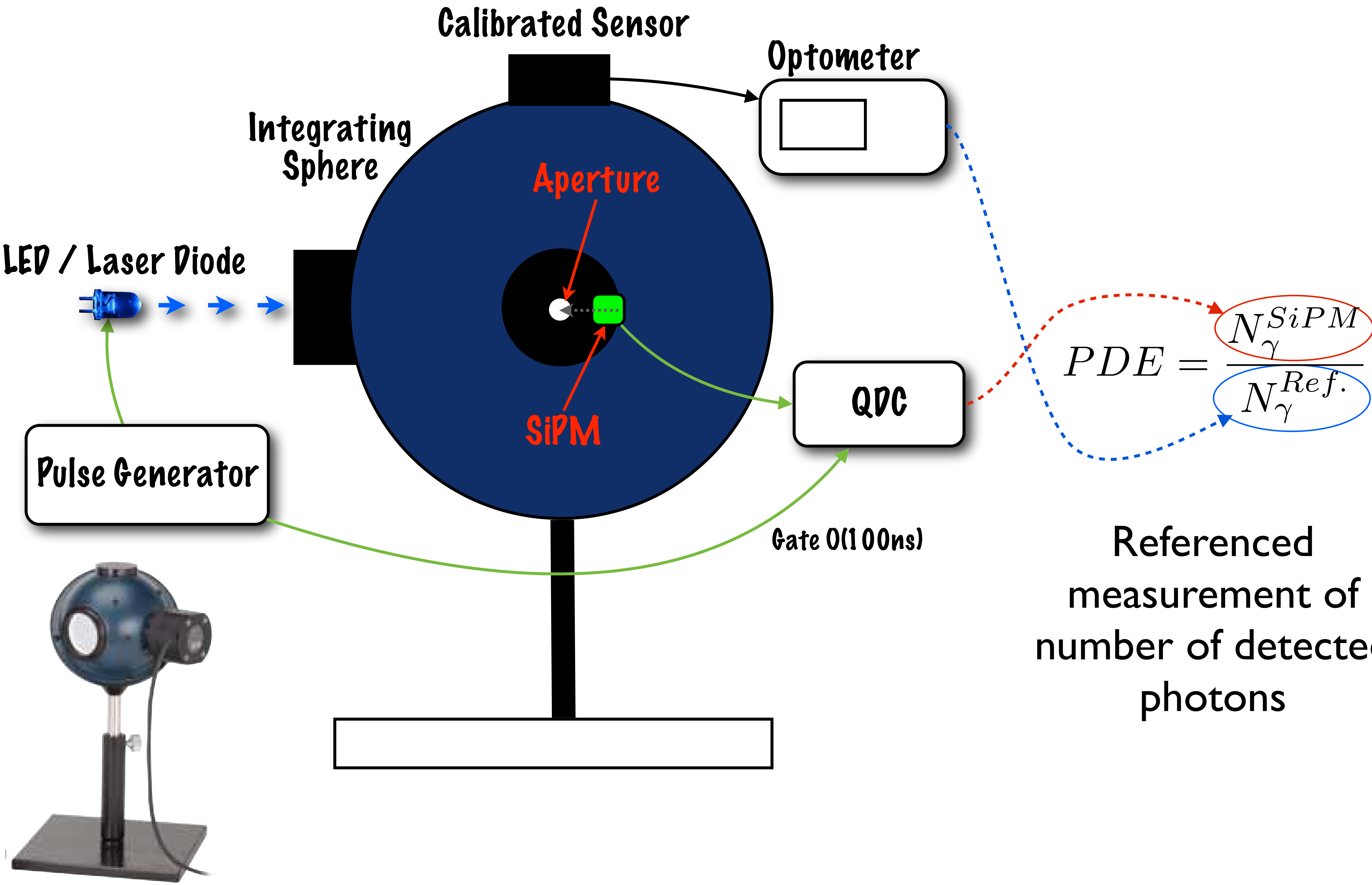
Old setup:

- Gain
- Dark-rate
- Photon Detection Efficiency (PDE)

New setup:

- Cross-talk
- After-pulses
- PDE without cross-talk & after-pulses
- Sensor Scans
- Temperature measurements

Photon Detection Efficiency

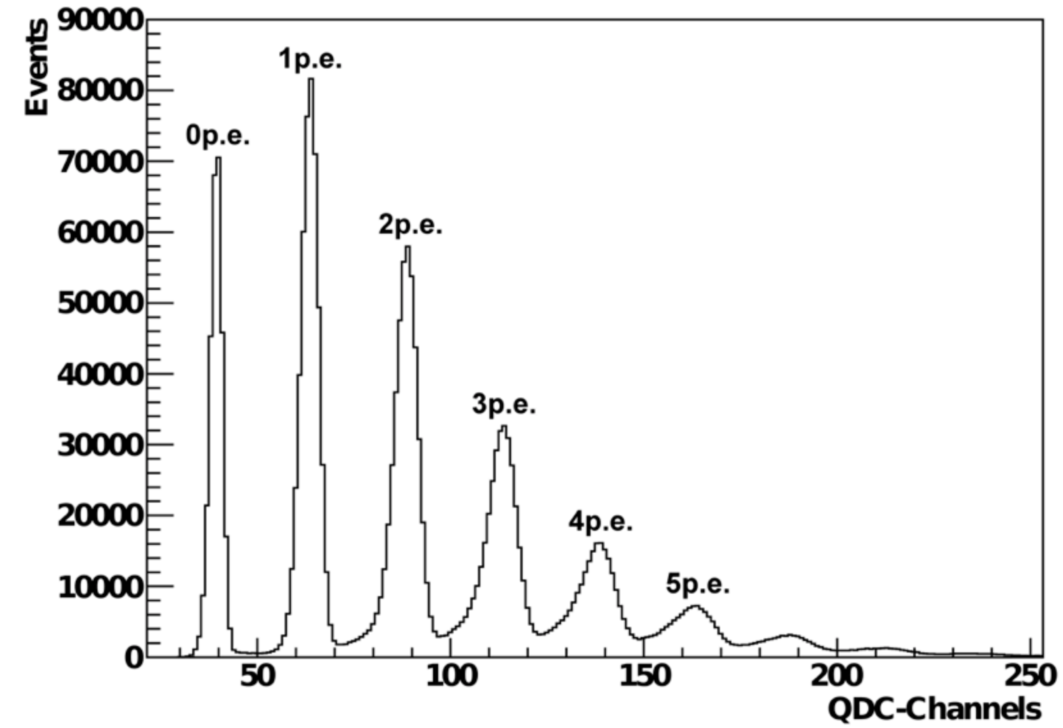


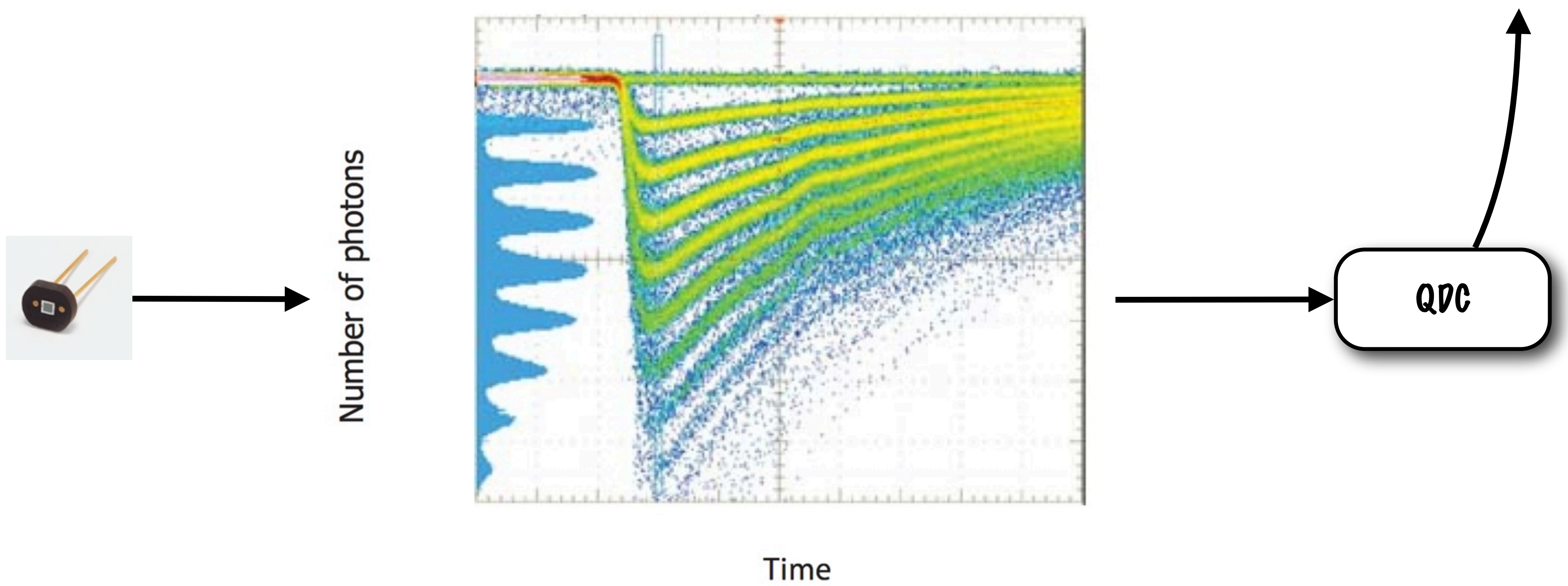
$$PDE = \frac{N_\gamma^{SiPM}}{N_\gamma^{Ref.}}$$

Referenced measurement of number of detected photons

Charge Spectrum

- Signal charge is integrated (integration gate O(100ns))
- Histogram with 10^5 entries is acquired automatically
- Charge spectrum:
  - Clear single photon separation
  - Information about gain & number of detected photons

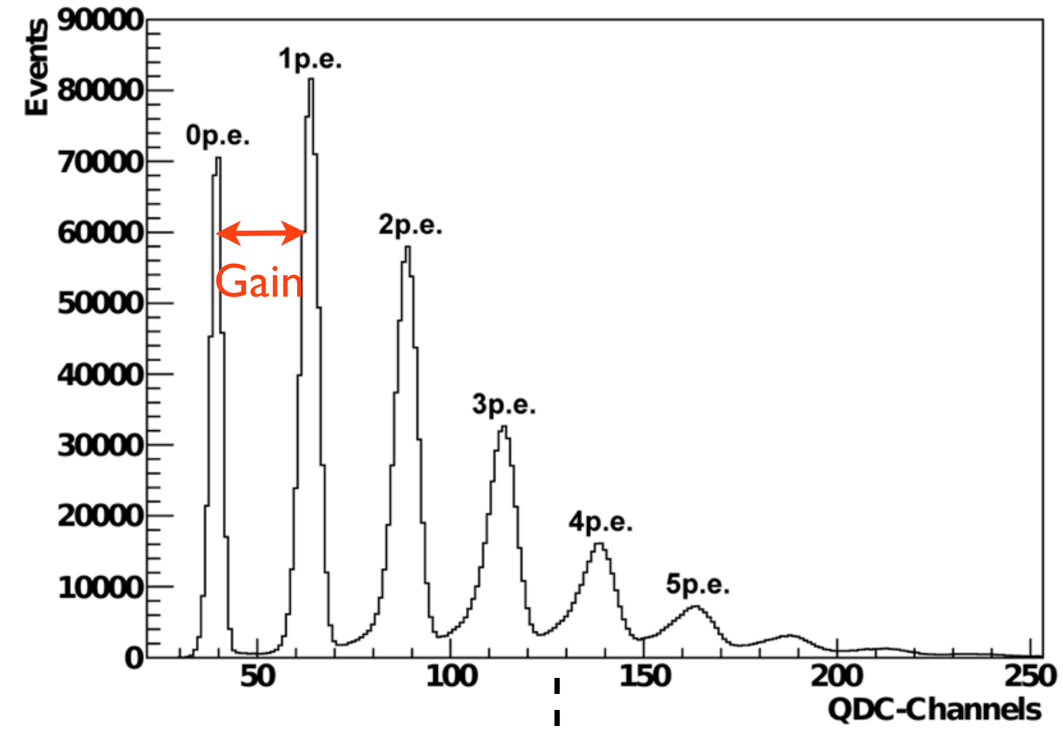


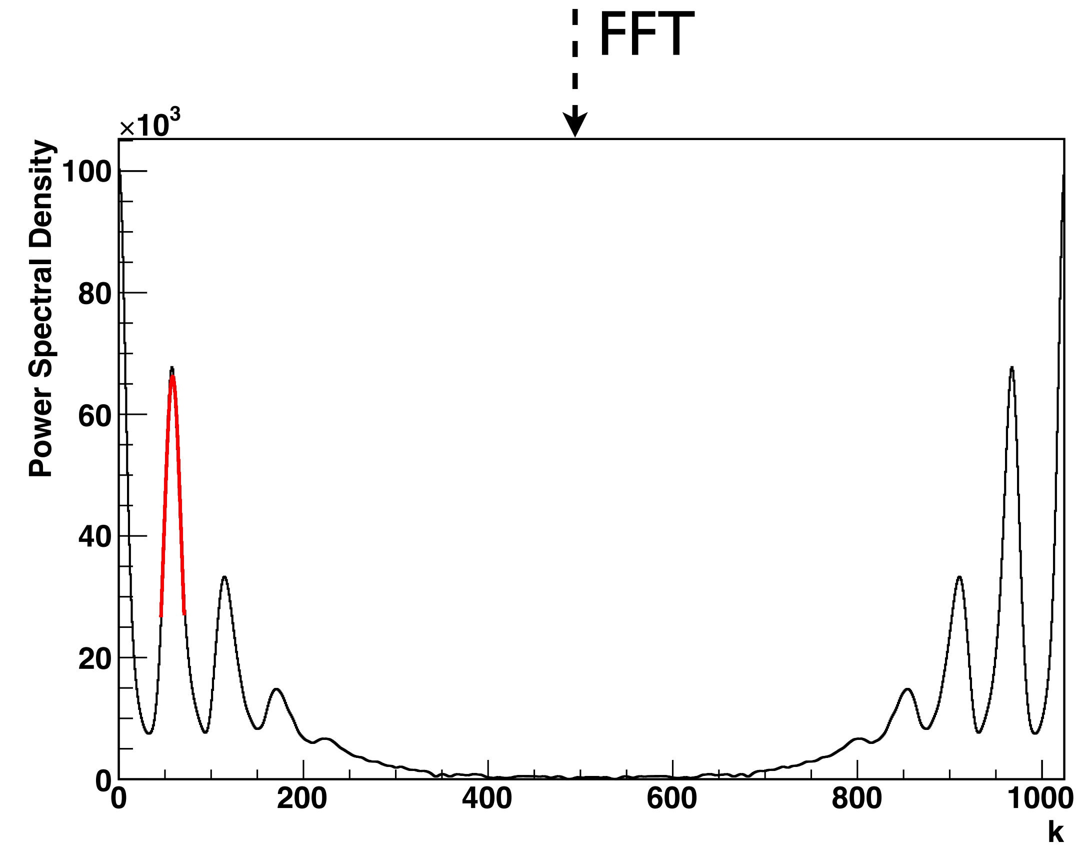


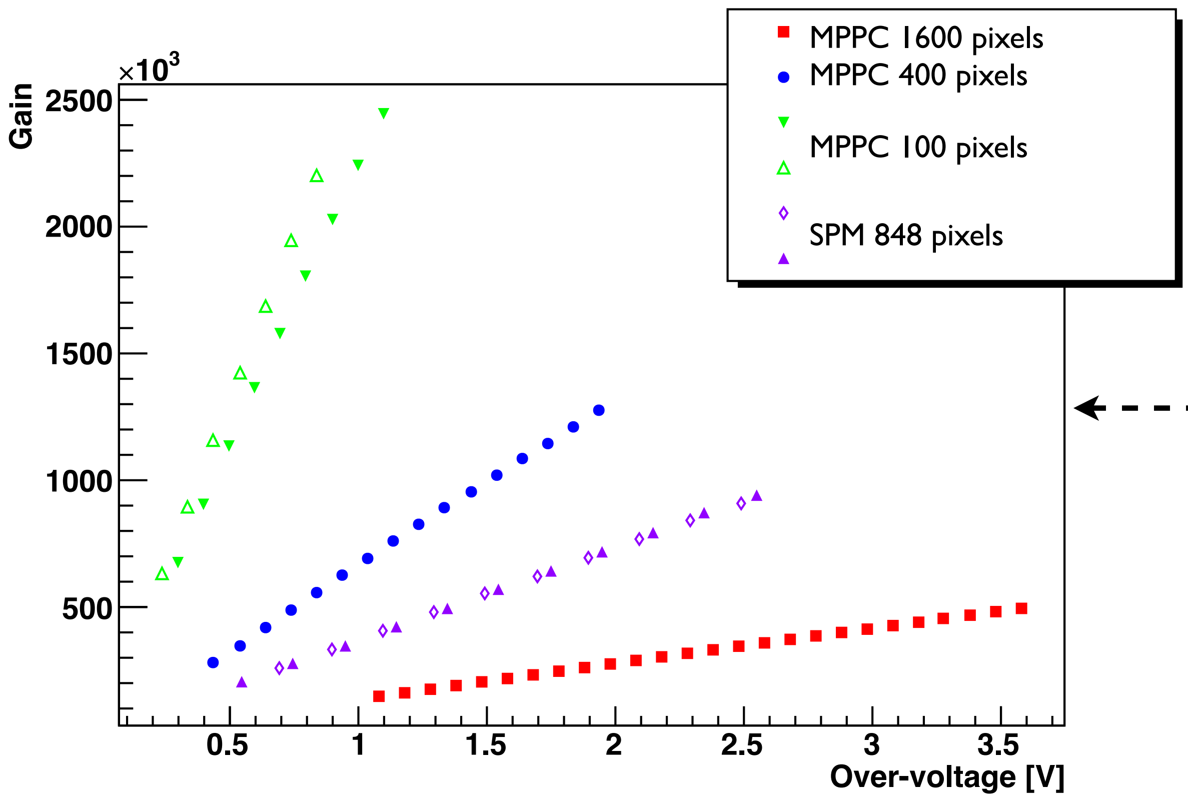
Gain

- Gain = charge difference between peaks
- Gain is automatically determined from frequency spectrum
- Breakdown voltage is automatically determined from a linear fit:

$$G = \frac{C_{pixel}}{q_e} \cdot \underbrace{(V_{bias} - V_{breakdown})}_{\text{Over-voltage}}$$







Statistical Analysis

•Mean of histogram = mean number of fired pixels (problem: contains cross-talk & after-pulses!)

•Number of incident & detected photons is Poisson distributed:

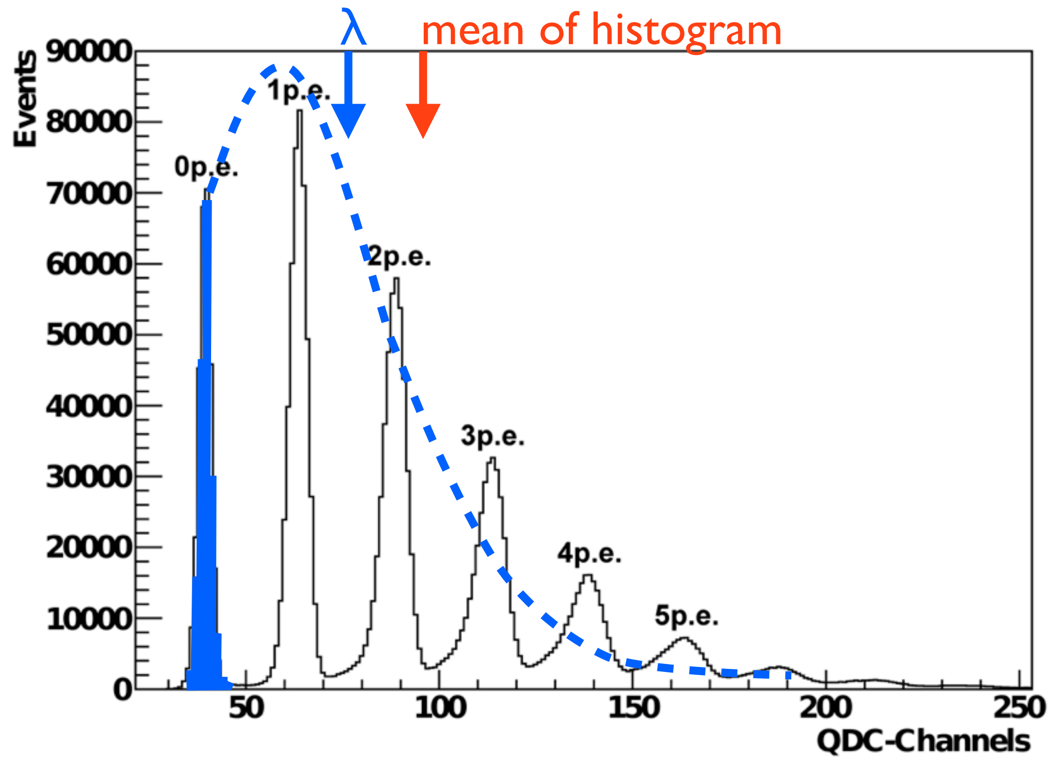
$$P(N,\lambda) = \frac{\lambda^N \cdot e^{-\lambda}}{N!}$$

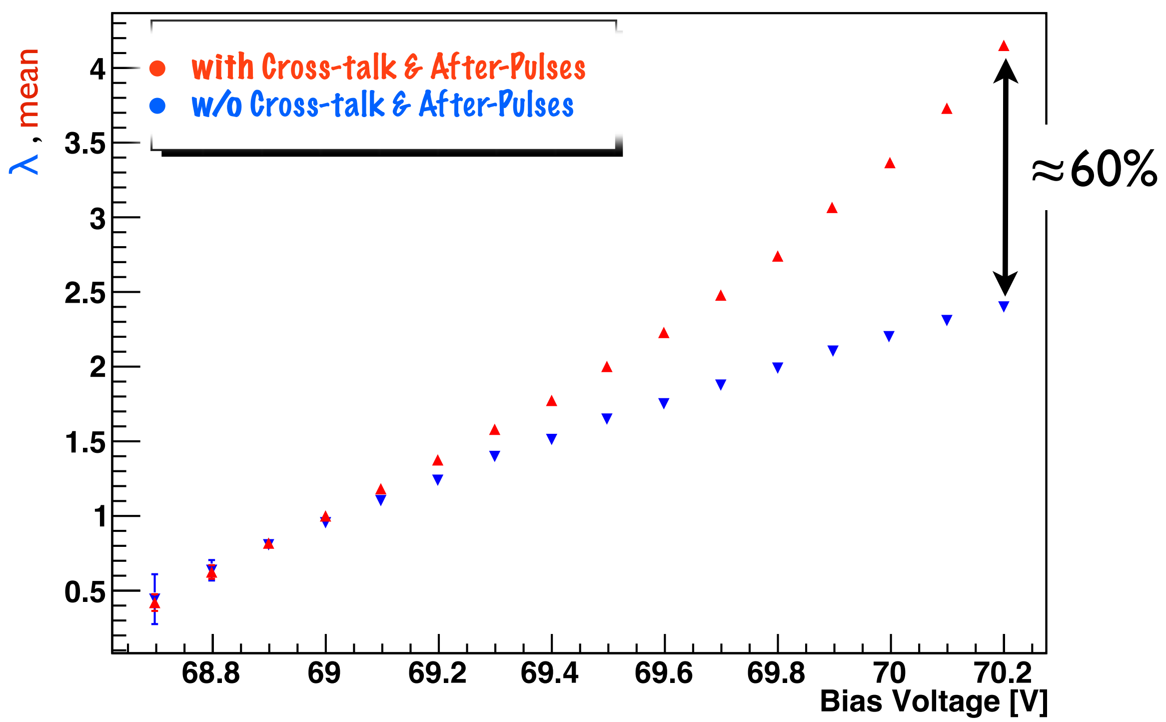
$$P(0,\lambda) = \frac{N_{Ped.}}{N_{Tot.}} = e^{-\lambda} \Rightarrow \lambda = -\ln\frac{N_{Ped.}}{N_{Tot.}} -ln(\alpha)$$

•Pedestal is not influenced by cross-talk and after-pulse!

➡ λ = mean number of detected photons without cross-talk & after-pulses

•Dark-rate can be measured and subtracted





PDE - Intensity Calibration

- PDE without cross-talk & after-pulses:

$$PDE = \frac{N_\gamma^{SiPM}}{N_\gamma} = \frac{N_\gamma^{SiPM}/T}{P_{opt}/(h \cdot \frac{c}{\lambda})} \cdot R$$

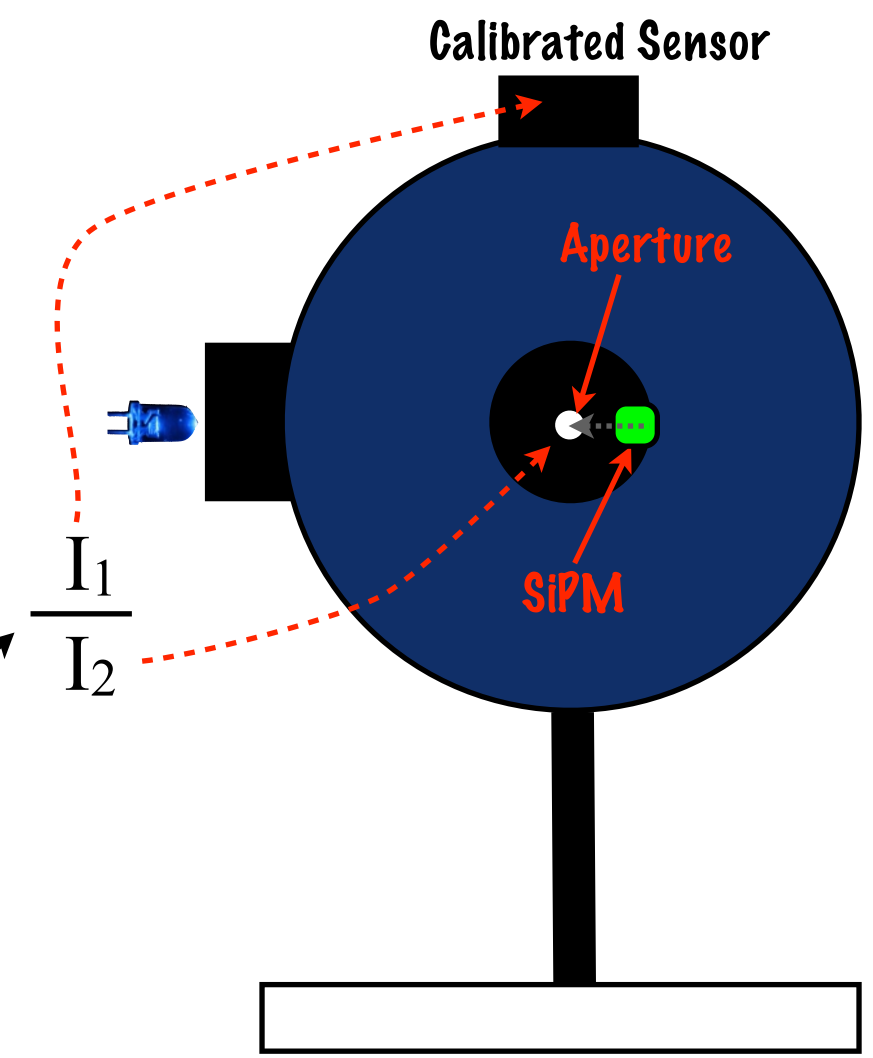
LED Pulse Period

Optical Power at Calibrated Sensor

Intensity Ratio Between Ports

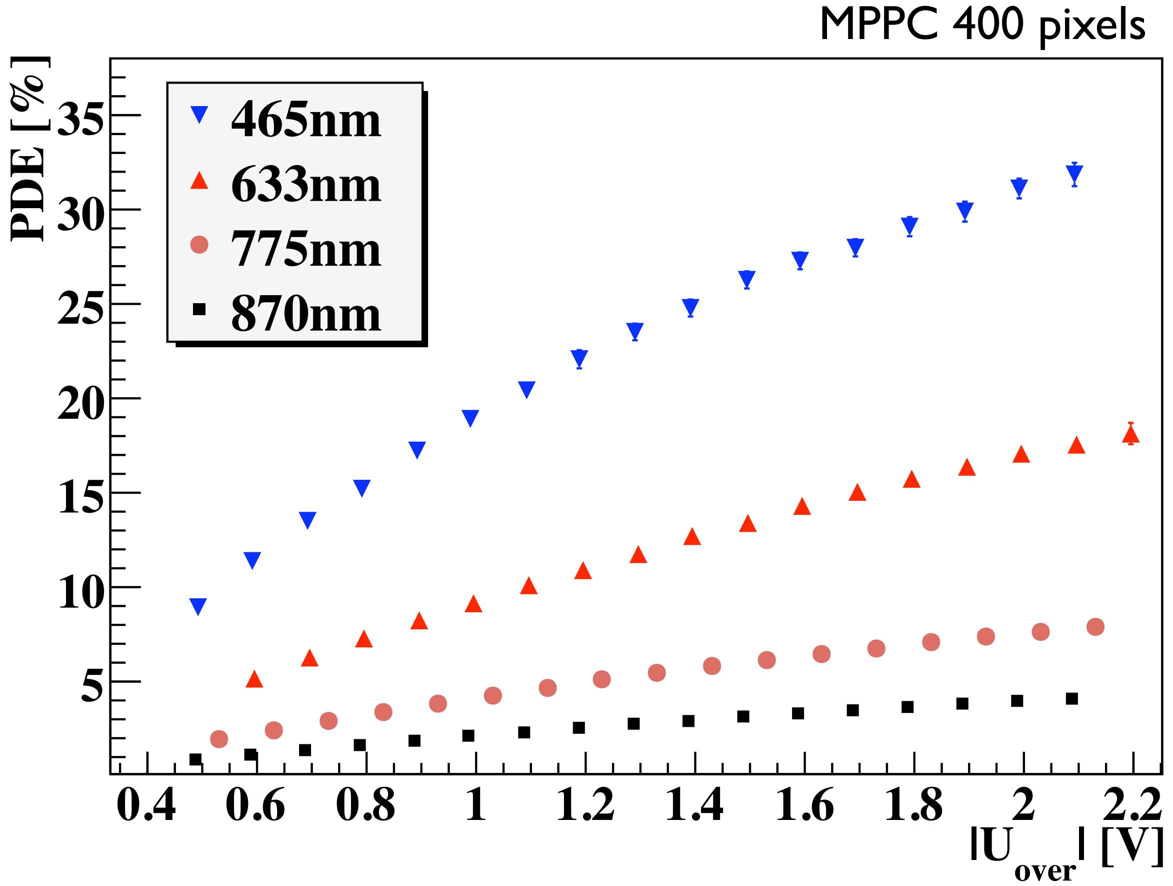
- SiPM is located behind an aperture to only illuminate the active area
- Intensity Ratio R between the two ports has to be calibrated:

Type	λ_{center}[nm]	$R_{0.6}$
LED	465	4200 ± 20
Laser Diode	633	3852 ± 18
Laser Diode	775	4328 ± 7
LED	870	4625 ± 55



PDE

- PDE is automatically measured for a sequence of bias voltages



- Measurement is limited to the wavelength of LEDs / laser diodes

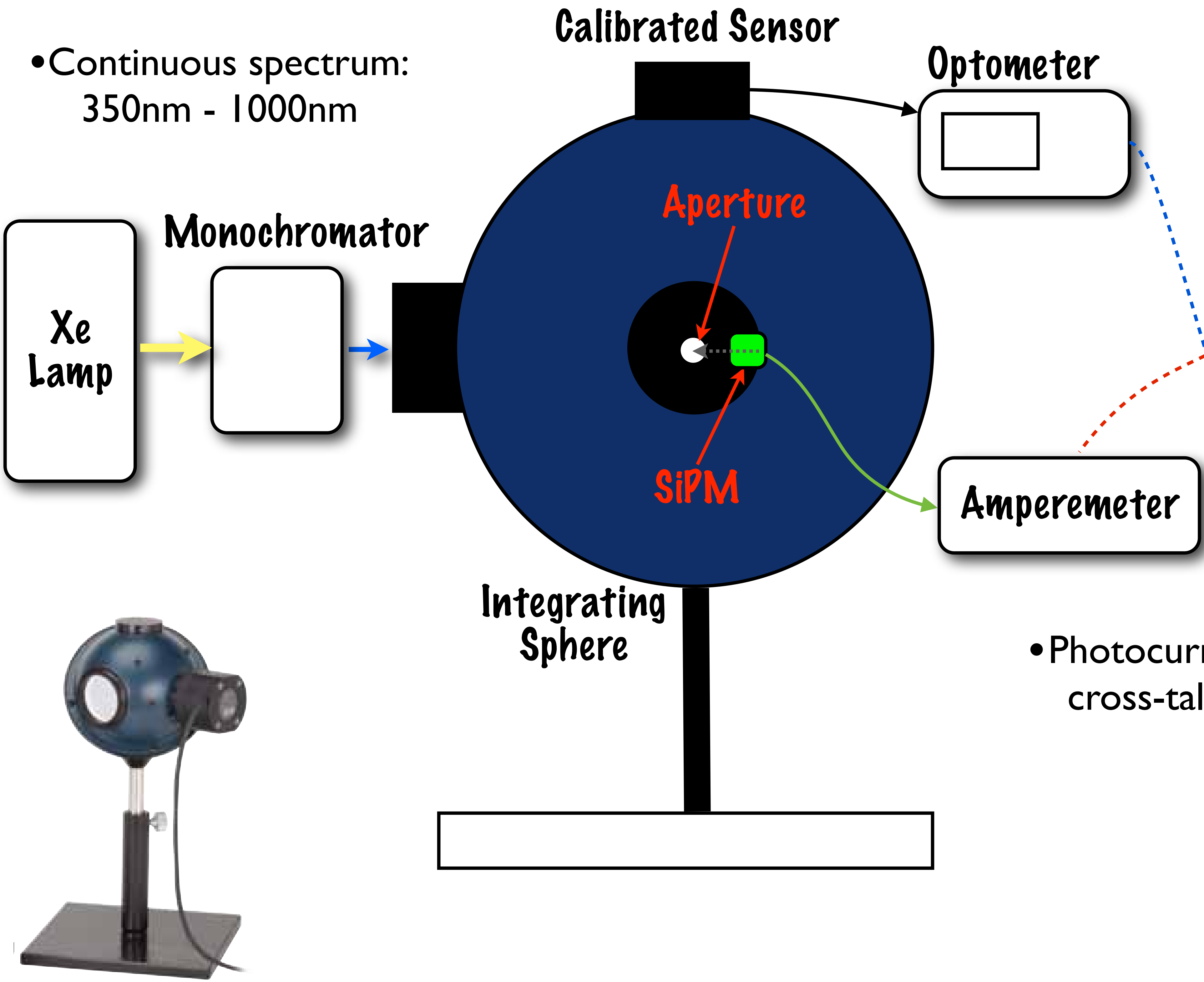
PDE depends on:

$$PDE = QE \cdot (1 - R) \cdot \epsilon_{geiger} \cdot \epsilon_{geo}$$

- Quantum Efficiency (Wavelength)
- Reflection at surface (Wavelength)
- Geiger probability (Bias voltage)
- Geometrical Fill Factor (Pixel Size)

Spectral Sensitivity

- Continuous spectrum: 350nm - 1000nm

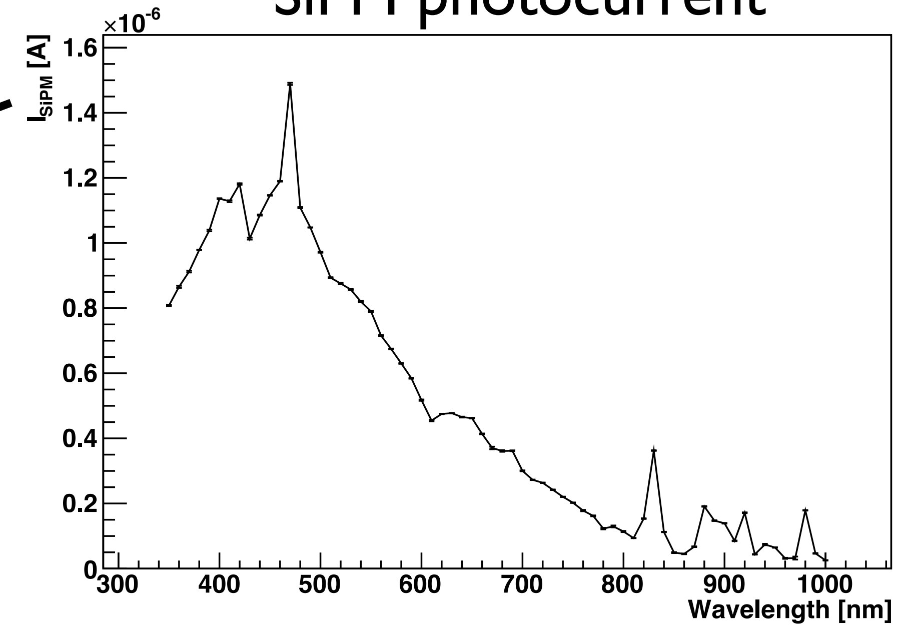


$$PDE = \frac{N_\gamma^{SiPM}}{N_\gamma^{Ref.}}$$

- Photocurrent influenced by cross-talk & after-pulses

Spectral Sensitivity

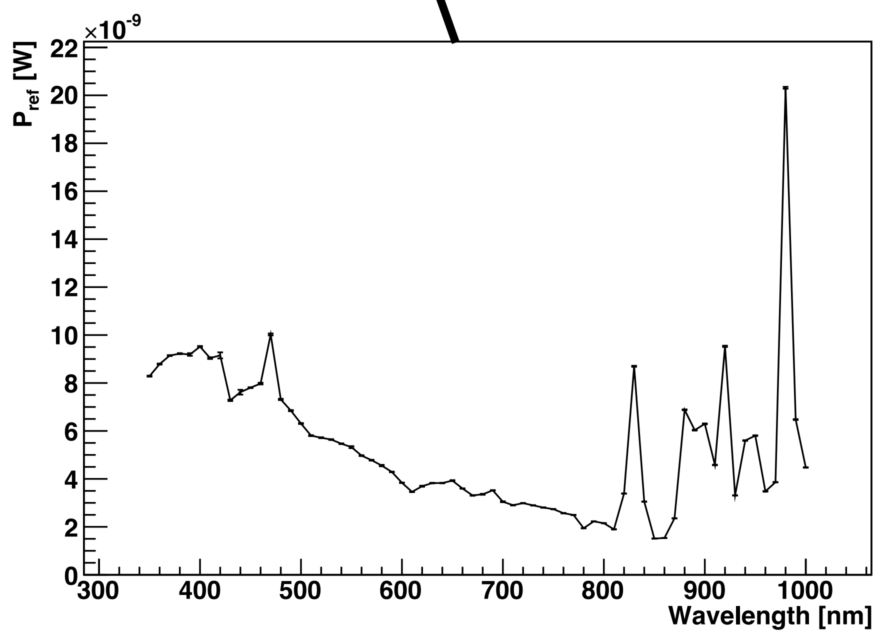
SiPM photocurrent



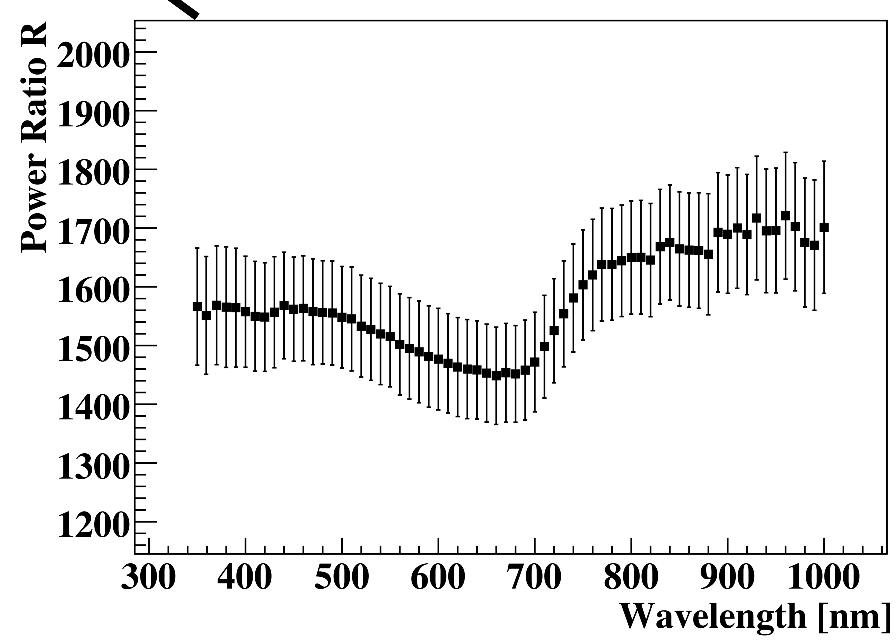
<u>Spectral sensitivity:</u>

Gain

$$S = \frac{I_{SiPM}/(q_e \cdot G)}{P_{opt}/(h \cdot \frac{c}{\lambda})} \cdot R$$



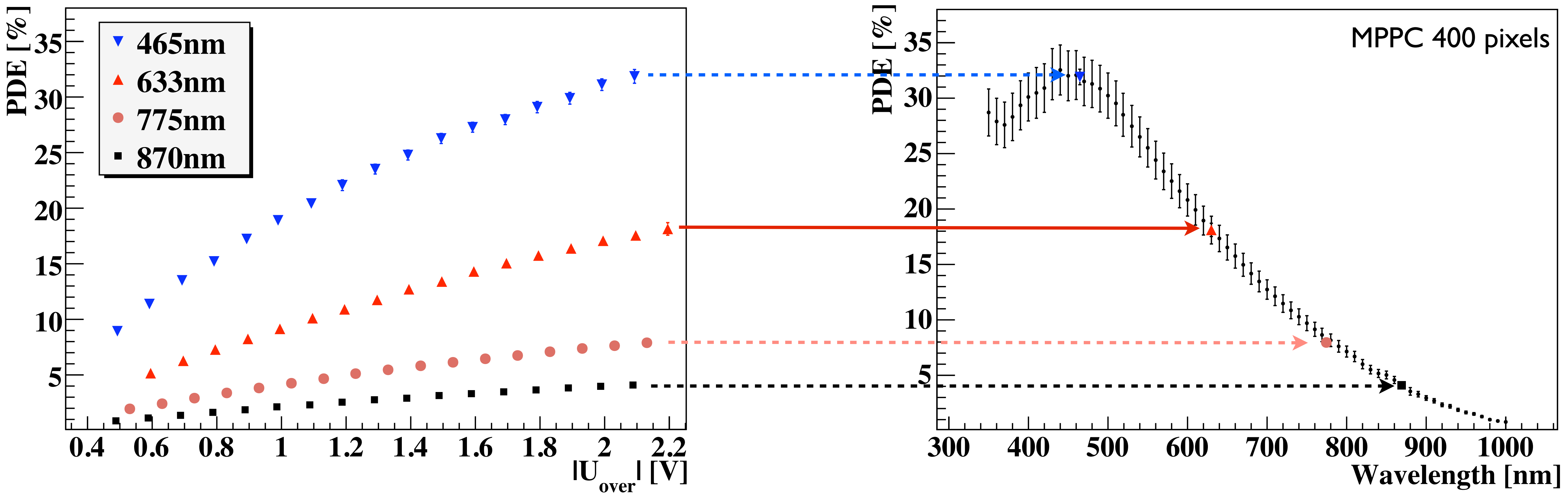
Optical power at calibrated sensor



Intensitiy ratio between ports

PDE - Spectral Sensitivity

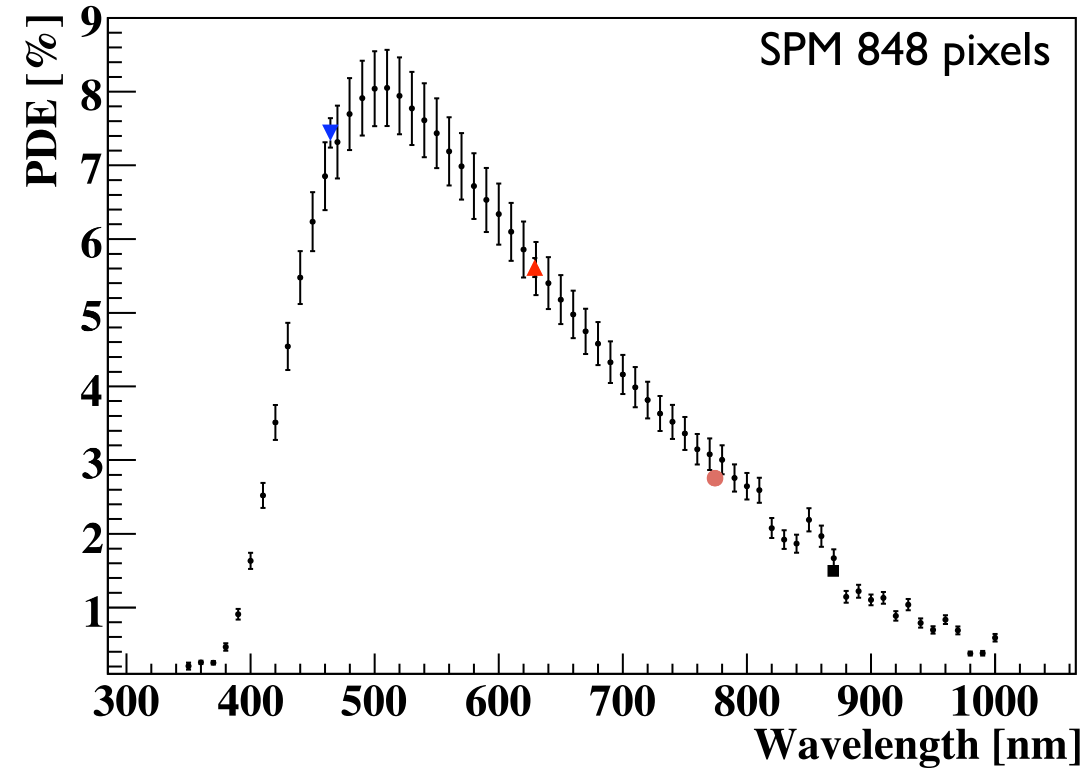
- Automated measurement over wide spectral range
- Measurement contains dark-rate, cross-talk & after-pulses
  ➡ only relative sensitivity
- Spectral sensitivity can be scaled to measured PDE values

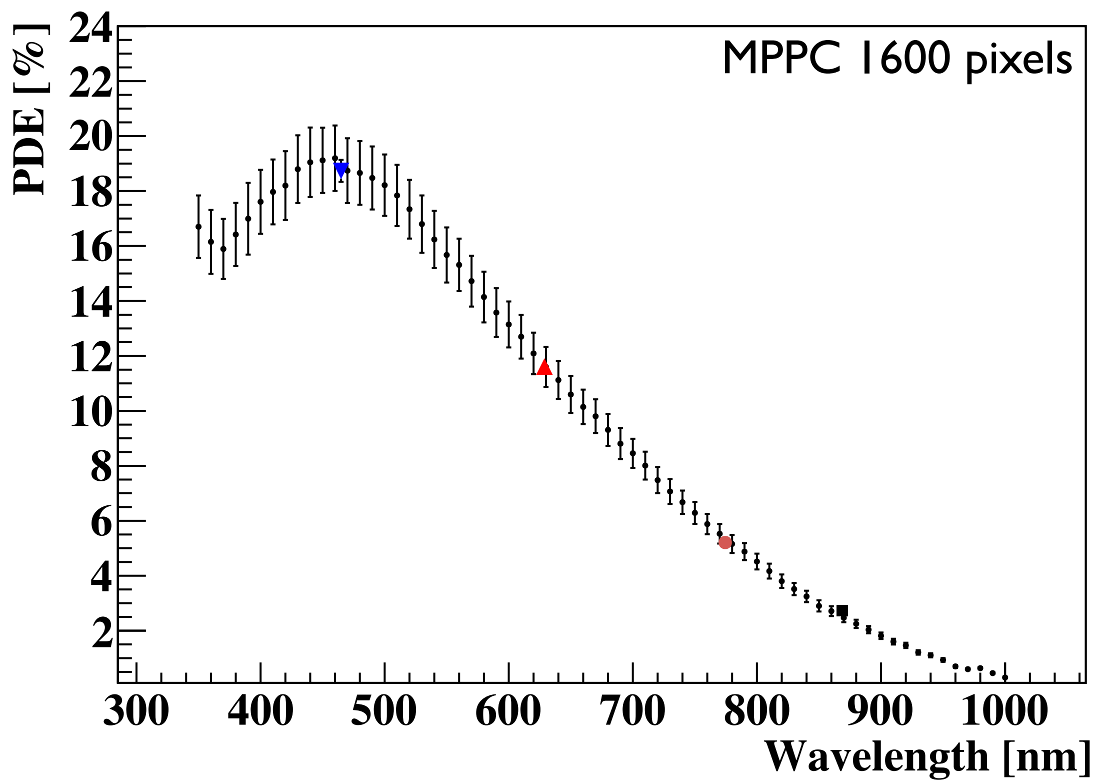


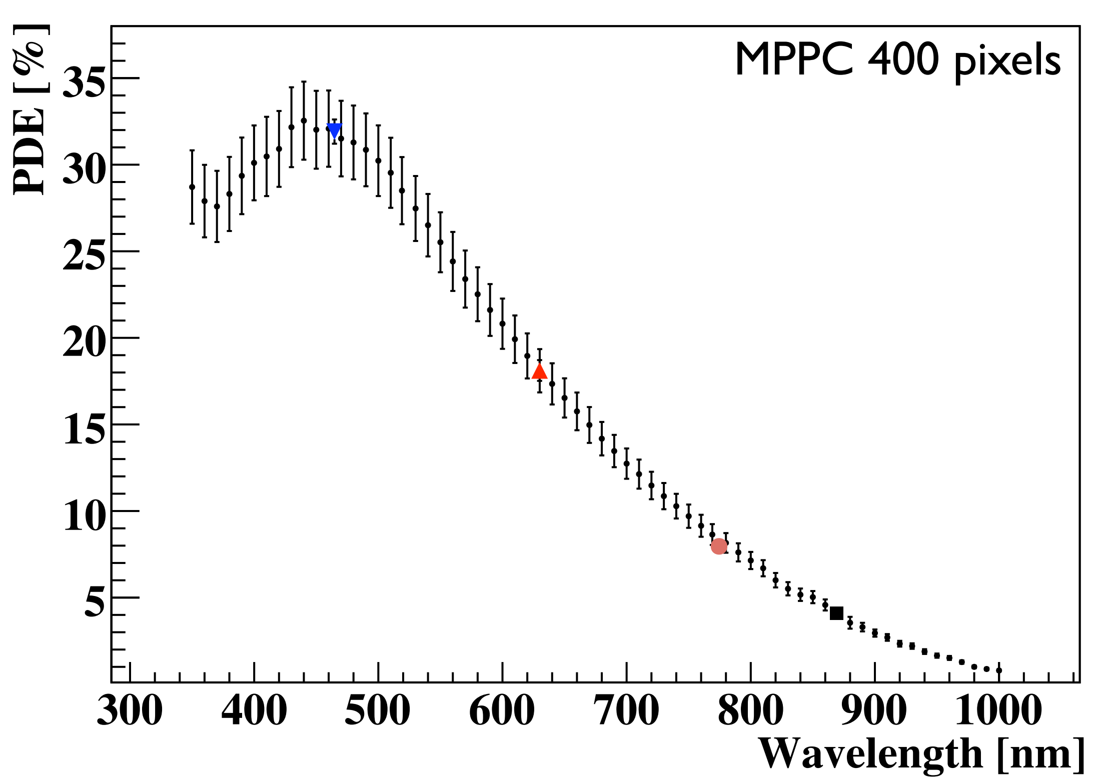
PDE - Spectral Sensitivity

$$PDE = QE \cdot (1 - R) \cdot \epsilon_{geiger} \cdot \epsilon_{geo}$$

- Spectral sensitivity determined by:
  - Quantum efficiency (absorption coefficient)
  - Doping profile
- PDE depends on pixel size (fill factor)

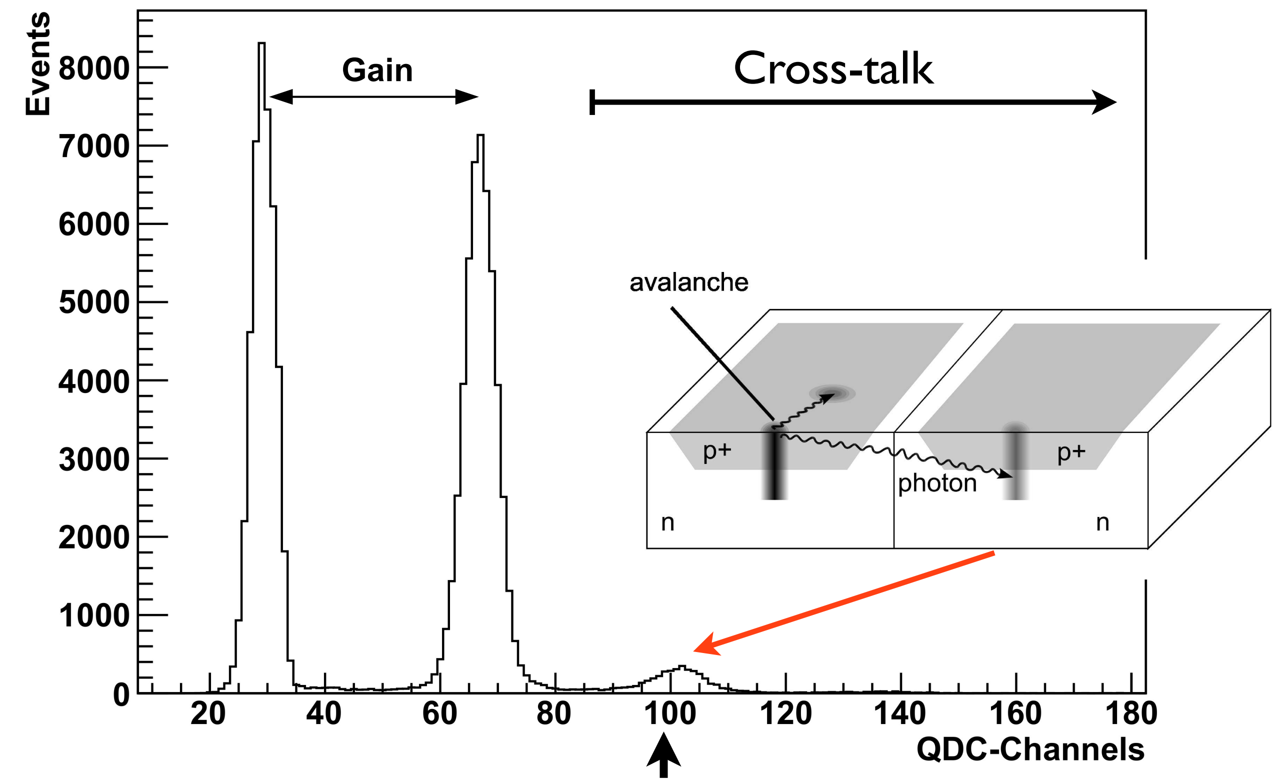




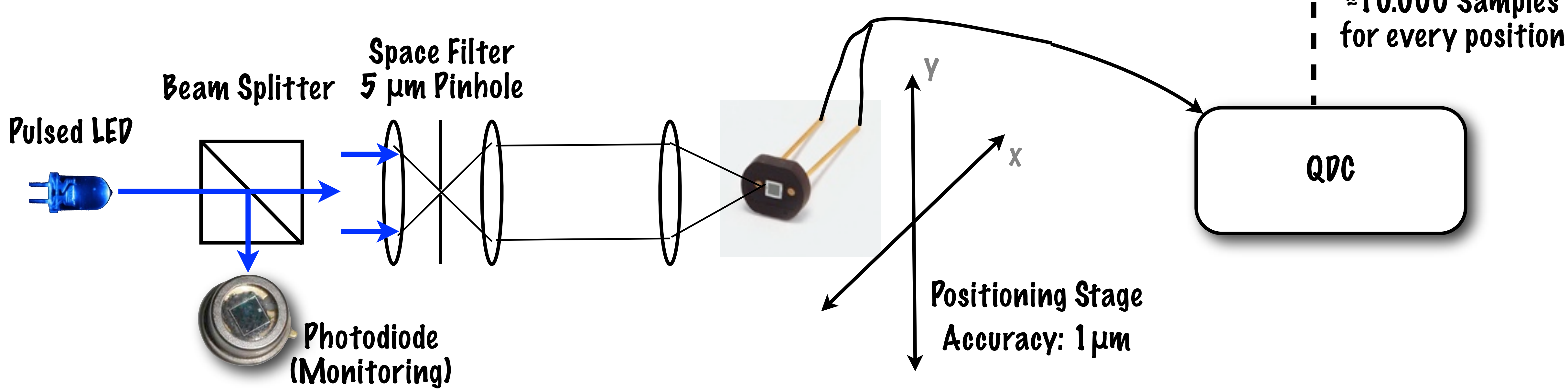


Sensor Scans

- Sensor is scanned with a focused light spot
- Gain & sensitivity can be determined for single pixels
- 2-pixel signals are caused by cross-talk
- Measurement is fully automated

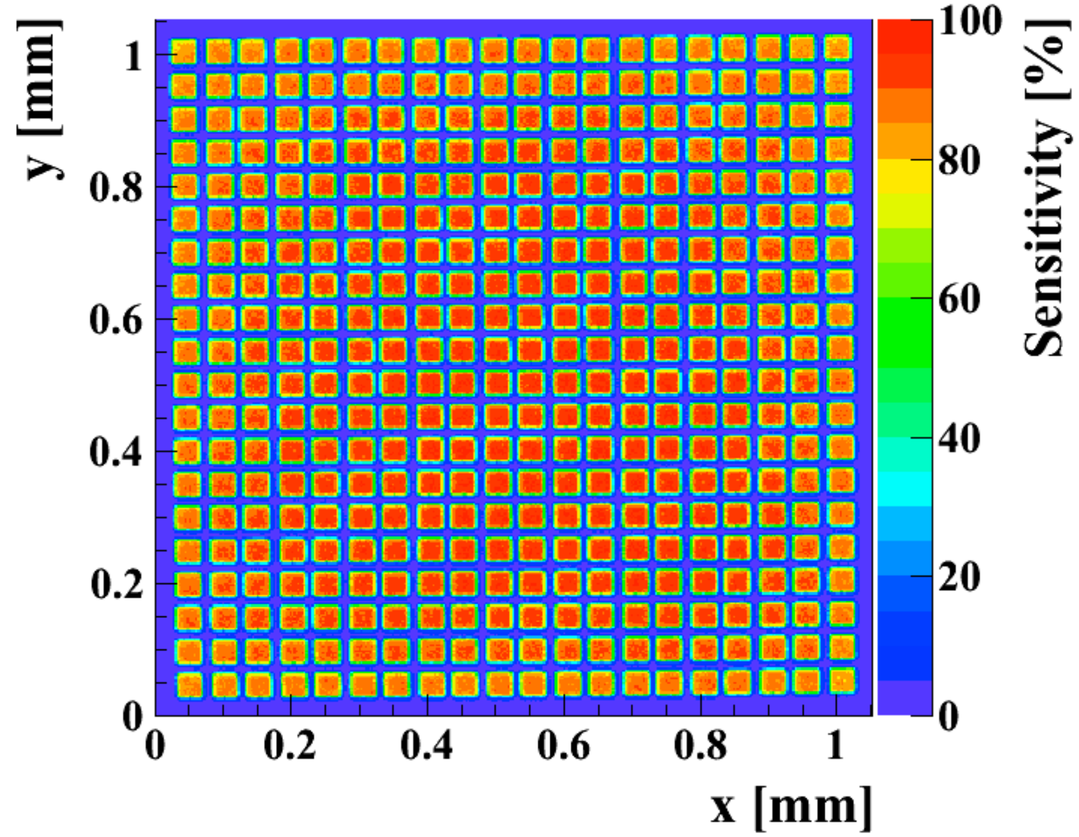


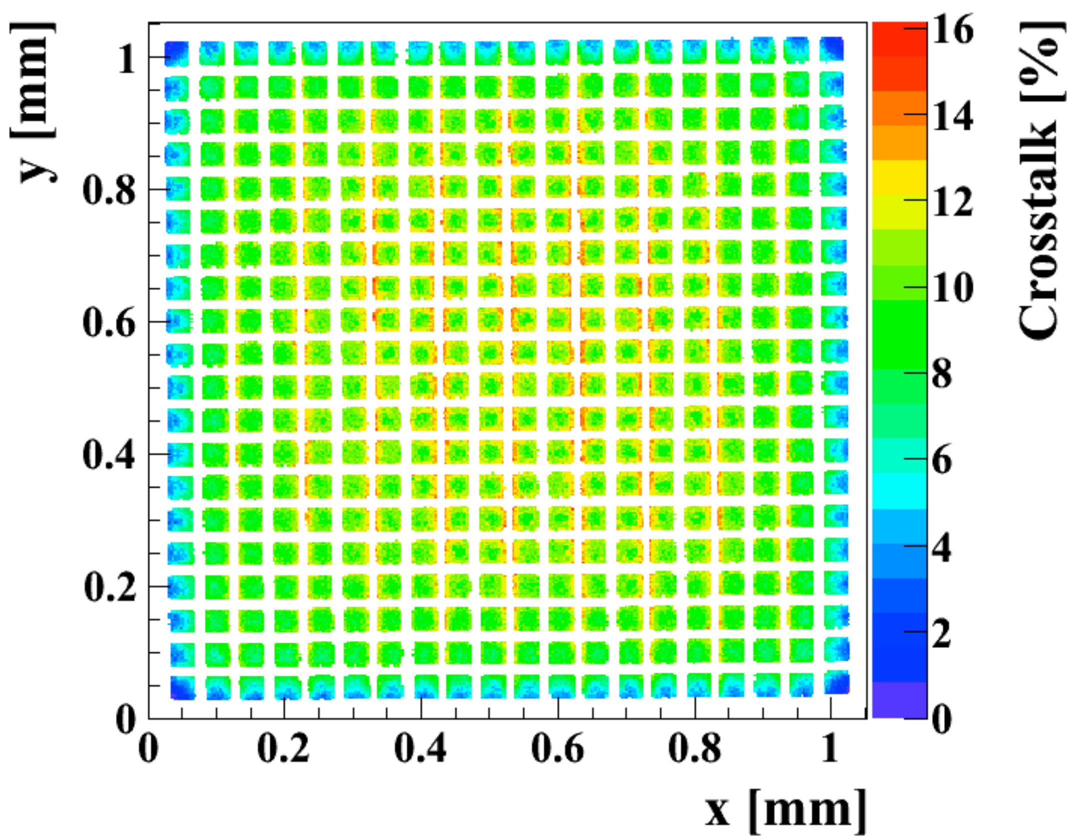
Scan setup:

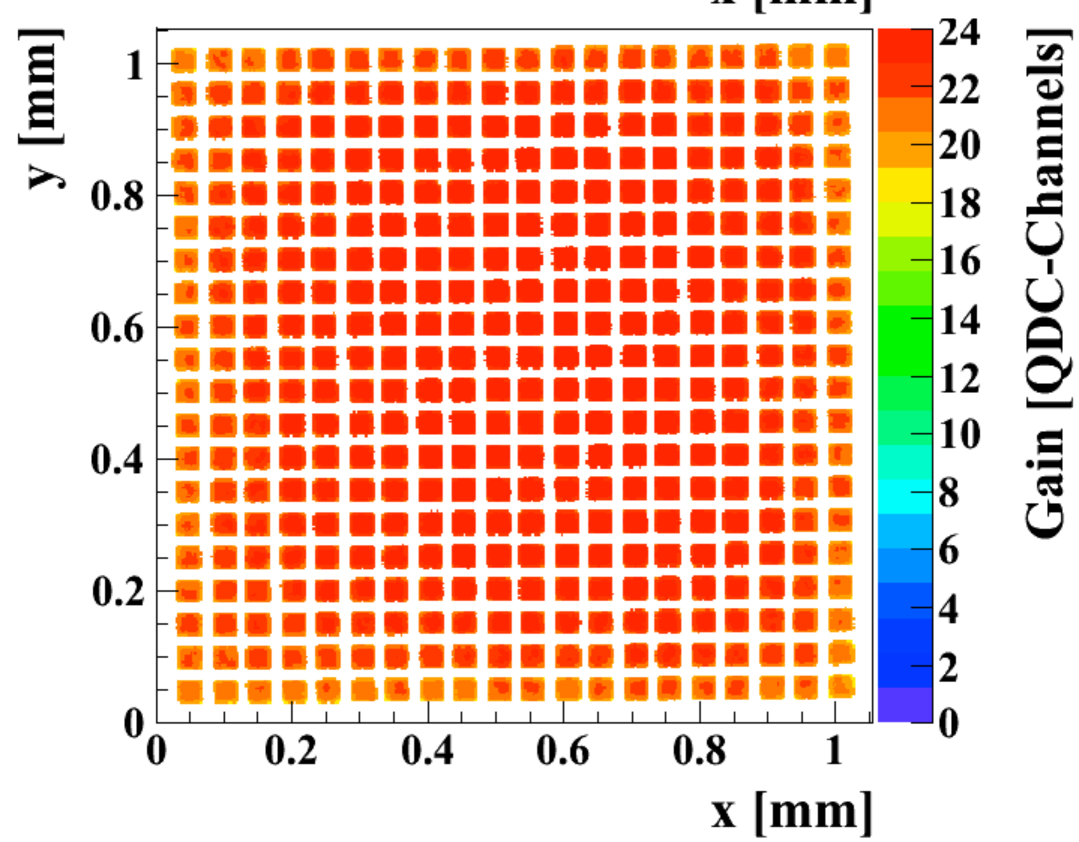


Sensor Scans

- Uniform sensitivity & gain
- Higher cross-talk in the center due to more neighboring pixels
- Cross-talk varies within pixel
  ➡Inhomogeneous avalanche?





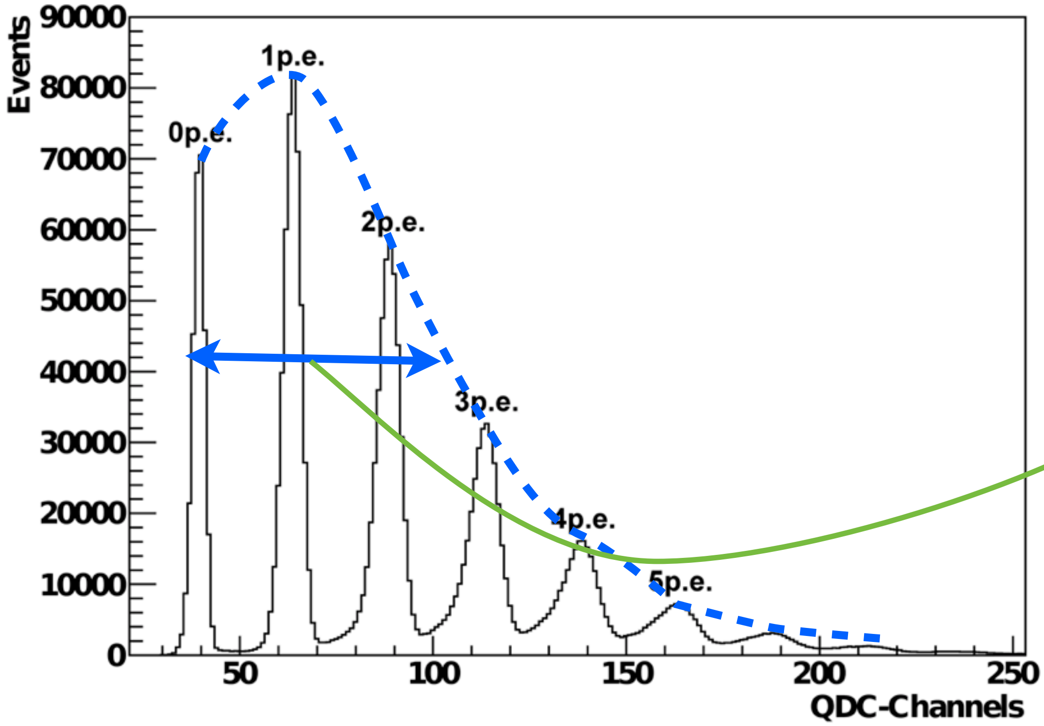


Photon-counting Resolution

• Resolution can be calculated from SiPM properties:

Ideal Sensor (no noise):

• Resolution determined by statistical fluctuation in the number of detected photons:



From PDE measurement:

$$\sigma_{N_{PDE}} = \sqrt{N_\gamma \cdot PDE(1 - PDE)}$$

(Only valid for the linear range!)

Real Sensor:

• Also dark-rate, cross-talk & after-pulses generate noise:

From dark-rate, cross-talk & after-pulse measurements

$$\sigma_{Signal} = \sqrt{\sigma^2_{N_{PDE}} + \sigma^2_{N_{CT}} + \sigma^2_{N_{AP}} + \sigma^2_{N_{DR}}}$$

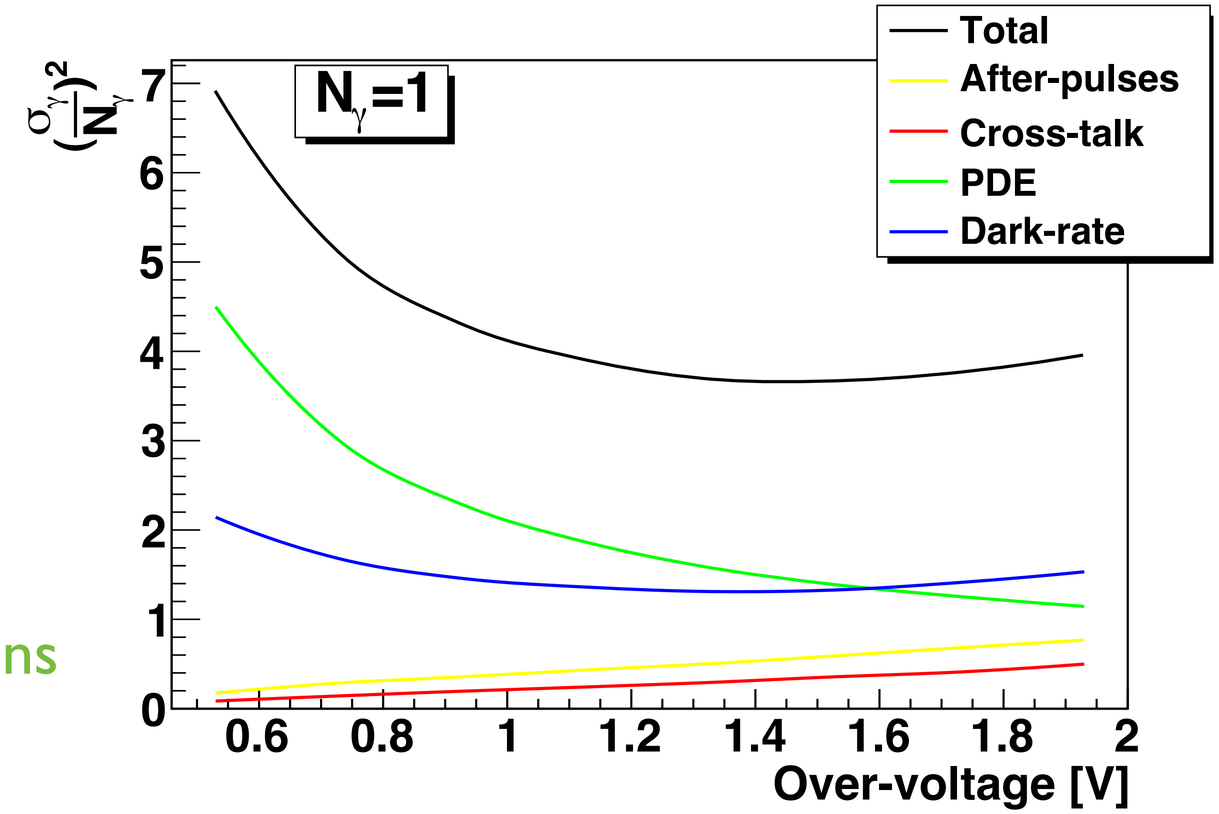
Photon-counting Resolution

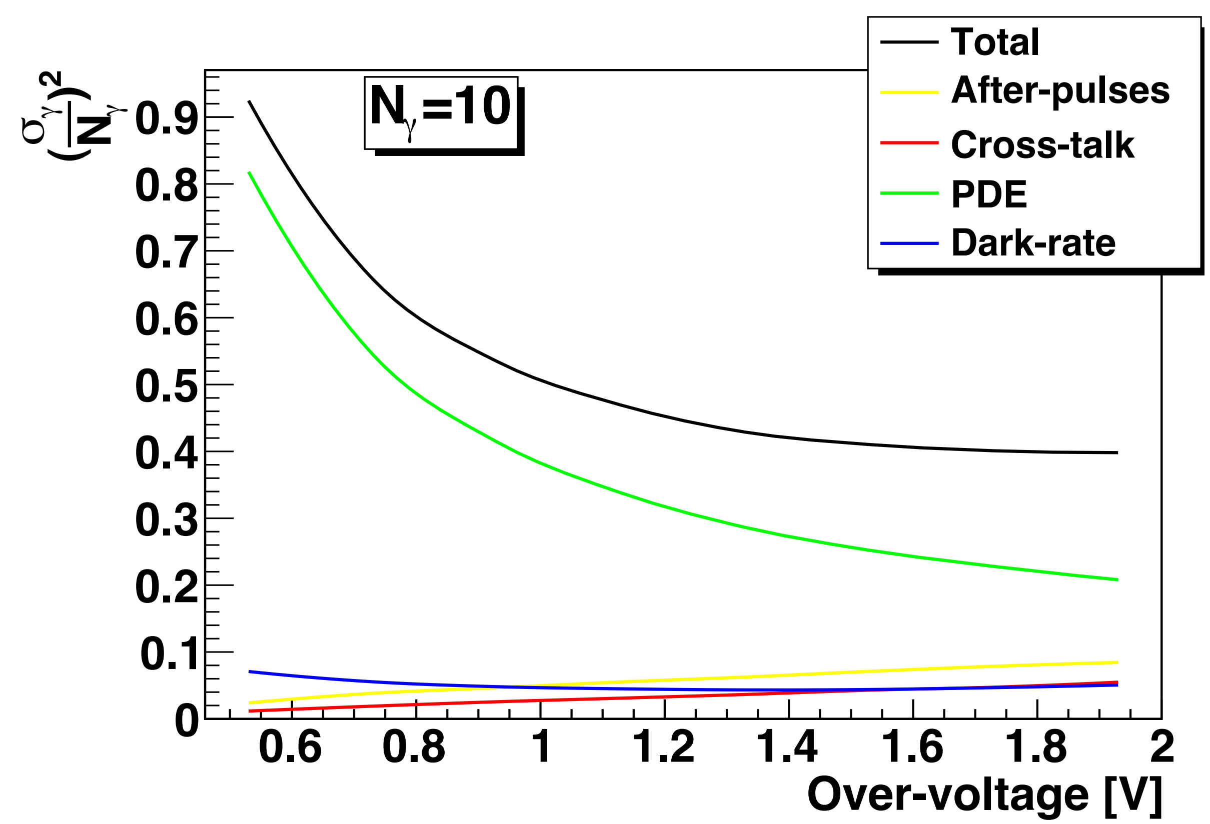
MPPC 400 pixels:

$$\frac{\sigma_{N_\gamma}}{N_\gamma} = \frac{2.93}{N_\gamma} \oplus \frac{1.90}{\sqrt{N_\gamma}}$$

Signals triggered by dark-rate

Signals triggered by photons





- „Optimal" operation voltage depends on photon flux
- Resolution limited by PDE
- Dark-rate can be neglected for moderate photon fluxes

Summary

- SiPMs are promising devices for many applications
- Our test stand allows a detailed characterization of the sensors
  - Gain
  - Dark-rate
  - Cross-talk & after-pulses
  - PDE w/o cross-talk & after-pulses
  - Sensor Scans
  - Temperature dependence
- Measurements are fully automated
- PDE is the limiting factor for the photon-counting resolution