Characterisation of Silicon Photomultipliers

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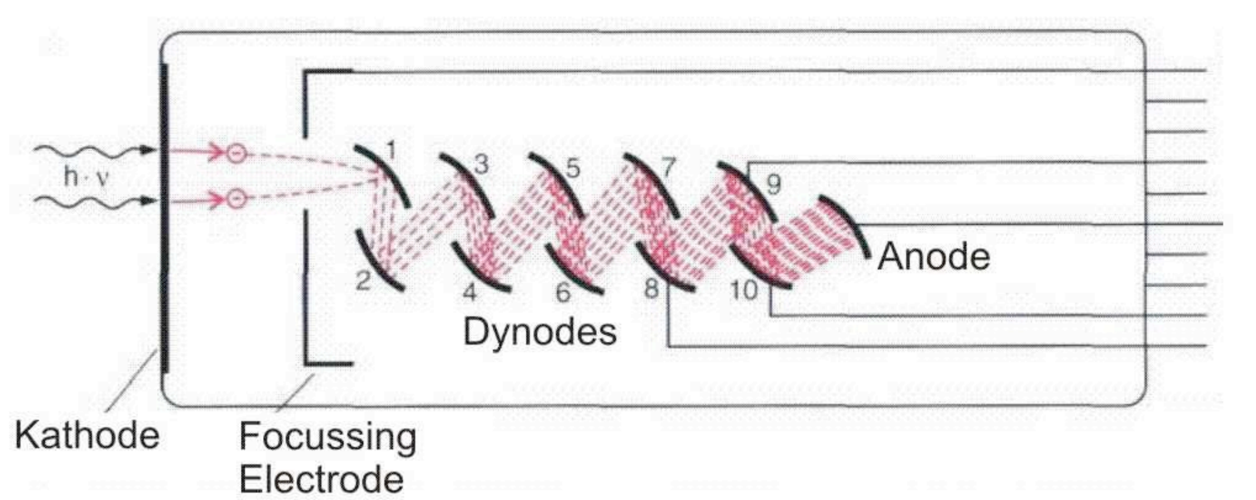
Outline

- Photomultipliers and Photodiodes
- Concept of a Silicon Photo-Multiplier SiPM
- International Linear Collider: Hadronic Calorimeter
- Characterisation Measurements
- Positron Emission Tomography

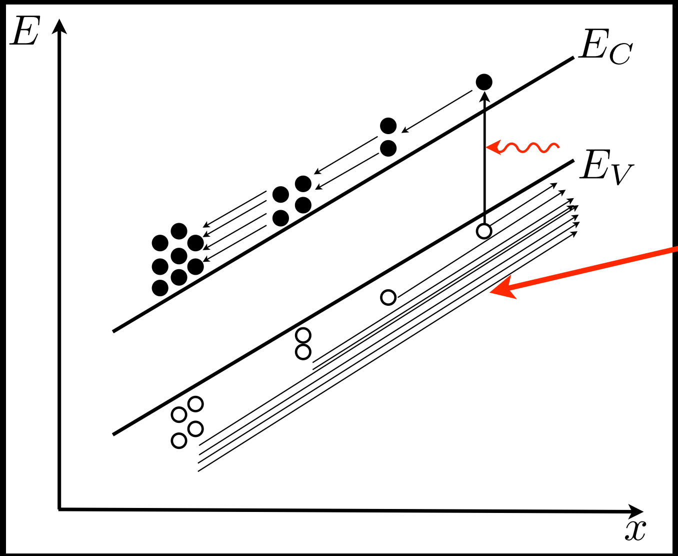
Photomultipliers

- Play important role in many physics experiments
- High Gain (internal amplification)
- typ. value: 10^6
- → 10^6 secondary electrons per initial photoelectron pe
- Low intensity light detection possible

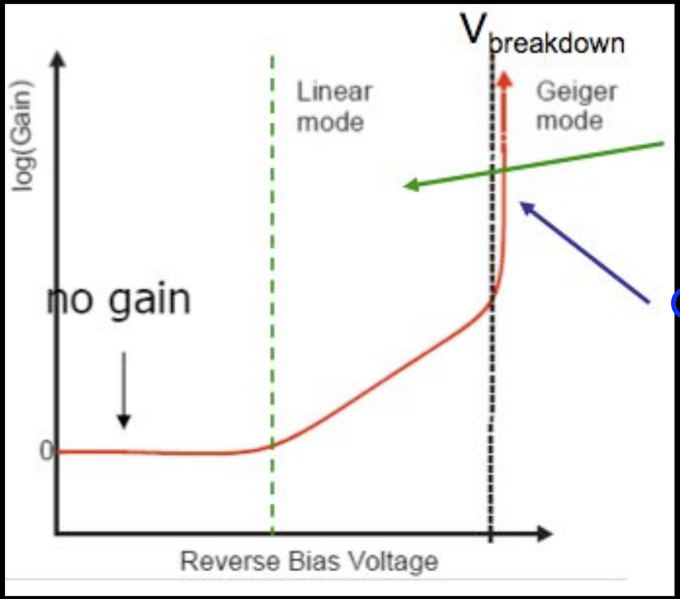


Semiconductor Detectors

- Photodiodes, PIN-Diodes (no Gain, linear response)
- Avalanche Photodiodes (APDs), applied reverse bias voltage, (gain up to 1000, linear response)
- Higher gain can be achieved when operating a few volts over $V_{Breakdown}$ (no linear response!)



Holes don‘t multiply in the linear mode



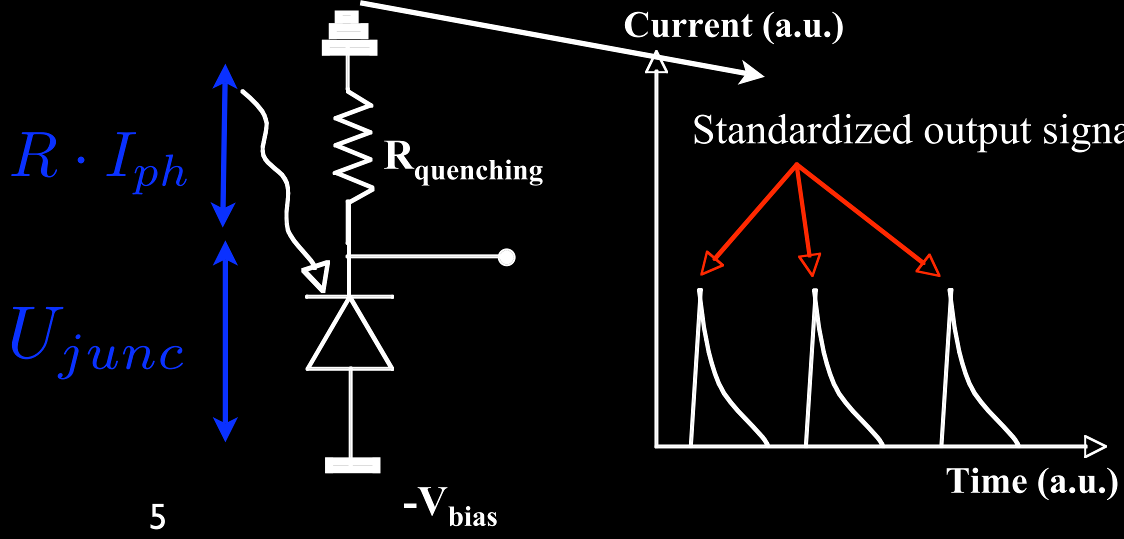
linear mode: gain up to 1000

Geiger mode Photodiode
gain $\approx 10^6$
binary device

Geiger Mode Avalanche Photodiode (GAPD)

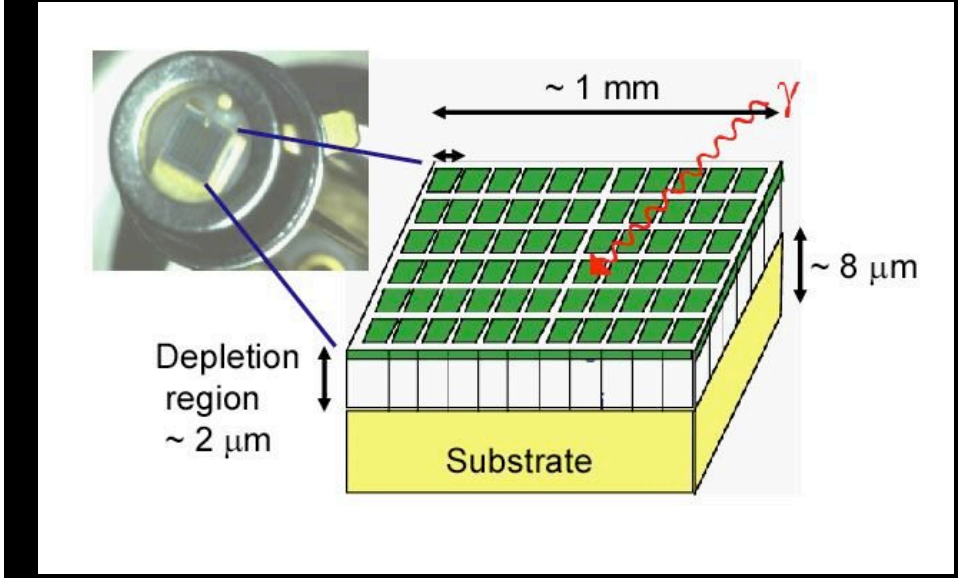
- Striking Photon results in „self sustaining“ avalanche which has to be stopped (quenched)
- Passive quenching: large resistor in series: reverse voltage on the pn-junction decreases because of large voltage drop on quench-resistor during breakdown.
- High Gain! Drawback: Resulting Signal is not proportional to the number of photons: binary (yes/no)! No information about number of photons!

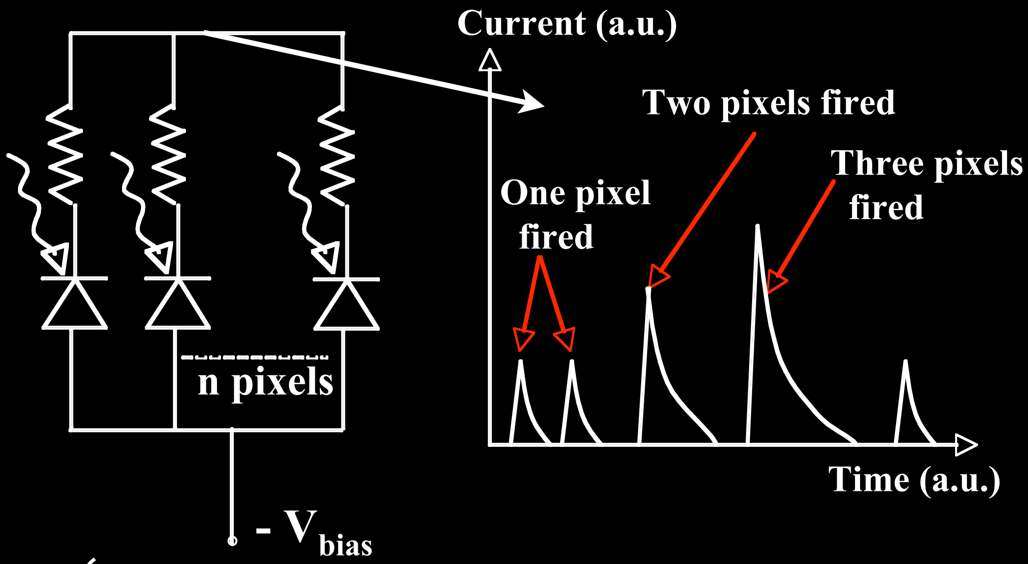
$$U_{junc} = U_{bias} + R \cdot I_{ph}$$



Concept of a Silicon Photomultiplier

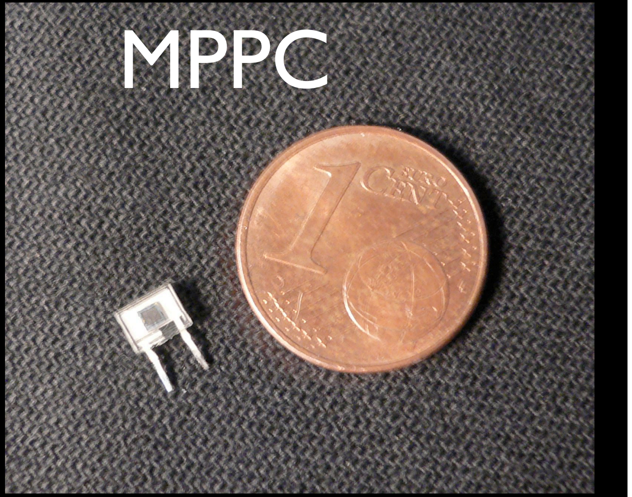
- Array of many GAPD‘s (typ. 1000/mm^2) connected to common output
- Resulting analogue signal is prop. to number of photons for $N_{ph} << N_{pix}$

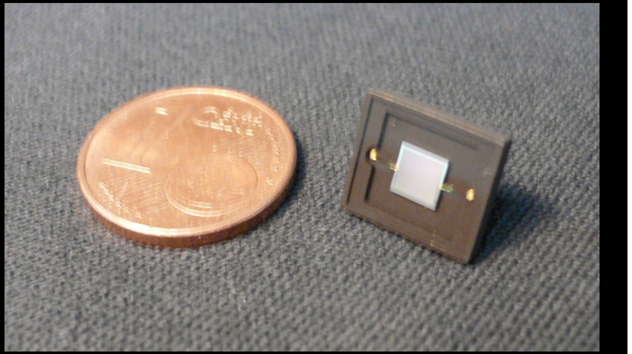




Summary of SiPM properties

- High Gain 10^5-10^6
- Very compact ($1x1$ - $5x5mm^2$)
- Robust
- Low operating voltage (<100V)
- Insensitive to magnetic field

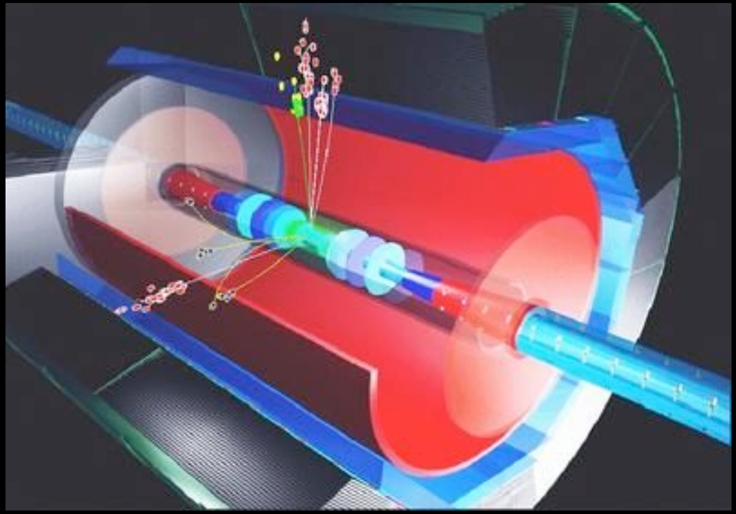




→ Broad spectrum of applications

Fields of Application

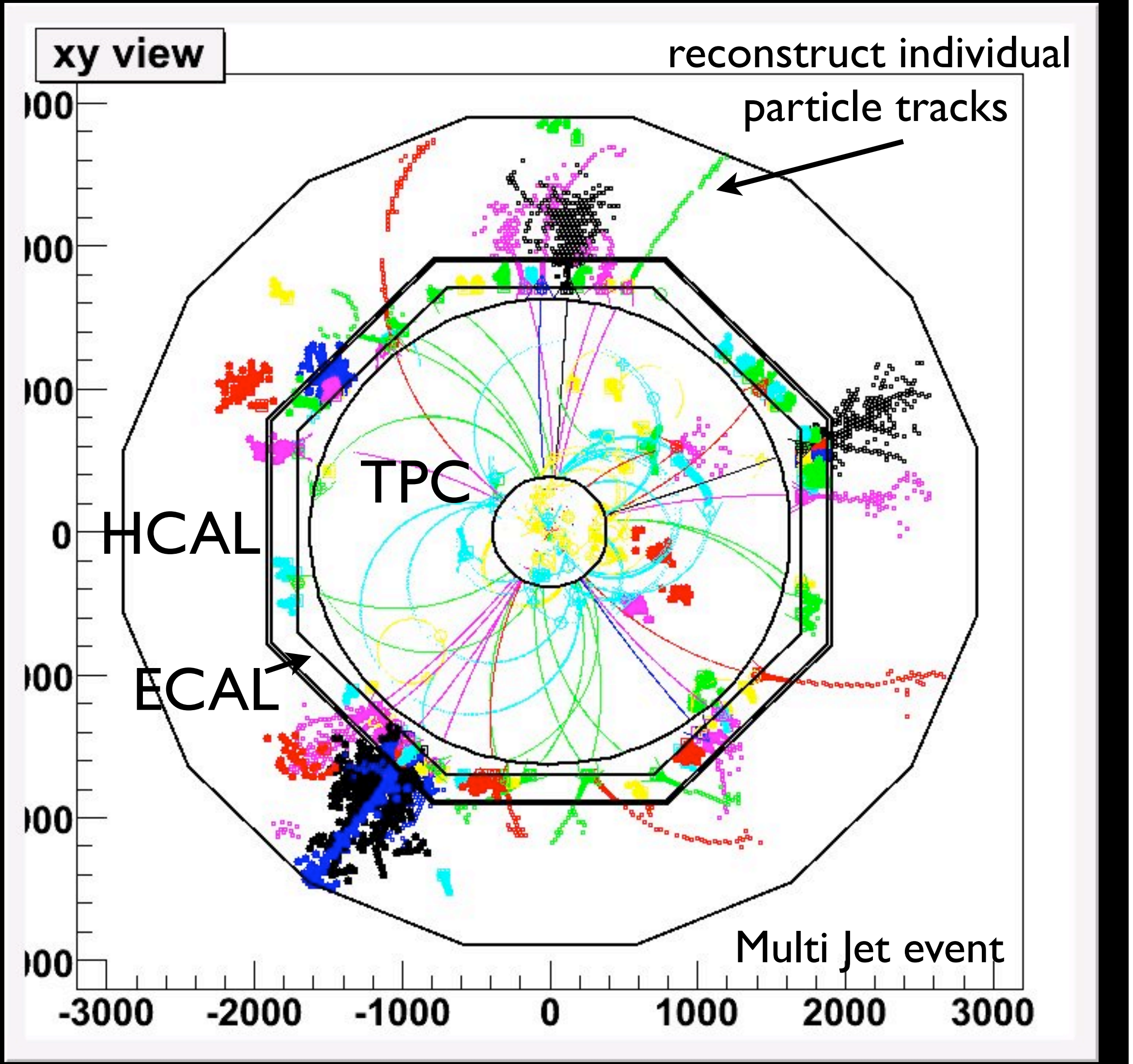
- Hadronic calorimeter of the future project: International Linear Collider (ILC)
  - e+ e- Collider with total length of 30km, $\sqrt{s} = 500\,GeV$ Upgrade: $\sqrt{s} = 1000\,GeV$



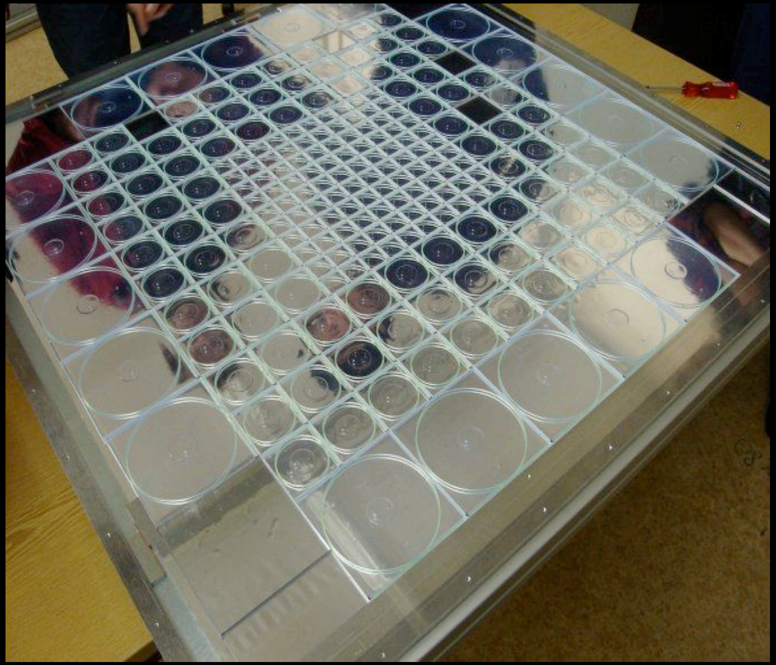
- Positron Emission Tomography (PET)

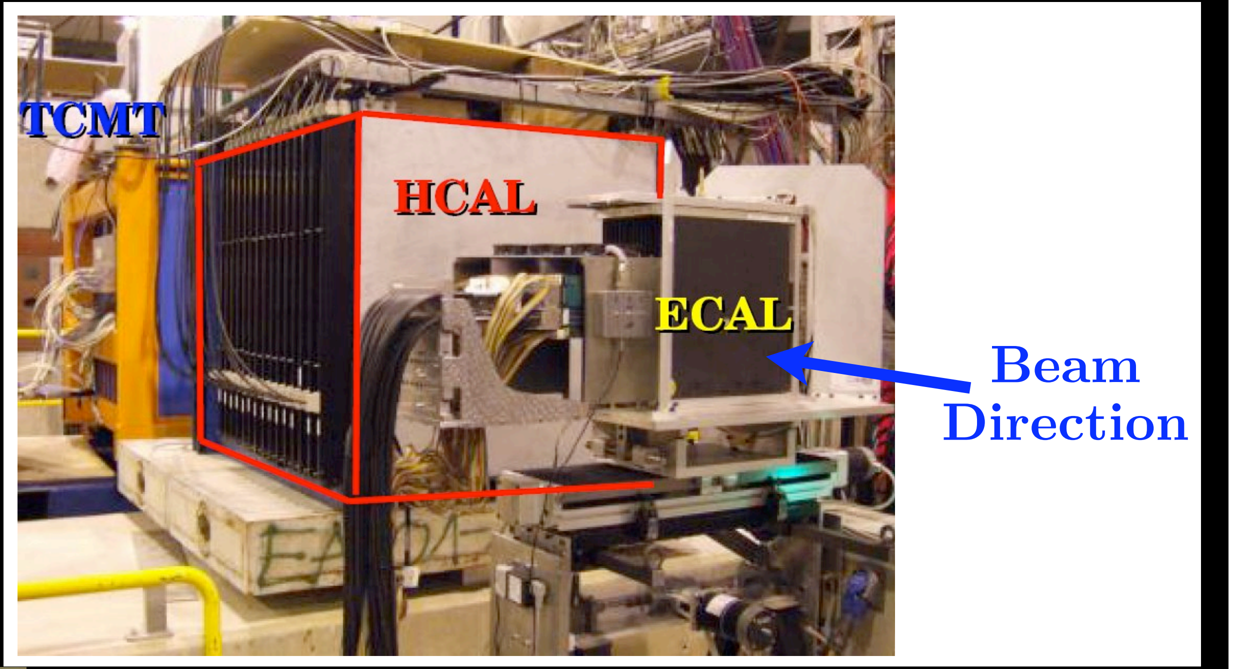
ILC Large Detector Concept (LDC)

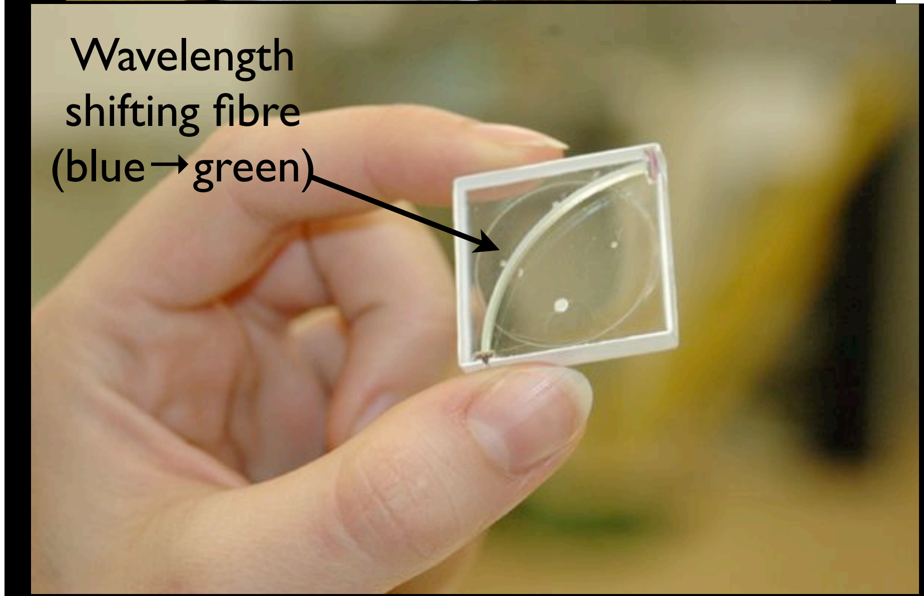
- Large Volume TPC as main tracking device
- High granular electromagnetic and hadronic calorimeter (HCAL)
- Compact design of HCAL within strong magnetic field of 4T
- High longitudinal and transversal segmentation: Cell-size 3x3x0.5cm^3 (Imaging Calorimeter)



HCAL Prototype, DESY

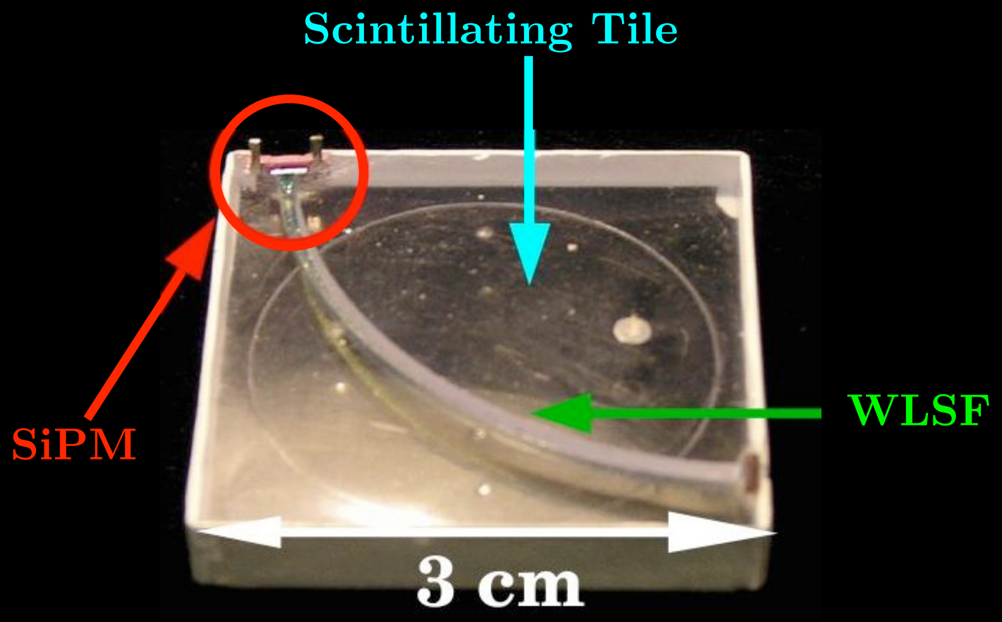






- Steel-scintillator Sandwich structure. Plastic scintillator (blue)
- 1 m^3 Prototype made of 38 Layers 216 Channels per Layer
- Equipped wit SiPM‘s from MEPHI/PULSAR (enhanced green sensitivity)

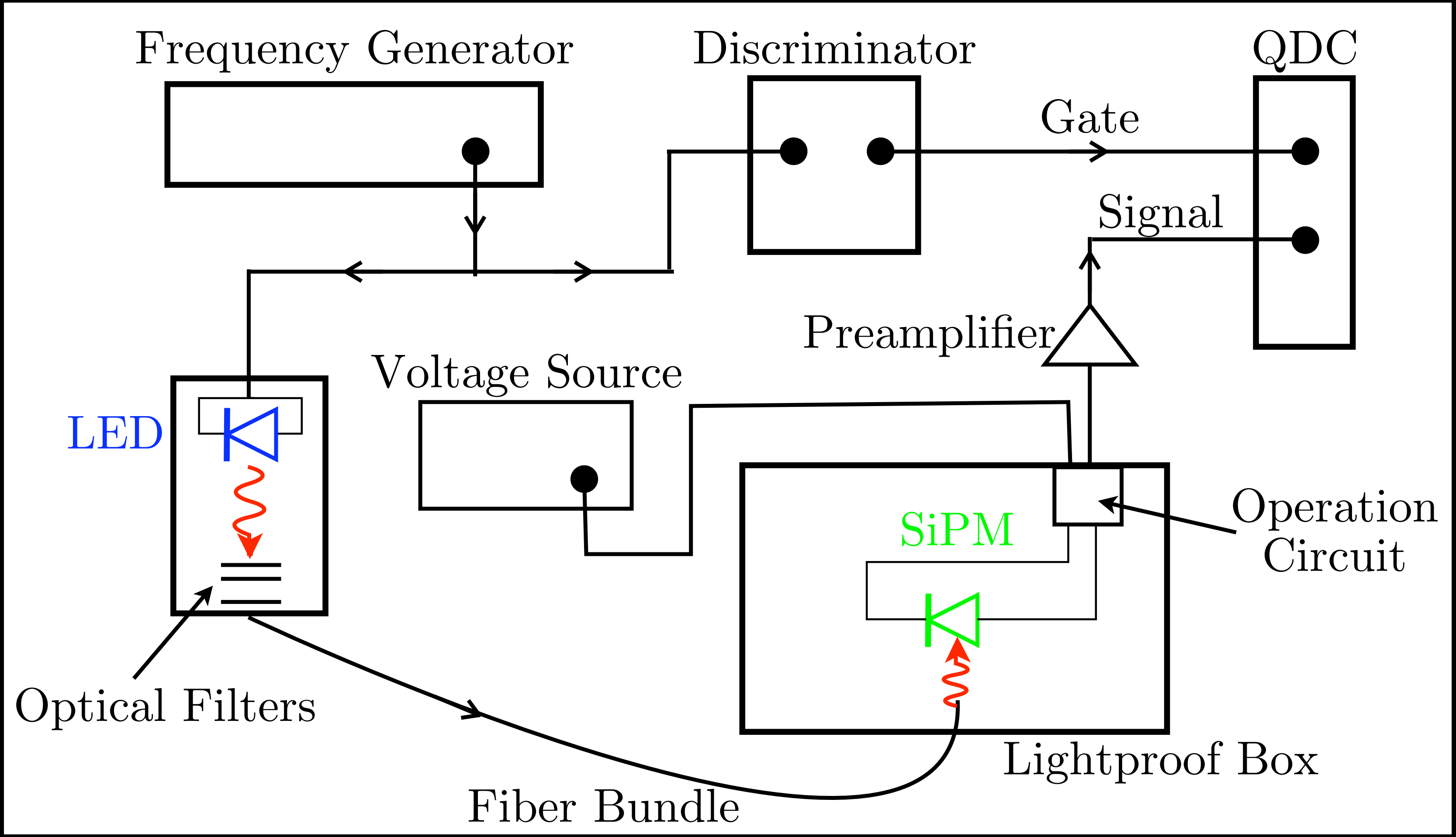
Scintillation Tile with SiPM Readout



- Wavelength shifting fibre converts blue scintillation light into green light (SiPM has enhanced green sensitivity)
- The MPPC from Hamamatsu gives the option for a direct readout without WLSF
- To ensure proper operation, SiPMs need to be tested and characterised

Characterisation Measurements

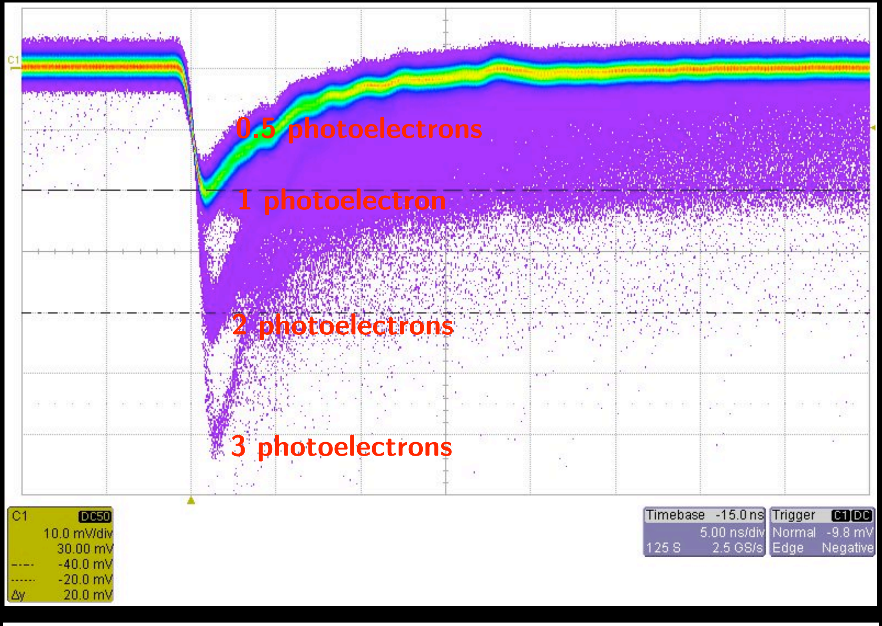
Gain Measurement

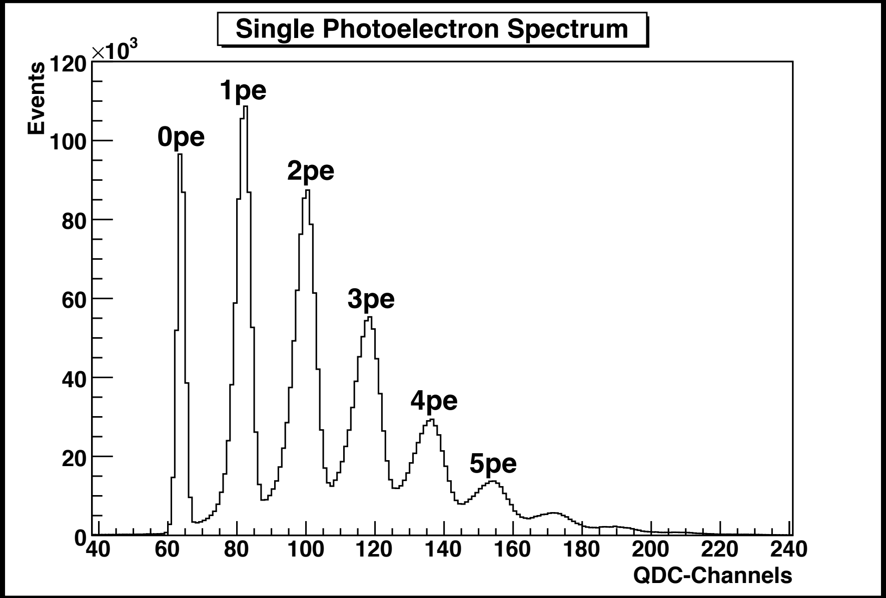


Photoelectron Spectrum

Oscilloscope picture,
V:10mV/div, H: 5ns/div

- Single Photon Signals can be discriminated.
- Histogram peaks correspond to a certain number of p.e.
- "Distance" between two neighbouring peaks equals the Gain M
- Obtained by applying the Fast Fourier Transformation



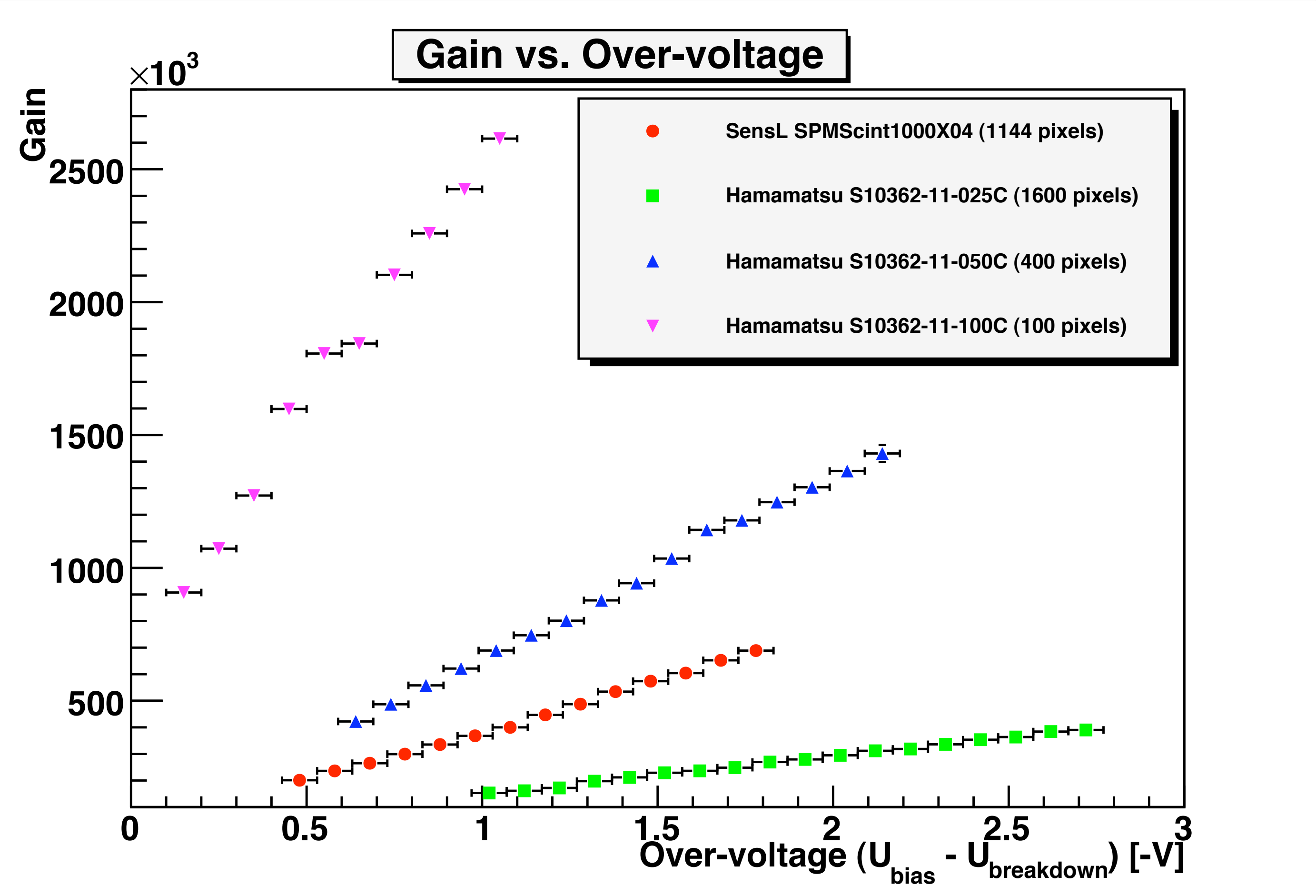


Gain measurement results

8 Samples from HAMAMATSU (MPPC) and SensL (SPM) have been tested.
All have an active area of 1×1mm^2
100 -1600 Pixels

$$M = \frac{C_{pixel}}{e}(U_{bias} - U_{break})$$

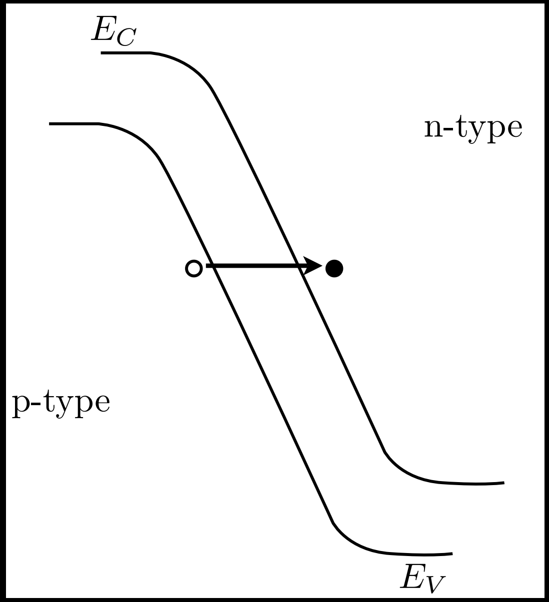
Fit Parameters



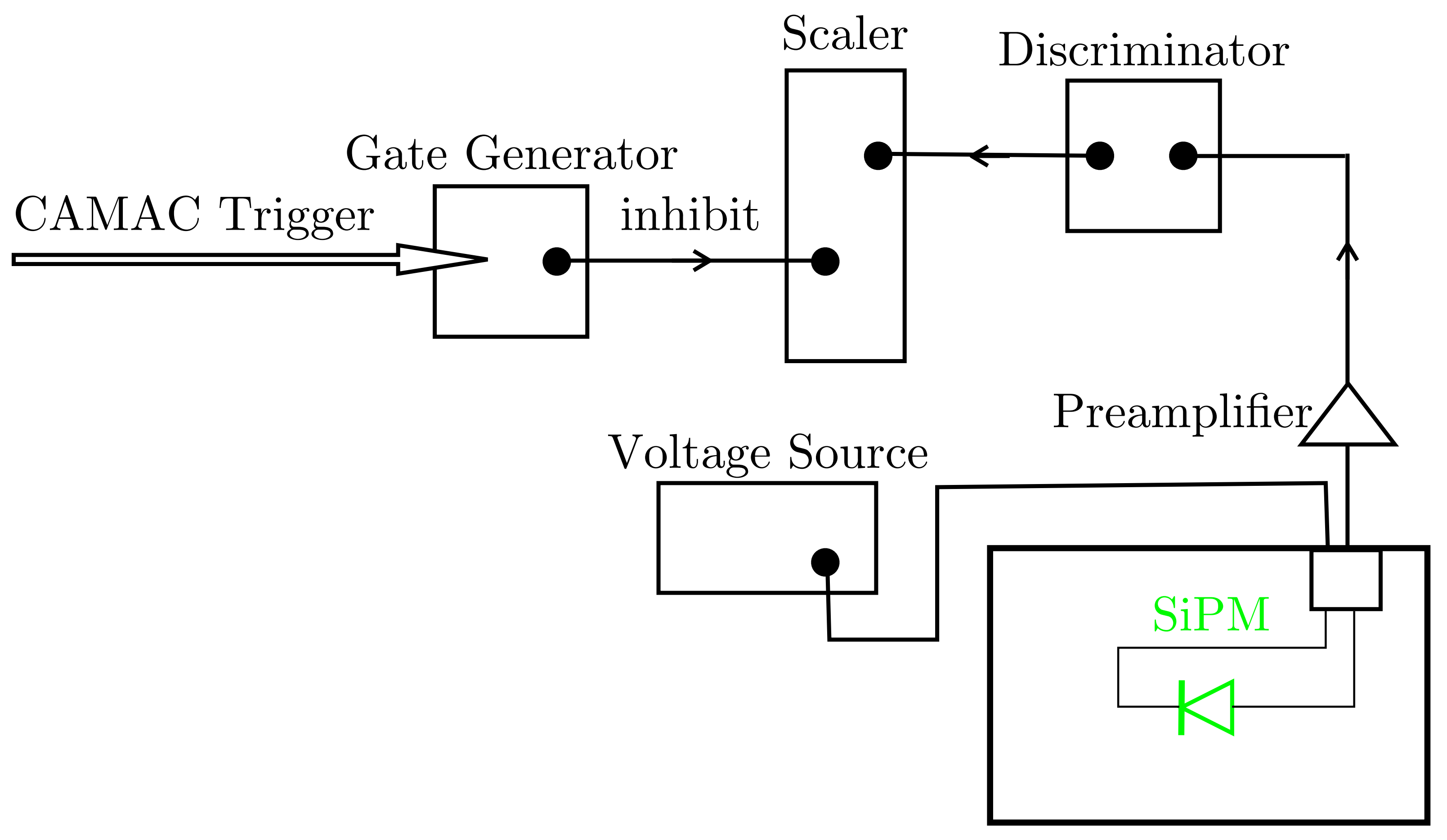
Dark-rate

- Electron hole pairs resulting in a Geiger discharge cannot only be generated by photons.
- Thermal excitation can occur if the band gap is smaller than the thermal energy of a charge carrier. (0.0259eV at room temp.)
- Tunnel excitation: If an electric field is present, charge carriers can tunnel through the band gap into a state in the conduction band with the same energy. Important for SiPMs because of the strong electric field.

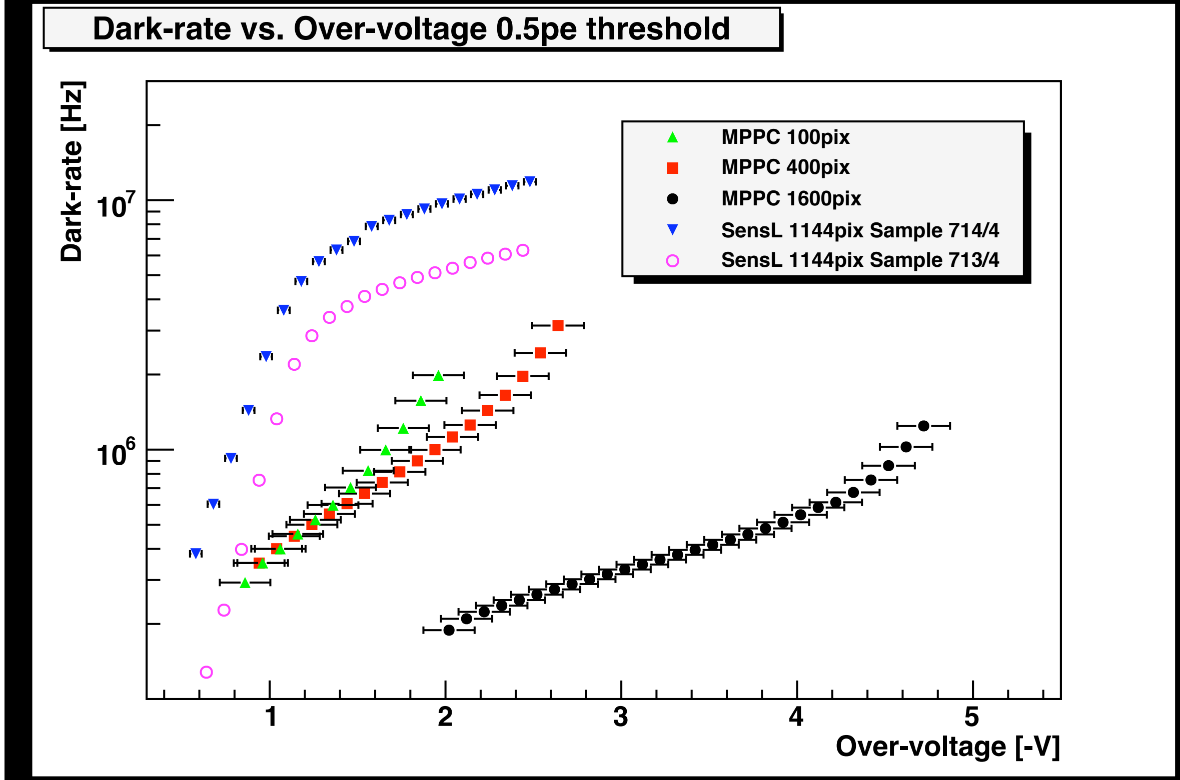
Tunnel excitation

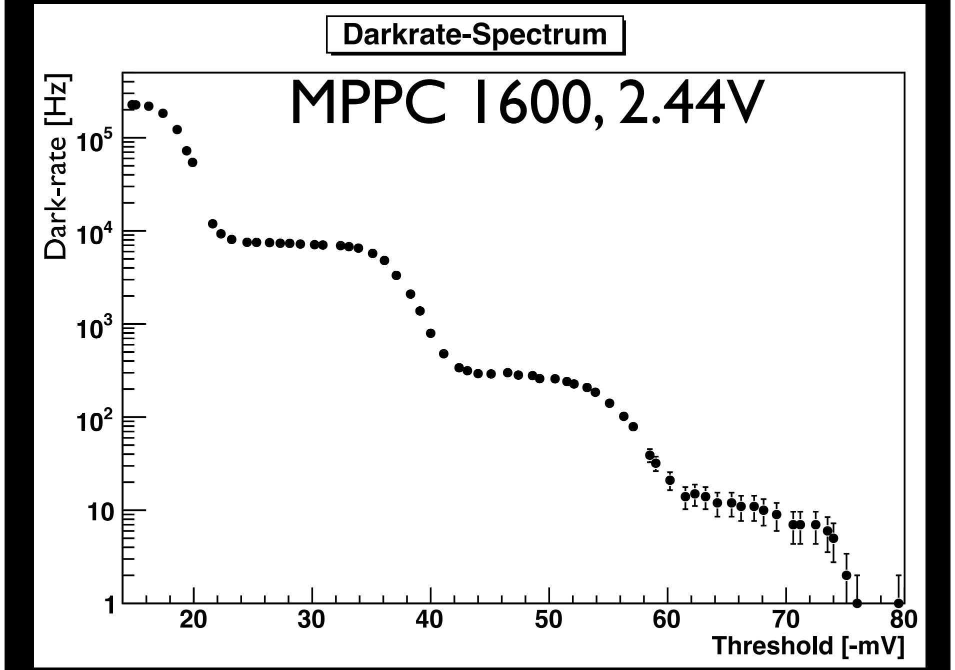


Dark-rate measurement



Dark-rate measurement results



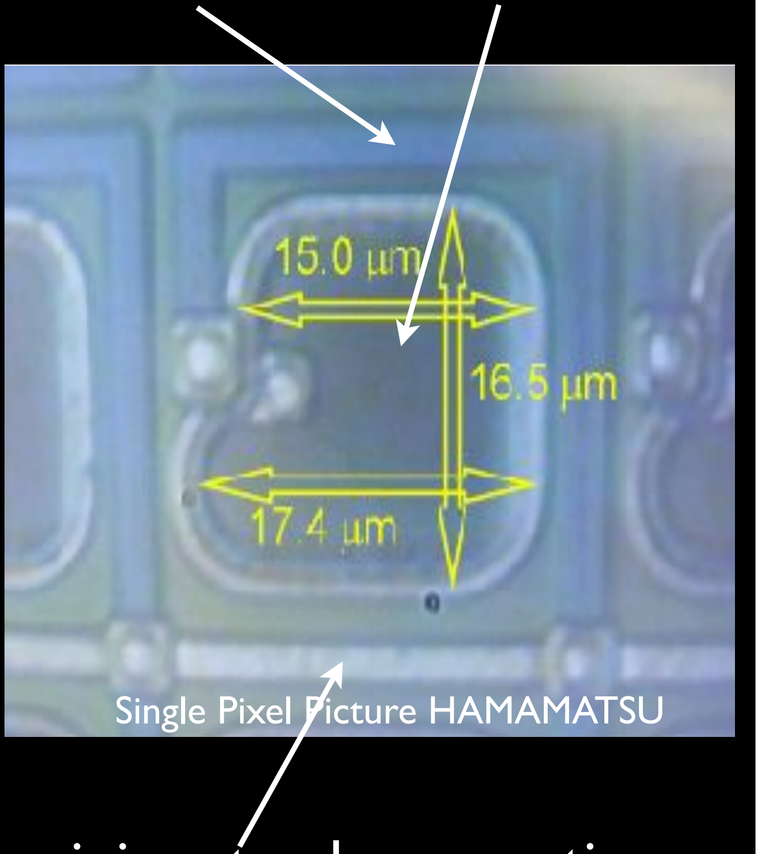


The two samples from SenSL show a high dark rate up to 10^7 Hz (at 0.5pe. threshold, strong reduction for higher counting threshold)

Photon Detection Efficiency (PDE)

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

- R : Reflection coefficient
- $\epsilon_{geo} = \frac{A_{Active}}{A_{Total}}$
- $\epsilon_{avalanche}$: Probability for a free charge carrier to initiate a Geiger discharge
- QE : Quantum efficiency (Probability for charge carrier generation)



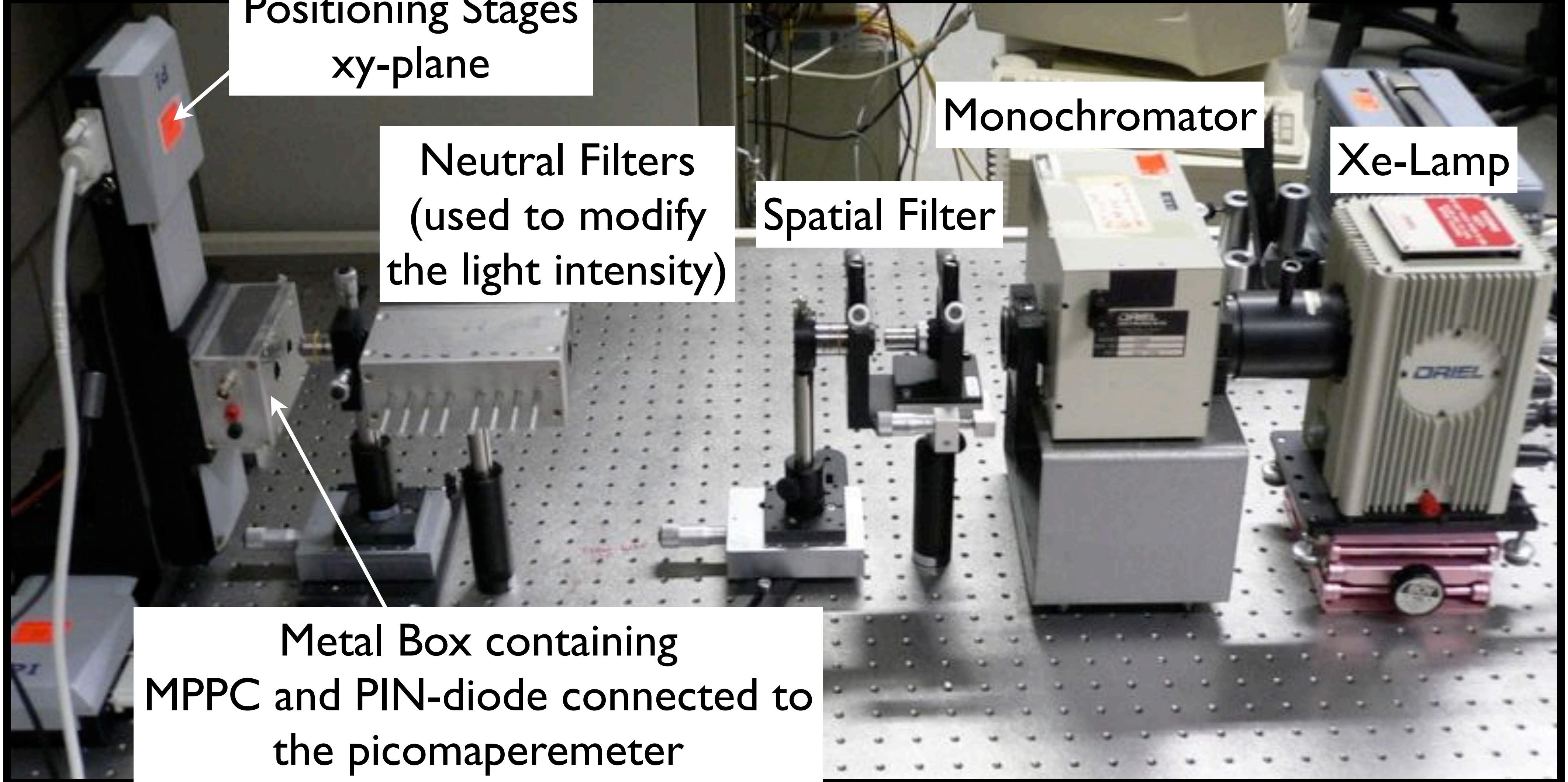
Quenching resistor

Active area

Single Pixel Picture HAMAMATSU

Aluminium track connecting individual pixels

PDE measurement



Micrometer
Positioning Stages
xy-plane

Neutral Filters
(used to modify
the light intensity)

Spatial Filter

Monochromator

Xe-Lamp

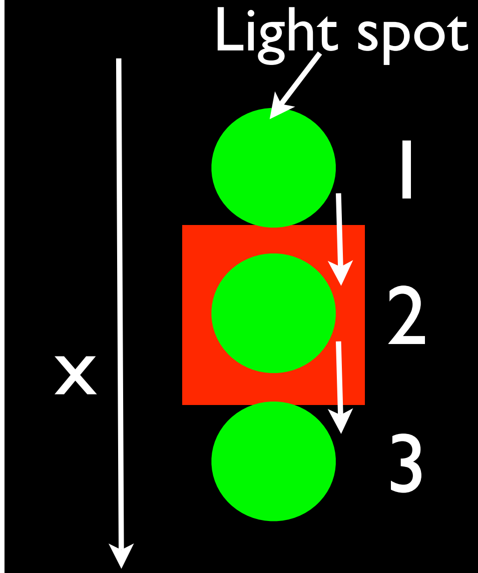
Metal Box containing
MPPC and PIN-diode connected to
the picomaperemeter

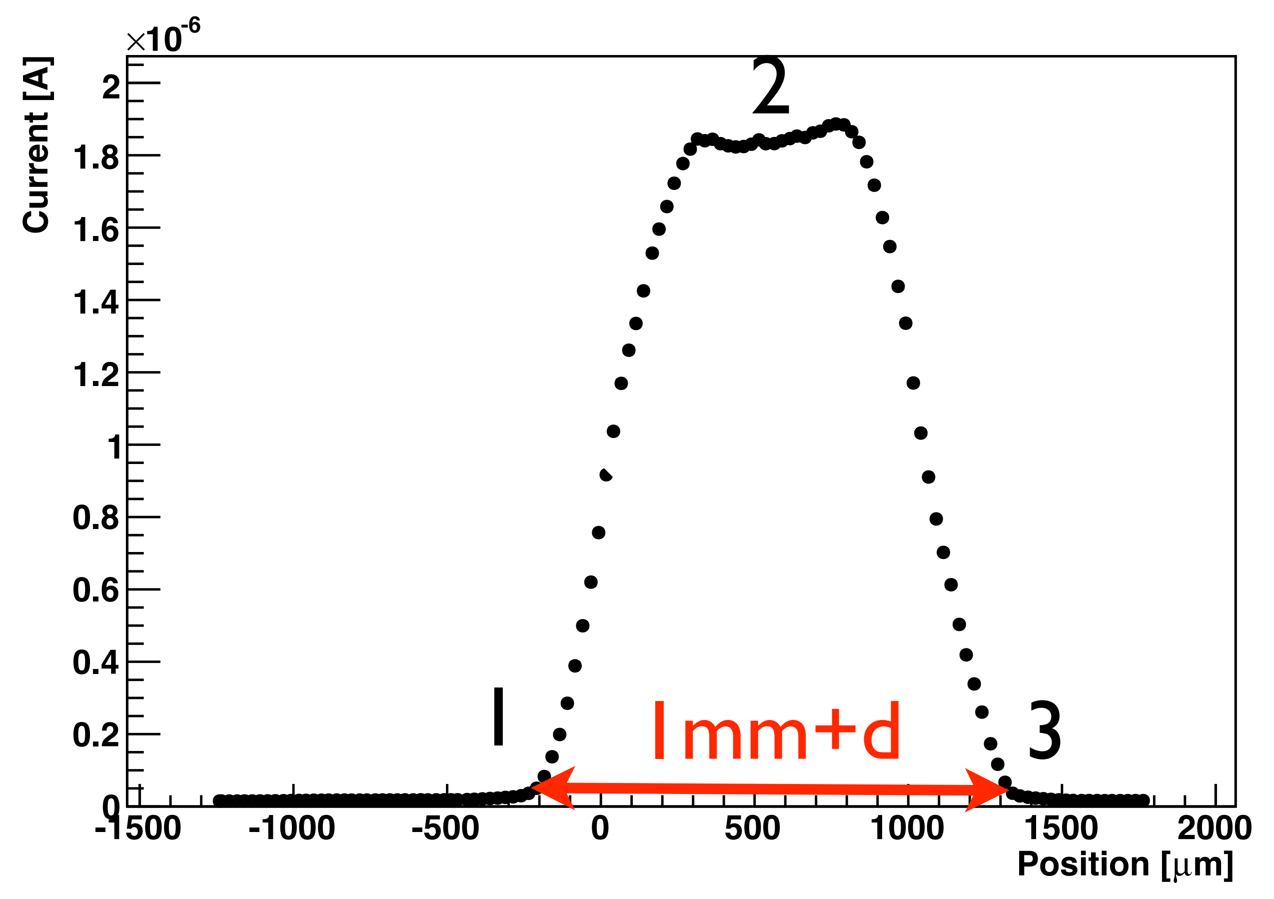
Size of the light spot

- Active area MPPC 1×1mm^2
- Active area PIN-diode 3×3mm^2
- Diameter of the light spot has to be smaller than 1mm. Otherwise light will be lost.
- The diameter was measured by moving the MPPC in the x- and y-direction, respectively while measuring the photocurrent.

Photocurrent Profile

Scan in x-direction





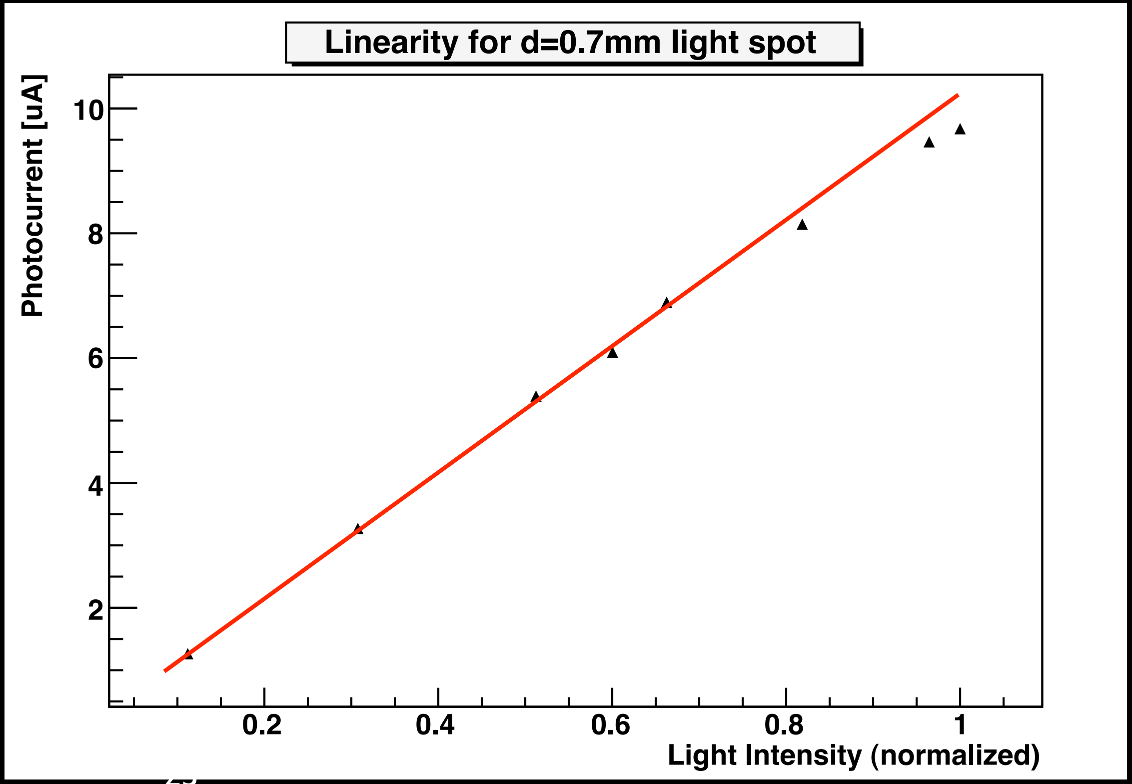
→ Light spot diameter d≈0.7mm

→ Centre is at 0.6mm

Linearity of the MPPC

1. Use PIN-diode (linear behaviour) for calibration of neutral optical filters
2. Measure photocurrent of MPPC (HAMAMATSU 1600 pix) as a function of light intensity

Light Intensity was chosen in order to ensure linear behaviour of the MPPC

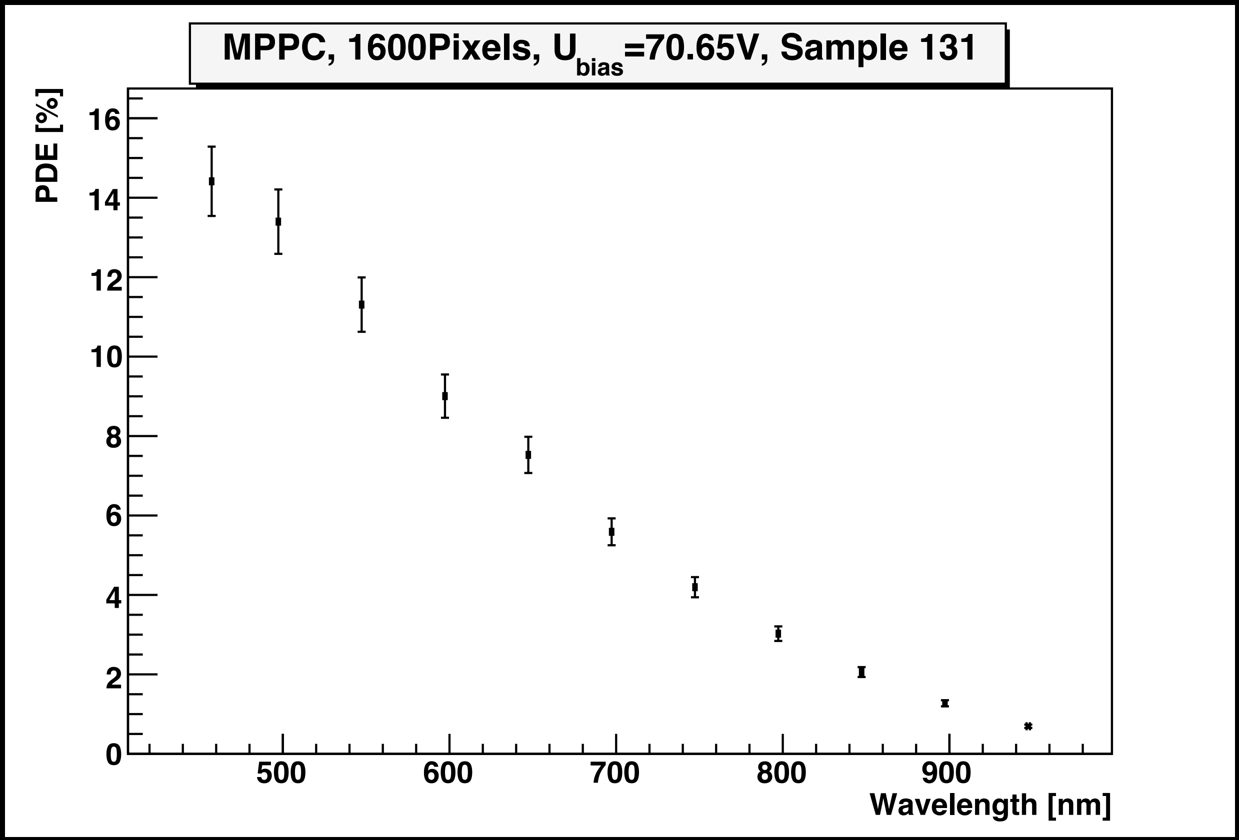


First Results

Calibration data sheet

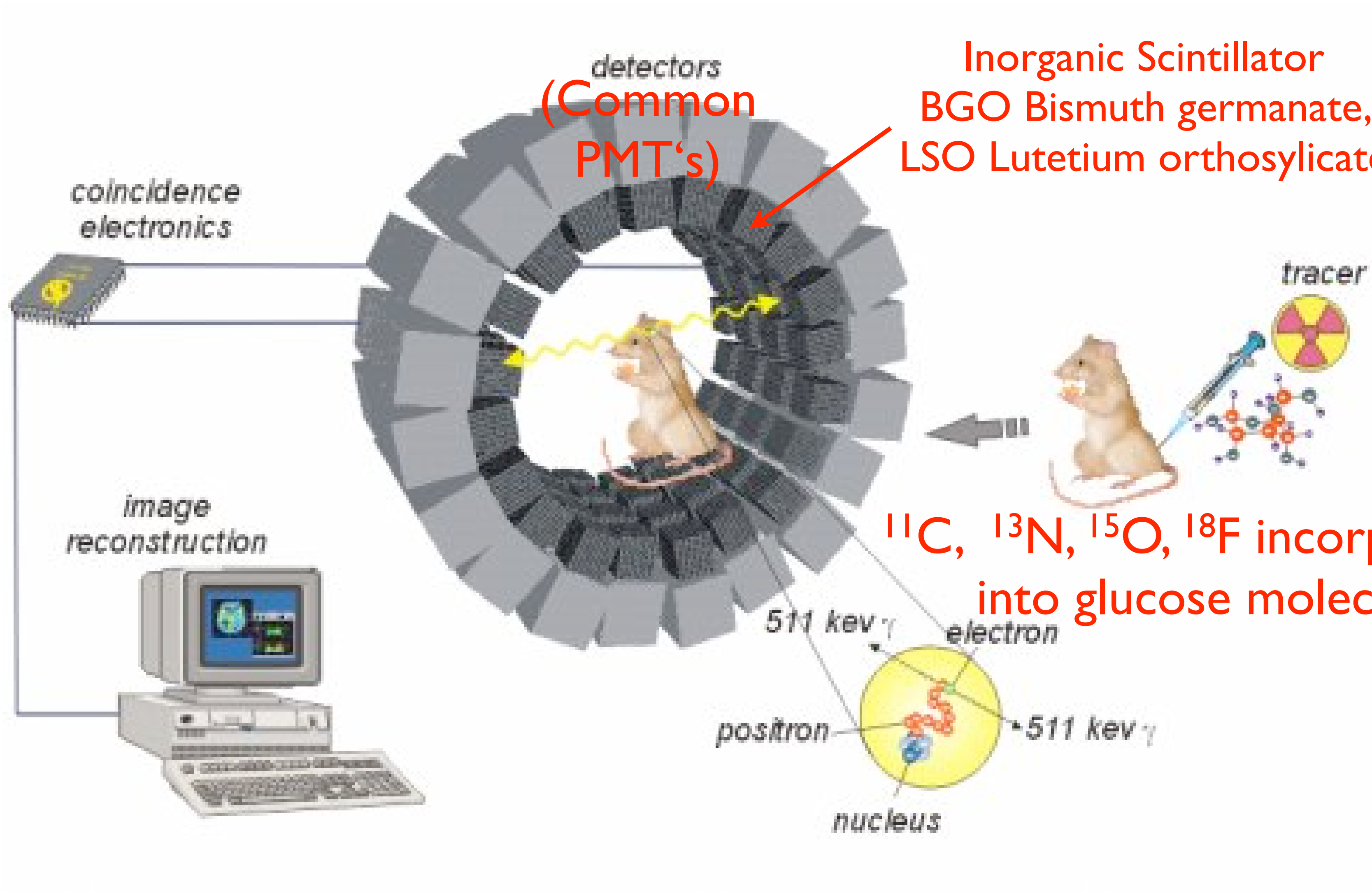
$$PDE = \frac{I_{MPPC} \cdot R \cdot h \cdot c}{M \cdot e \cdot I_{PIN} \cdot \lambda}$$

The measured shape of the curve is in agreement with the expectation. The functionality of the setup was proven, however more systematic measurements are needed.



Other Application: Positron Emission Tomography (PET)

Introduction to PET



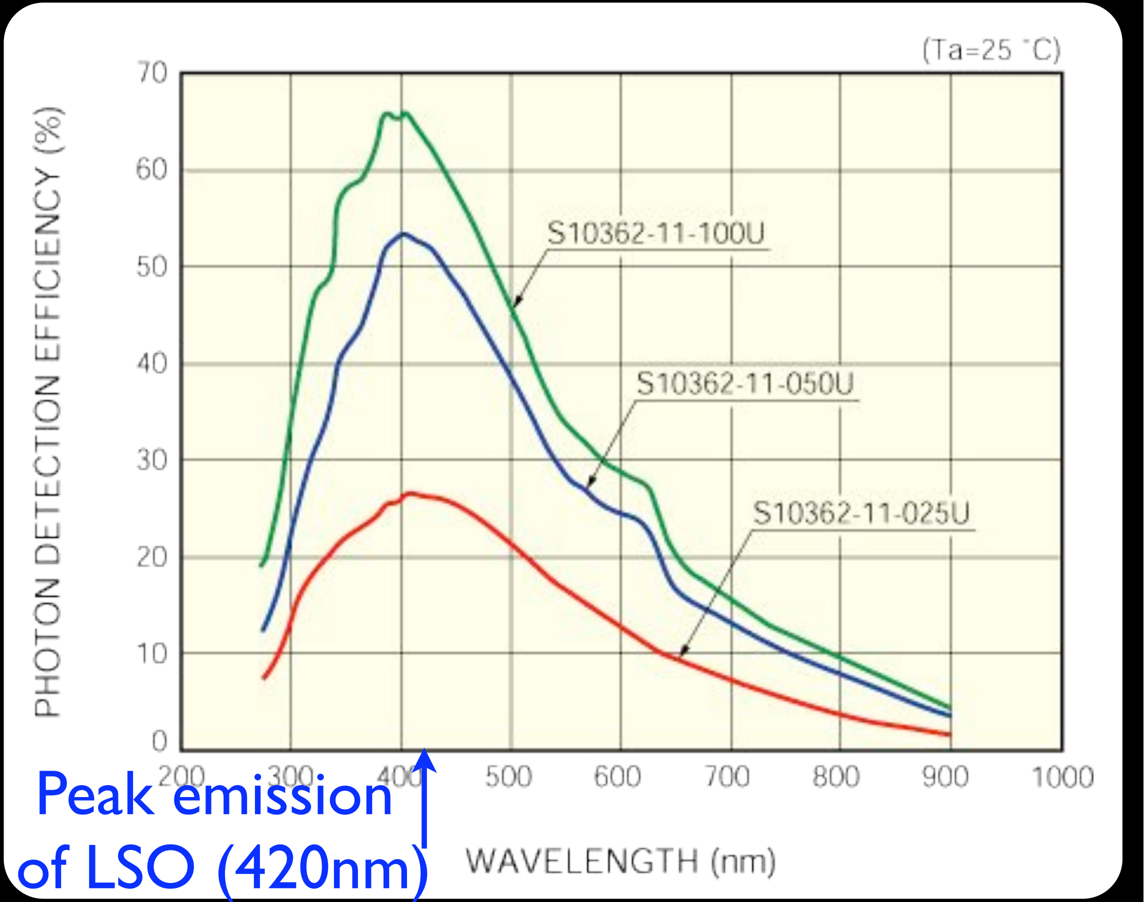
(Common PMT's)

Inorganic Scintillator
BGO Bismuth germanate,
LSO Lutetium orthosylicate

^{11}C, ^{13}N, ^{15}O, ^{18}F incorporated into glucose molecule

Why use MPPC's

- Scintillation light from LSO is blue (Peak at 420nm)
- MPPC has an enhanced sensitivity in the blue range



Peak emission of LSO (420nm)

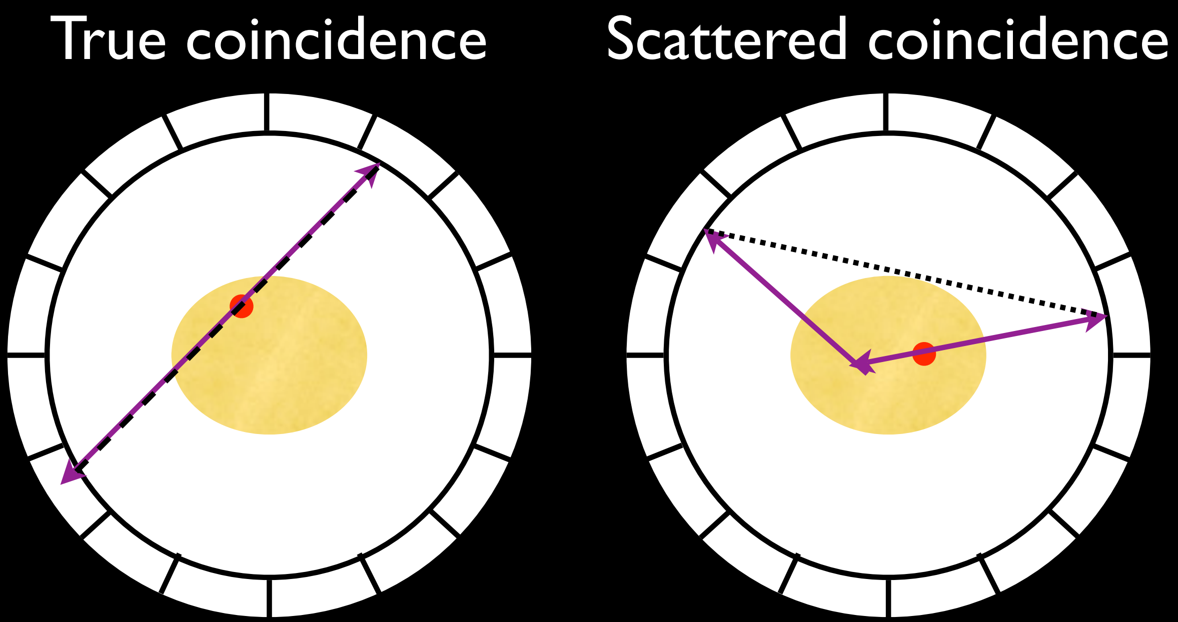
Source: Hamamatsu

Why use MPPC's

- Spatial Resolution
  - Small size
    ➥ possibility to study single crystal readout with size from 1×1-3×3mm^2
- Study the fusion of PET and Magnetic Resonance Imaging (MRI) (small PET detector contained in MRI) because of the insensitivity to magnetic fields.
- High gain, low operation voltage

Reduction of Background

Energy Resolution


True coincidence

Scattered coincidence

● Annihilation point

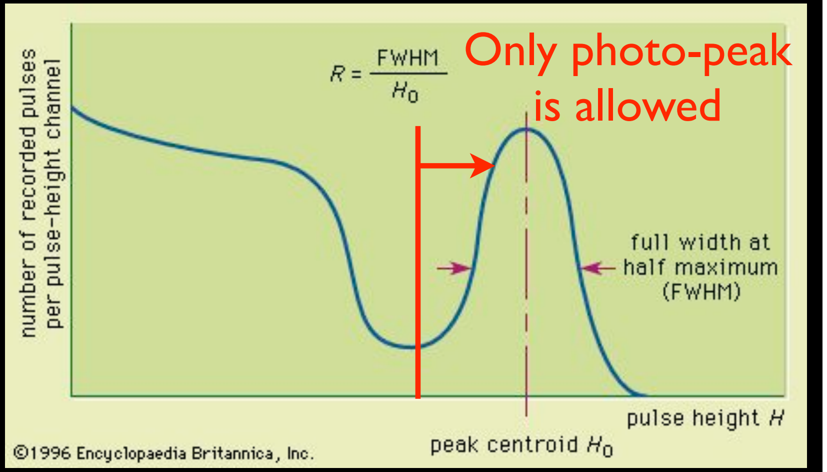
→ Gamma ray

········ Line of response

Why is energy resolution crucial for PET?

Cut scattered events but keep true events

➥ need good energy resolution



Only photo-peak is allowed

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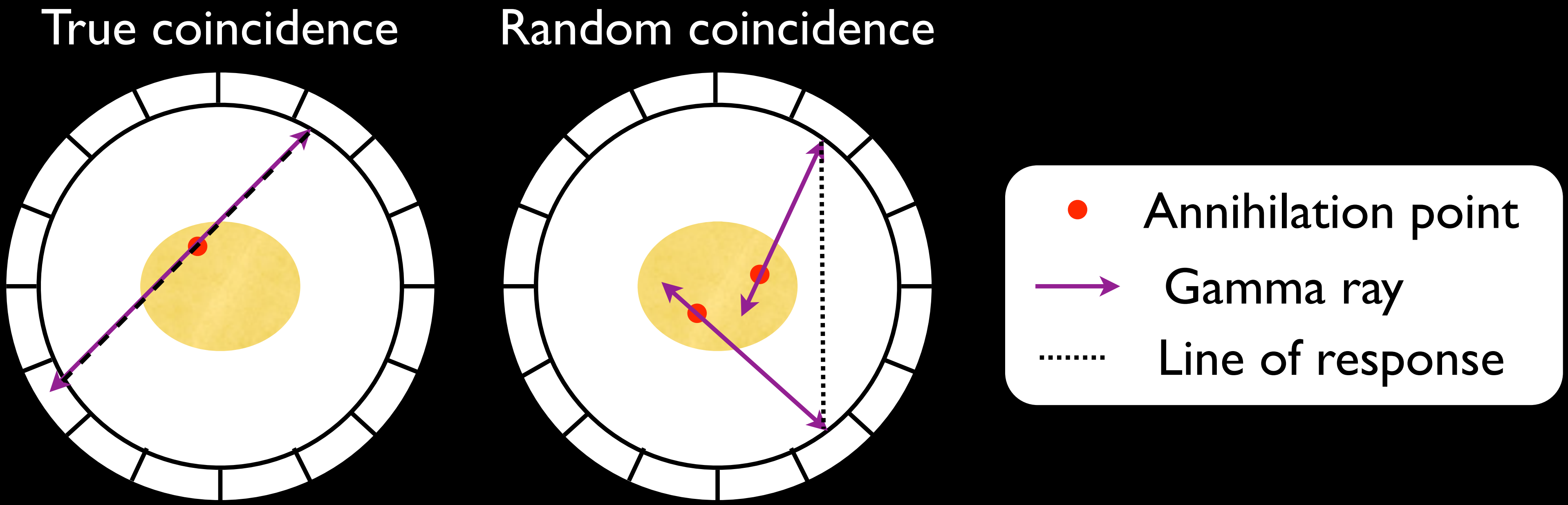
Timing Resolution



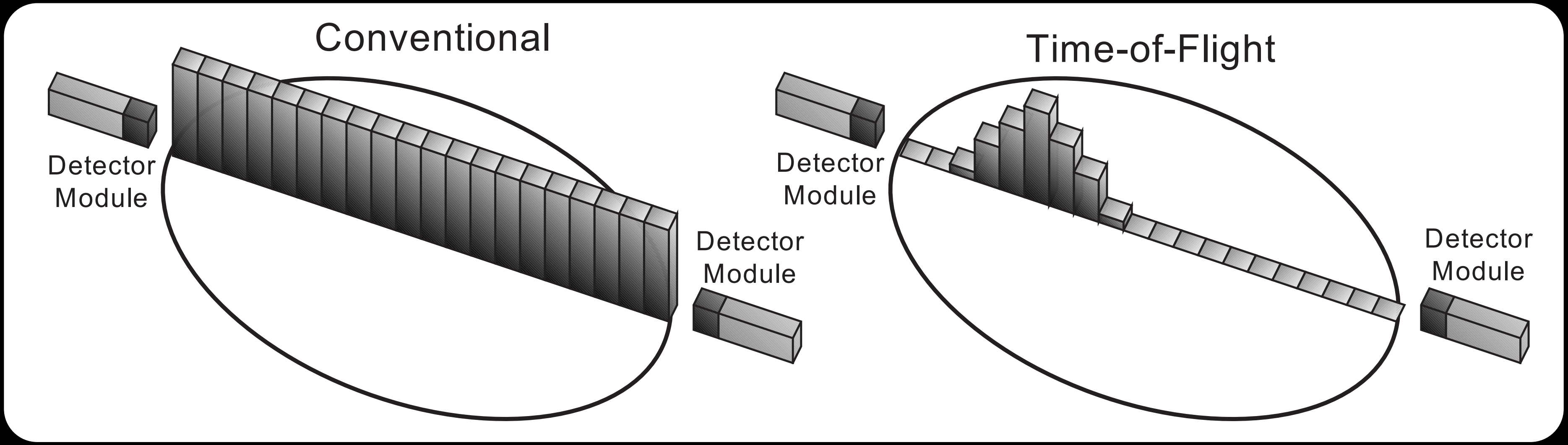
Good timing resolution helps to keep the coincidence window as small as possible to reduce Random coincidences.

Time of Flight PET

- Accuracy of position measurement is: (for Δt = 500ps)

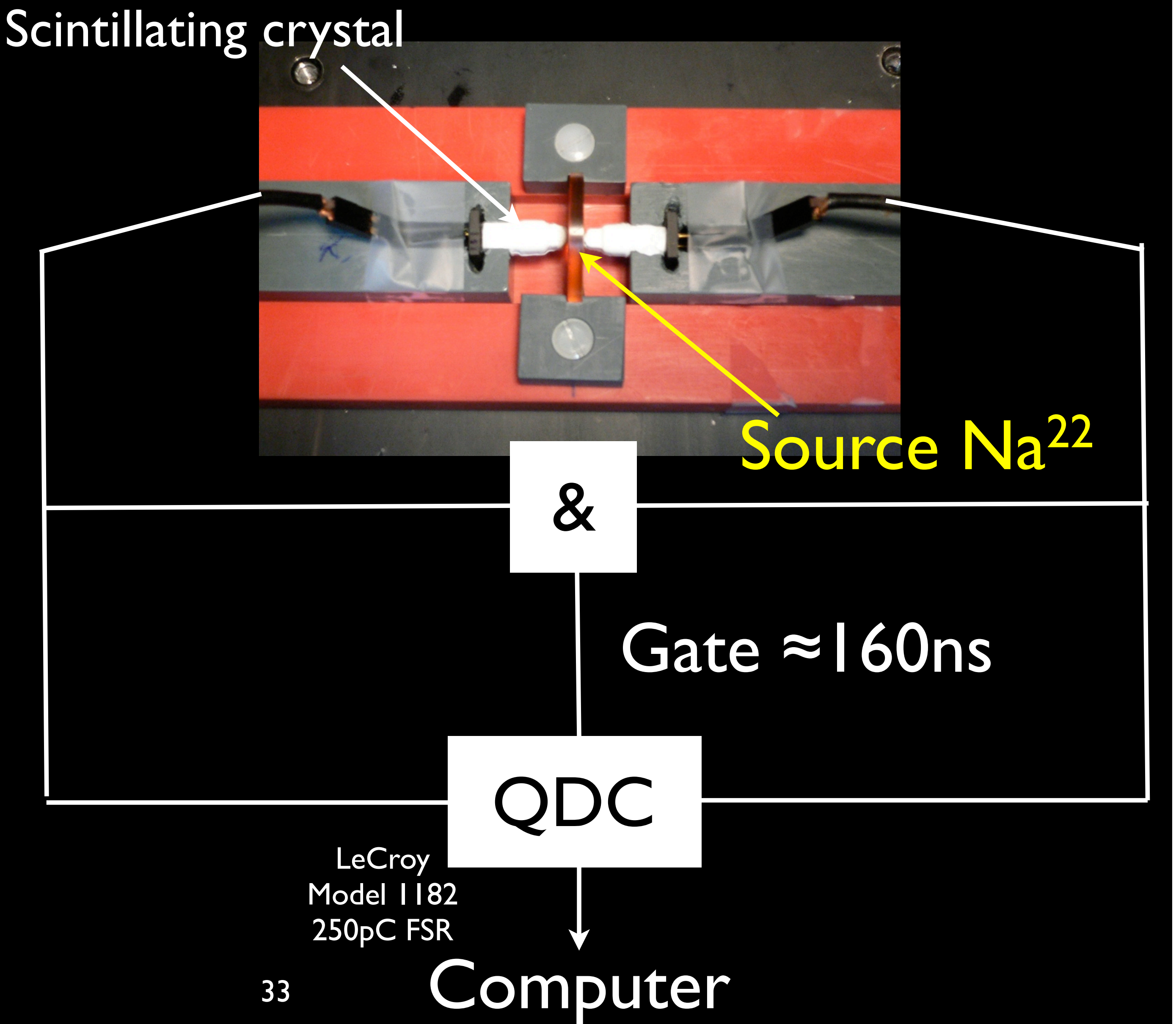
$$\Delta x = \frac{c}{2}\Delta t = 7.5cm$$

- ➥ No gain in spatial resolution (typical value 4-6mm), but the signal to noise ratio improves. (Improving the sensitivity of the detector)



Advantages of Improved timing accuracy in PET Cameras using LSO Scintillator, W.W. Moses LBNL-51788

Setup



Scintillating crystal

Source Na^{22}

&

Gate ≈160ns

QDC

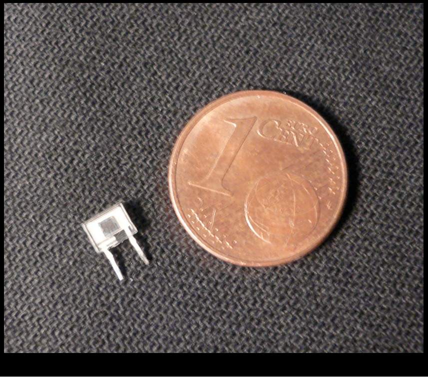
LeCroy
Model 1182
250pC FSR

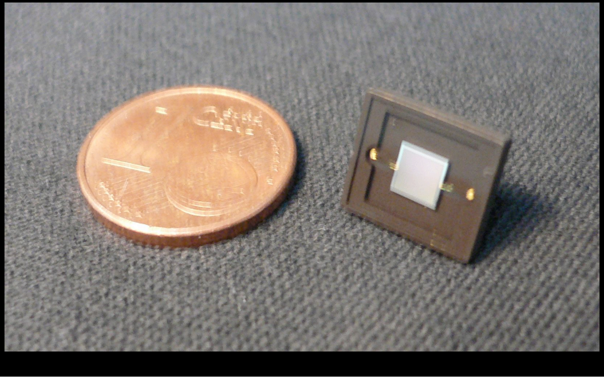
Computer

Used Scintillators

Crystal	Size	Peak emission	Decay time
LSO (Lutetium Orthosilicate), Hilger Crystals	1×1×15mm^3 3×3×15mm^3	420nm	40ns
LFS (Lutetium Fine Silicate), Lebedev Institute	3×3×15mm^3	blue	similar to LSO

Readout with MPPC‘s from Hamamatsu





Pixels	Active area	Operating voltage	Dark rate 0.5 pixels	Dark rate 1.5 pixels	Gain 10^5
400	1×1mm^2	76V	220k - 250kHz	9k - 10kHz	7.4 - 7.5
3600	3×3mm^2	70V	3.2 - 3.3 MHz	320k - 330kHz	7.4 - 7.5

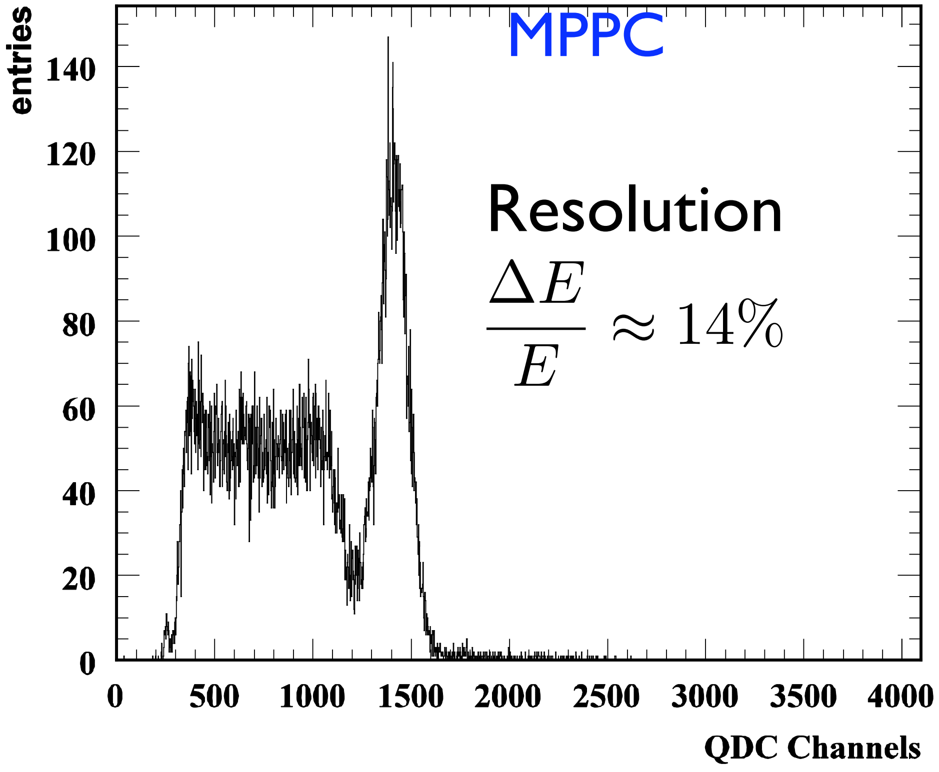
1×1×15mm^3 LSO with 1×1mm^2 MPPC

$$\left(\frac{\Delta(E)}{E}\right)^2 \approx \left(\frac{2.35}{\sqrt{N}}\right)^2 + \left(\frac{\Delta_{intr}(E)}{E}\right)^2 + \left(\frac{\Delta_{noise}}{E}\right)^2$$

blue sensitive MPPC

~8% for LSO

negligible

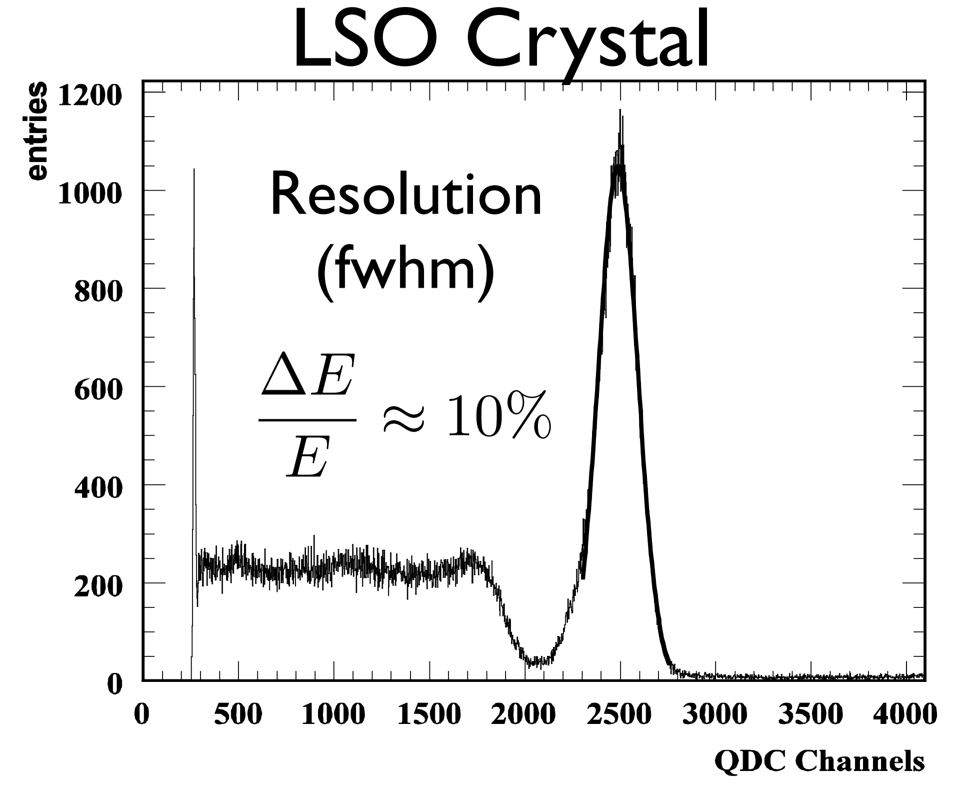


Energy resolution of 14% (fwhm) was measured

Coupling between crystal and MPPC is main systematic error for the small crystals ≈10%

Improvement possible!

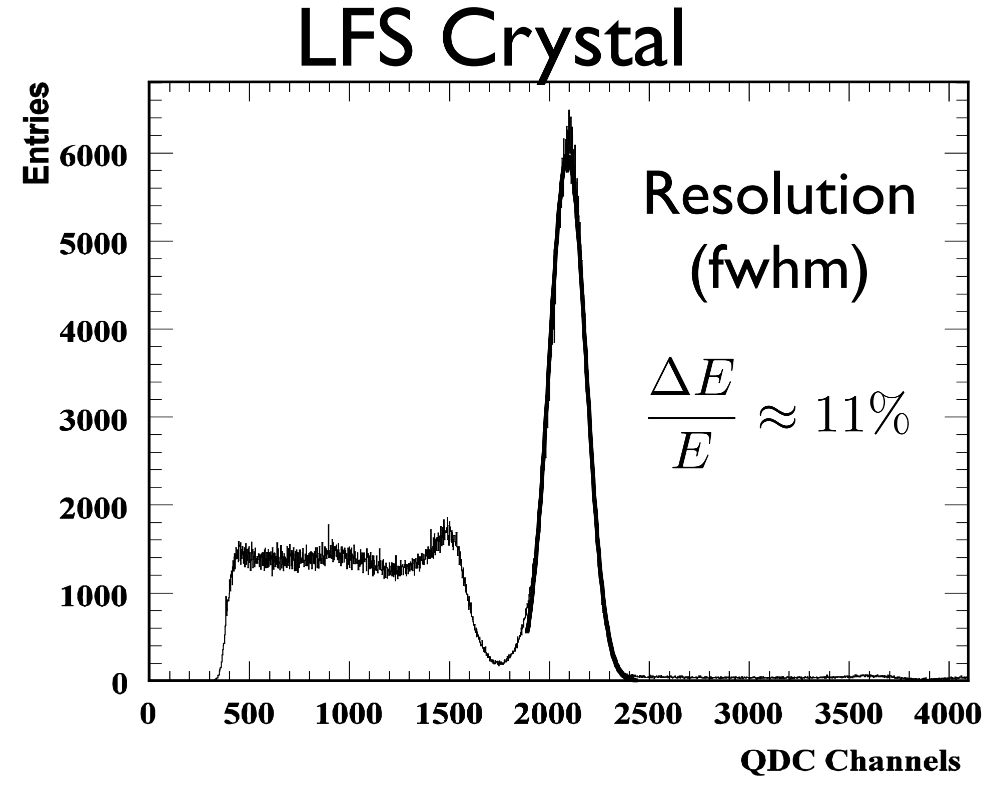
$3 \times 3 \times 15\,\text{mm}^3$ LSO & LFS with $3 \times 3\,\text{mm}^2$ MPPC‘s



LSO Crystal

Resolution (fwhm)

$$\frac{\Delta E}{E} \approx 10\%$$



LFS Crystal

Resolution (fwhm)

$$\frac{\Delta E}{E} \approx 11\%$$

LSO and LFS are equal within systematics ~3%

Typical value with “traditional“ Photomultiplier tube (511key) : 10%

Timing Measurement

Setup

No Preamplifiers needed!
Direct evaluation with
oscilloscope

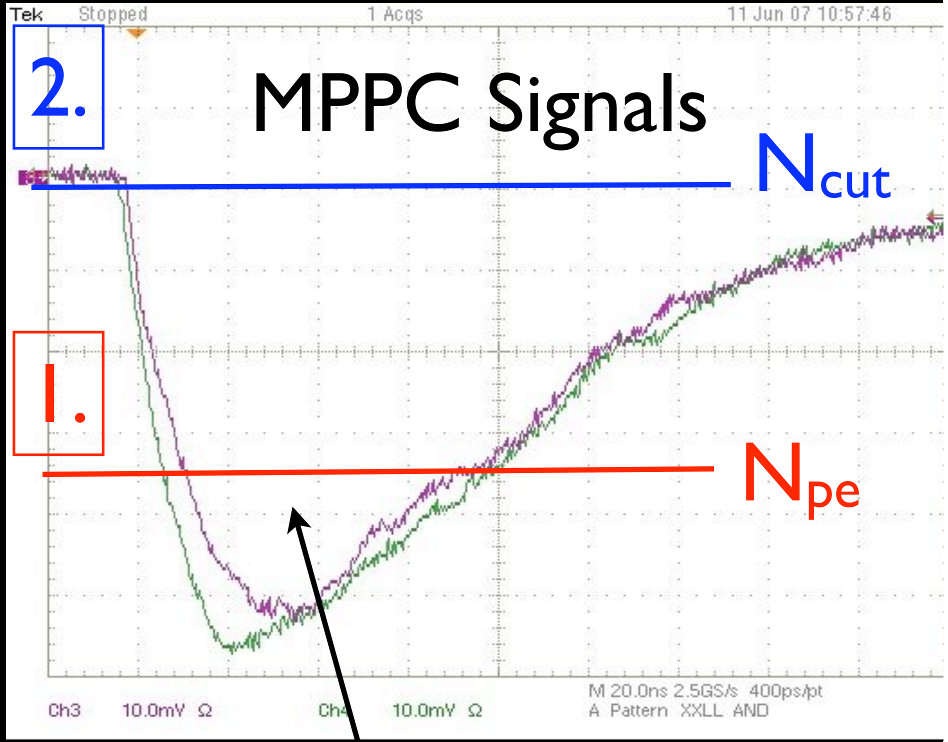
Oscilloscope:
Tektronix Model
7204, Bandwidth
4GHz, 20GS/s
⇒Time

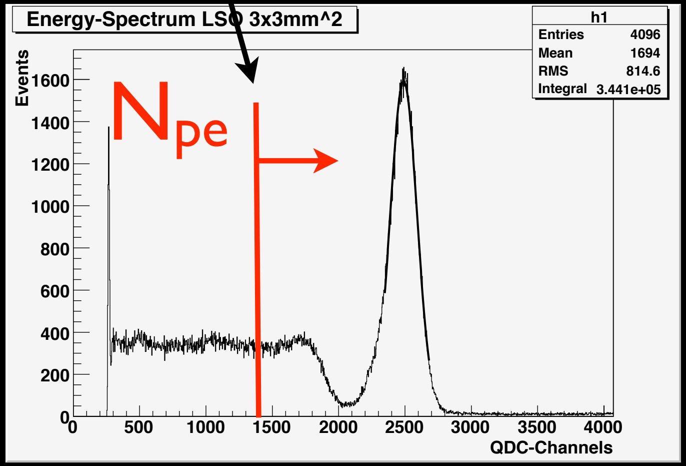
resolution 50ps

Timing Measurement

1. Define coincidence threshold N_{pe}
2. Define timing threshold N_{cut}

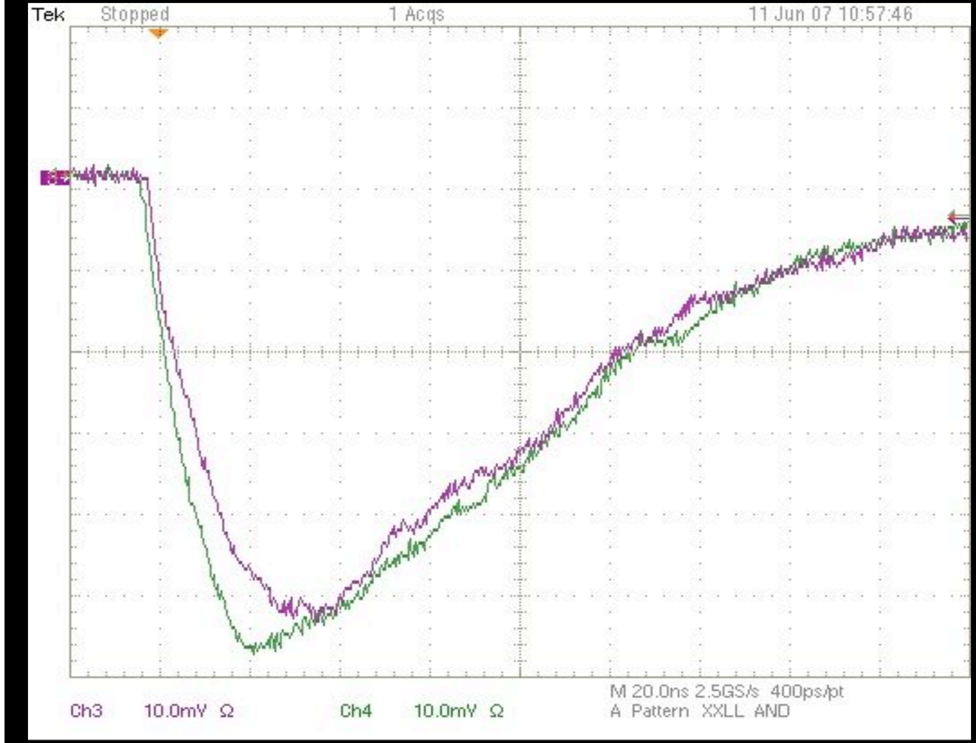
$$S_1 > N_{pe} \wedge S_2 > N_{pe}$$
$$\Delta t = t_1(N_{cut}) - t_2(N_{cut})$$



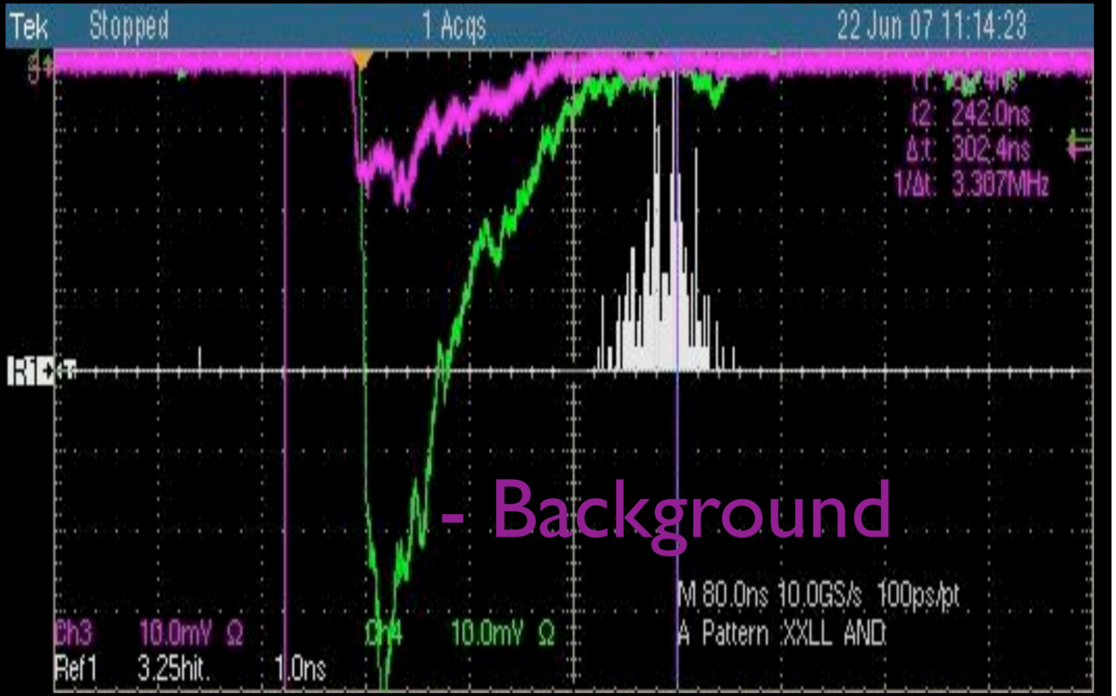


Timing Measurement

“Photoelectric event“

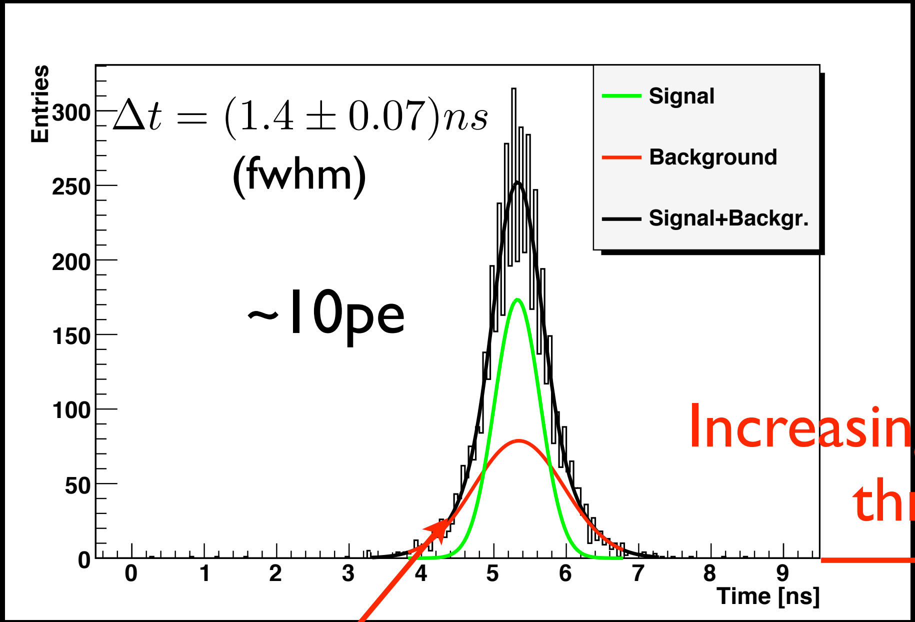


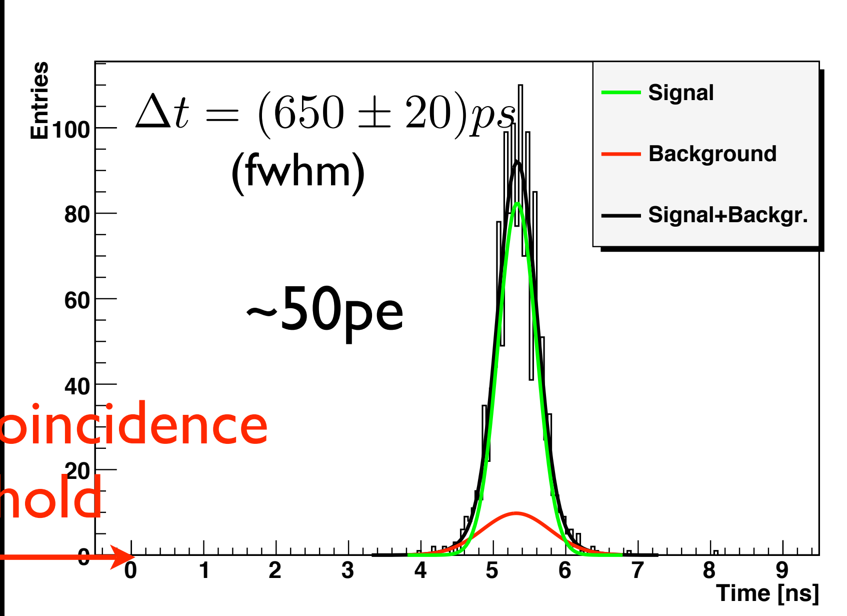
“Background event“



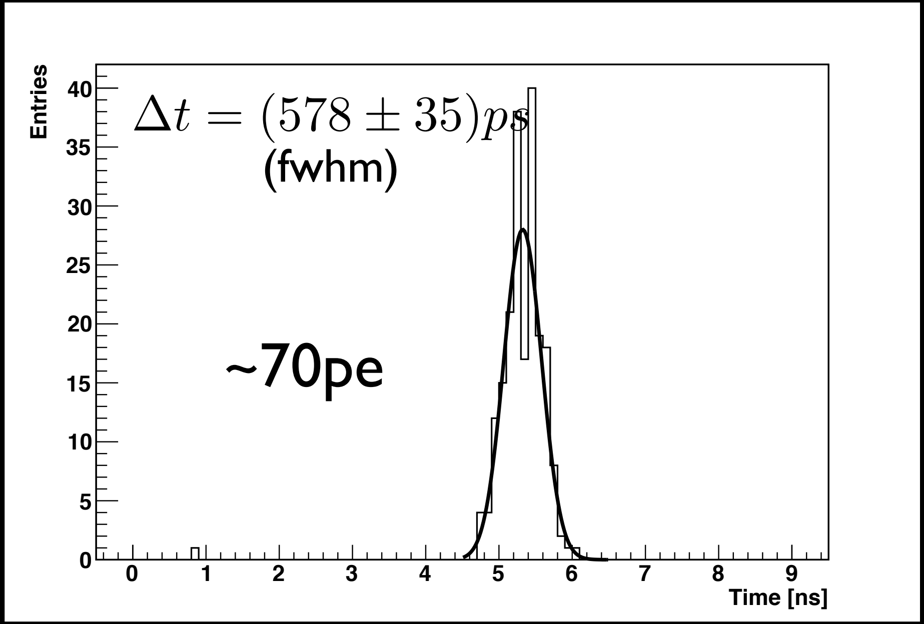
A Background is superimposed and degrades the timing
➥Need to go to high coincidence threshold

Results Timing





Increasing coincidence threshold



Background worsens timing from 700ps to 1.4ns

A timing resolution of 500ps improves the signal to noise ratio by a factor of 2

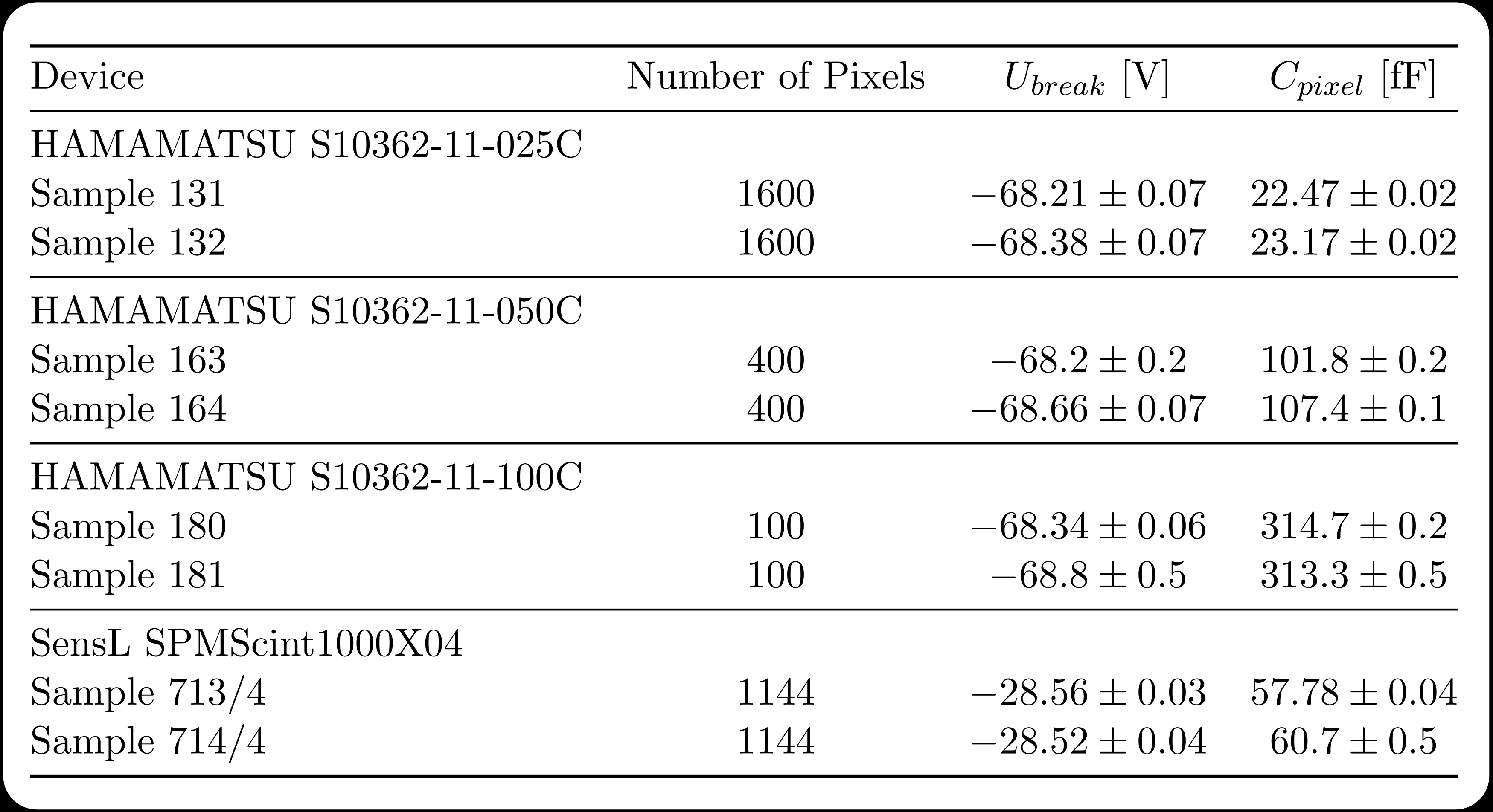
Conclusion

- New kind of photon detector is available
- Application in high energy and medical physics possible
- Characterisation setup was assembled
- Build PET-prototype to verify the concept

Thank you for your attention!

Backup

C_{pixel} and U_{break}



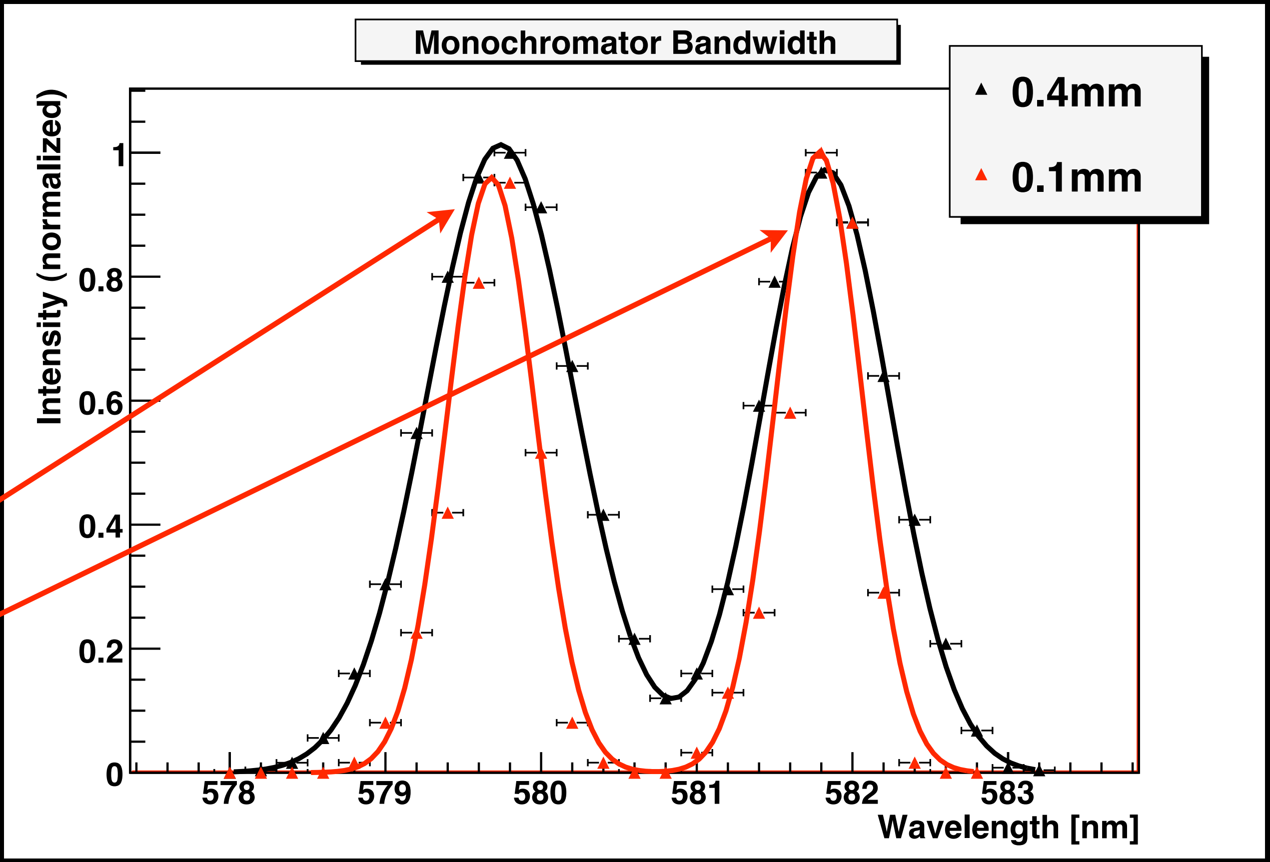
Device	Number of Pixels	U_{break} [V]	C_{pixel} [fF]
HAMAMATSU S10362-11-025C			
Sample 131	1600	-68.21 ± 0.07	22.47 ± 0.02
Sample 132	1600	-68.38 ± 0.07	23.17 ± 0.02
HAMAMATSU S10362-11-050C			
Sample 163	400	-68.2 ± 0.2	101.8 ± 0.2
Sample 164	400	-68.66 ± 0.07	107.4 ± 0.1
HAMAMATSU S10362-11-100C			
Sample 180	100	-68.34 ± 0.06	314.7 ± 0.2
Sample 181	100	-68.8 ± 0.5	313.3 ± 0.5
SensL SPMScint1000X04			
Sample 713/4	1144	-28.56 ± 0.03	57.78 ± 0.04
Sample 714/4	1144	-28.52 ± 0.04	60.7 ± 0.5

Bandwidth and Absolute Scale of the Monochromator

- Mounted grating (1200 lines/mm)
- Suitable for wavelengths λ≥450nm
- The light, present at the exit of the monochromator contains not a single wavelength, but an „area“ around the chosen value which is called bandwidth.
- Illuminate monochromator with light of well known wavelength and measure intensity profile I(λ)

Spectral Calibration Lamp

6035 Hg(Ar)
184.9
187.1
194.2
253.65
265.4
284.8
302.2
312.571
313.151
313.181
320.8
326.4
345.2
365.02
404.66
435.84
546.07
576.96
579.07
615.0
1014.0
1357.0
1692.0
1707.3
1711.0



→ Peaks are shifted by 2.7 nm

→ Bandwidth can be tuned to 1nm

HeNe-Laser

- Wavelength (632,8nm)
- Intensity is not constant over long time-period (few min.)
- Intensity was observed on a screen.
- Maximum appears at ~635,5nm

  ➔Absolute Calibration (Scale is globally shifted by 2.7nm)

PDE Measurement (Preliminary)

- Measure Photocurrent with PIN-diode.
- Measure Photocurrent with SiPM.

$$PDE = \frac{n_e}{n_p} \qquad n_e = \frac{I_{SiPM}}{M \cdot e} \qquad n_p = \frac{P \cdot \lambda}{h \cdot c} \qquad P = \frac{I_{PIN}}{R}$$

Calibration data sheet

$$PDE = \frac{I_{MPPC} \cdot R \cdot h \cdot c}{M \cdot e \cdot I_{PIN} \cdot \lambda}$$

Still contains Crosstalk and Afterpulses!