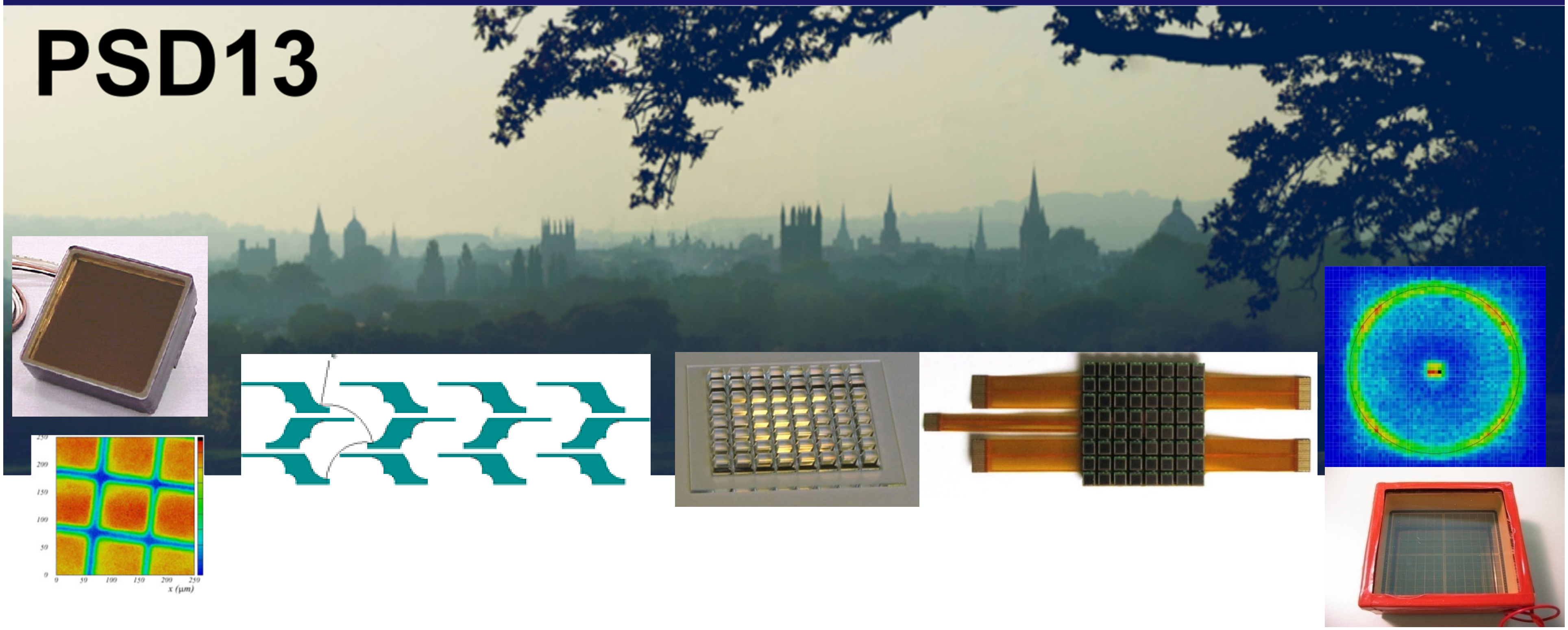
The 13th International Conference on Position Sensitive Detectors PSD13
St. Catherine's College, Oxford, September 3-8, 2023



Novel photon detectors

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Introduction: why?

Photon detectors are at the heart of most experiments in particle physics. Moreover, they are also finding application in other scientific fields (chemistry and biology) and are ubiquitous in society in general.

New environments where we need to detect light (in particular low light levels) → need advances in existing technology and transformative, novel ideas to meet the demanding requirements.

Two main lines of R&D to be pursued have been identified by the ECFA Detector R&D Roadmap:

- Enhance timing resolution and spectral range of photon detectors.
- Develop photosensors for extreme environments.

This talk: photosensors will be discussed in this spirit; also: the main emphasis will be on low light level detection.

Contents

Introduction: why and what kind of photosensor?

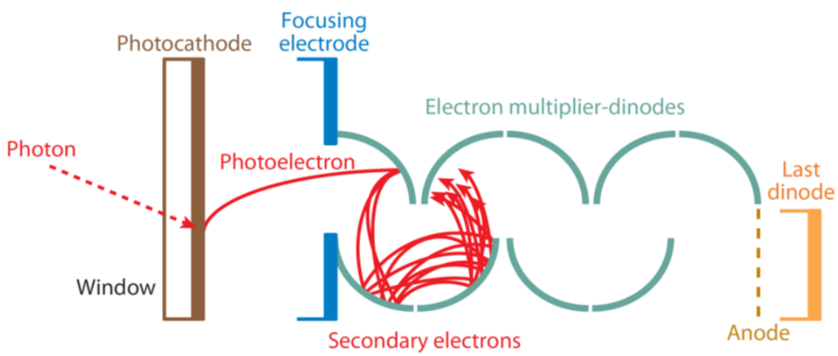
Vacuum-based photodetectors

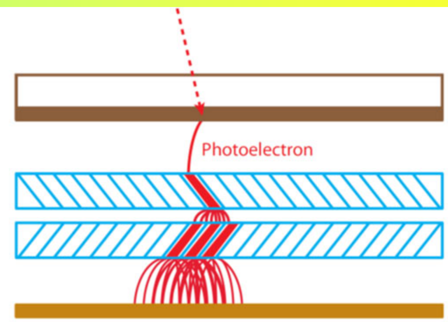
Solid state low light level photosensors

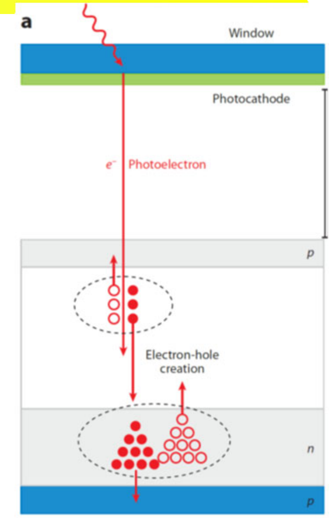
Gas-based photodetectors

Summary and outlook

Vacuum-based photodetectors

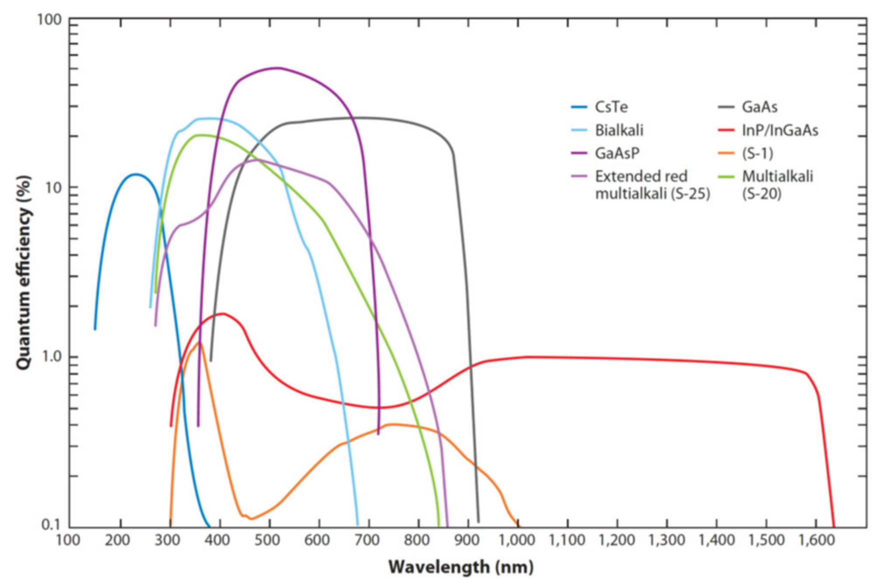




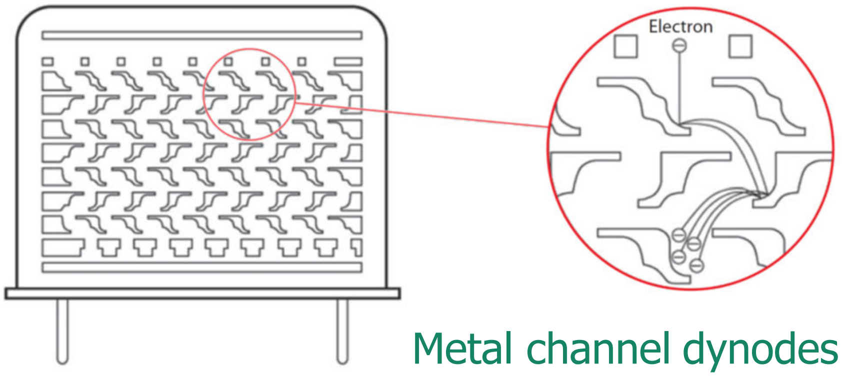


Generic steps:

- Photon → photoelectron conversion
- Photoelectron collection in the multiplication system
- Mutiplication (dynodes, microchannel plates, high E field + Si)
- Signal collection

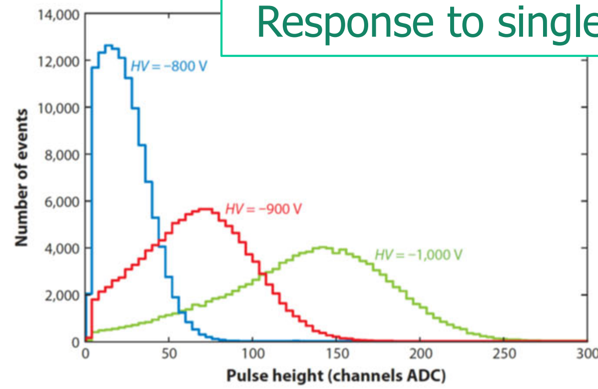


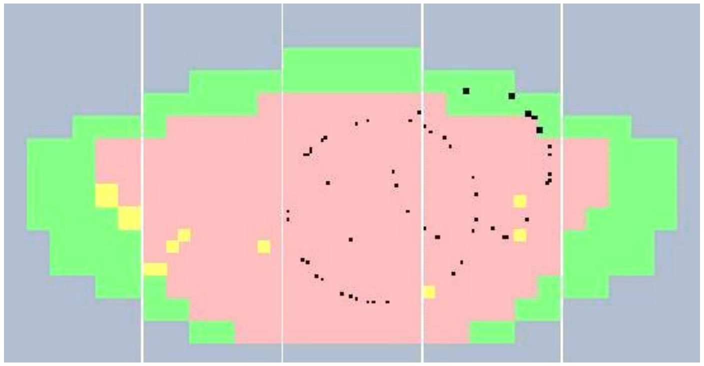
Multianode photomultiplier tubes (PMTs)



Metal channel dynodes

Response to single photons



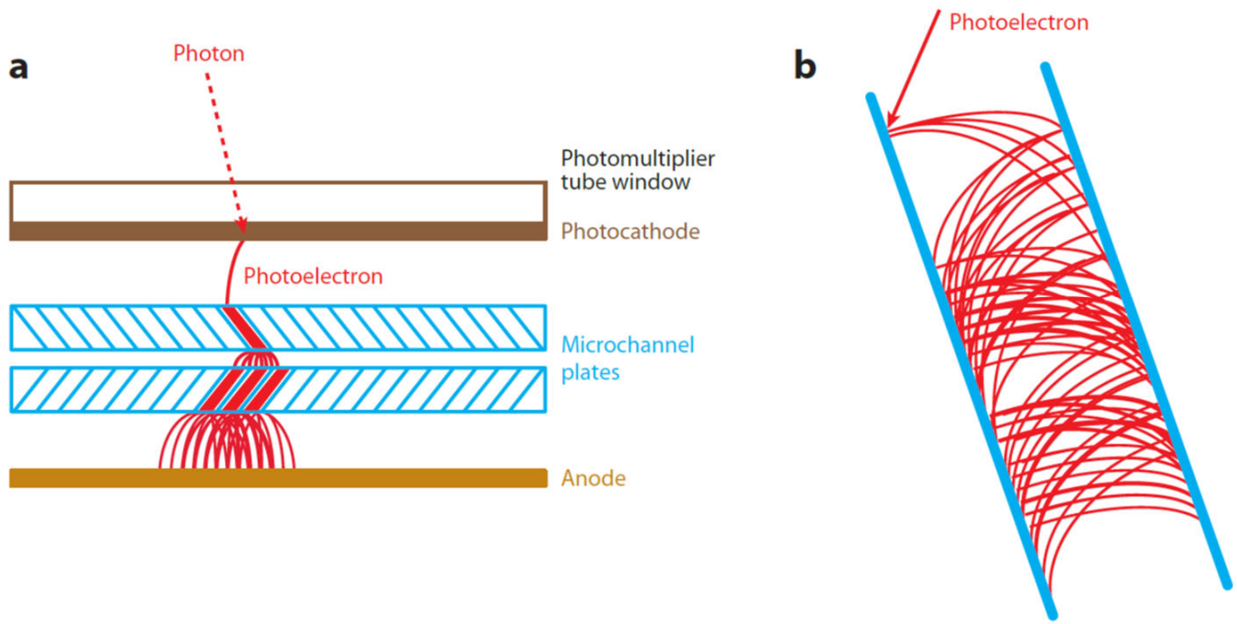


Pioneered in the HERA-B RICH, later used in the COMPASS, CLASS12 and GlueX RICH detectors

Recent use in the upgraded LHCb RICH detectors; planned for CBM RICH

Excellent performace (excellent single photon detection efficiency, very low noise, low cross-talk), best choice for large areas with no B field

Micro Channel Plate PMT (MCP-PMT)



Multiplication step: a continuous dynode – a micro-channel

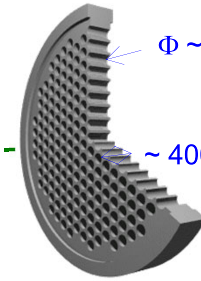
Micro Channel Plate PMT (MCP-PMT)

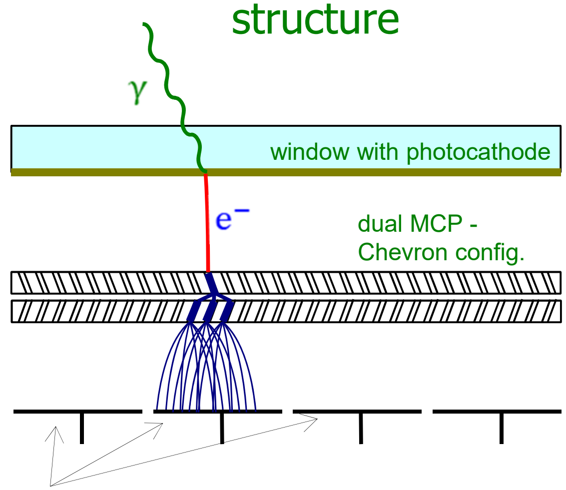
Similar to ordinary PMT – the dynode structure is replaced by MCPs.

Basic characteristics:

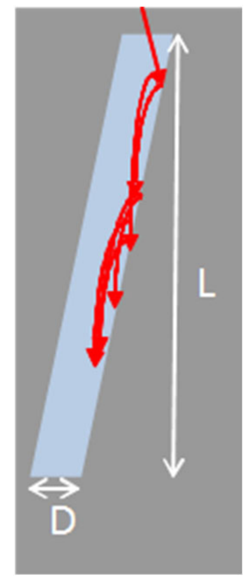
- Gain ~ 10^6 → single photon
- Collection efficiency ~ 60%
- Small thickness, high field → small TTS
- Works in magnetic field
- Segmented anode
  → position sensitive

MCP is a thin glass plate with an array of holes (<10-100 μm diameter) - - a continuous dynode structure

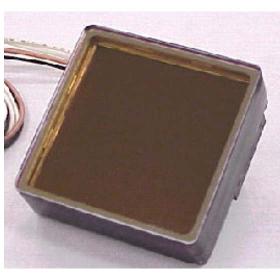




Anodes → can be segmented according to application needs

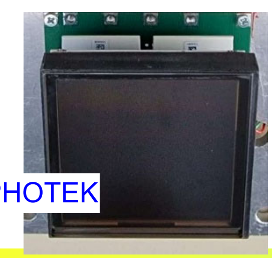


MCP gain depends on L/D ratio – typically 1000 for L/D=40

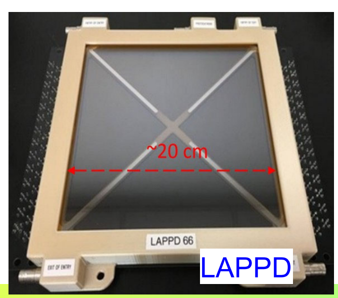


PHOTONIS

HAMAMATSU



PHOTEK



LAPPD

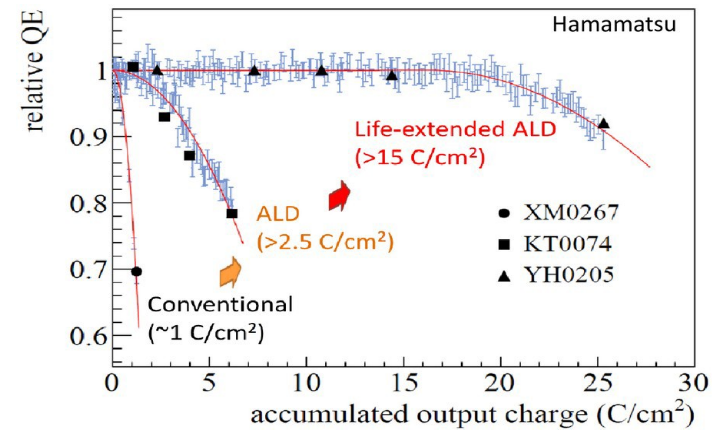
MCP PMT ageing

MCP PMTs: photo-cathode degradation due to ion feedback, main concern in high intensity experiments

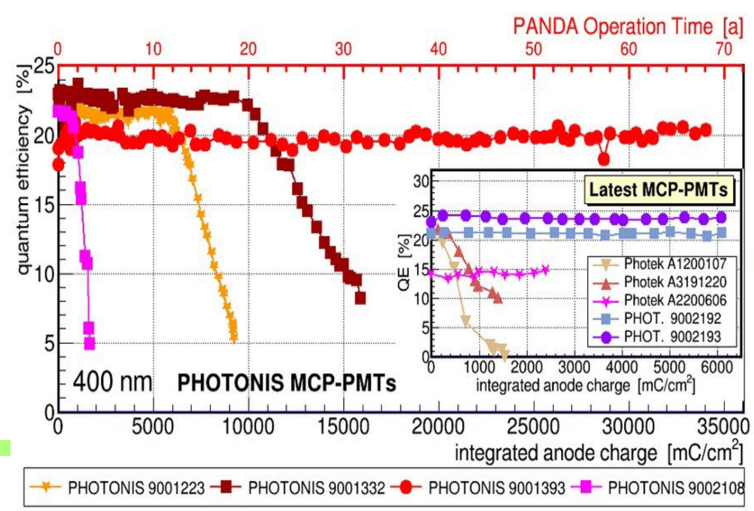
ALD (atomic layer deposition) coating of MCP pores → ~100x photo-cathode lifetime increase

- Hamamatsu 1-inch YH0205 (>20 C/cm²) [K. Inami, 2021]
- No QE degradation for Photonis MCP-PMT (R2D2) to >34 C/cm²
- Little QE degradation in LAPPD 8-inch up to 5.6 C/cm² [V. A. Chirayath, CPAD2021]

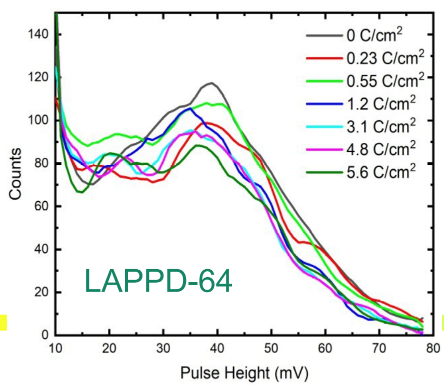
K. Inami, 2021, Talk at ECFA TF4 Symposium



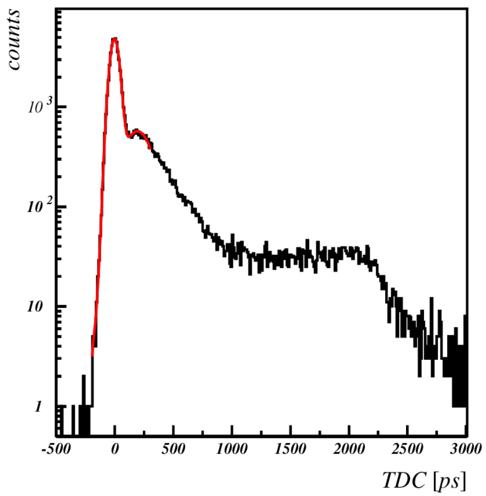
A. Lehmann, RICH2022



V.A. Chirayath et al., Talk at CPAD 2021



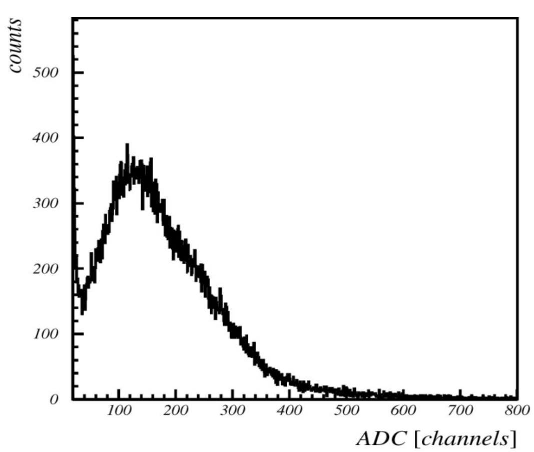
MCP-PMT: single photon pulse height and timing



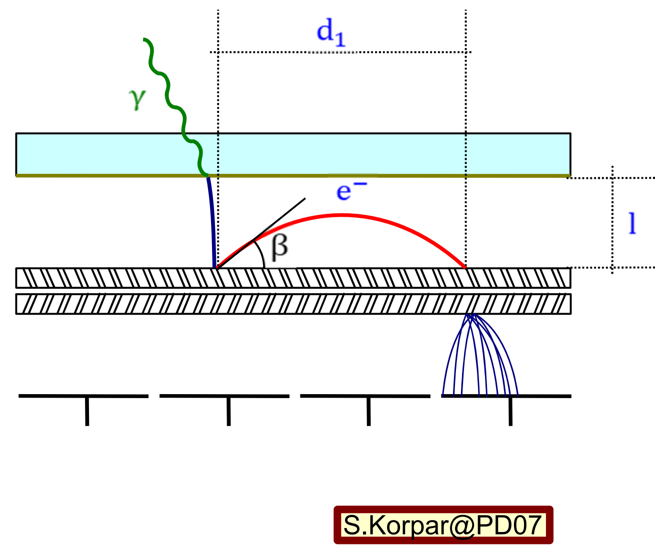
Typical single photon timing distribution with a narrow main peak (σ ~ 40 ps) and contributions from photoelectron elastic (flat distribution) and inelastic back-scattering.

Photoelectron back-scattering produces a rather long tail in timing distribution and position resolution.

Photoelectron backscattering reduces collection efficiency and gain, and contributes to cross-talk in multi-anode PMTs



Gain in a single channel saturates at high gains due to space charge effect → peaking distribution for single photoelectrons



Photoelectron in uniform electric field

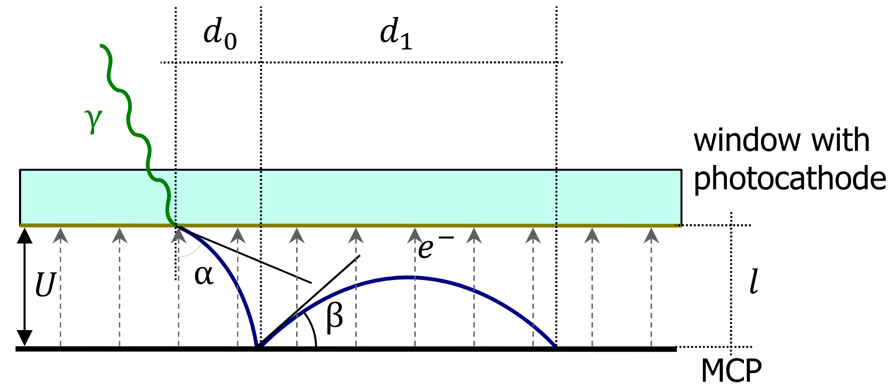
Photoelectrons travel from photocathode to the electron multiplier (uniform electric field $\frac{U}{l}$, initial energy $E_0 \ll Ue_0$):

- photoelectron range
$$d_0 \approx 2l\sqrt{\frac{E_0}{Ue_0}}sin(\alpha)$$
- and maximal travel time (sideway start)
$$t_0 \approx l\sqrt{\frac{2m_e}{Ue_0}}$$
- time difference between downward and sideways initial direction
$$\Delta t \approx t_0\sqrt{\frac{E_0}{Ue_0}}$$

Example ($U = 200\,V$, $\mathrm{E}_0 = 1eV$, $l = 6mm$)

photoelectron:
- max range $d_0 \approx 0.8\,mm$
- p.e. transit time $t_0 \approx 1.4\,ns$
- $\Delta\mathrm{t} \approx 100$ ps

backscattering:
- max range $d_1 = 2l = 12$ mm
- max delay $t_1 = 2.8\,ns$



Backscattering delay and range (maximum for elastic scattering):

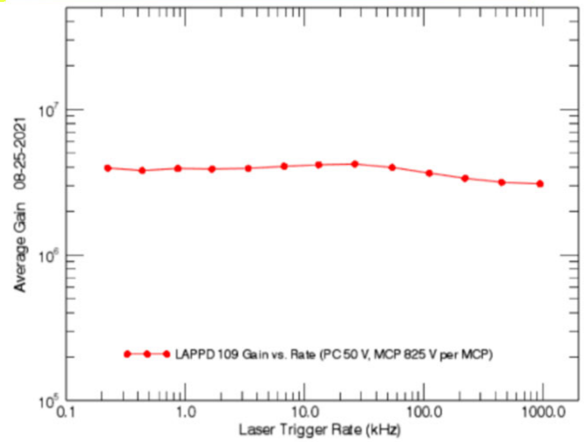
- maximum range vs. angle
$$d_1 = 2lsin(2\beta)$$
maximum range for backscattered photoelectron is twice the photocathode – first electrode distance
- maximum delay vs. angle
$$t_1 = 2t_0sin(\beta)$$
maximum delay is twice the photoelectron travel time
- time of arrival of elestically scattered photoelectrons: flat distribution up to max $t_1 = 2t_0$

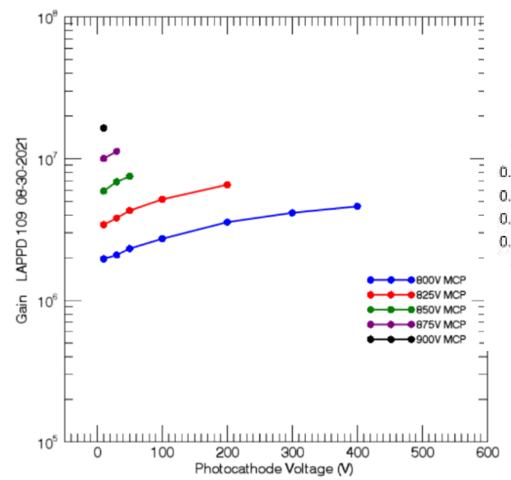
S.Korpar@PD07

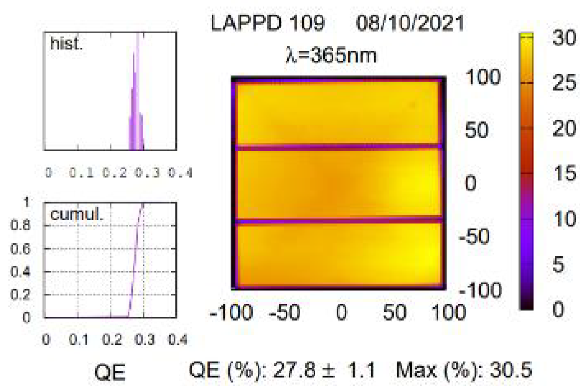
LAPPD (large area picosecond photodetector) Gen II

Characteristics (Incom):

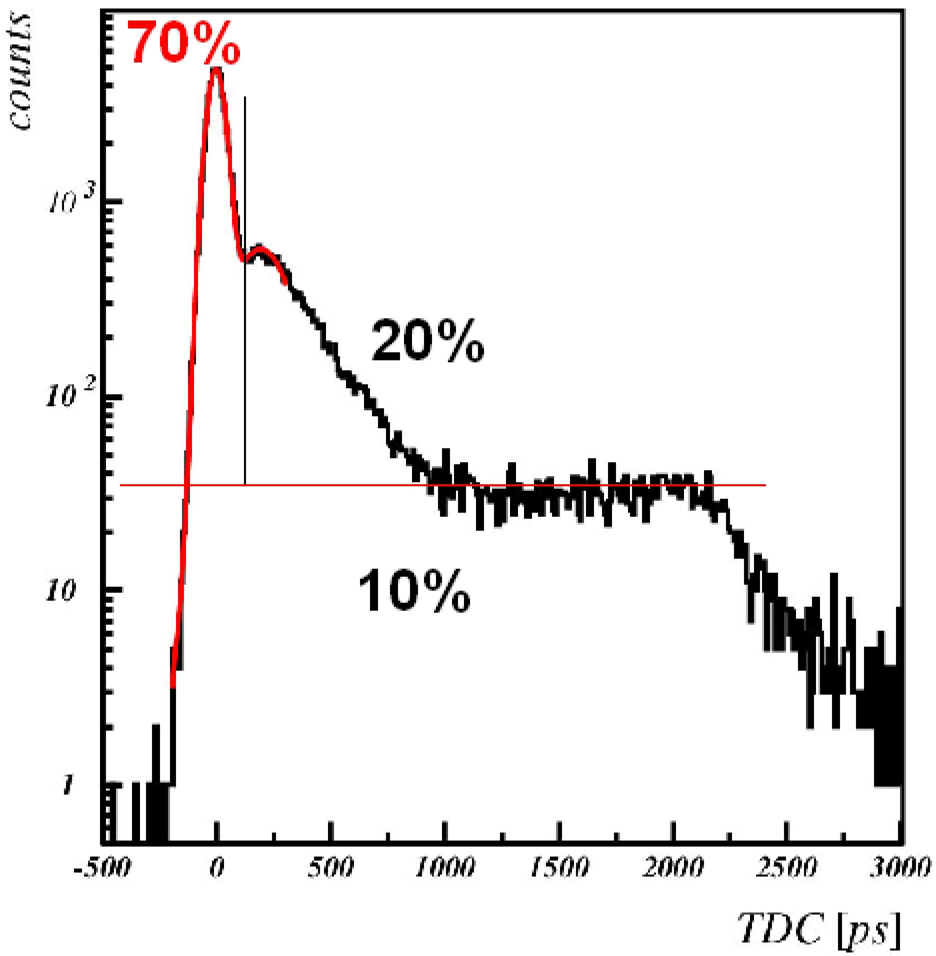
- borosilicate back plate with interior resistive ground plane anode – 5 mm thick
- capacitively coupled readout electrode
- MCPs with 20 μm pores at 20 μm pitch
- two parallel spacers (active fraction ≈ 97 %)
- gain $\approx 5 \cdot 10^6$ @ ROP (825 V/MCP, 100 V on photocathode)
- peak QE $\approx 25\%$
- size 230 mm x 220 mm x 22 mm (243 mm X 274 mm X 25.2 mm with mounting case)
- Dark Count rate @ ROP: ~ 70 kHz/cm2 with 8×10^5 gain







MCP PMT timing



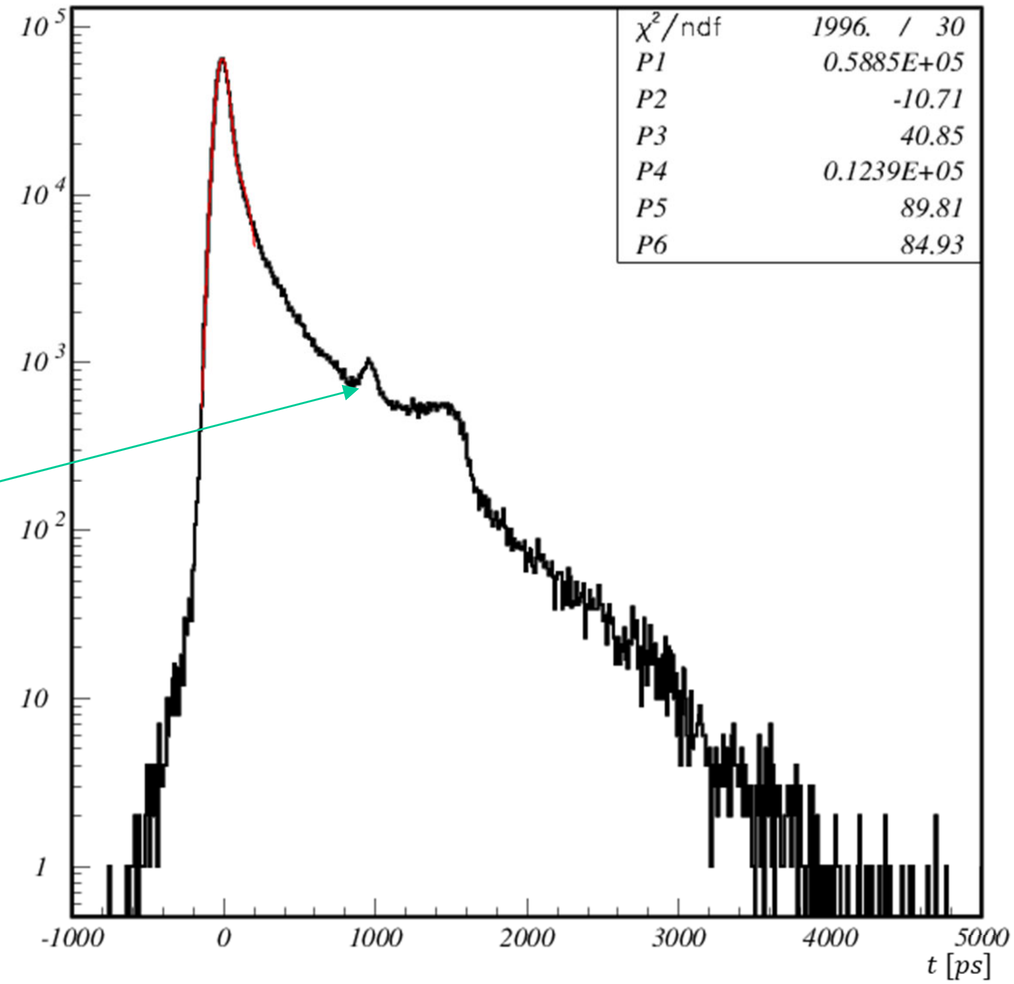
Tails understood (eleastic and inelastic scattering of photoelectrons off the MCP), can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

LAPPD – timing distribution

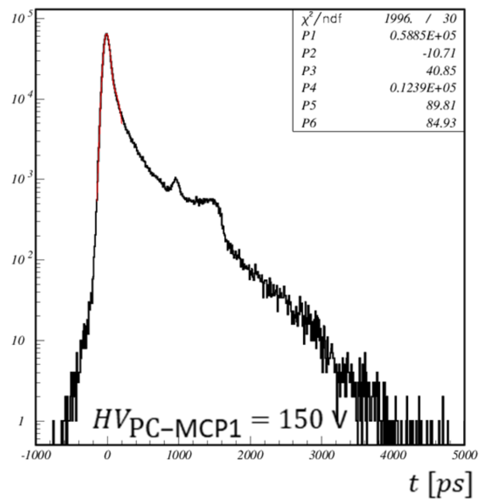
- measured timing distribution typical for MCP-PMT
- main prompt peak with some inelastic and elastic backscattering contribution
- additional small peak at about 1 ns delay probably due to some reflection (light?), delay not affected by PC-MCP1 voltage
- The plot is for the PC-MCP1 voltage of 150 V and recommended HV for others

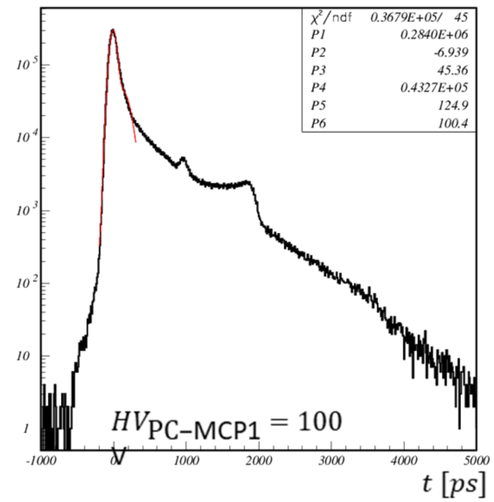


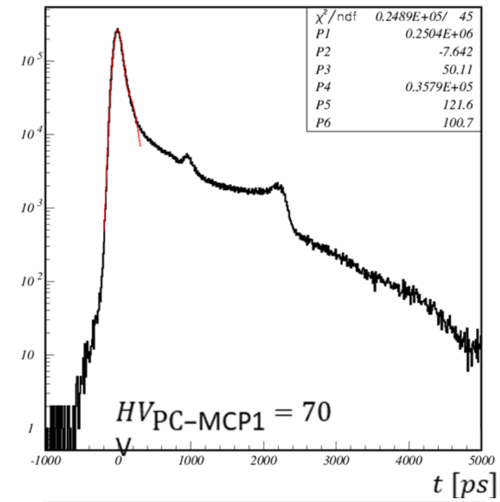
S. Korpar et al., to be submitted to NIMA

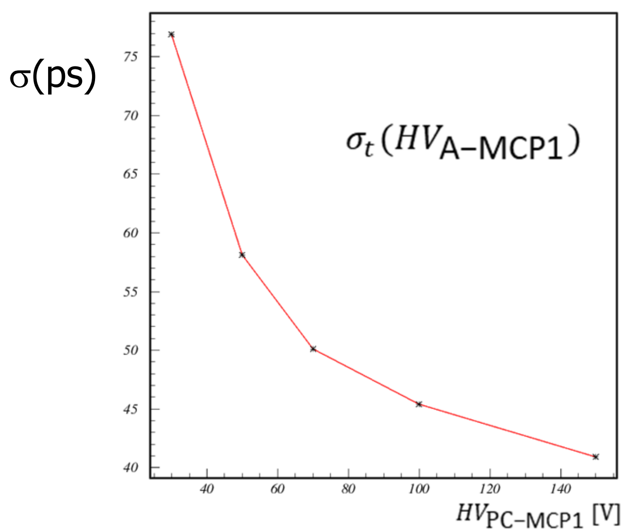
LAPPD – timing vs PC-MCP1 voltage

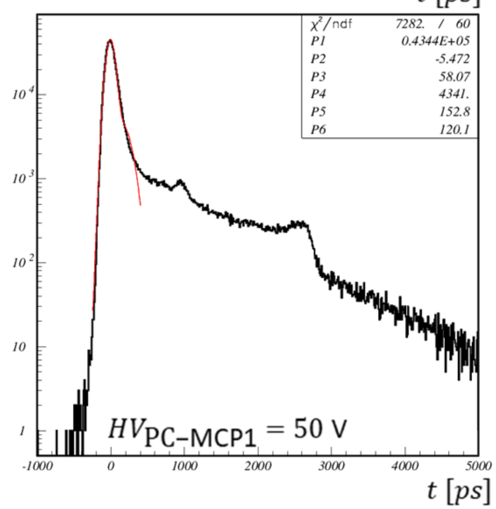
Time-walk corrected TDCs for different PC-MCP1 voltages

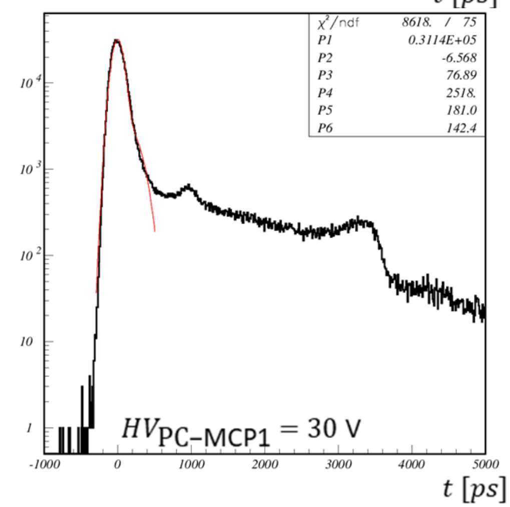










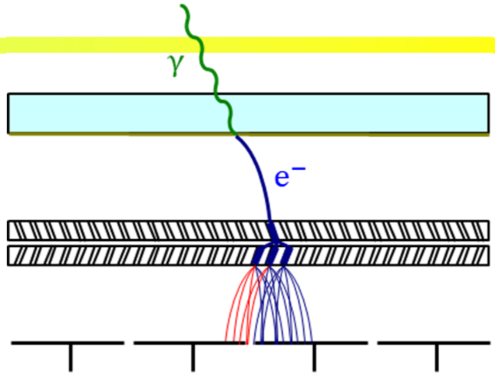


Time resolution vs PC-MCP1 voltage

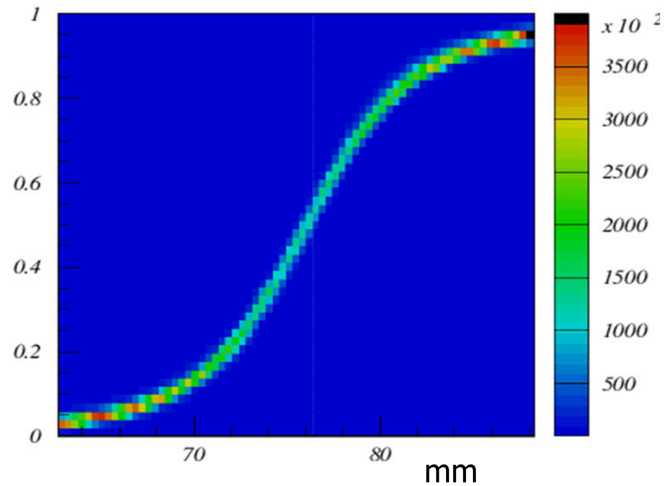
MCP PMT readout: capacitive coupling vs. internal anodes

Secondary electrons spread out when traveling from the MCP-out electrode to the anode and can hit more than one anode → Charge sharing

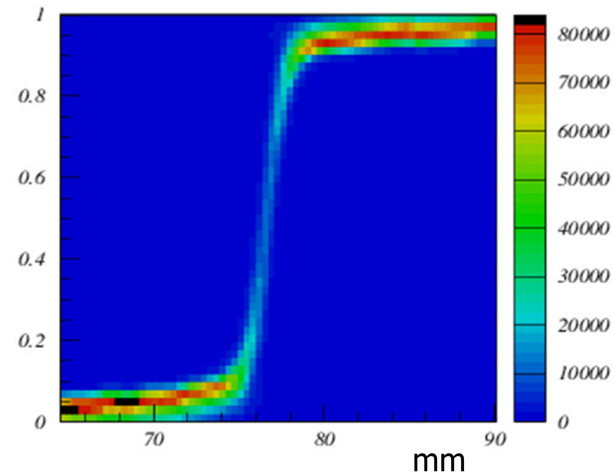
Can be used to improve spatial resolution.



LAPPD (capacitive coupling through the backplane)



BURLE/Photonis PLANACON (internal anodes)



Fraction of the charge detected by the right pad as a function of red laser spot position

Capacitive coupling vs. internal anodes: signal spread comparison for two MCP PMTs with the same pad size, same range: charge sharing is more effective for capacitive coupling (spreads over larger area) - advantage or not: depends on the usage

Possible Future of Electron Multiplication

Tynodes (→ Time Photon Counter)

Transmission mode dynode → tynode

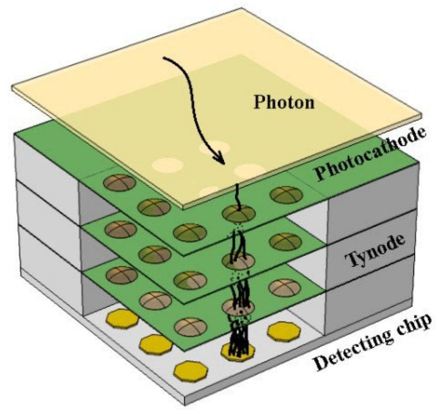
Fabrication of tynodes (MgO ALD, diamond) using MEMS technology

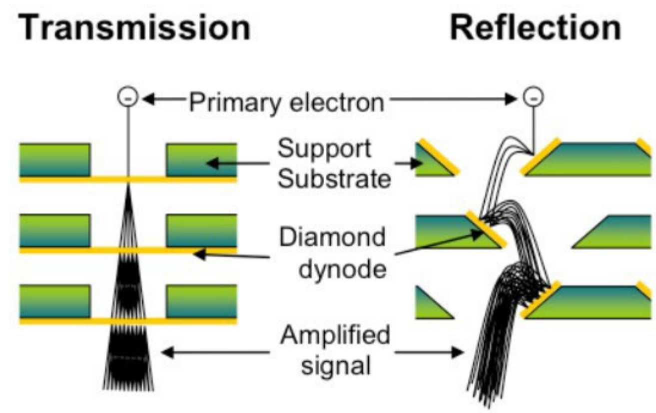
"Anode" is a CMOS chip (e.g., TimePix)

Very promising properties

- Very compact; high B-field tolerance; very fast
- Very low DCR; very good 2D spatial resolution

H. van der Graaf et al., NIM A847 (2017) 148





MCP-PMT with CMOS anode

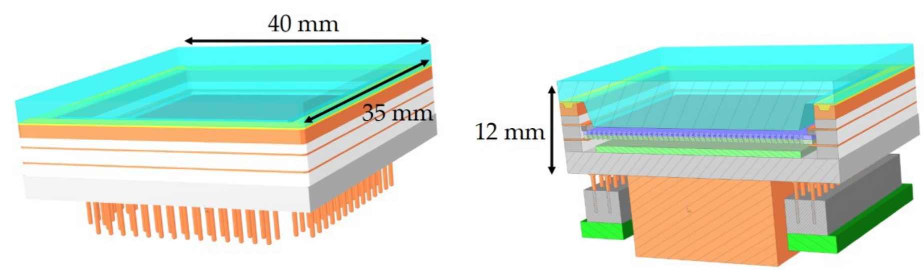
Conceptual design for 4D detection of single photons

- Hybrid concept: MCP-PMT where the pixelated anode is an ASIC (CMOS) embedded inside the vacuum
- Prototype with Timepix4 ASIC as anode (array of 23k pixels)

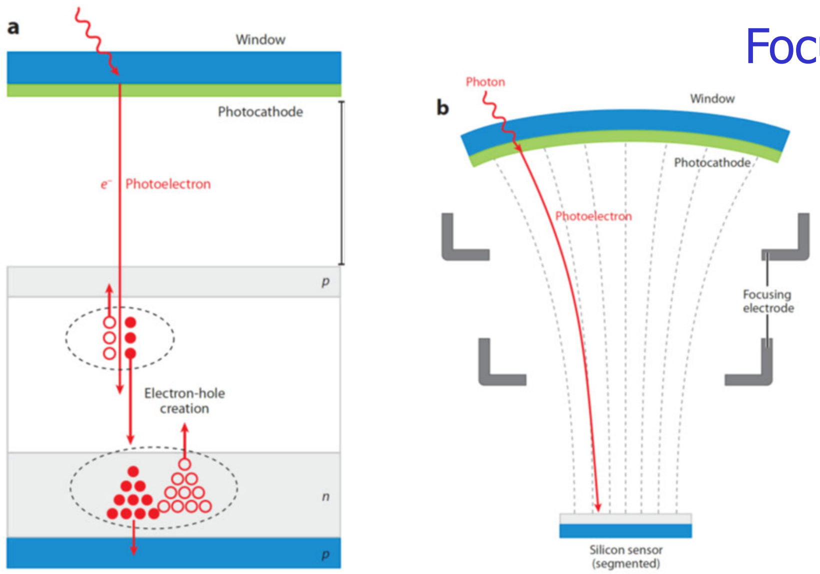
Envisaged performance

- <100 ps time resolution and 5-10 μm spatial resolution
- Rate capability of >100 MHz/cm² (<2.5 Ghits/s @ 7 cm² area)
- Low gain (~10^4) operation possible → x100 lifetime increase

M. Fiorini, RICH2022



Hybrid photodetectors (HPD, HAPD)



Focusing and proximity focusing configurations

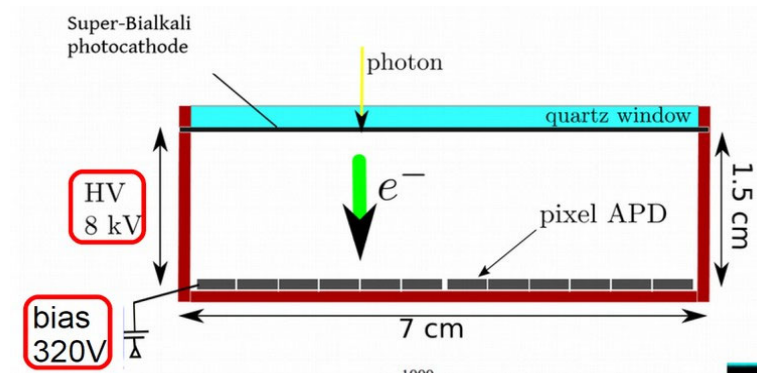


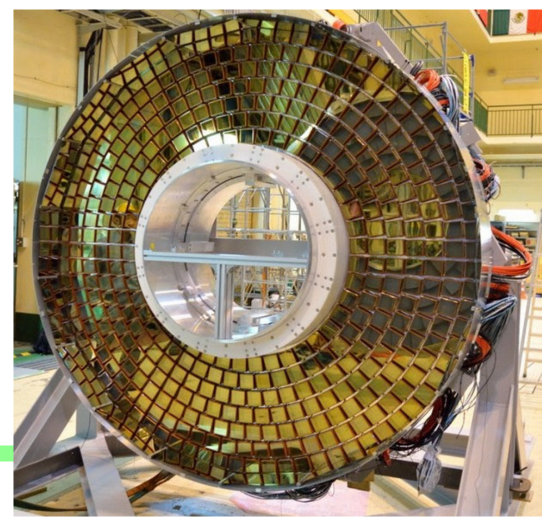
Photo-electron acceleration in a static electric field (8kV to 25 kV)

Photo-electron detection with

- Segmented PIN diode (HPD)
- Avalanche photo diode (HAPD)
- Silicon photomultiplier (VSiPMT)

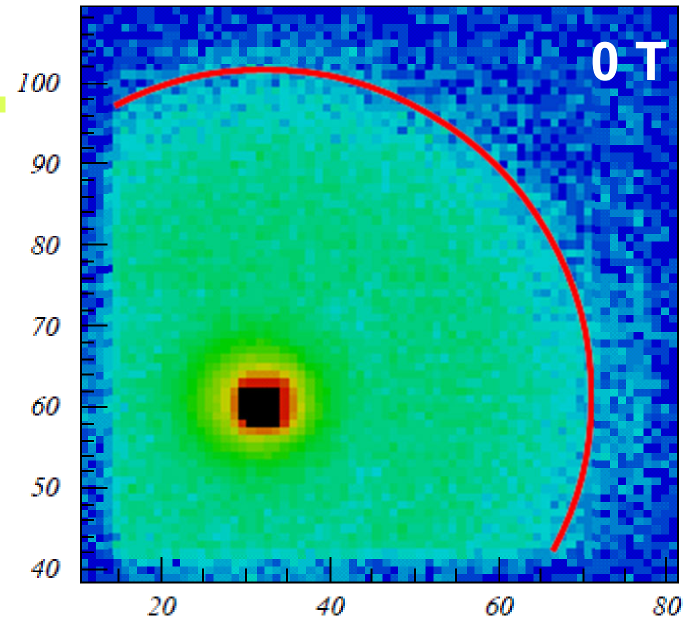
Employed on a large scale:

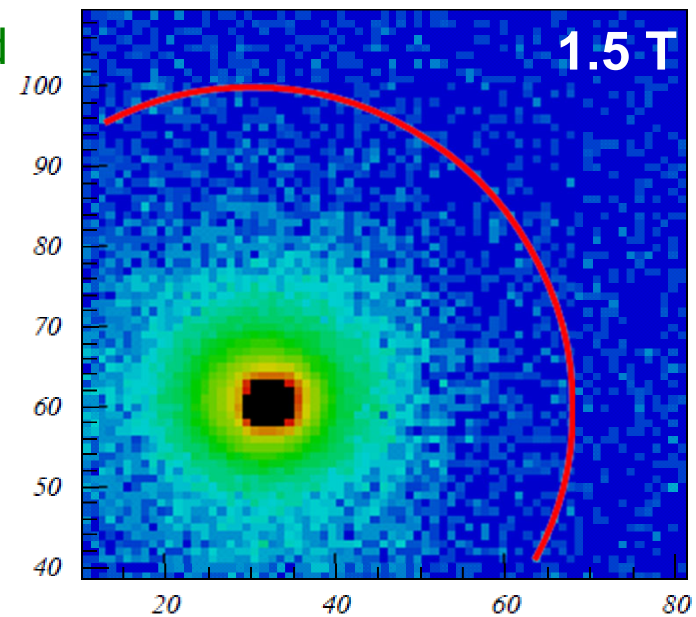
- HPD: RICH1+RICH2 of LHCb (Run 1+2), CMS HCAL
- HAPD: Aerogel RICH detector of Belle II

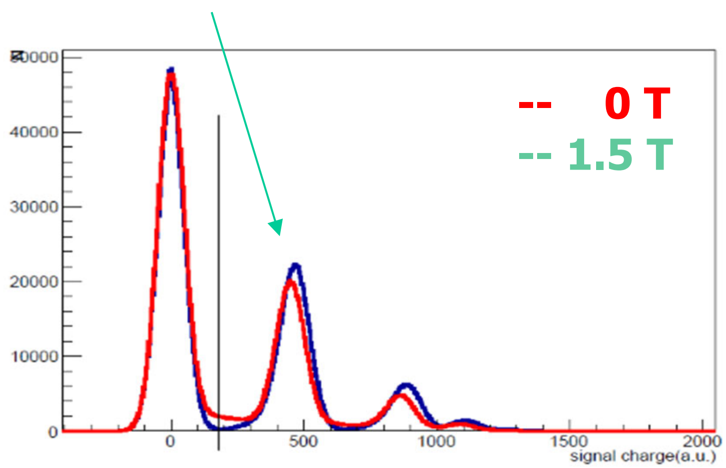


HAPD: photoelectron backscattering in magnetic field

- around 20% of photoelectrons back-scatter and the maximum range is twice the distance from photocathode to APD ~40mm
- in magnetic field (perp. to the HAPD window) scattered photoelectrons follow magnetic field lines and fall back to the same pad
- photoelectron energy is deposited at the same pad





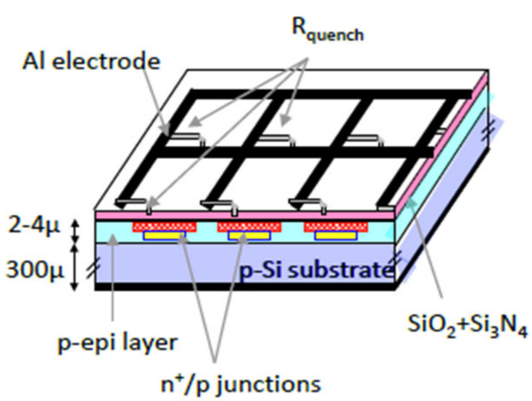


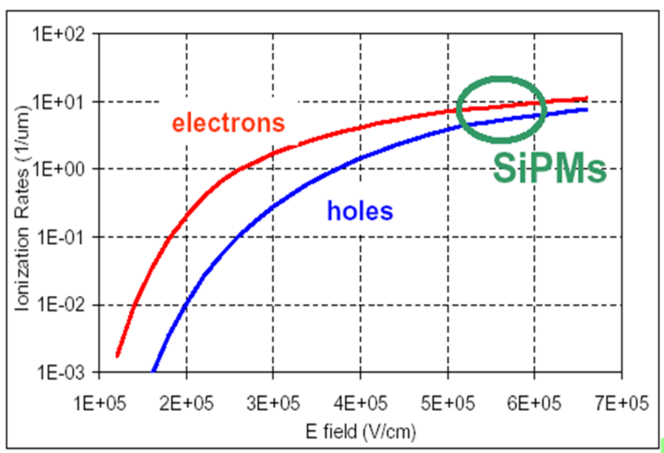
Solid state low light level photosensors: Silicon photomultipliers SiPM

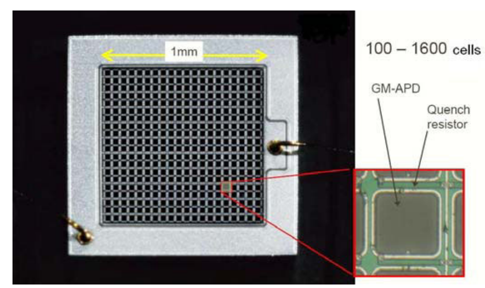
An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

Detection of photons:

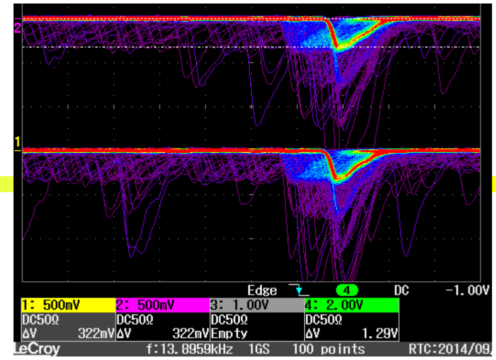
- absorbed photon generates an electron-hole pair
- an avalanche is triggered by the carrier in the high field region → signal
- voltage drops below breakdown and avalanche is quenched (passive or active quenching)
- each triggered microcell contributes the same amount of charge to the signal



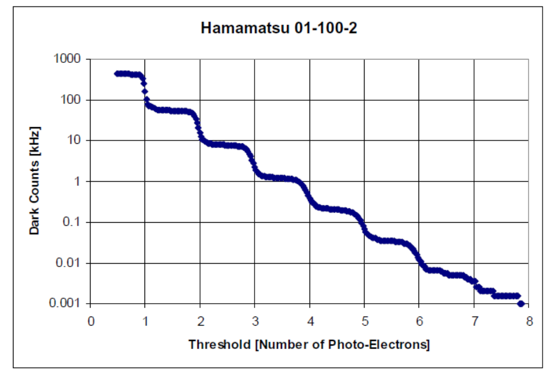




SiPM: noise

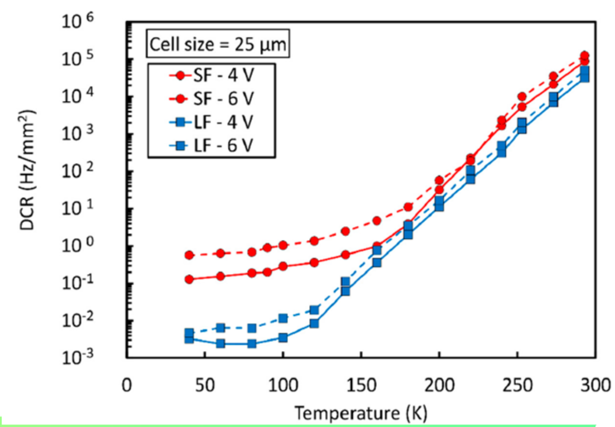


- dark counts are produced by thermal generation of carriers, trap assisted tunnelling or band gap tunnelling
- signal equal to single photon response
- typical rate went from $\approx 1\mathrm{MHz/mm^2}$ to below $100\mathrm{kHz/mm^2}$ for more recent devices
- roughly halved for every -$8^{o}\mathrm{C}$
- increases linearly with fluence



- optical cross-talk produced when photons emitted in avalanche initiate signal in neighbouring cell, reduced by screening – trenches

A. Gola et al. Sensors 19(2019)308

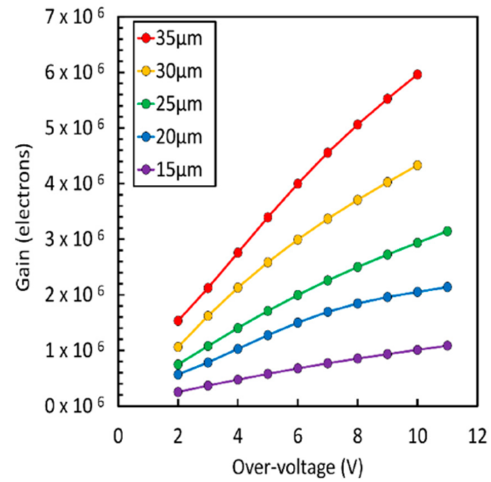


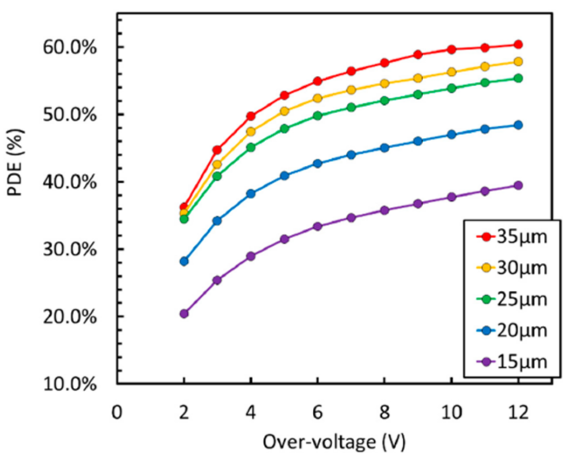
- after-pulses produced by trap-release of carriers or delayed arrival of optically induced carrier in the same cell

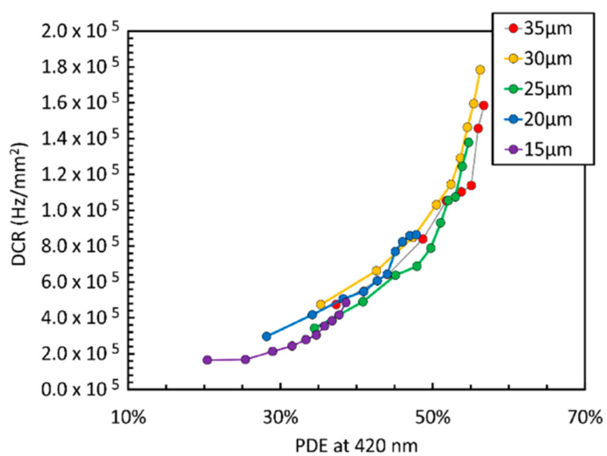
SiPM: parameter correlation

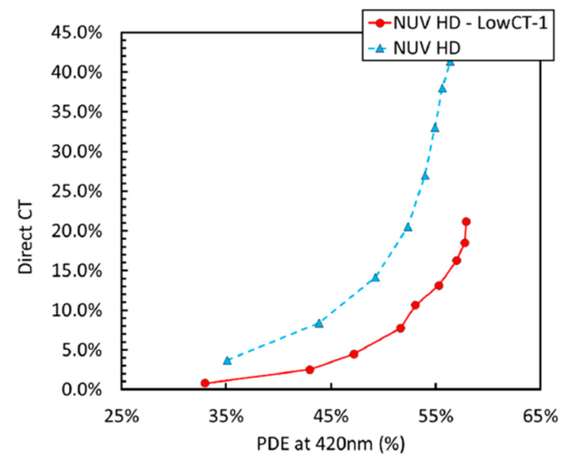
Higher overvoltage:

- higher field:
  - higher avalanche trigger probability → higher PDE
  - faster signal → better timing
- higher gain:
  - better signal to noise (electronic)
  - more optical cross-talk → higher ENF, worse timing
  - more after-pulses







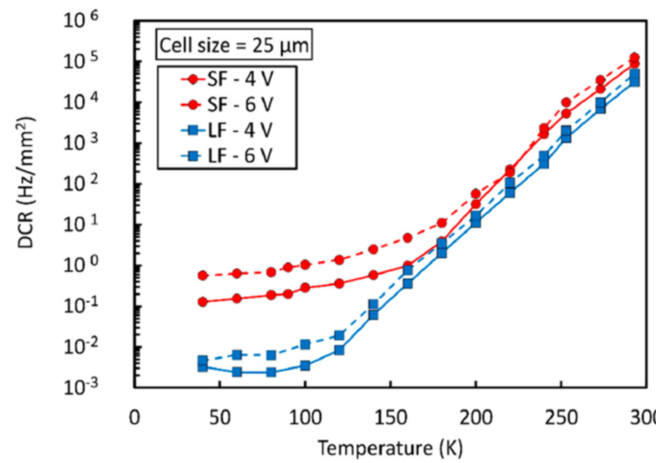


A. Gola et al. Sensors 19(2019)308

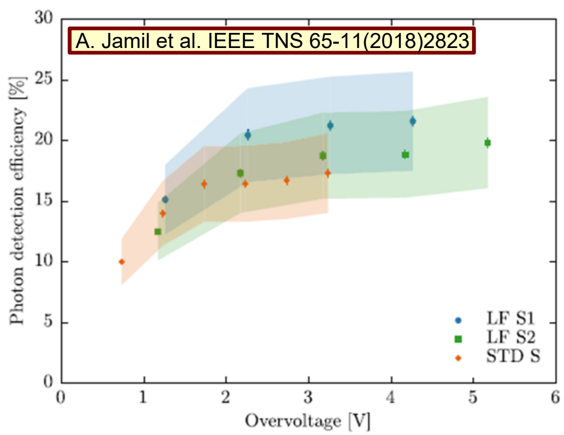
VUV SiPM for cryogenic applications

LAr, LXe applications:

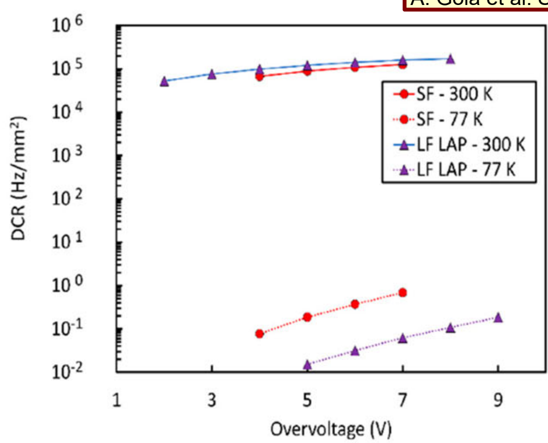
- VUV sensitivity required:
  - 128 nm (LAr), 178 nm (LXe)
  - optimization of anti-reflective coating ARC
  - PDE $\approx 20\ \%$

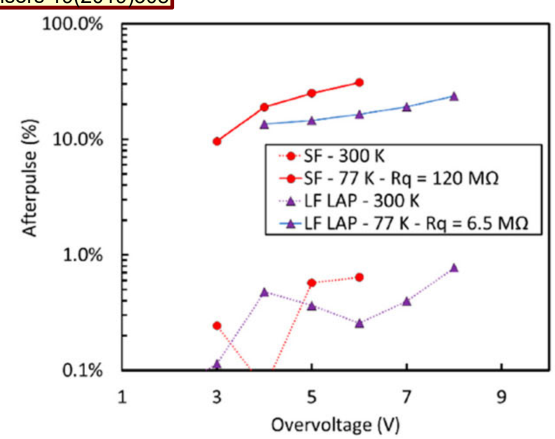


- cryogenic temperatures:
  - low DCR $\approx 10\mathrm{mHz/mm^2}$ dominated by band-band tunnelling, reduced by low-field avalanche region
  - higher after-pulse rate $\approx 10\%$



A. Gola et al. Sensors 19(2019)308

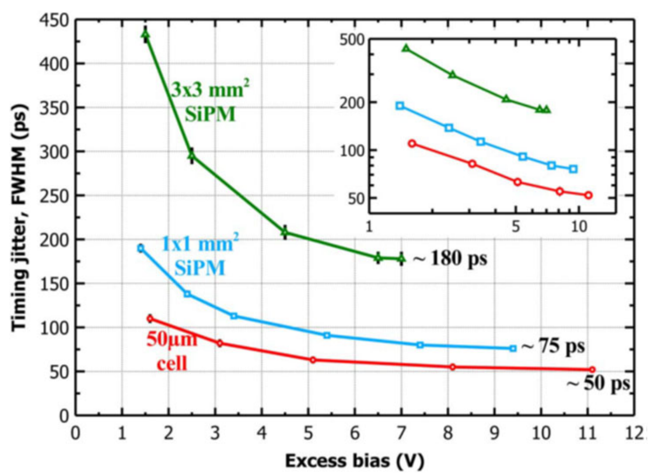




SiPM: single photon timing

Intrinsic TTS of SiPM microcells is extremely fast, $< 20\ \mathrm{ps}$ for single microcells (SPAD), but timing deteriorates for larger devices. The main contributions:

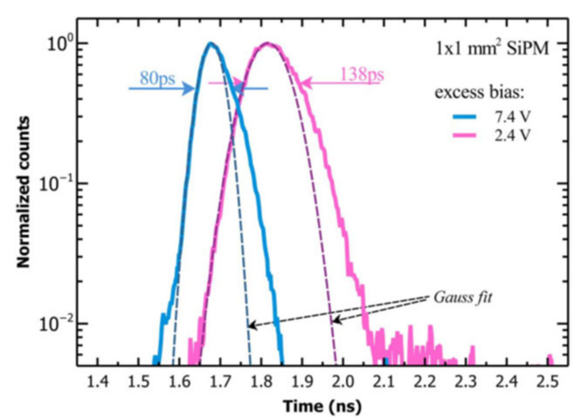
- nonuniformity within microcell (edges)
- spread between microcells
- overall SiPM capacitance
- λ dependence - tails



F. Acerbi et al. IEEE TNS 61(2014)2678

Comparison of timing properties for single $50\mu\mathrm{m}$ SPAD, $1 \times 1\ \mathrm{mm}^2$ and $3 \times 3\ \mathrm{mm}^2$ SiPMs with the same SPAD for microcells:

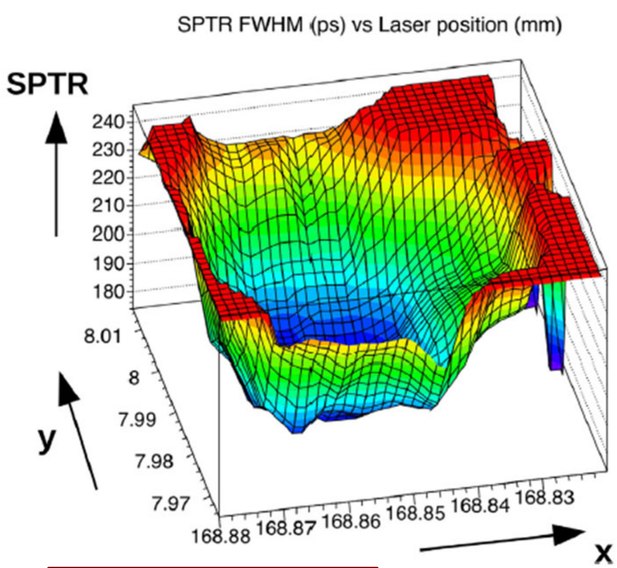
- timing improves with higher overvoltage – larger pulses, at the expense of increased SiPM noise
- best timing resolutions for single cell signals are $\sigma \approx 21\ \mathrm{ps}, 32\ \mathrm{ps}$ and $77\ \mathrm{ps}$
- TTS deterioration mainly due to a larger overall capacitance → reduced signal slope, $\sigma_t \approx \sigma_{el.} \left(\frac{dU}{dt}\right)^{-1}$



SiPM: timing variation

Variation of TTS over the device surface can contribute to overall time spread:

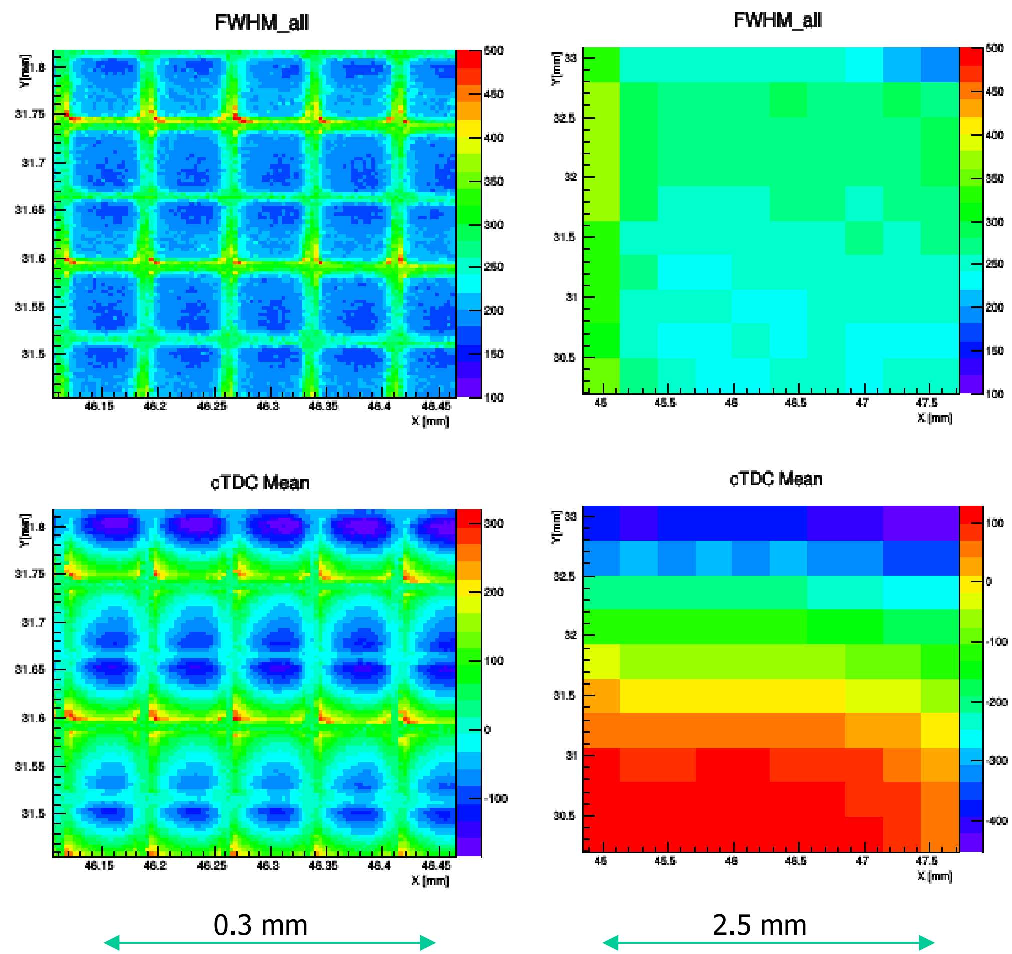
- variation within micro-cell
- variation for different micro-cells



F. Acerbi et al. NIM A926(2019)16

KETEK PM3375TS-SBO (early design)

S. Korpar et al. @IEEE 2015

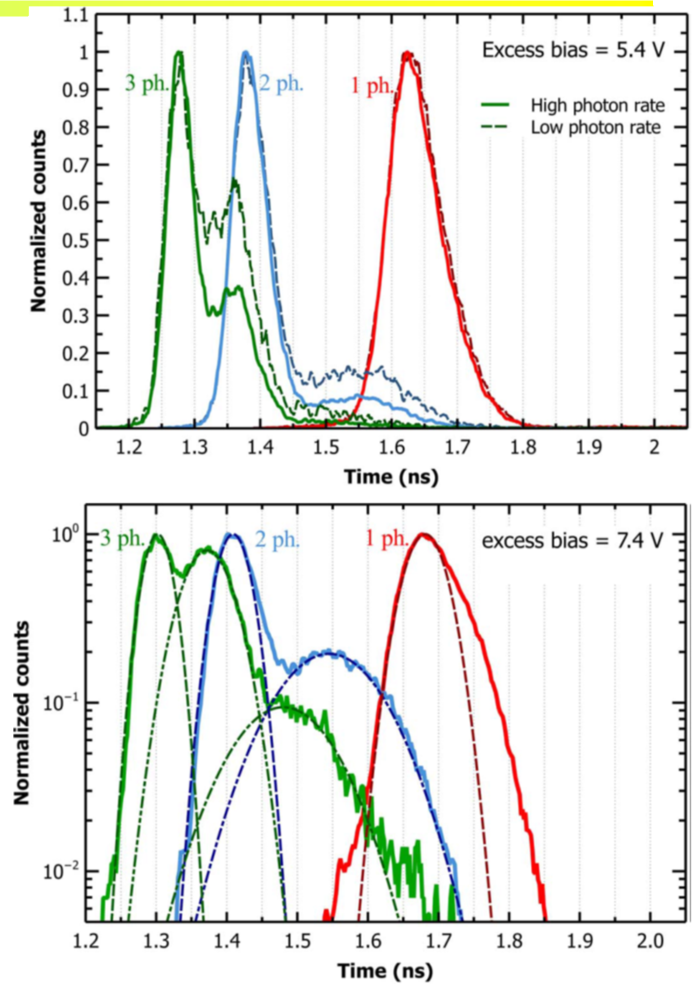


FBK: Masking of outer regions of micro-cells: Improve signal peaking and mask areas of micro-cell with worse timing

SiPM: timing for multi-cell signals

Optical cross-talk contribution to multi-cell signals spoils timing distribution – does not scale with $\frac{1}{N^{1/2}}$:

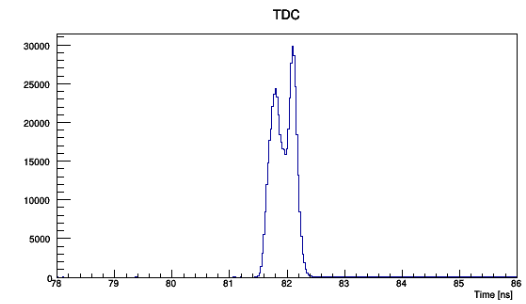
- two components for 2-micro-cell signals:
  - double photon events – proper scaling
  - single photon with cross-talk, timing somewhere between single and double micro-cell signals and resolution is worse
- ratio between contributions changes with light intensity confirming optical cross-talk origin
- even more components for multi-micro-cell signals

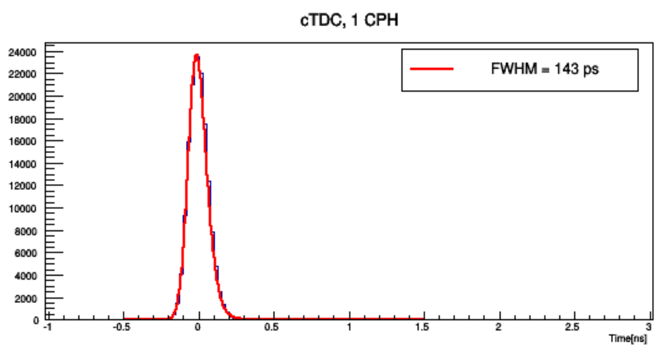


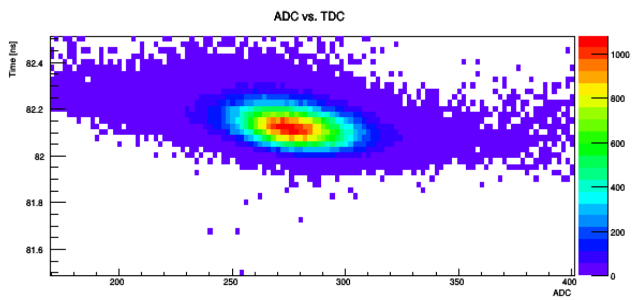
F. Acerbi et al. IEEE TNS 61(2014)2678

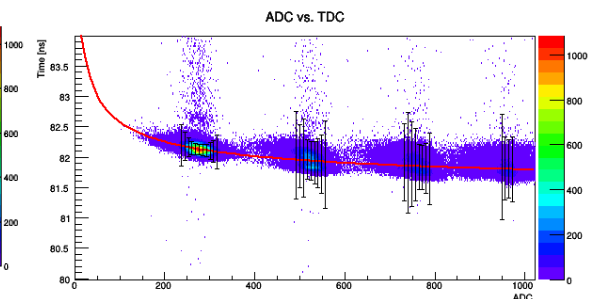
SiPM: timing test with pico-second laser

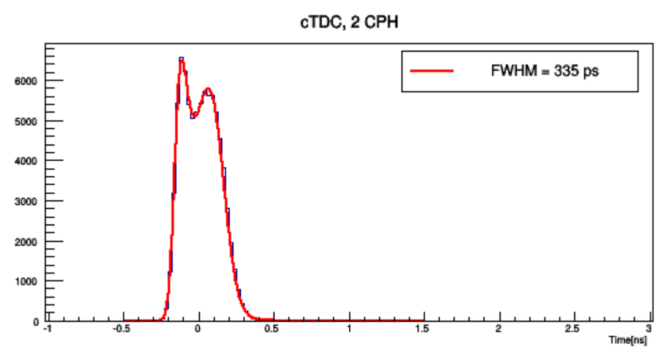
- AdvanSiD SiPM ASD-NUV3S-P-40
- OV=6V, T=-2n5^{o} C
- blue laser λ =408nm, ~ 35ps FWHM

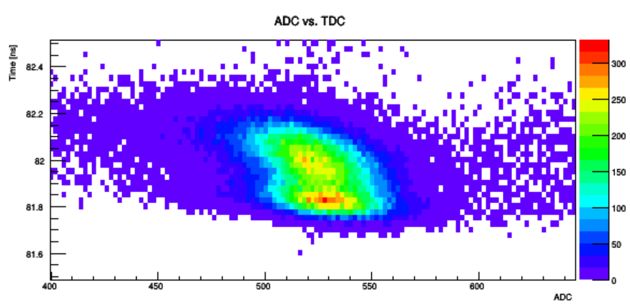




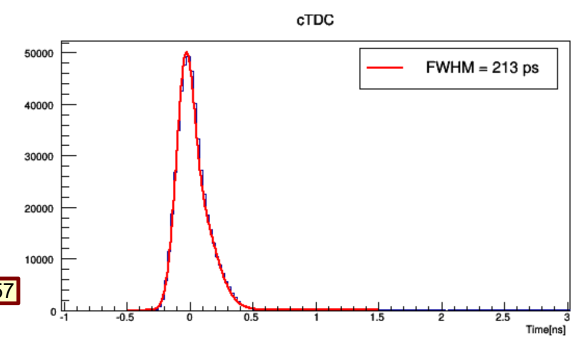








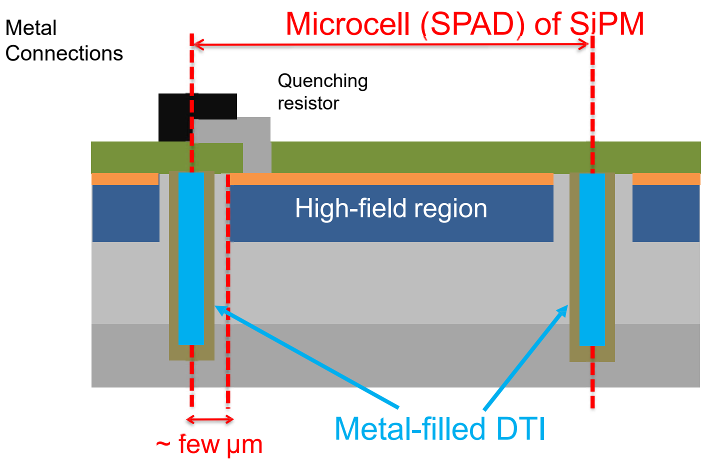
R. Dolenec et al. NIM A876(2017)257



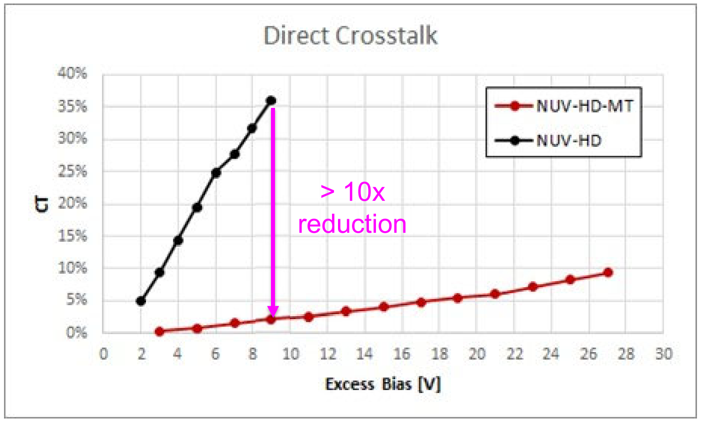
Reduction of optical crosstalk

Starting from the NUV-HD technology, FBK and Broadcom jointly developed the NUV-HD-MT technology, adding metal-filled deep trench isolation to strongly suppress optical crosstalk.

Other changes: low electric field variant, layout optimized for timing.



Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.



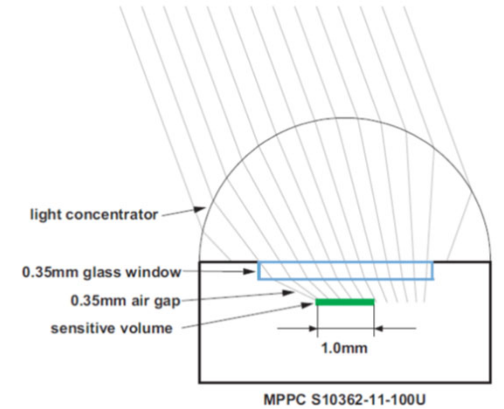
Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. only considering internal crosstalk probability.

A. Gola, RICH2022

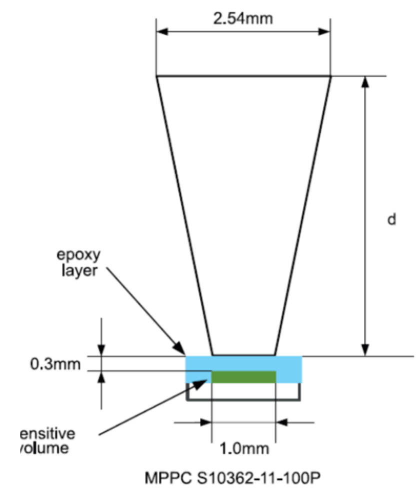
Light concentrators

At the device level (lenses, Winston cones):
- reduce active are – reduce DCR (tolerate higher fluences)
- use smaller faster devices

At the micro-cell level (micro-lenses, diffractive lenses, meta lenses):
- compensate for low fill factor – small cells, dSiPM
- concentrate light in cell centre – better timing

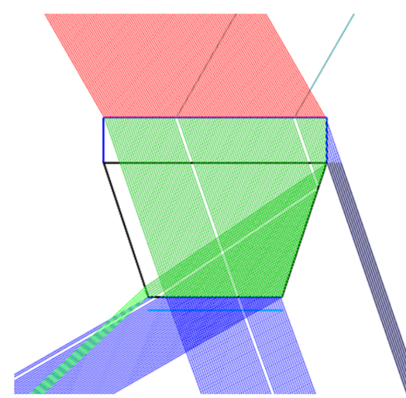


Higher concentration – narrower angular acceptance



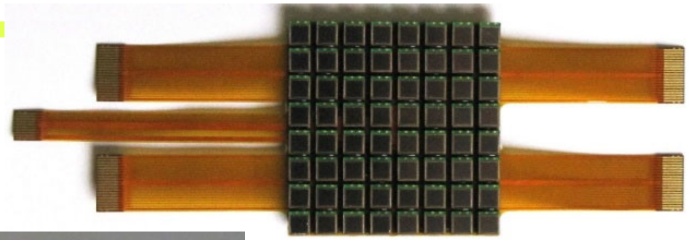
Imaging light concentrators:
- smaller photon impact angles on the sensor
- can be used with position sensitive arrays

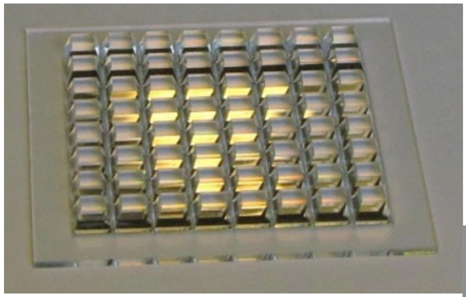
Non-imaging light concentrators:
- larger photon impact angles on the sensor – directly coupled to sensor



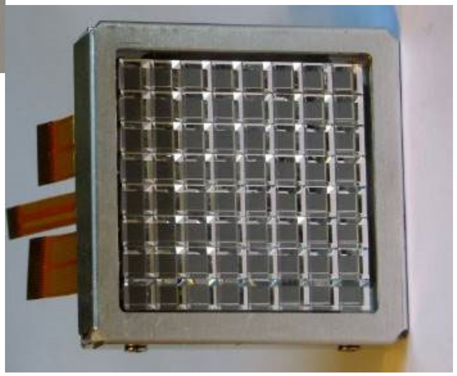
SiPM RICH with light concentrators

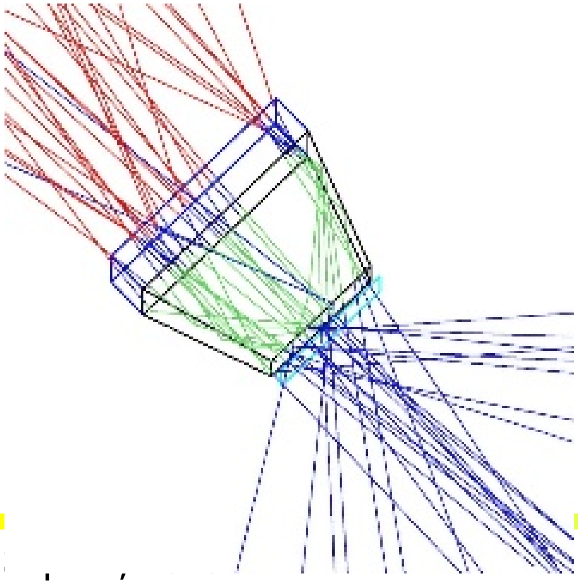
RICH photon detector module prototype:

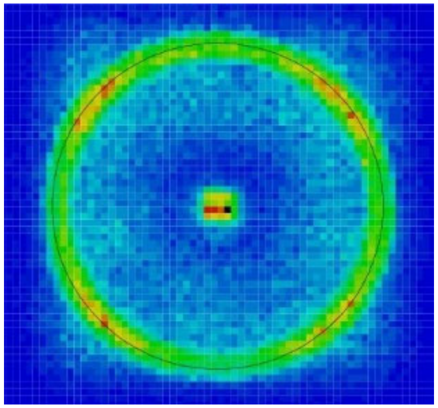




- Hamamatsu 64 channel MPPC module S11834-3388DF, 8×8 array of $3 \times 3\ \mathrm{mm}^2$ SiPMs @ $5\ \mathrm{mm}$ pitch
- matching array of quartz light concentrators used
- two $20\ \mathrm{mm}$ thick aerogel tiles in focusing configuration ($\mathrm{n} = 1.045, 1.055$)
- tested in $5\ \mathrm{GeV}$ electron beam at DESY





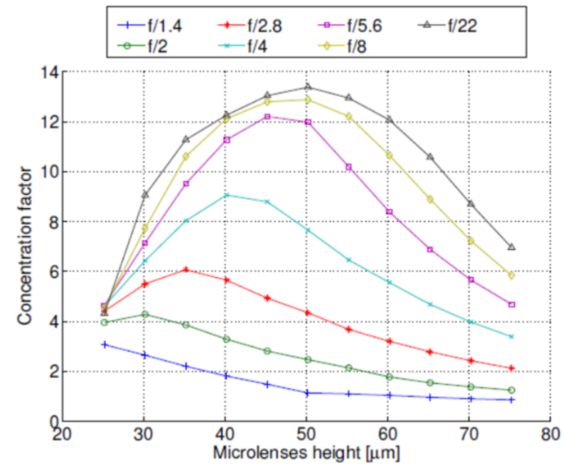


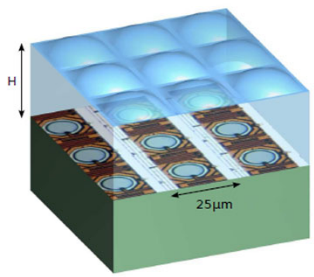
E. Tahirović et al., NIM A787 (2015) 203

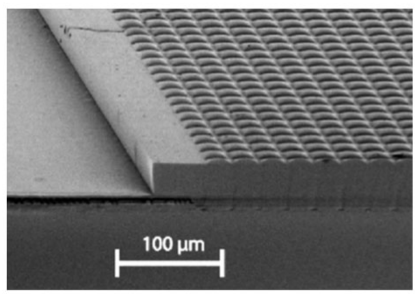
Microlenses

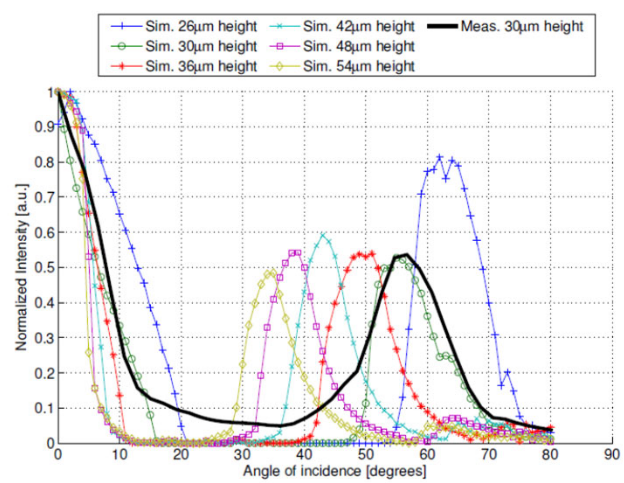
Micro-lens array coupled to SPAD array

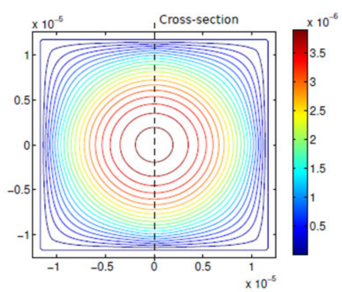
- CMOS SPAD array, 128x128 $6\mu m$ diameter @$25\ \mu m$ pitch – 5% fill factor
- matching polymer plano-convex micro-lens array

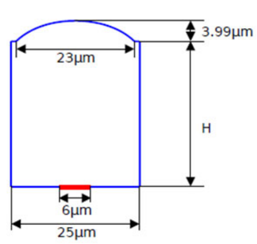


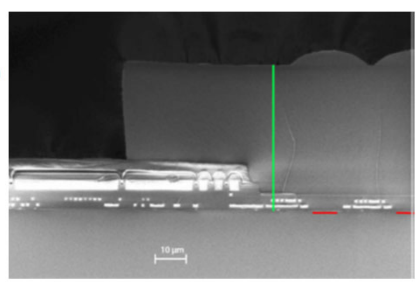






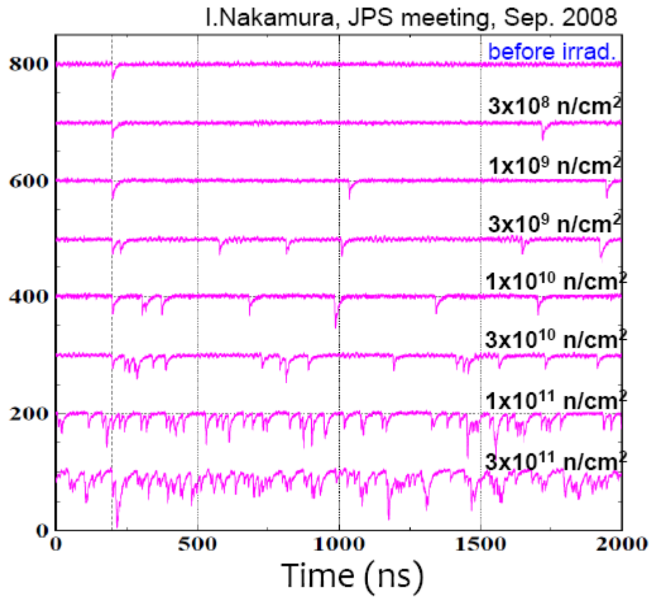






J.M. Pavia et al. Opt.Exp. 22-4(2014)4202

SiPMs: Radiation damage



Show stopper at fluences above ~10^{11} in case single (or few) photon sensitivity is required!

(e.g. expected fluence in the ARICH area of Belle II: 2-20 10^{11} n cm^{-2})

→ Use of wave-form sampling readout electronics

→ Operating the SiPMs at lower temperature

→ Annealing periodically (annealing at elevated temperature is preferred)

→ Reducing recovery time to lower cell occupancy

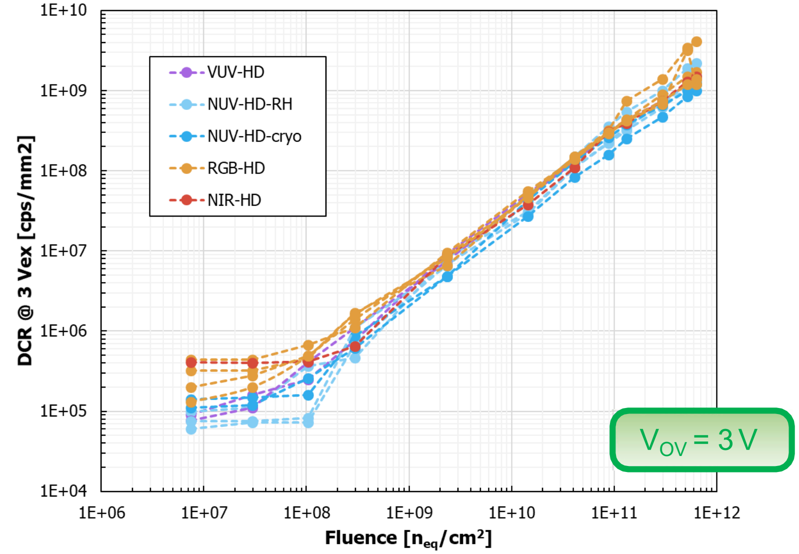
→ Radiation resistant SiPMs, other materials?

SiPMs: Radiation damage

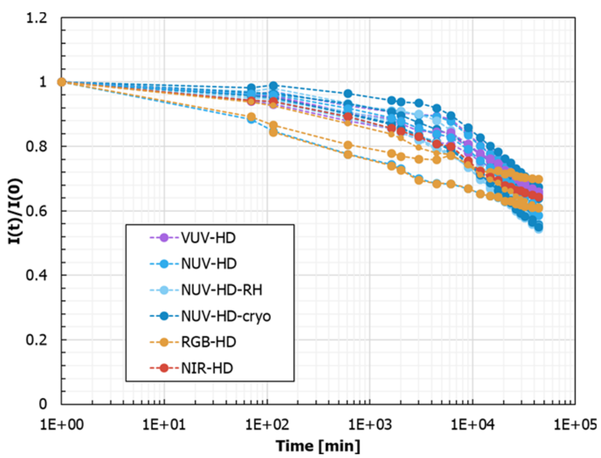
A. Gola, RICH2022

Beyond $10^7 \div 10^8$ n_{eq}/cm^2 little correlation between the DCR before and after irradiation:

- All technologies seem to "converge" towards similar values
- Independence of bulk damage from contaminants in the SiPM starting material?



DCR (dark count rate) vs fluence



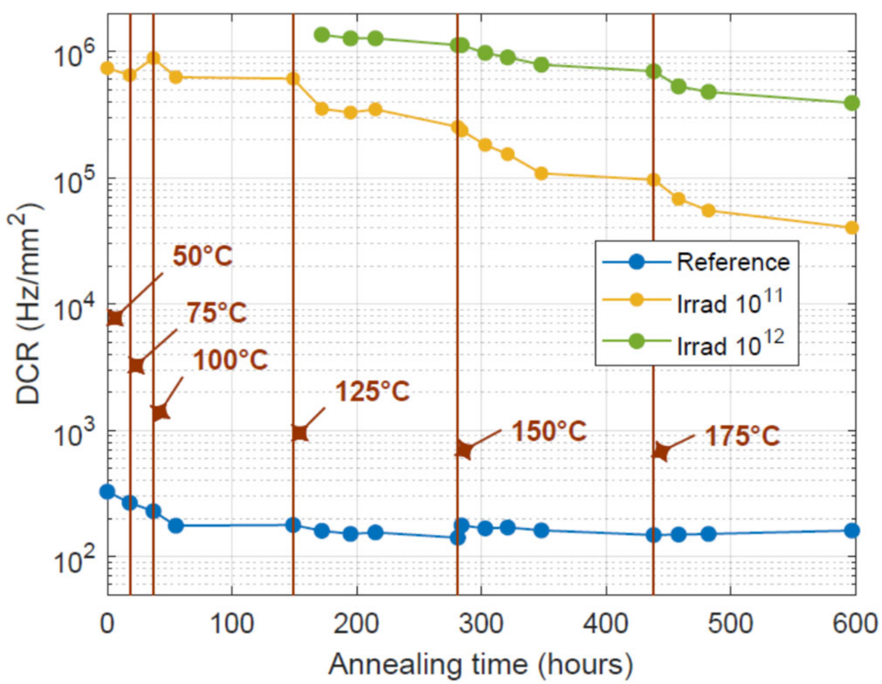
Room temperature annealing (20-25°C) for samples irradiated to $6.4 \cdot 10^{11}$ 1 MeV n_{eq}/cm^2

Little effect, knee point at around $1.5 \cdot 10^3$ min (~1 day)

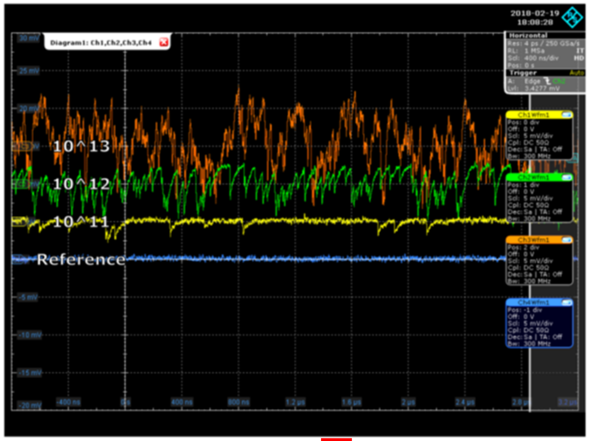
A. Gola, RICH2022

SiPMs: Radiation damage, annealing at elevated temperatures

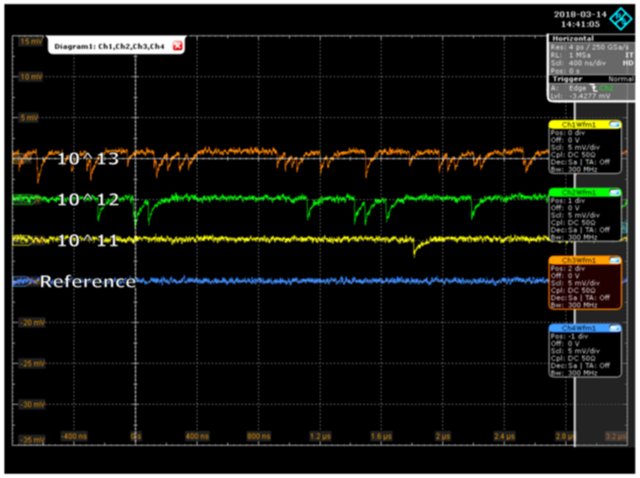
Dark counts at -30C of a Hamamatsu S13360-1350CS SiPMs: non irradiated (blue) and irradiated up to 10^{11} (yellow), 10^{12} (green) and 10^{13} (orange) n_{eq}/cm^2



M. Calvi et al., NIMA 922 (2019) 243-249

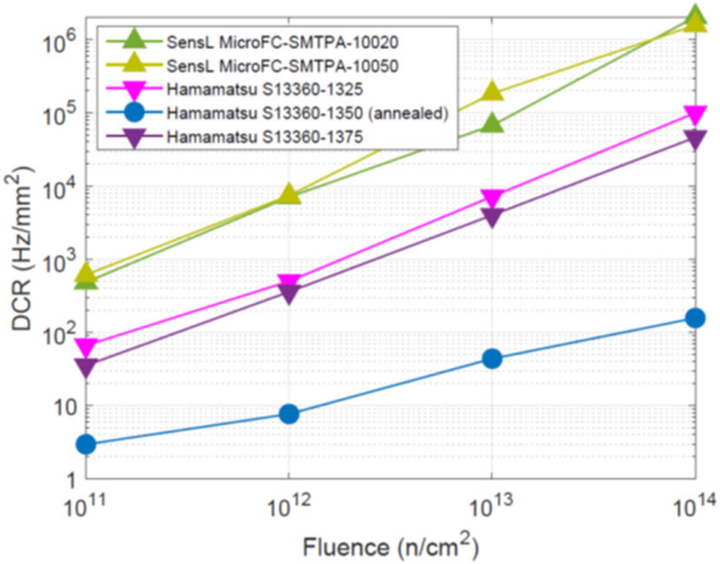


annealing



SiPMs: Radiation damage, annealing at elevated temperatures

M. Calvi et al., NIMA 922 (2019) 243-249



DCR at 77 K versus neutron fluence

Blue circles: annealed sample

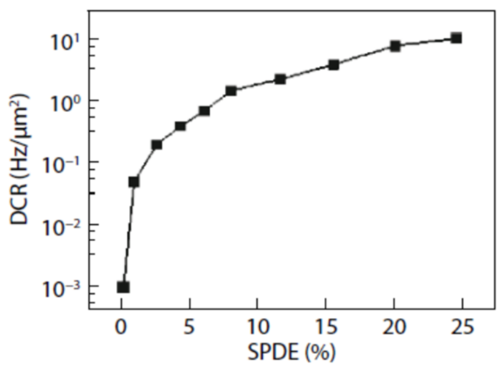
→ Annealing helps also at 77 K

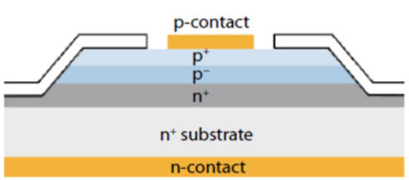
New materials

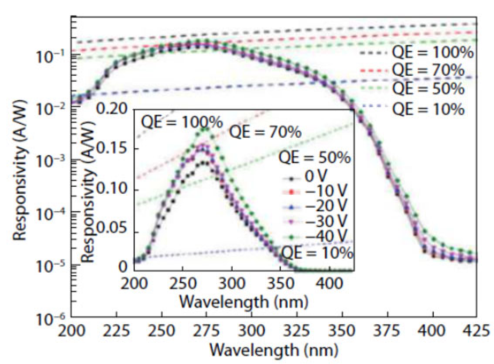
- new higher band gap materials - possibly lower DCR - higher radiation resistance, higher temperature
- (V)UV sensitive
- high dark count rate – dominated by trap assisted tunnelling

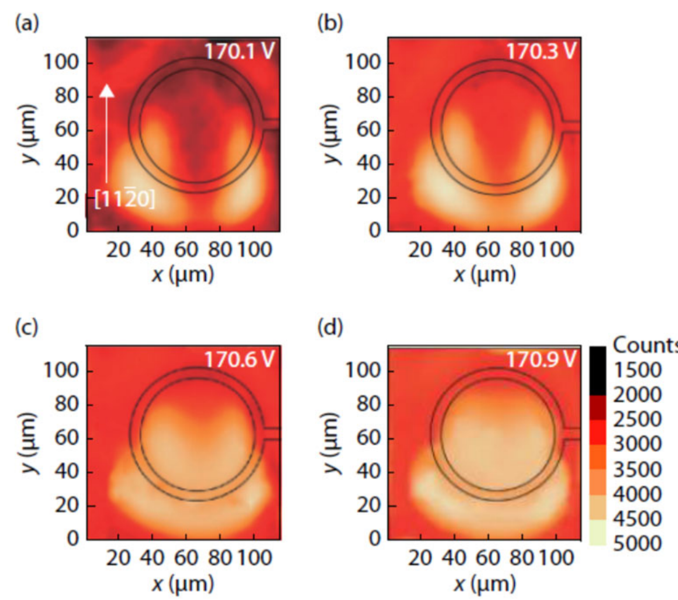
4H-SiC:

- $E_g = 3.26$ eV
- PDE $\approx 10\%$
- DCR $> 1\ \mathrm{MHz/mm^2}$
- nonuniform response



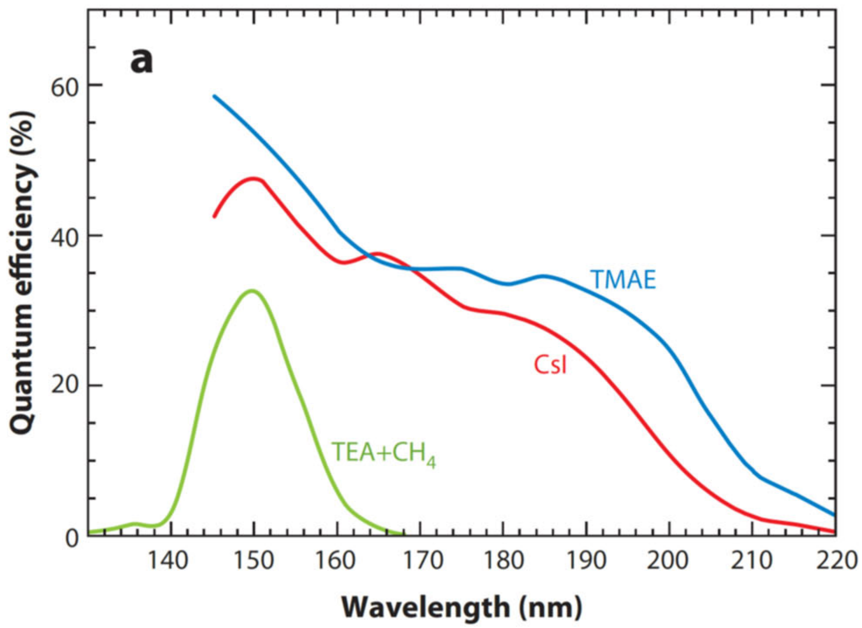


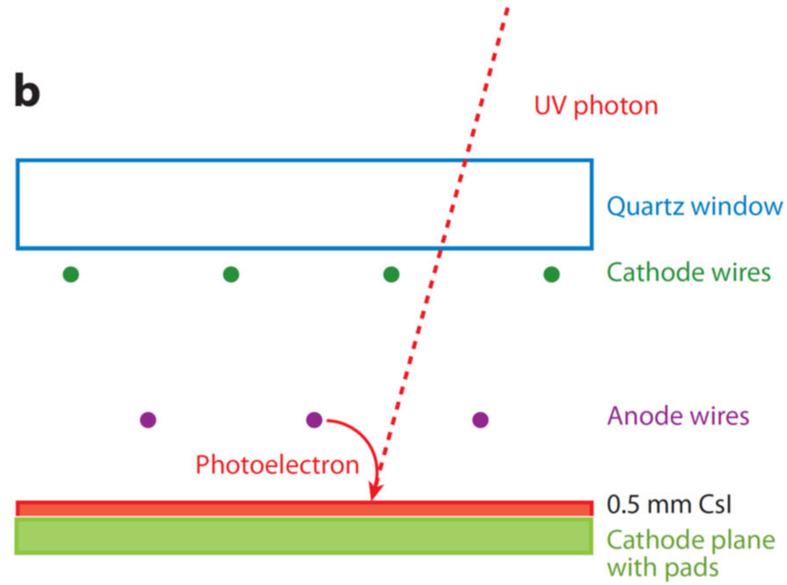


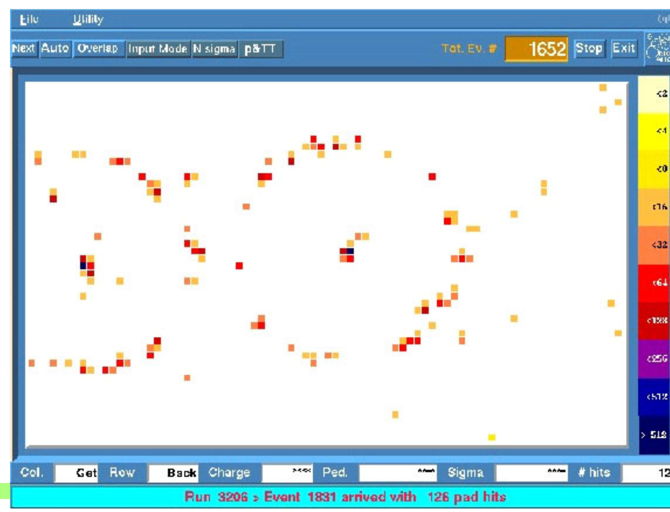


L. Su et al. J. Semicond. 40(2019)121802

Gas based photon detectors







Standard photosensitive substance: CsI evaporated on one of the cathodes.

Large scale application: ~11 m^2 ALICE RICH

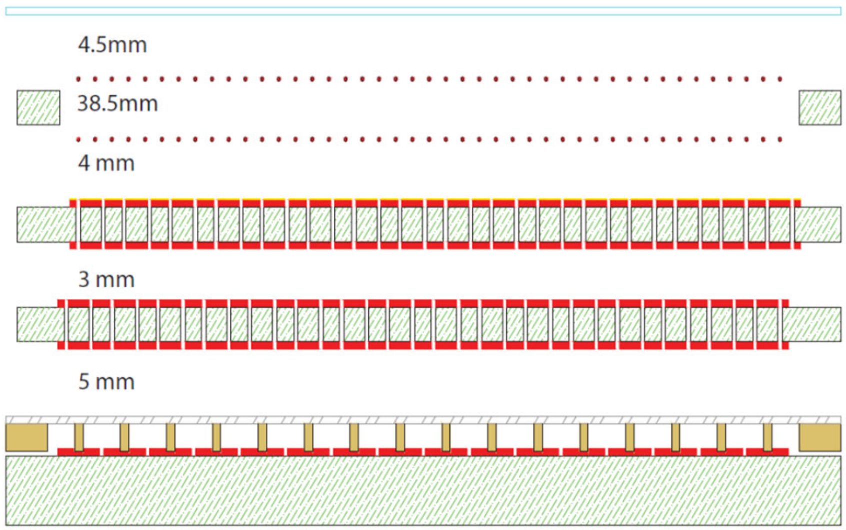
Gas based photon detectors: recent developments

Instead of MWPC:

•Use chambers with multiple GEM or thick GEM (THGEM) gas amplification stages with transm. or refl. photocathode

•COMPASS RICH: trans. photocathode and 2x THGEM + MicroMegas

S. Dalla Torre, NIM A 970 (2020) 163768



Ion damage of the photocathode:

blocking ions – non-aligned GEM holes

New developments:

- Smaller pads
- Novel photocathode material: nano-diamond layer

Summary and outlook

Next generation of experiments in particle physics: faster timing, wider spectral range and improved radiation tolerance.

Many new interesting developments underway, in particular in SiPMs and MCP-PMTs – not all of them could be covered in this talk.

A detector R&D collaboration (DRD4) is being set-up to facilitate collaboration in this area of research, expected to start in January 2024.

Back-up slides

Rate Capability

MaPMT

MaPMT R13742: no gain loss to up 10 MHz/mm²

MCP-PMTs

Gain decreases at high photon rates

2-inch MCP-PMTs: ~1 MHz/cm² (with 10^6 gain)

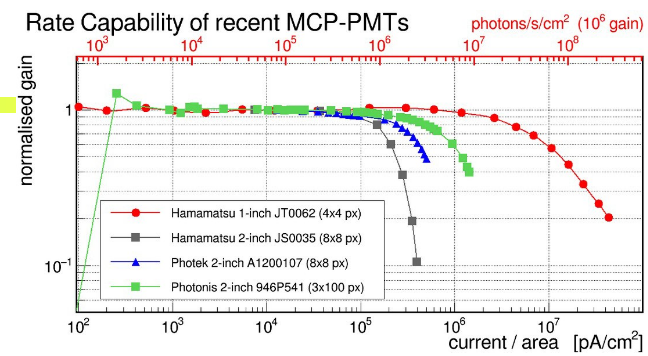
1-inch Hamamatsu R10754 PMTs: ≥10 MHz/cm²

8-inch LAPPD-64: ~100 kHz at 4.6 mm Ø laser spot

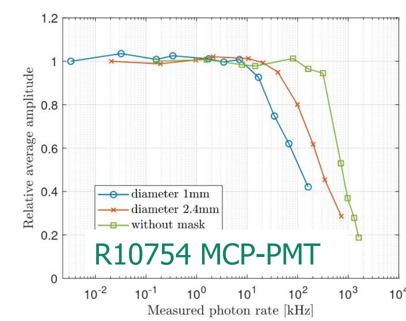
Improving the rate capability in MCP-PMTs

- Lower MCP resistance (ranging at tens of MΩ)
- Lower capacitance - subdivision of MCP layers into smaller partial areas; the second MCP layer was divided in the previous version of Hamamatsu tubes
- Low gain operation (for single photon detection) - may be possible with amplifiers included directly in the anode (e.g., monolithic or CMOS designs)

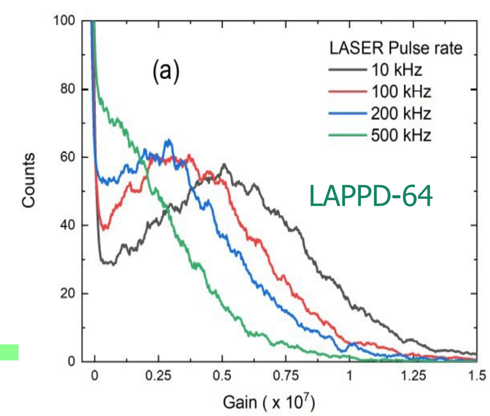
A. Lehmann, RICH2022



M. Calvi et al., JINST 15 (2020) P10031

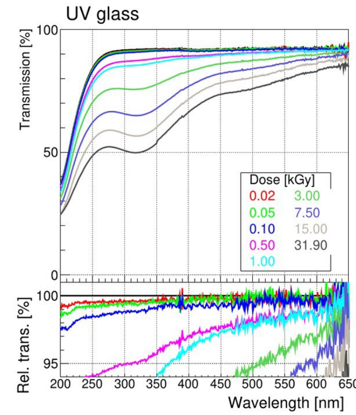


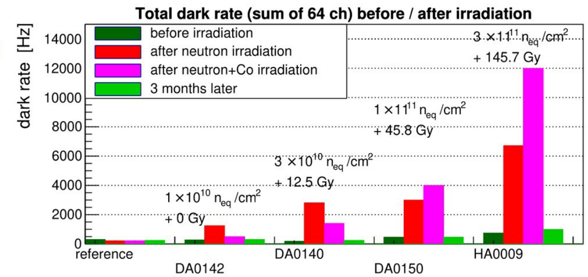
V.A. Chirayath et al., Talk at CPAD 2021



Radiation Tolerance

C. Pauly et al., NIM A1040 (2022) 167177





MaPMT

Recently tested for CBM (H12700 and H8500)

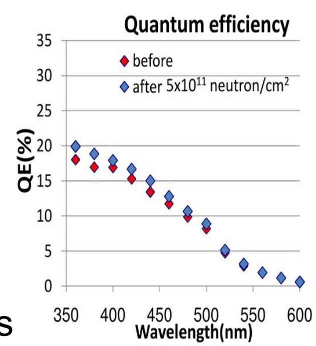
- Irradiation dose up to **$3x10^{11}$ n/cm²** and **150 Gy gammas**
- Few kHz increase of DCR but recovers after few months
- UV glass: 1-2% transmission loss @ 400 nm up to 1 kGy
- **No negative effects on gain and pulse height spectrum**
- **Neutron activation of Kovar metal alloy is a minor effect**

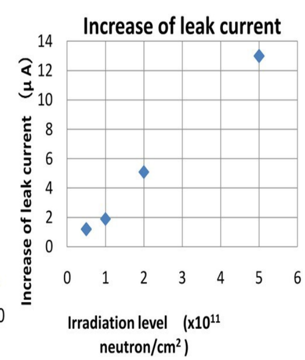
H(A)PD

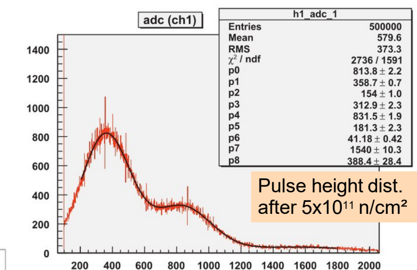
Radiation tolerance dominated by silicon detector Intensively studied for 144ch HAPD for ARICH @Belle II

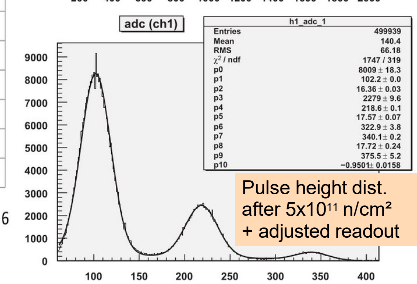
- Basically **no QE loss at $5x10^{11}$ n/cm²**
- **Increase of APD leakage current** leads to significantly worse S/N ratio: ~17 before, ~3 after irradiation
- S/N ratio partly regained by adjusted readout parameters

.S. Shiizuka, Talk at VCI 2010









I. Adachi, NIM A639 (2011) 103

MCP-PMT

Entrance window: should be similar to other PMTs

MCPs: currently no data

SiPM: p-on-n vs. n-on-p

n-on-p: green/red light sensitive:
- electrons drift to Geiger region from substrate and holes from surface side
- higher dark count rate – most of the thermally generated carriers arriving to Geiger region are electrons

p on n - green/blue light sensitive:
- electrons drift to Geiger region from surface and holes from substrate side
- lover dark count rate – most of the thermally generated carriers arriving to the Geiger region are holes