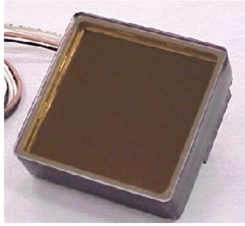
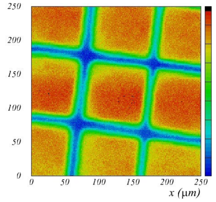
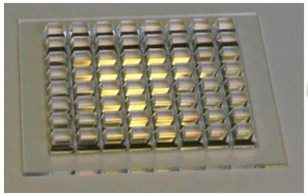
ANIMMA

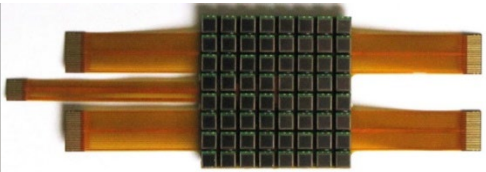
JUNE 9–13 2025

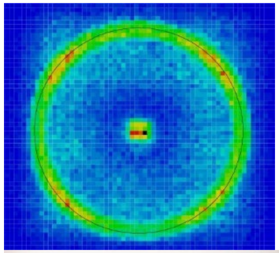
VALENCIA – SPAIN









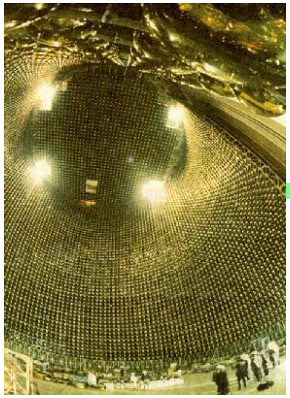
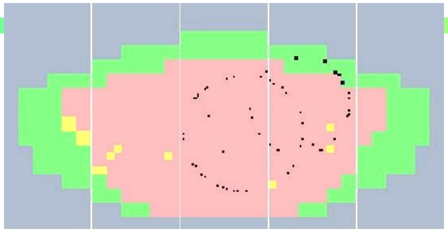
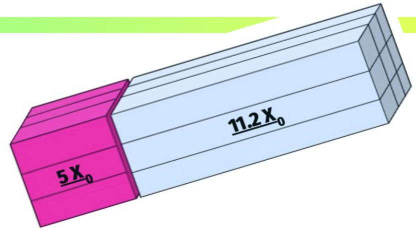


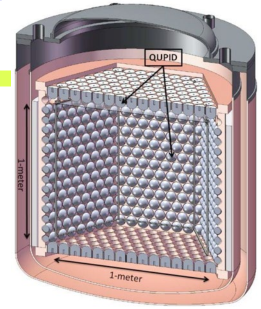
Novel photon detectors

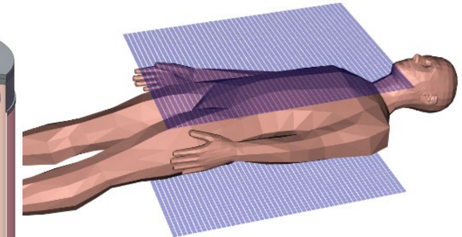
Peter Križan

University of Ljubljana and J. Stefan Institute

Introduction: why?





Photon detectors are at the heart of most experiments in particle and nuclear physics. Moreover, they are also finding applications in other scientific fields (chemistry, biology, medical imaging) 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, 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?

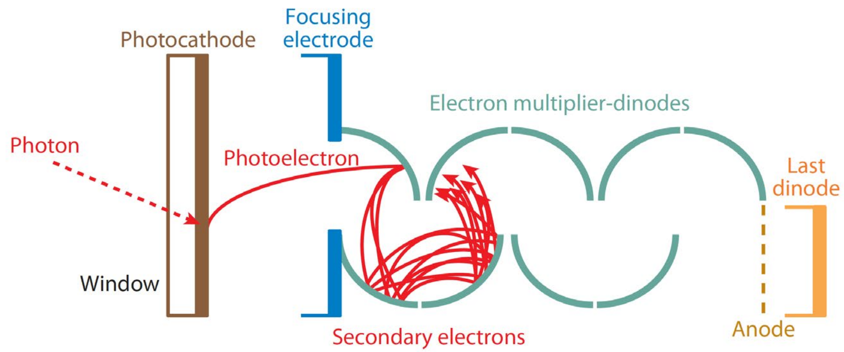
Vacuum-based photodetectors

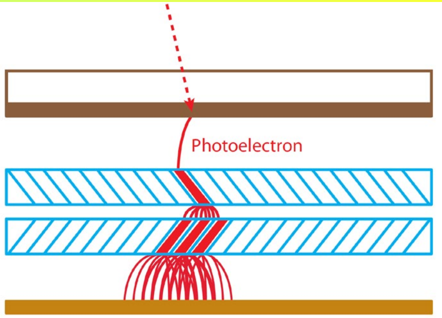
Solid state low light level photosensors

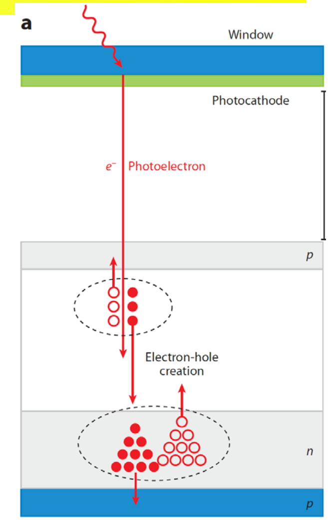
Gas-based photodetectors

Summary and outlook

Vacuum-based photodetectors

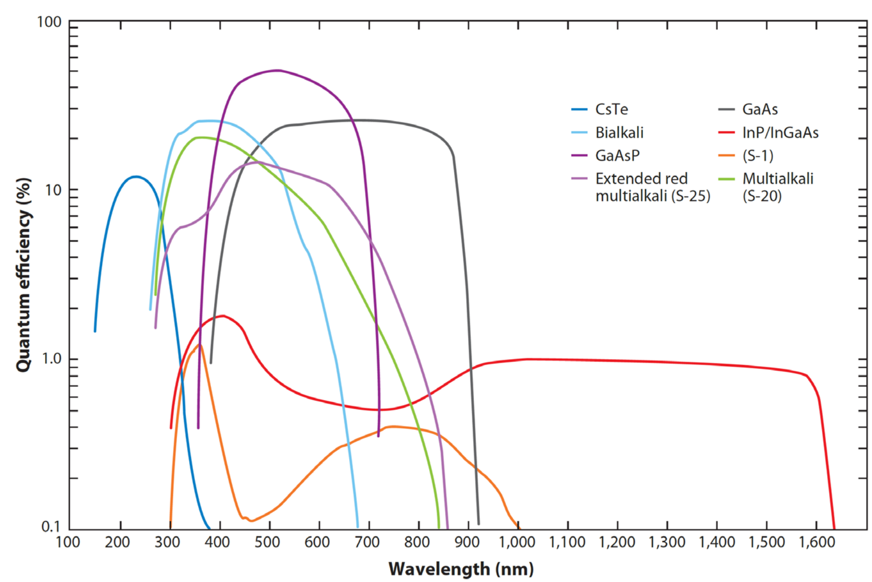




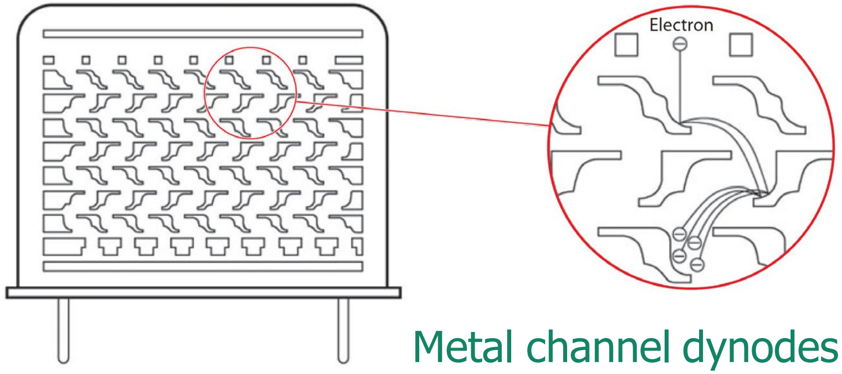


Generic steps:

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

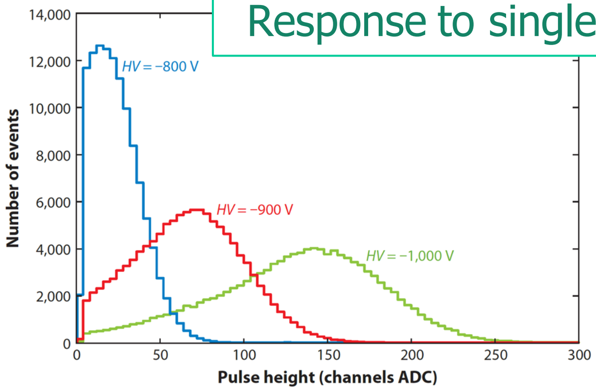


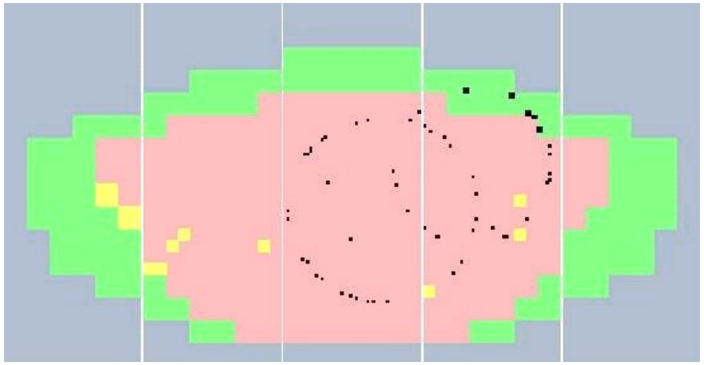
Multianode photomultiplier tubes (PMTs)



Metal channel dynodes

Response to single photons



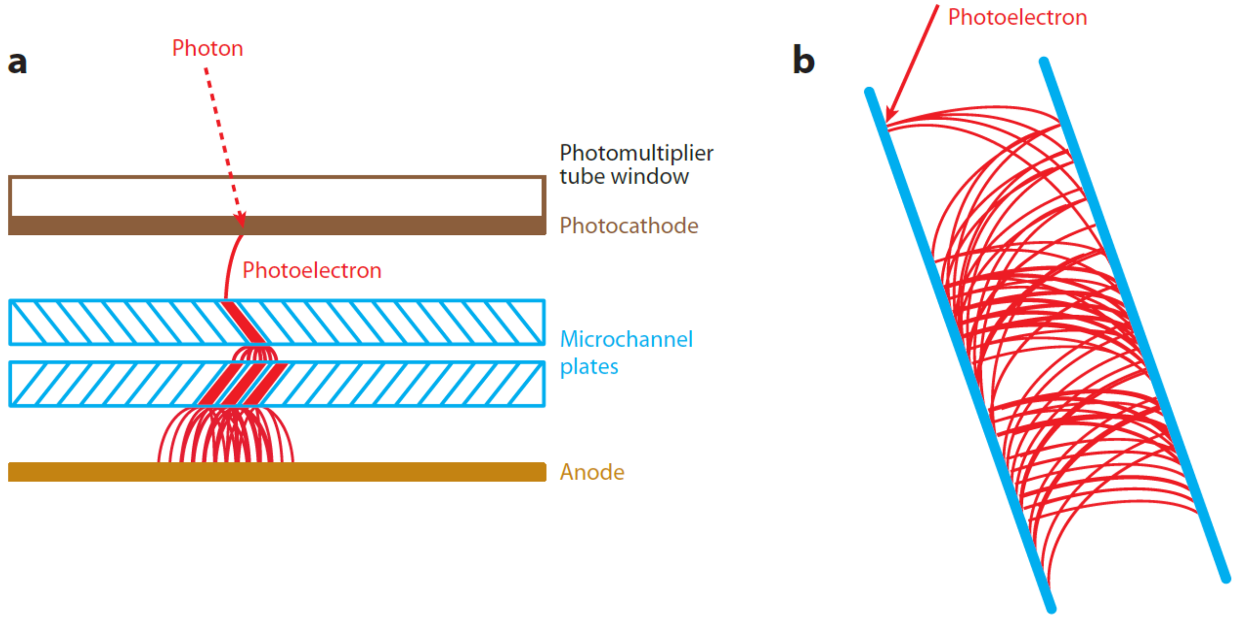


Pioneered in the HERA-B RICH, later used in RICH detectors of COMPASS, CLASS12 and GlueX

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

Excellent performance (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)

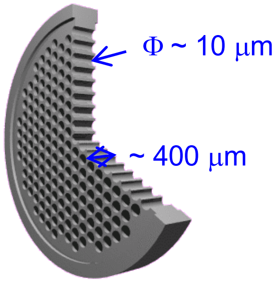


Multiplication step: a continuous dynode – a micro-channel

Micro Channel Plate PMT (MCP-PMT)

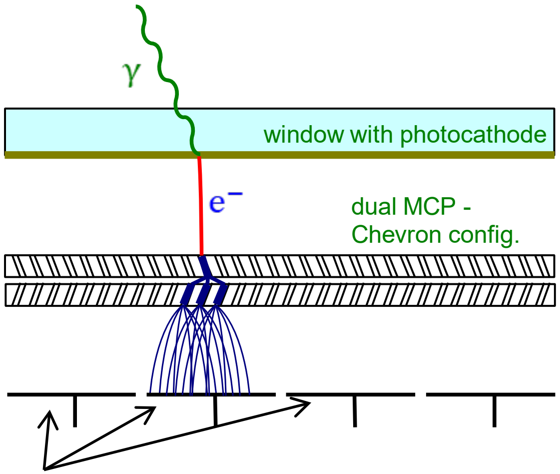
Similar to ordinary PMT – the dynode structure is replaced by MCPs.

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

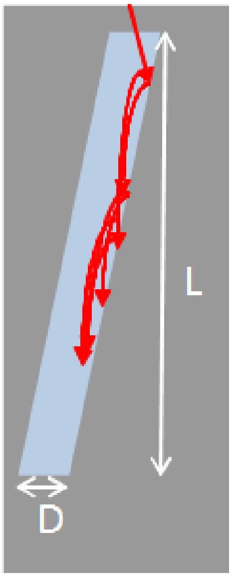


Basic characteristics:

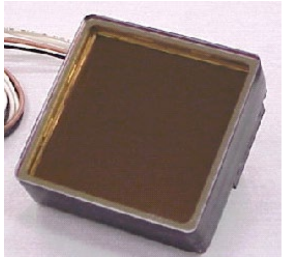
- Gain ~ 10^6 → single photon
- Collection efficiency ~ 60%
- Small thickness, high field → small TTS
- Works in magnetic field
- Segmented anode
  → position sensitive



Anodes → can be segmented according to application needs



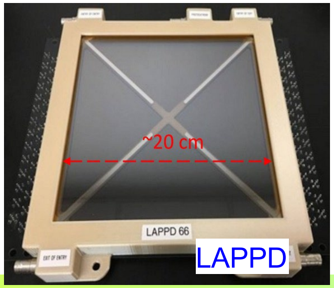
MCP gain depends on L/D ratio – typically 1000 for L/D=40



PHOTONIS

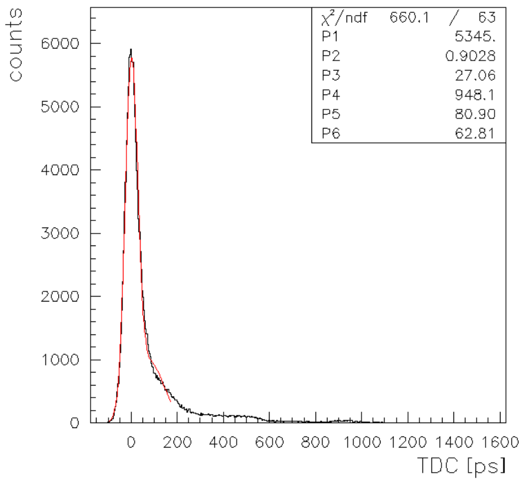
HAMAMATSU

PHOTEK



LAPPD

MCP-PMT: single photon pulse height and timing

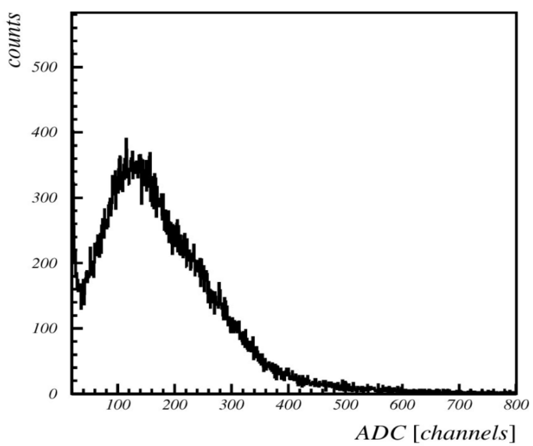


Very thin→ very fast

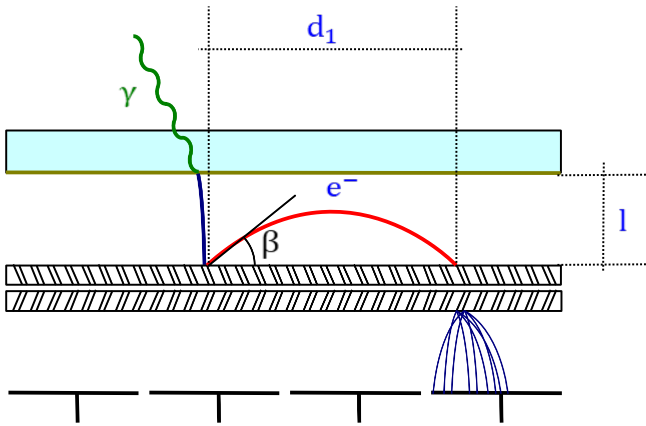
Typical single photon timing distribution with a narrow main peak ($\sigma \sim$ 40 ps) and contributions from photoelectron elastic (flat distribution) and inelastic back-scattering.

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. Improves in B field perp to PMT.

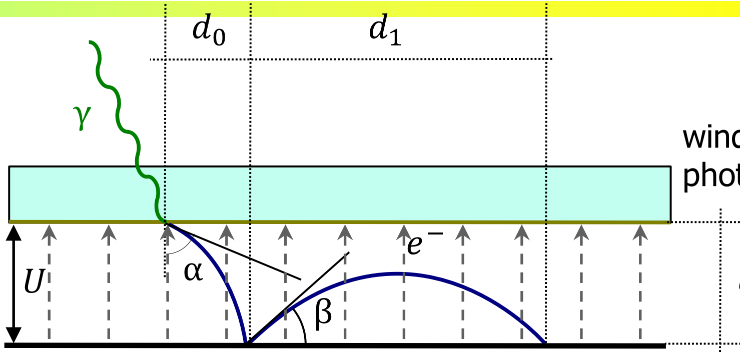


Gain in a single channel saturates at high gains due to space charge effect → peaking distribution for single photoelectrons



S.Korpar, talk at PD07

MCP-PMT modeling: photoelectron in a 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 $t_0 \approx 1.4\,ns$
- $\Delta \mathrm{t} \approx 100\ \mathrm{ps}$

backscattering:
- max range $d_1 = 2l = 12\ \mathrm{mm}$
- 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

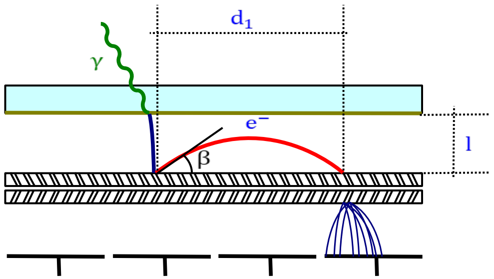
$$t_1 = 2t_0 sin(\beta)$$

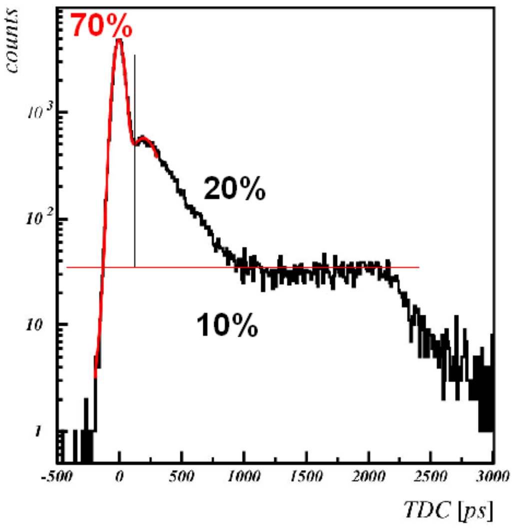
  maximum delay is twice the photoelectron travel time
- time of arrival of elastically scattered photoelectrons: flat distribution up to max $t_1 = 2t_0$

- Note: the maximum range is dramatically reduced in high B-field perpendicular to the MCP-PMT window

S. Korpar, Talk at PD07

MCP PMT modeling





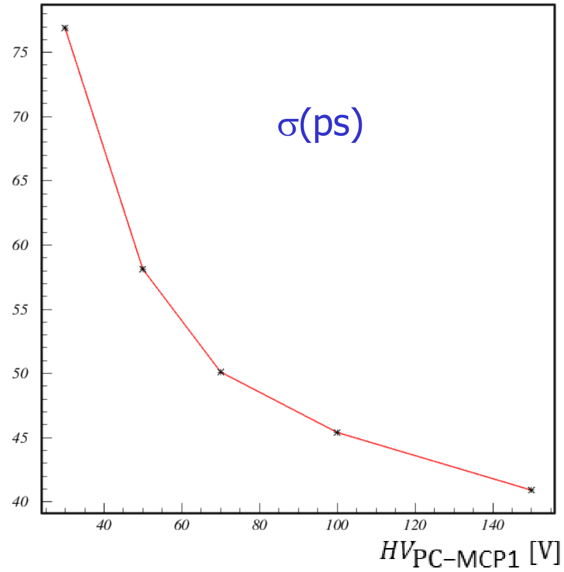
Tails understood (elastic and inelastic scattering of photoelectrons off the MCP), can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased photocathode-MCP voltage difference

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

Timing: Expect to improve with increased photocathode-MCP voltage difference as sqrt($HV_{PC\text{-}MCP1}$)

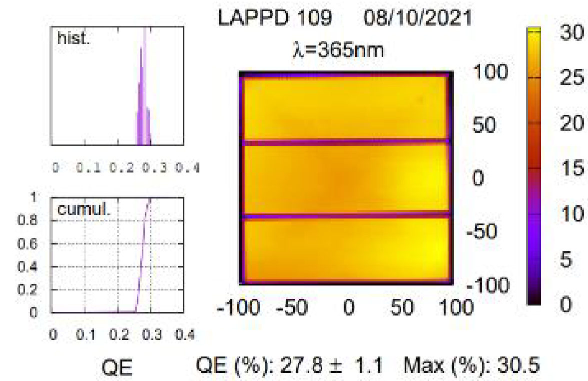
MCP-PMT LAPPD – timing vs PC-MCP1 voltage →



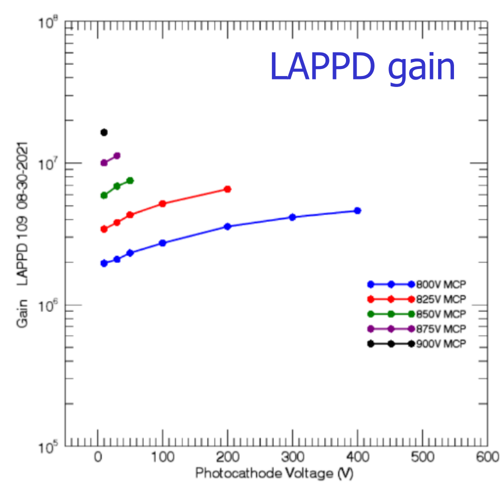
LAPPD (large area picosecond photodetector) Gen II

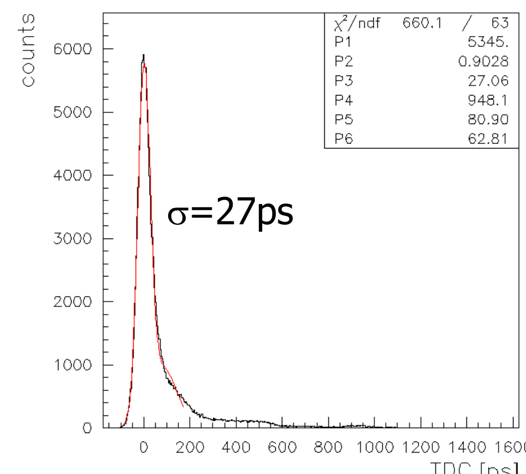
Characteristics (Incom):

- borosilicate back plate with interior resistive ground plane anode – 5 mm thick
- capacitively coupled readout electrode
- MCPs with a novel, cheaper production method (ALD-coated glass)
- 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/cm^2 with 8x10^5 gain



LAPPD Q.E.

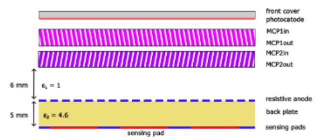


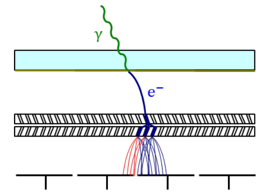


LAPPD – timing

MCP PMT readout: capacitive coupling vs. internal anodes

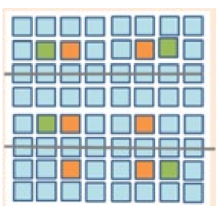
Secondary electrons spread out when traveling from the MCP-out electrode to the anode and can hit more than one anode → Charge sharing



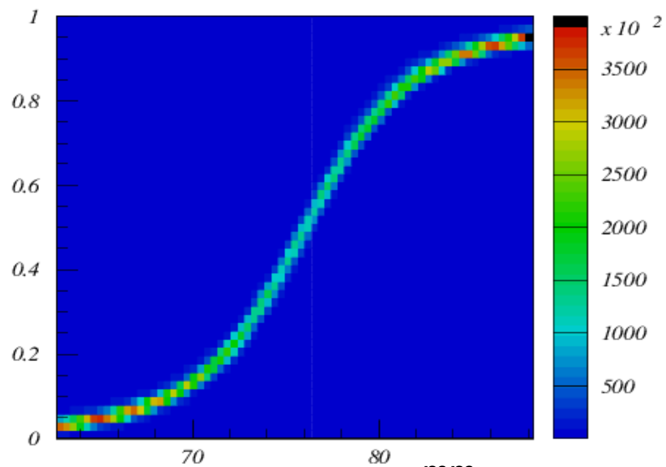


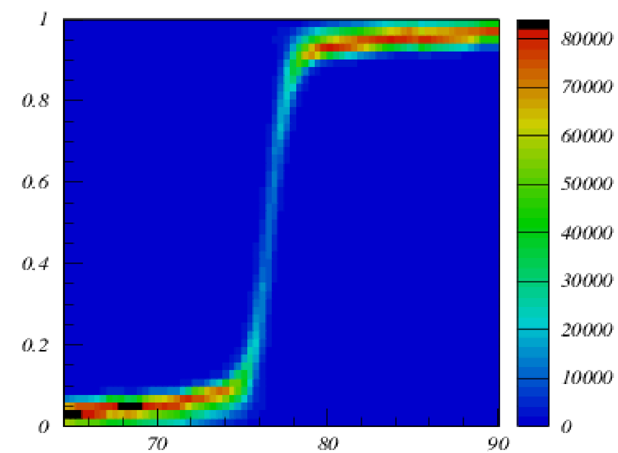
LAPPD (capacitive coupling through the backplane)

BURLE/Photonis PLANACON (internal anodes)



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





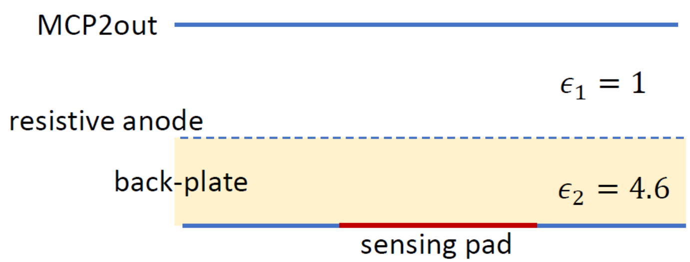
Capacitive coupling vs. internal anodes: signal spread comparison for two MCP PMTs with the same pad size, same range: charge sharing is more effective for capacitive coupling (spreads over larger area).

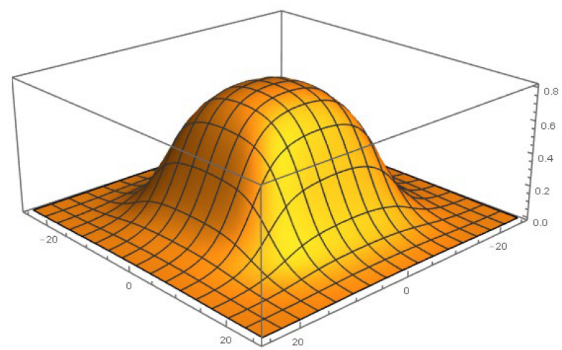
Advantage or not? Depends on the usage

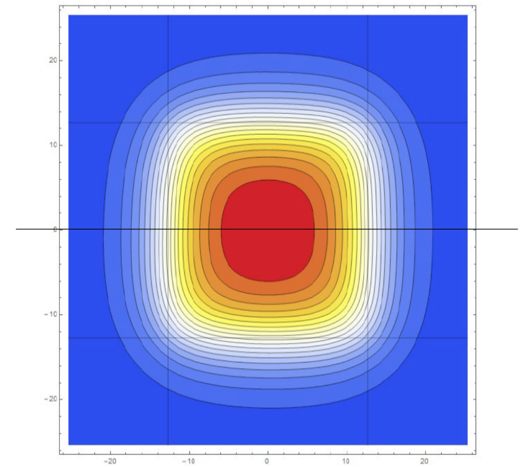
MCP PMT readout: capacitive coupling, modeling

LAPPD charge sharing

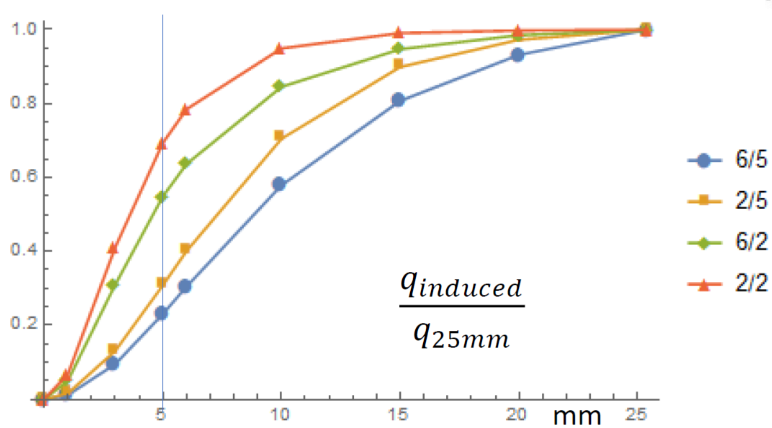
- calculation of charge sharing for different MCP2out-resistive anode/resistive anode-sensing electrode distances (6/5-measured, 2/5, 6/2, 2/2)

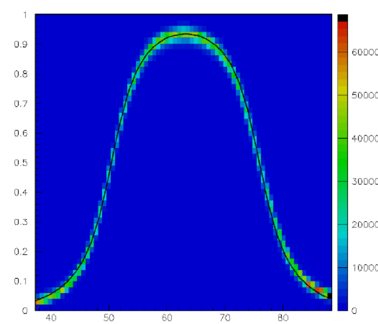


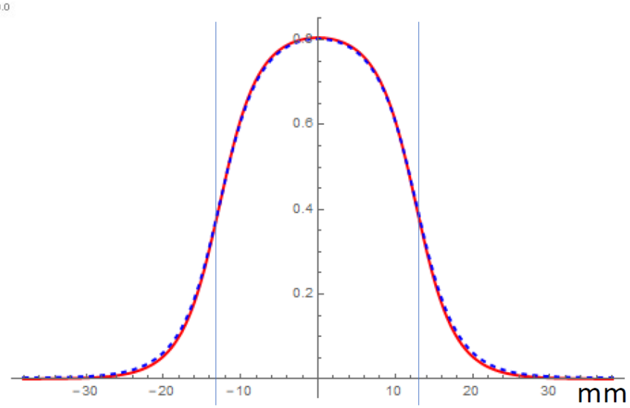




- fraction of the charge induced vs. square pad size when signal is produced in the centre of the pad







S. Korpar, DRD4 Coll. Meeting April 2025, to be submitted

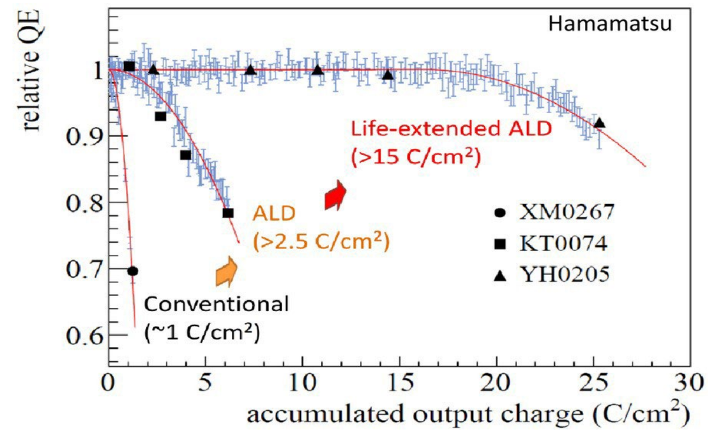
MCP PMT ageing

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

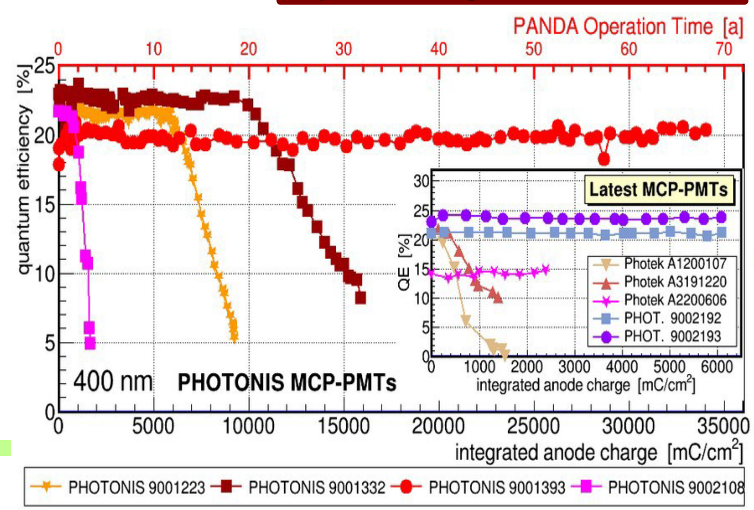
ALD (atomic layer deposition) coating of MCP pores → ~100x photo-cathode lifetime increase

- 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]

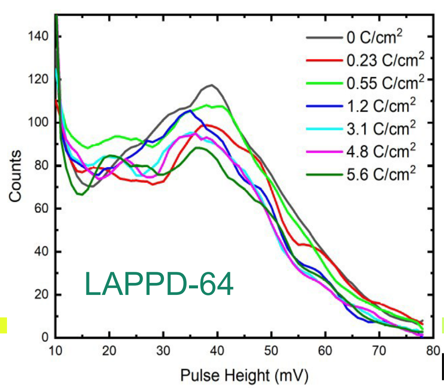
K. Inami, 2021, Talk at ECFA TF4 Symposium



A. Lehman et al., https://arxiv.org/abs/2403.13938

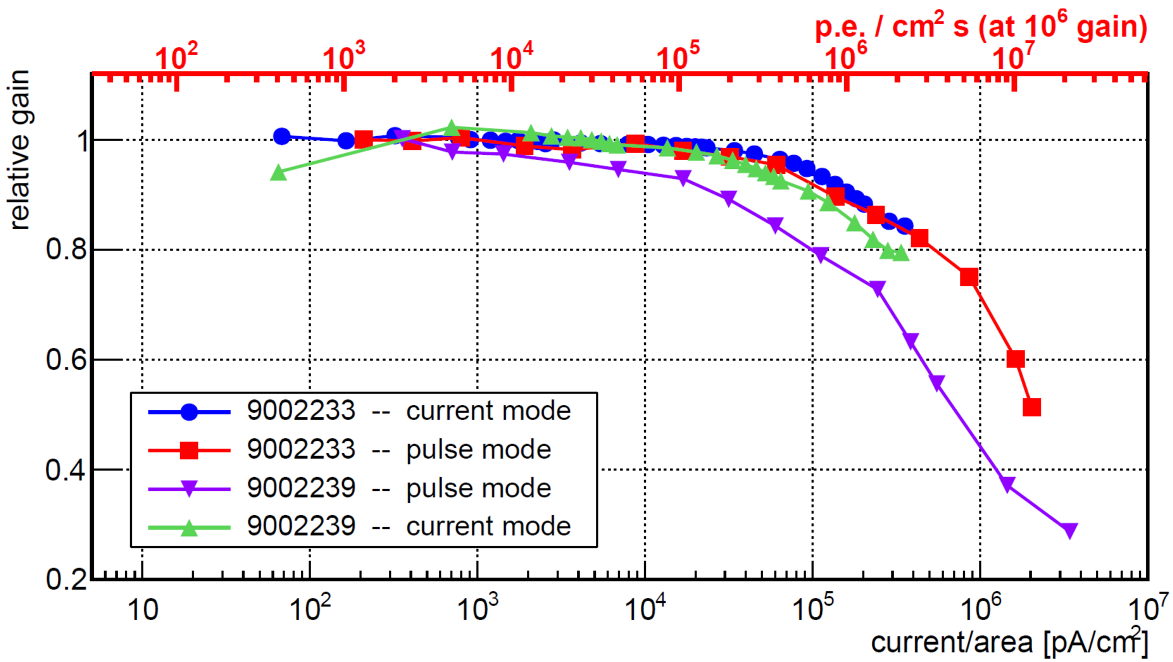


V.A. Chirayath et al., Talk at CPAD 2021



MCP PMTs: high rate operation

High rate performance studies



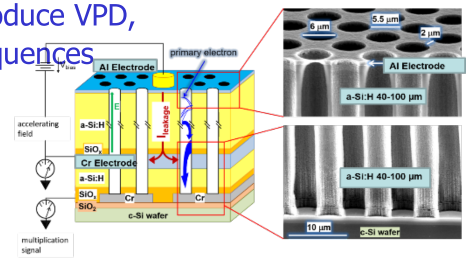
A. Lehman et al.,
https://arxiv.org/abs/2403.169536

→ Gain degradation at fluxes of 10^7 photoelectrons per cm^2

MCP-PMTs: New materials and read-out options

New materials, new coatings, longevity and rate capability study

This concerns the R&D on new materials to produce VPD, new shapes and new coatings and their consequences on their longevity and rate capability

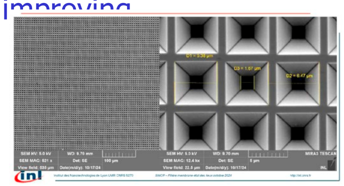


[1] A. Franco *et al.* Sci. Rep. 1 (2014).

Amorphous Si MCPC(Geneva)

New photocathode materials, structure and high quantum efficiency

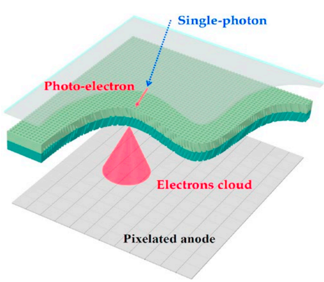
New photocathode materials, new structures and their impact on improving the quantum efficiency for different wavelengths

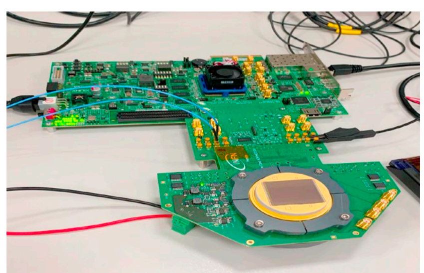


Si nanometric structure for reflective photocathode (Lyon)

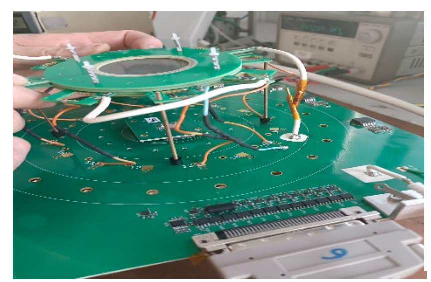
Time and spatial resolution performance

Study of VPD timing and spatial performance using appropriate readout electronics and appropriate anode structures

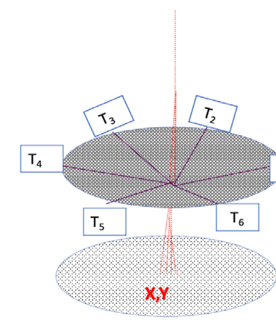




MCP+Timepix4 (Ferrara)



MCP+PICMIC concept (Lyon)



time

Woven strips

Novel vaccum-based devices

MCP-PMT with CMOS anode

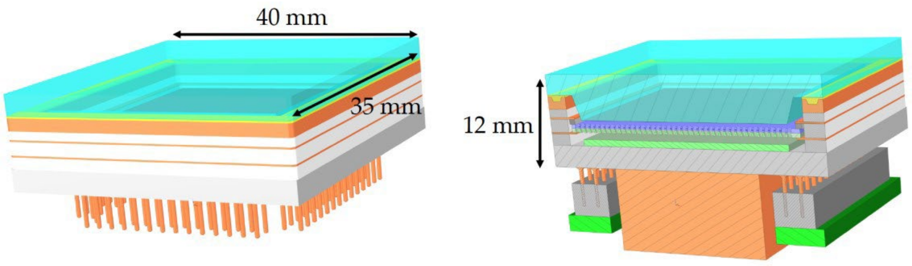
Conceptual design for 4D detection of single photons

- 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

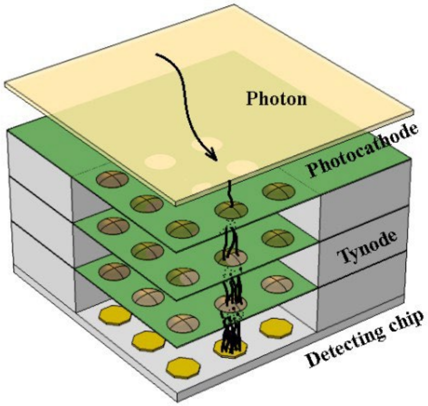
- <100 ps time resolution and 5-10 µm spatial resolution
- Rate capability of >100 MHz/cm² (<2.5 Ghits/s @ 7 cm² area)
- Low gain (~10^4) operation possible → x100 lifetime increase

M. Fiorini, RICH2022

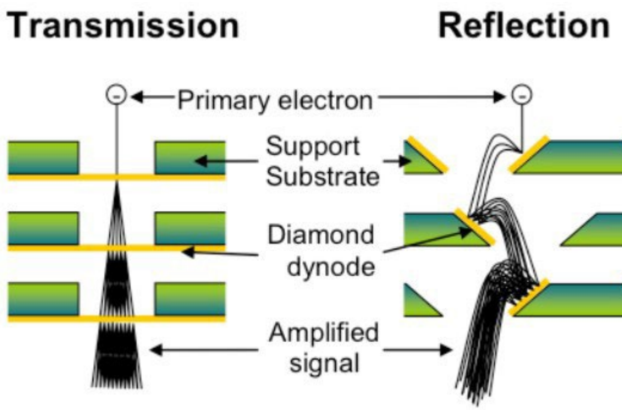


Tynodes (→ Time Photon Counter)

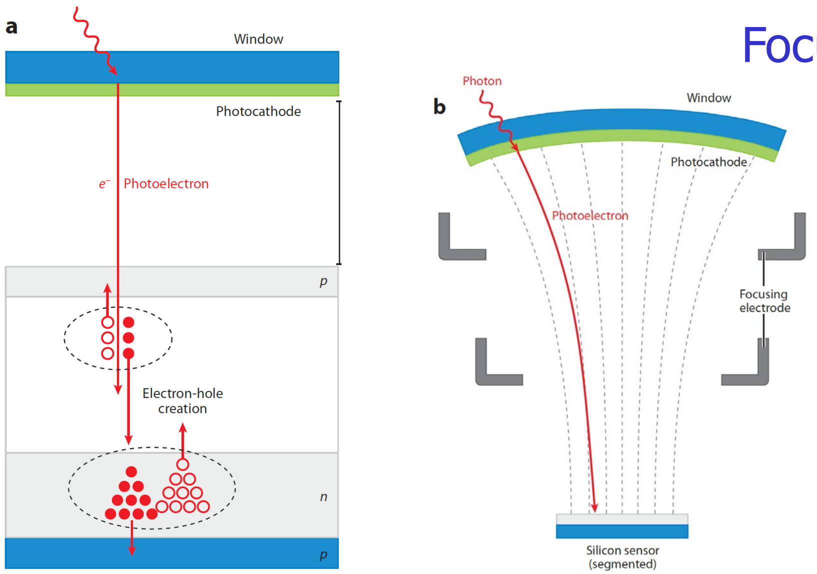
- Transmission mode dynode → tynode
- Fabrication of tynodes (MgO ALD, diamond) using MEMS technology
- "Anode" is a CMOS chip (e.g., TimePix)
- Very promising properties
  - Very compact; high B-field tolerance; very fast
  - Very low DCR; very good 2D spatial resolution



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



Hybrid photodetectors (HPD, HAPD)



Focusing and proximity focusing configurations

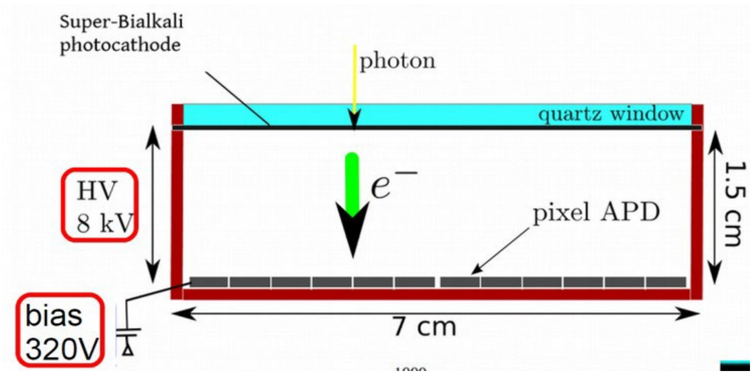


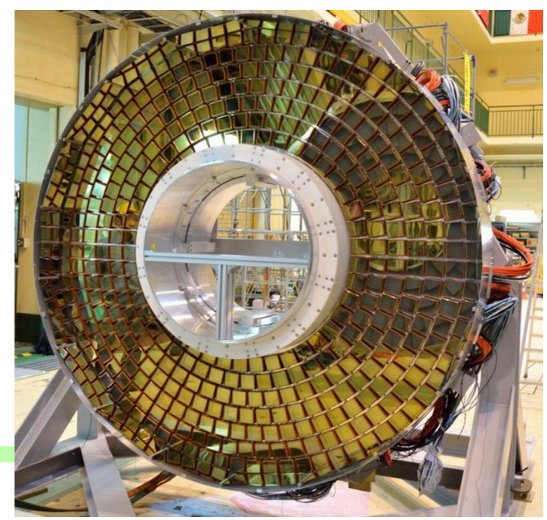
Photo-electron acceleration in a static electric field (8kV to 25 kV)

Photo-electron detection with

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

Employed on a large scale:

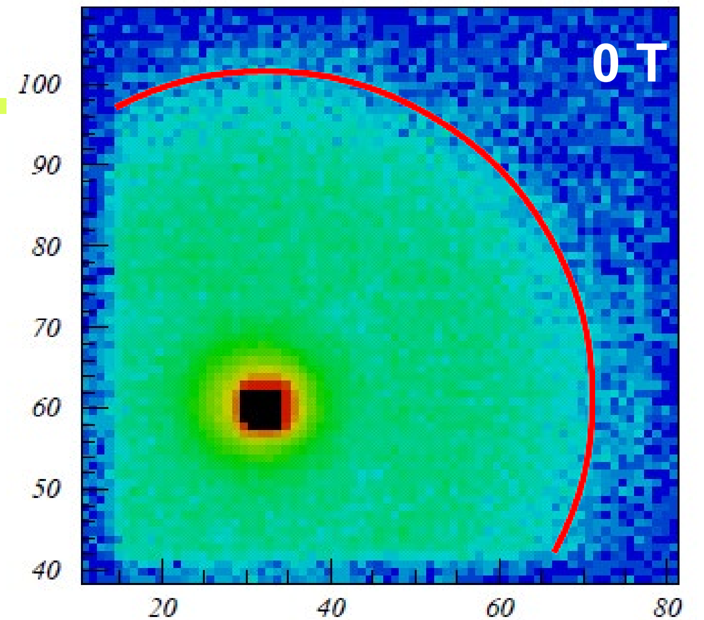
- HPD: RICH1+RICH2 of LHCb (Run 1+2), CMS HCAL
- HAPD: Aerogel RICH detector of Belle II

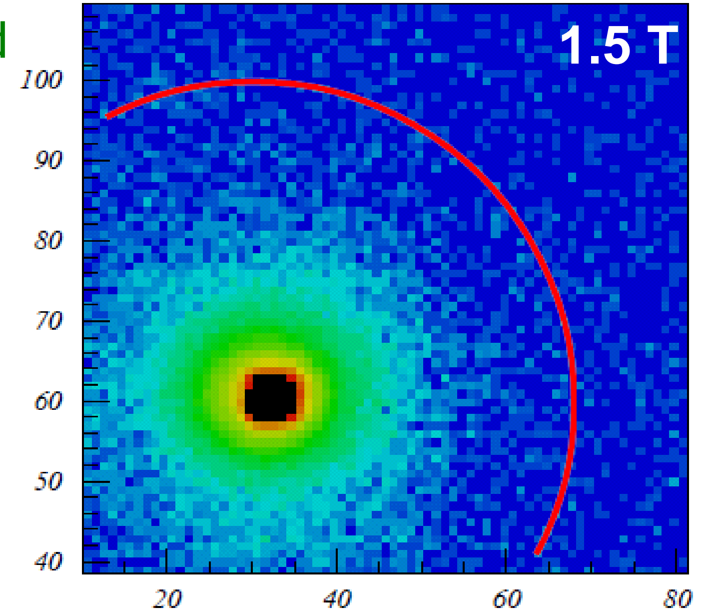


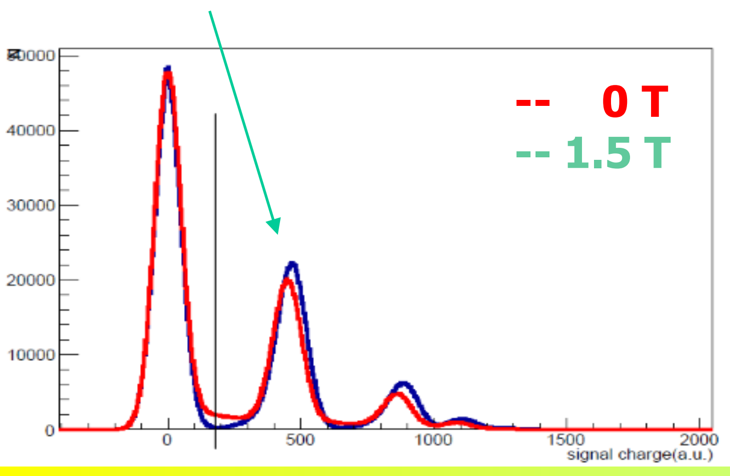
HAPD: photoelectron backscattering in magnetic field

- around 20% of photoelectrons back-scatter and the maximum range is twice the distance from photocathode to APD ~40mm

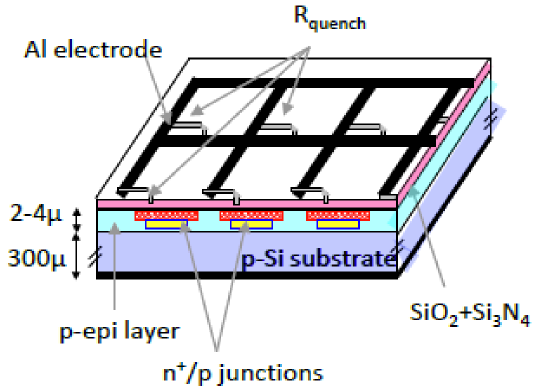
- in a strong magnetic field (perp. to the HAPD window) scattered photoelectrons follow magnetic field lines and fall back to the same pad
- photoelectron energy is deposited at the same pad







Solid state low-light-level sensors

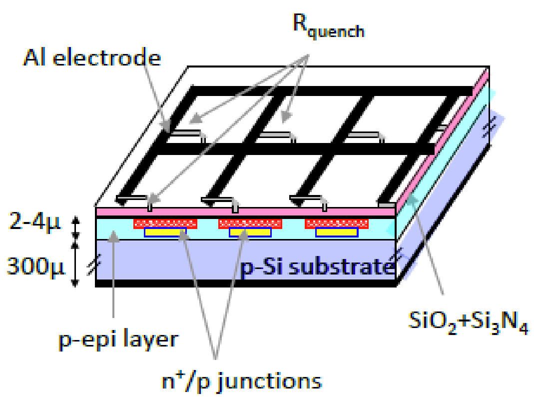


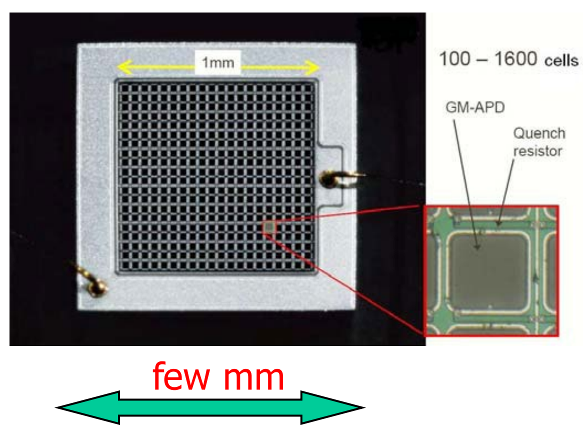
Solid state low light level photosensors: Silicon photomultipliers SiPM

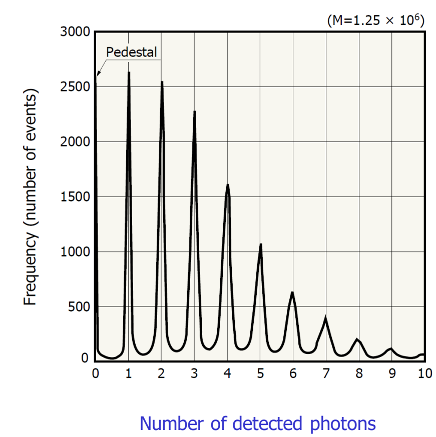
An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

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

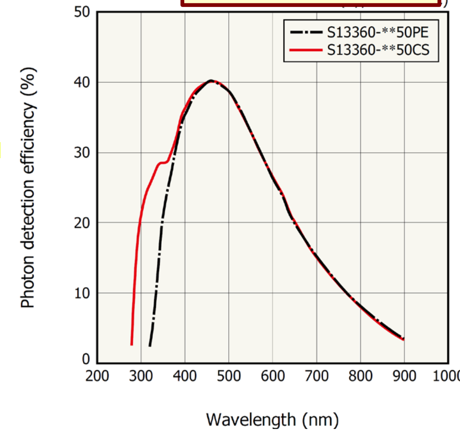






SiPMs as single photon detectors

Hamamatsu data sheet



SiPM as low-light-level sensors.
Characteristics:

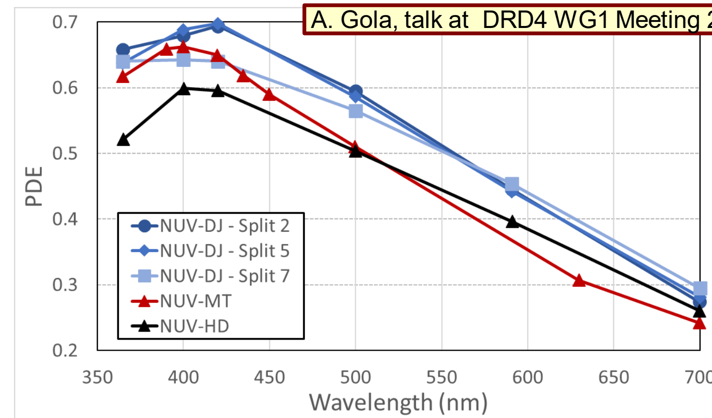
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

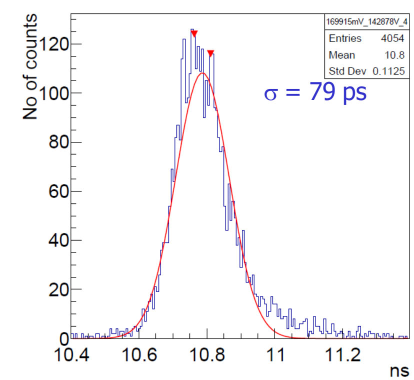
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field

- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)

*PDE = photon detection efficiency

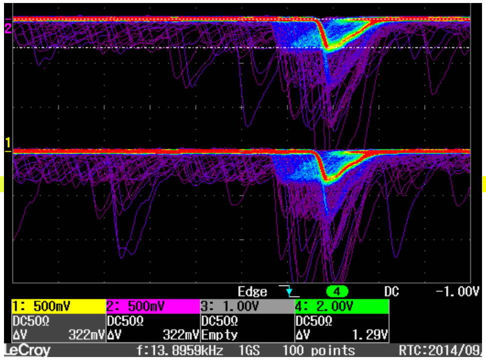
A. Gola, talk at DRD4 WG1 Meeting 2024

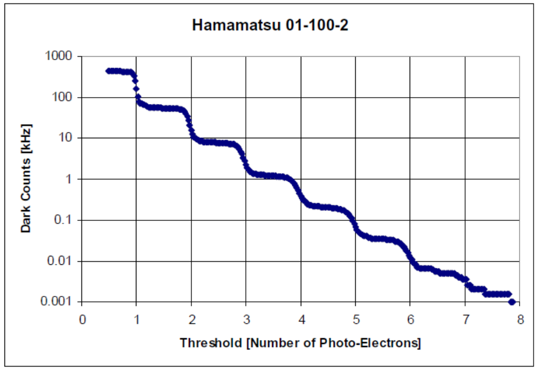




M.V. Nemallapudi et al
2016 JINST 11 P10016

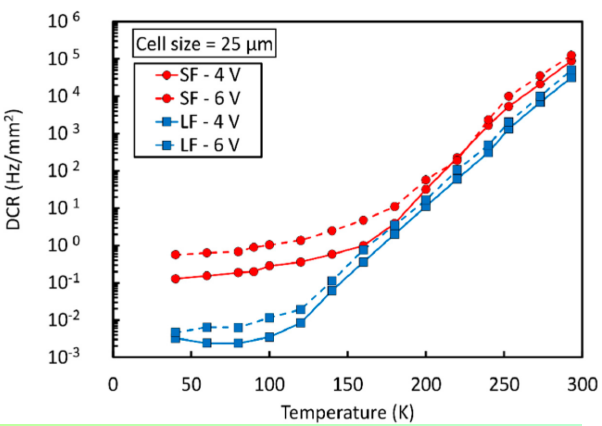
SiPM: noise





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

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



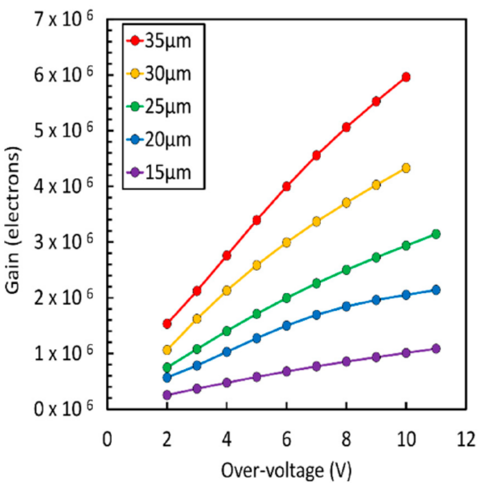
- optical cross-talk produced when photons emitted in avalanche initiate signal in neighbouring cell; reduced by screening – trenches

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

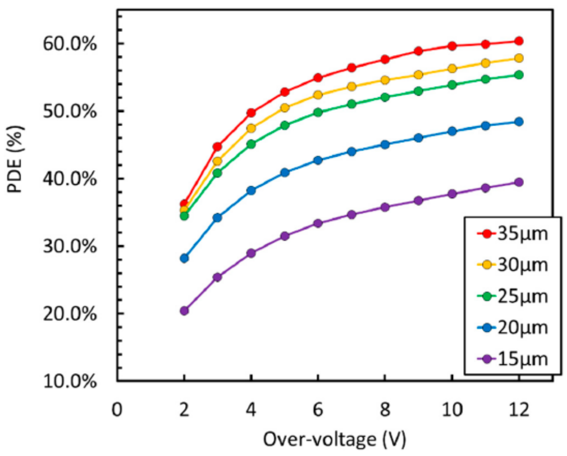
SiPM: parameter correlation

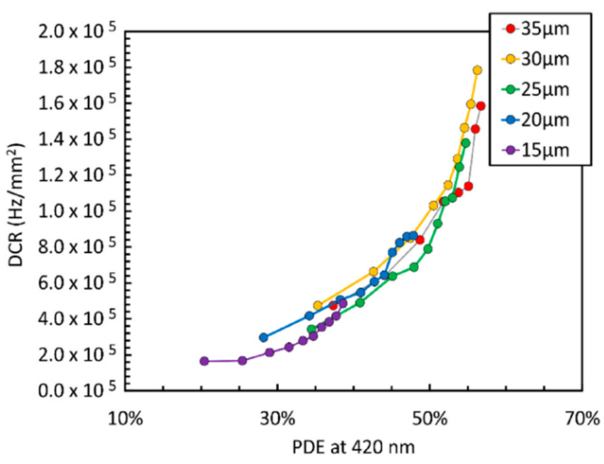
Higher overvoltage:

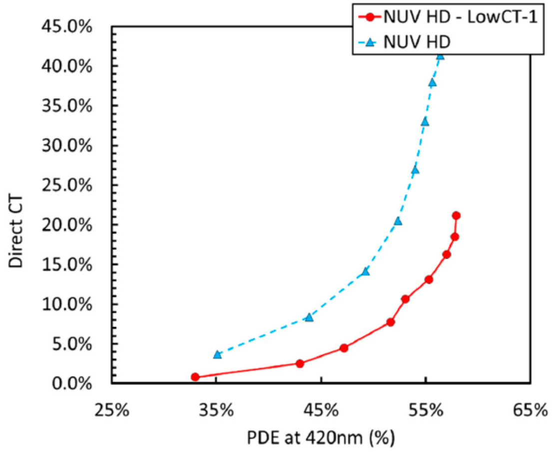
- higher field:
  - higher avalanche trigger probability → higher PDE
  - faster signal → better timing
- higher gain:
  - better signal to noise (electronic)
  - more optical cross-talk → higher ENF, worse timing
  - more after-pulses



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



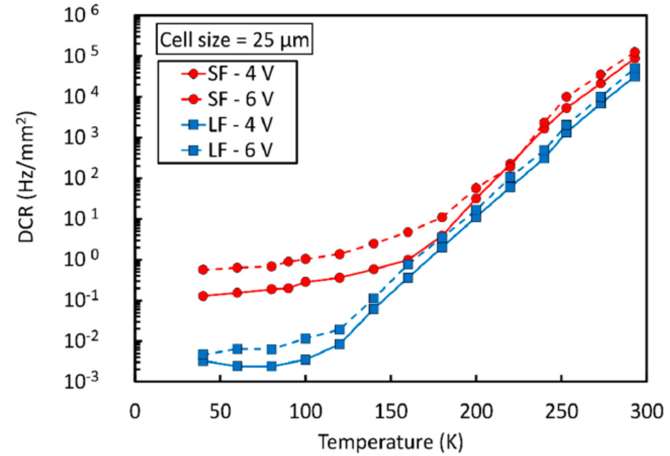




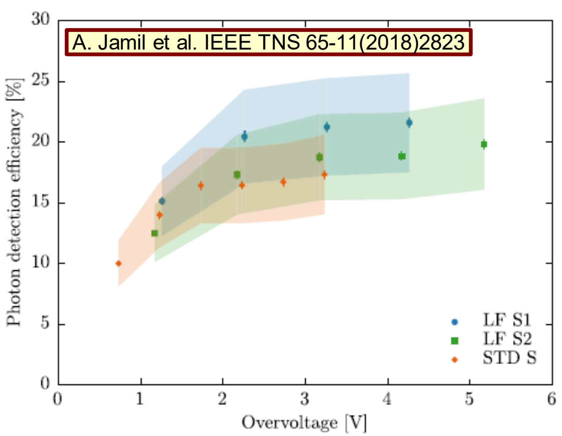
VUV SiPM for cryogenic applications

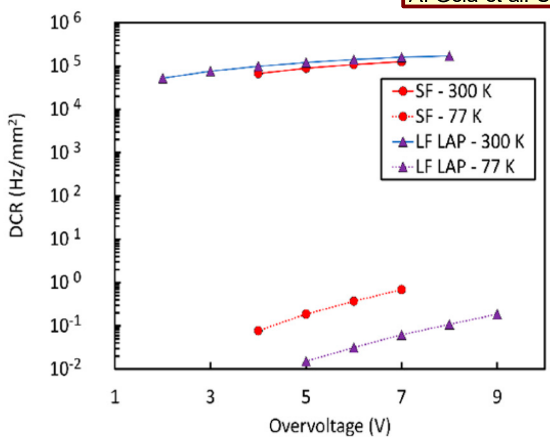
LAr, LXe applications:

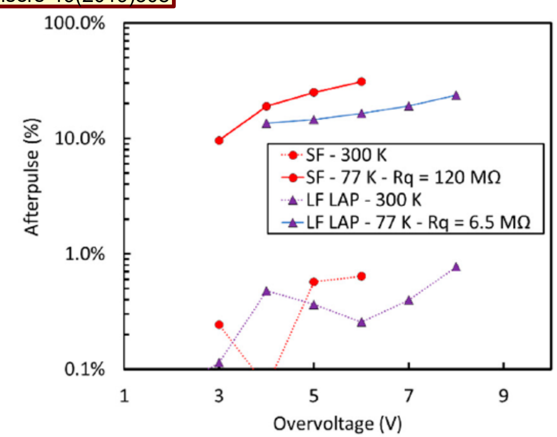
- VUV sensitivity required:
  - 128 nm (LAr), 178 nm (LXe)
  - optimization of anti-reflective coating ARC
  - PDE $\approx 20\ \%$
- cryogenic temperatures:
  - low DCR $\approx 10\mathrm{mHz/mm^2}$ dominated by band-band tunnelling, reduced by low-field avalanche region
  - higher after-pulse rate $\approx 10\%$



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







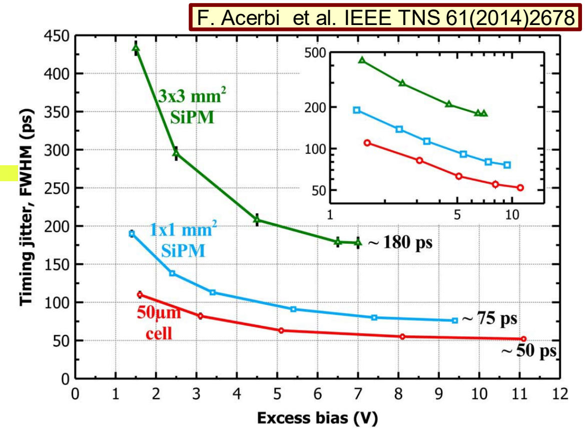
SiPM: single photon timing

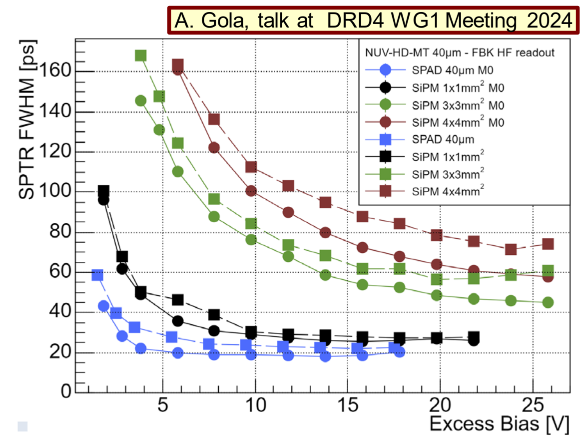
Intrinsic TTS of SiPM microcells is extremely fast, $< 20\ \mathrm{ps}$ for single microcells (SPAD), but timing deteriorates for larger devices. The main contributions:

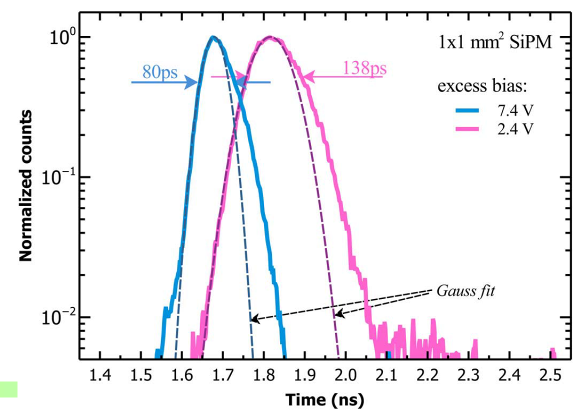
- nonuniformity within microcell (edges)
- spread between microcells
- overall SiPM capacitance
- λ dependence - tails

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, $\sigma_t \approx \sigma_{el.} \left(\frac{dU}{dt}\right)^{-1}$



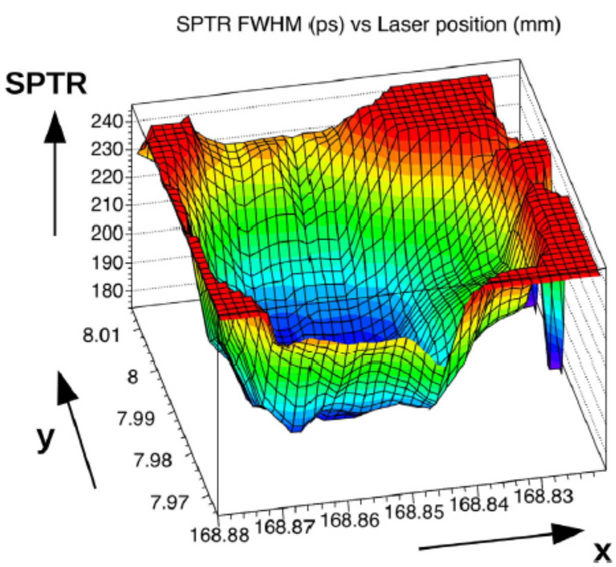




SiPM: timing variation

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

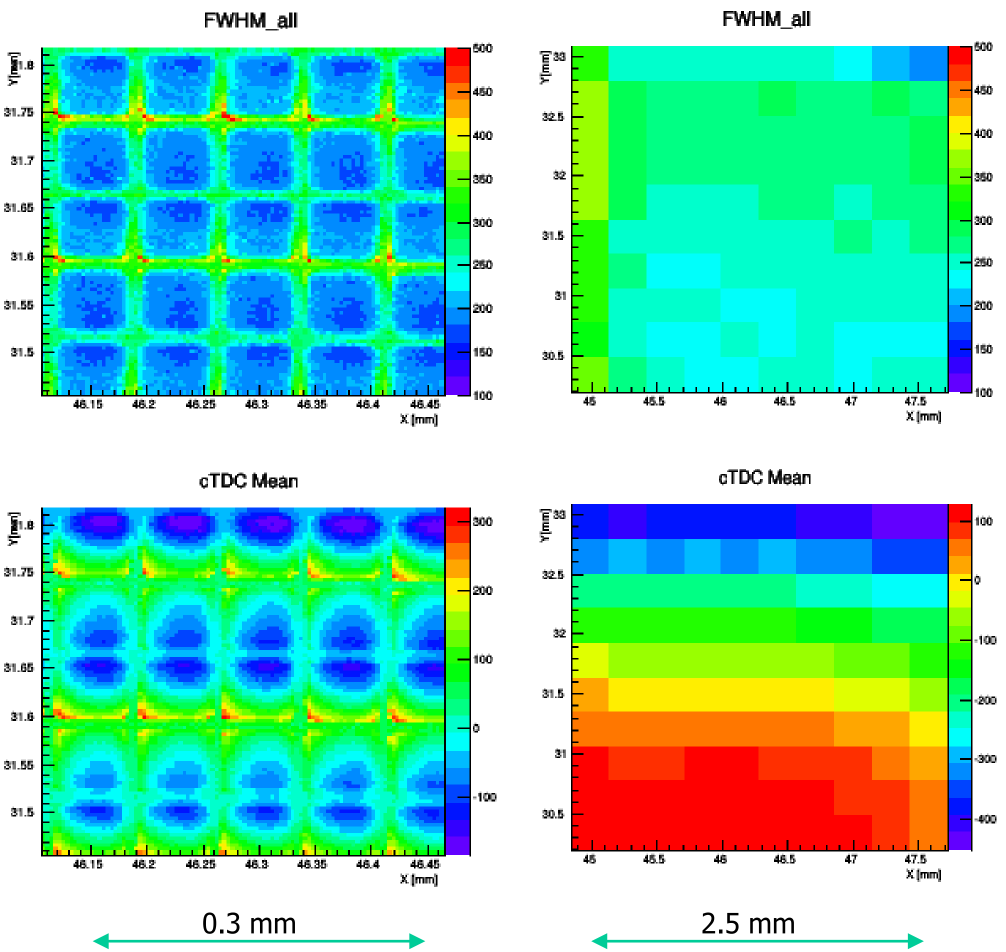
- variation within micro-cell
- variation for different micro-cells



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

KETEK PM3375TS-SBO (early design)

S. Korpar et al. @IEEE 2015

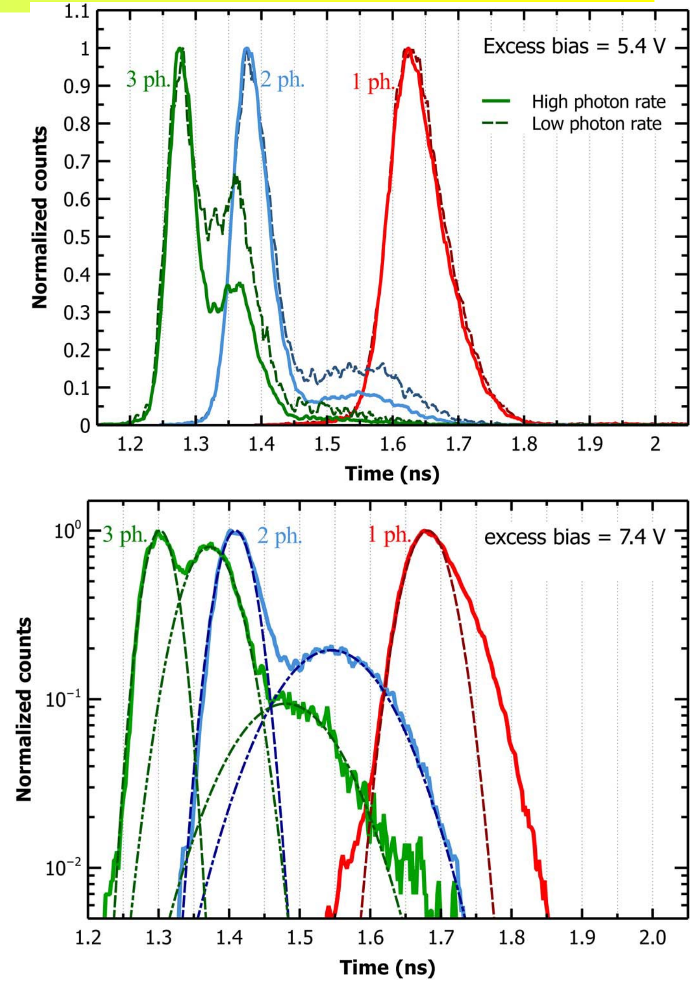


FBK: Masking of outer regions of micro-cells: Improve signal peaking and mask areas of micro-cell with worse timing

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

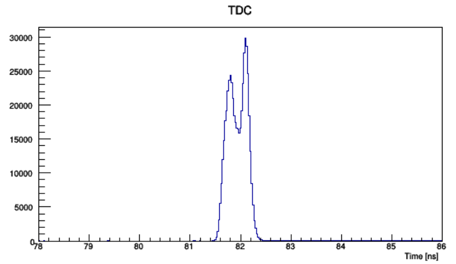


F. Acerbi et al. IEEE TNS 61(2014)2678

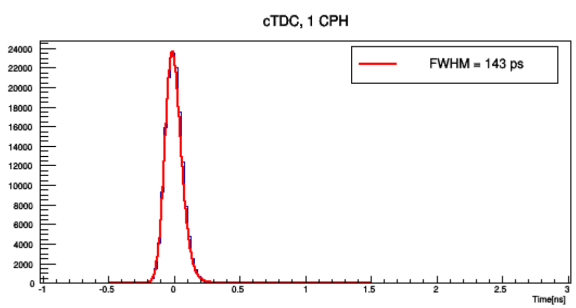
SiPM: timing test with pico-second laser

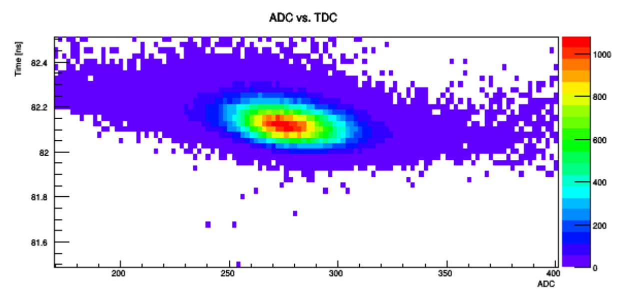
Optical cross-talk contribution to multi-cell signals spoils timing distribution-
two components for 2-micro-cell signals:

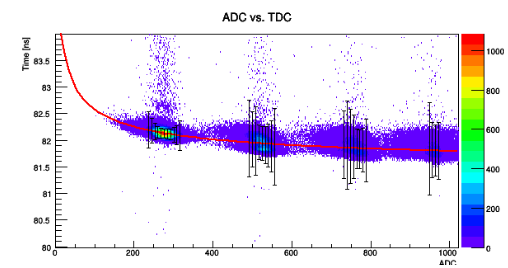
- double photon events – proper scaling
- single photon with cross-talk, timing somewhere between single and double micro-cell signals and resolution is worse

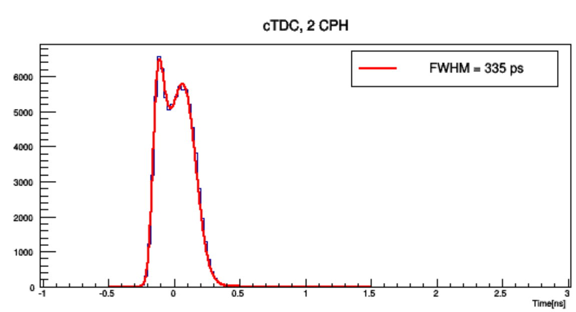


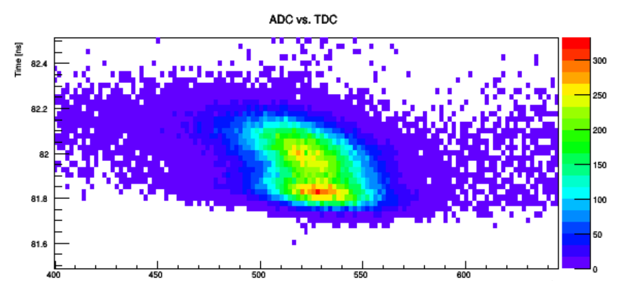
- AdvanSiD SiPM ASD-NUV3S-P-40
- OV=6V, T=-25^{o}C, blue laser λ=408nm, ~35ps FWHM

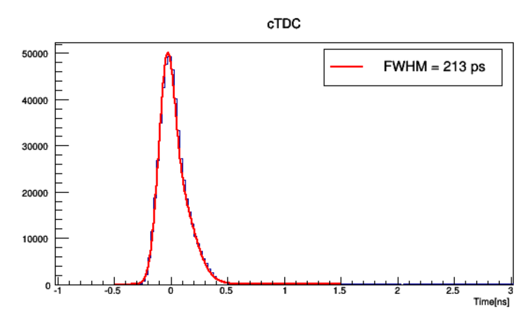










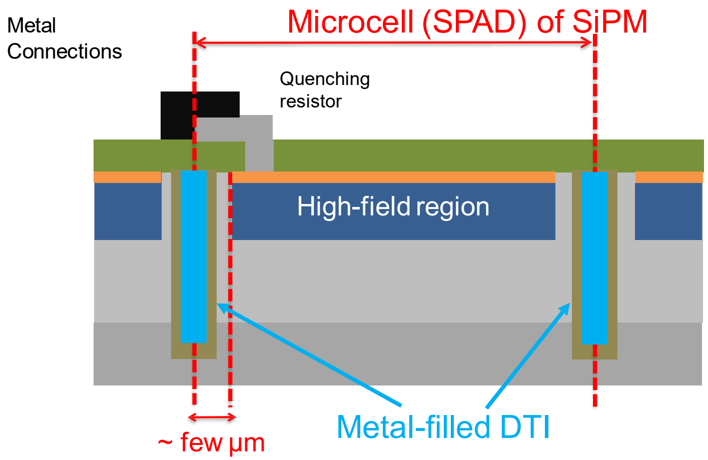


R. Dolenec et al. NIM A876(2017)257

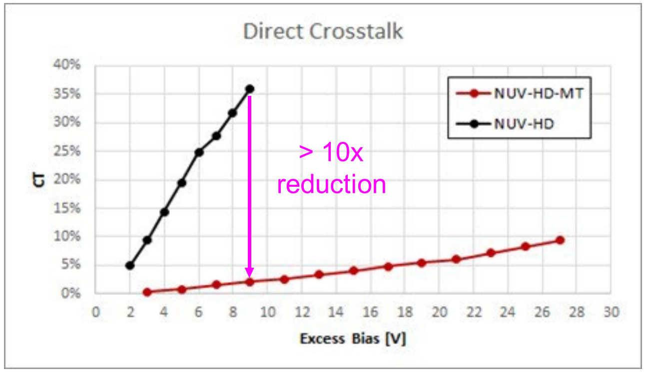
Reduction of optical crosstalk

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.

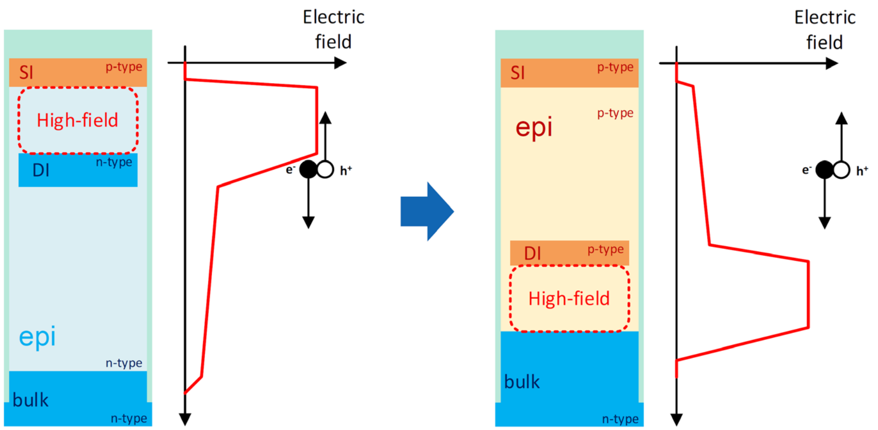
A. Gola, talk at RICH2022

SiPMs: structure optimization, example

By moving the high-field region towards the bottom of the epitaxial layer, the PDE is enhanced.

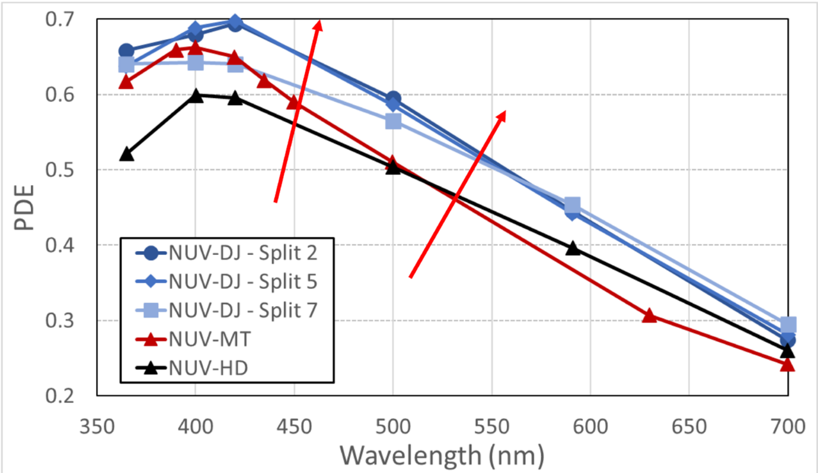
Avalanche is mostly triggered by electrons.

Conceptual drawing of the different NUV.MT (left) and NUV-DJ (right) microcell structures →



Conceptual drawing of the different NUV.MT and NUV-DJ microcell structures (cross-sections, not to scale)

PDE increase: from holes to electrons triggering the avalanche



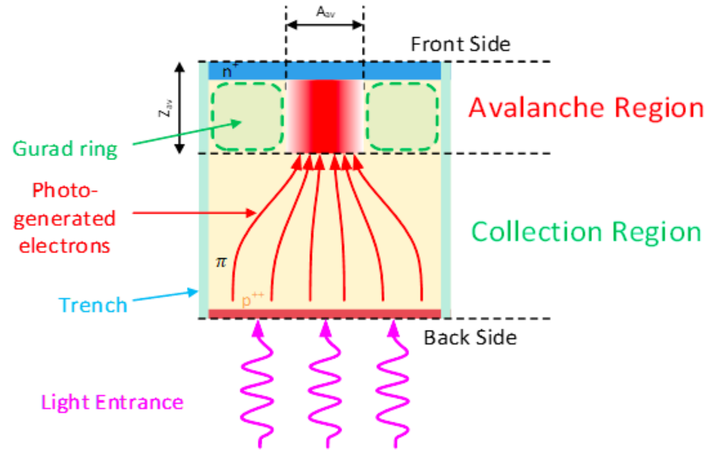
PDE vs. wavelength measured on the 45 μm cell of the NUV-HD-MT technology (12 V) and on the 40 μm cell of the NUV-HD and of the newly introduced NUV-DJ SiPM technologies (9 V).

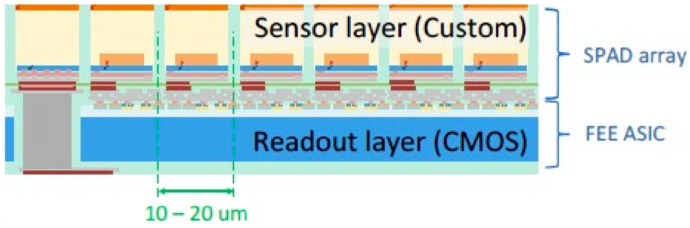
PDE vs. wavelength measured on the 45 μm cell of the NUV-HD-MT technology (12 V) and on the 40 μmcell of the NUV-HD and of the newly introduced NUV-DJ SiPM technologies (9 V).

A. Gola, talk at DRD4 WG1 Meeting 2024

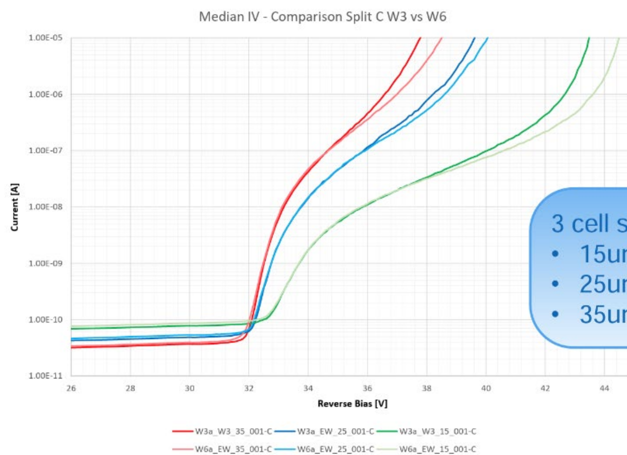
Backside illuminated SiPMs

Backside illuminated (BSI) SiPMs: potential for an enhanced PDE and a better radiation tolerance.





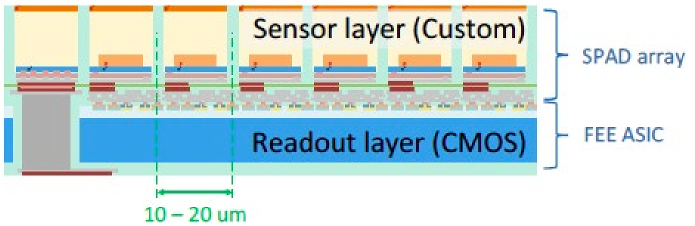
The first results of the FBK IBIS Run samples



3 cell sizes tested:
- 15um
- 25um
- 35um

Hybrid SiPMs

Separated sensing and readout layers, both in CMOS



Custom SiPM technology for sensing layer

- CMOS-compatible → transfer to large-volume foundries is possible
- ~10 lithographic masks - Lower cost per unit area compared to a full CMOS process (>40 masks)
- Customized fabrication process, no constraint form transistor fabrication → best electro optical performance possible, also after irradiation (e.g. DCR, DCR vs.T , PDE, correlated noise, etc)
- Cheap to iterate/adjust the design → Different sensing layers for different applications, room for subsequent upgrades without changing readout ASIC
- All the wafer area is sensitive to light → maximum detection efficiency (PDE)

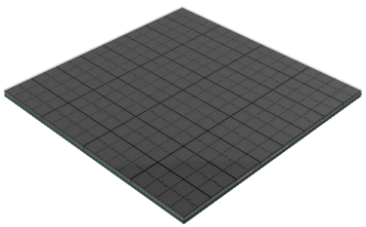
CMOS technology for readout layer

- Free choice of CMOS node → optimal performance of readout.
- CMOS area can be smaller than sensing area (2.5D) → lower cost
- Independent design cycles of the sensing layer and readout layer → more efficient R&D phase

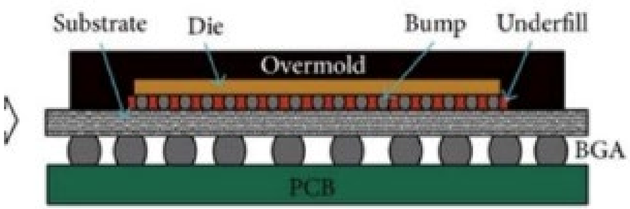
A. Gola, talk at DRD4 WG1 Meeting 2024

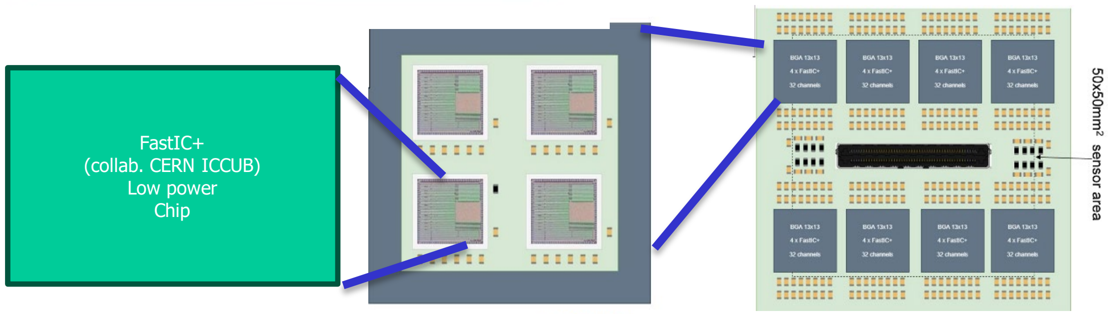
Ultragranular SiPMs with integrated electronics

Timing of SSPD & Developing ultra-granular SiPM that integrates with the readout electronics



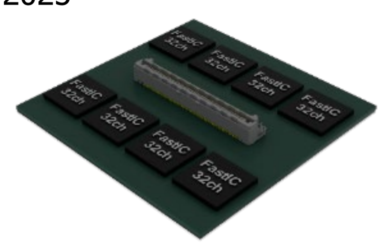
3x3 mm^2 SiPM array



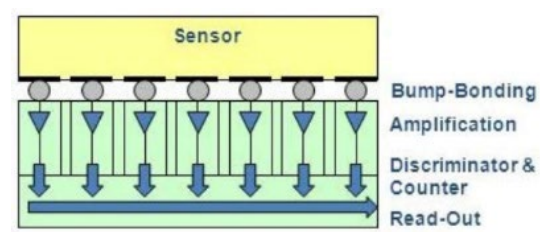


2024 Produced and evaluated

design & production 6.2025



256 Ch 5x5cm^2 Module proposal

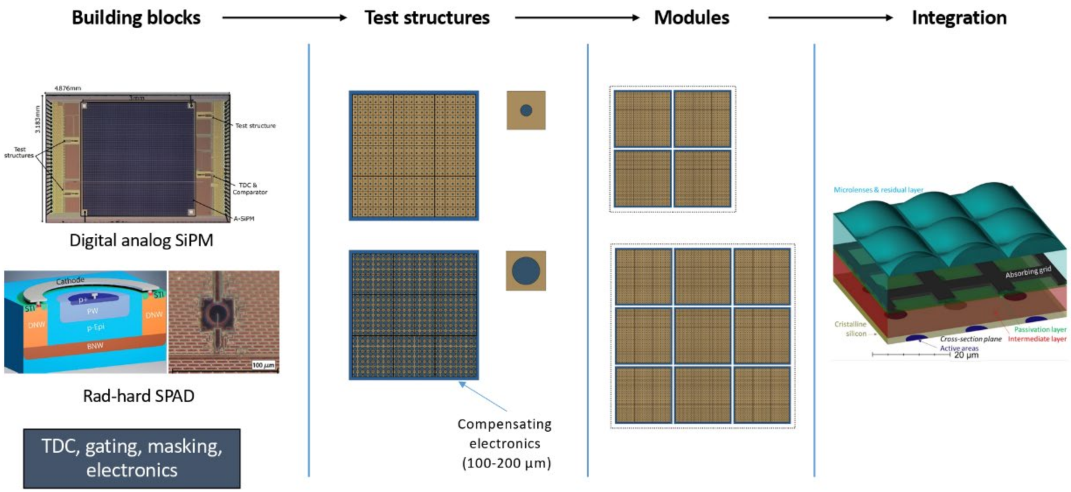


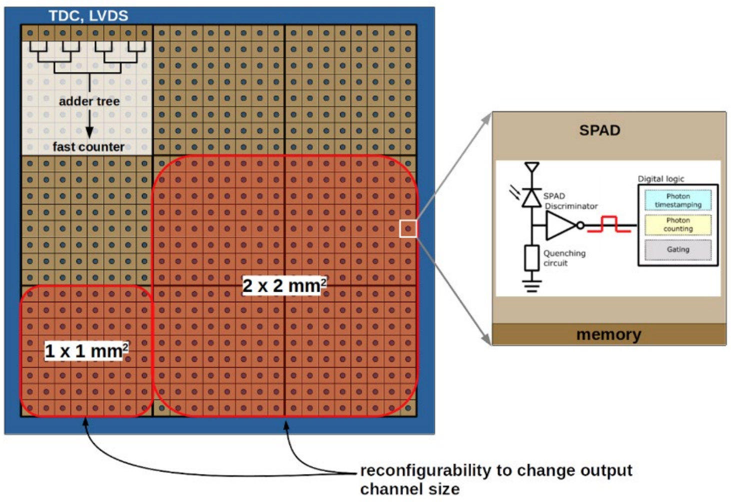
Ultra granular SiPMs

SiMs: SPAD with micro-lenses

CMOS-SPAD light sensors: co-integration of SPADs and electronics, digitised output signals

spadRICH - Radiation-hard digital analog silicon photomultipliers for future upgrades of Ring Imaging Cherenkov detectors





aqualab EPFL

Institut "Jožef Stefan" Ljubljana, Slovenija

Light concentrators

At the device level (lenses, Winston cones):

- For a given active area reduce sensor area – reduce dark count rate (tolerate higher fluences)
- use smaller faster devices

Higher concentration – narrower angular acceptance

Imaging light concentrators:

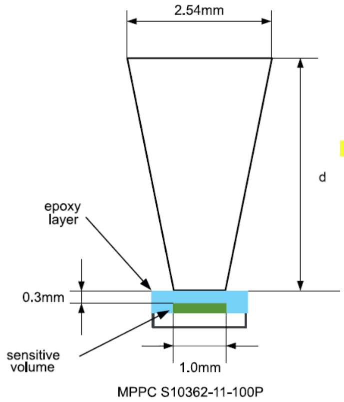
- smaller photon impact angles on the sensor
- can be used with position-sensitive arrays

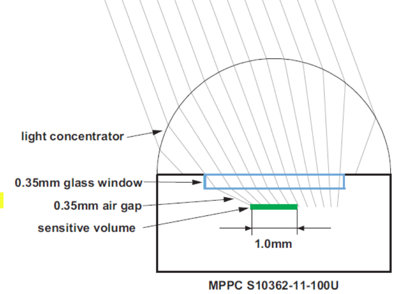
Non-imaging light concentrators:

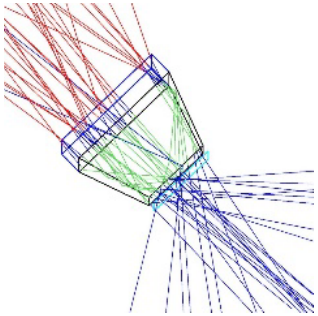
- larger photon impact angles on the sensor – directly coupled to the sensor

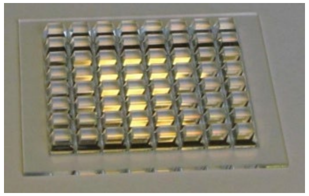
At the micro-cell level (micro-lenses, diffractive lenses, meta lenses):

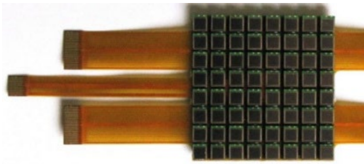
- compensate for low fill factor – small cells, dSiPM
- concentrate light in cell centre – better timing

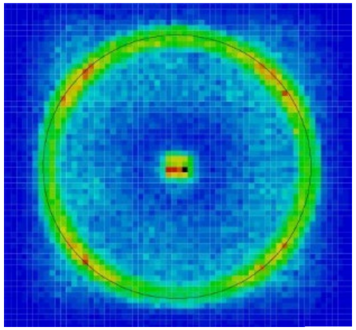


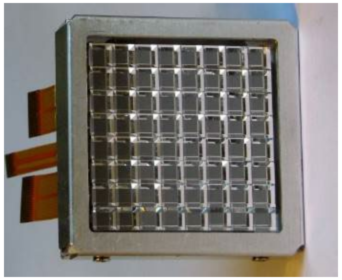












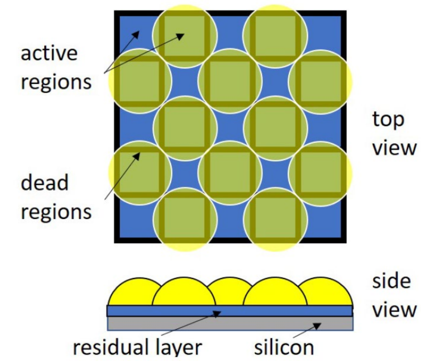
RICH with SiPMs + light concentrators

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

Microlenses for light collection

Light concentration at the micro-cell level (micro-lenses, diffractive lenses, meta lenses):

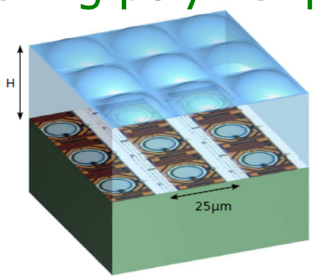
- compensate for low fill factor – small cells, dSiPM
- concentrate light in cell centre – better timing

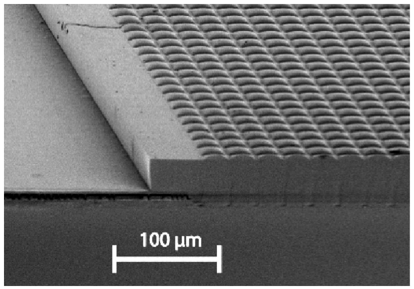


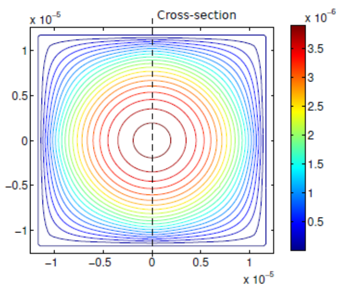
G. Haefeli et al., TNS, DOI 10.1109/TNS.2025.3542597

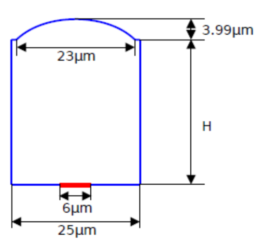
Micro-lens array coupled to SPAD array

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

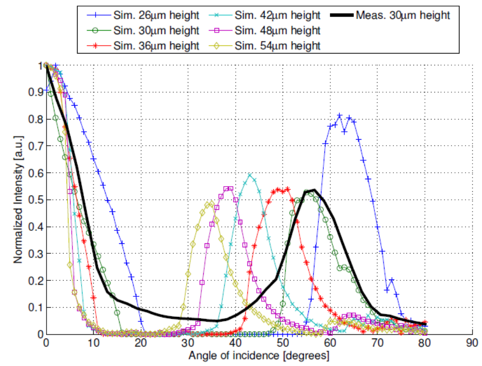


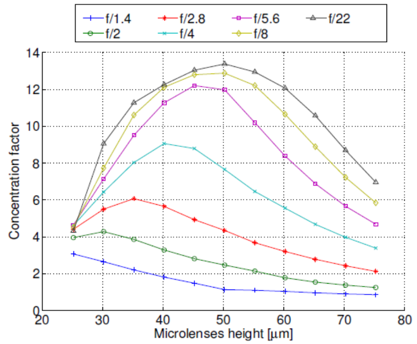




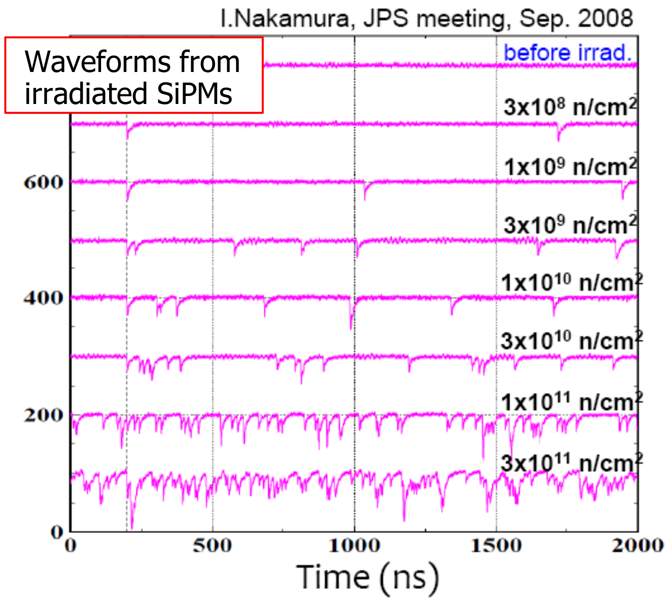


J.M. Pavia et al. Opt.Exp. 22-4(2014)4202





SiPMs: Radiation damage



Show stopper at fluences above ~10^{11} n cm^{-2} in case single (or few) photon sensitivity is required!

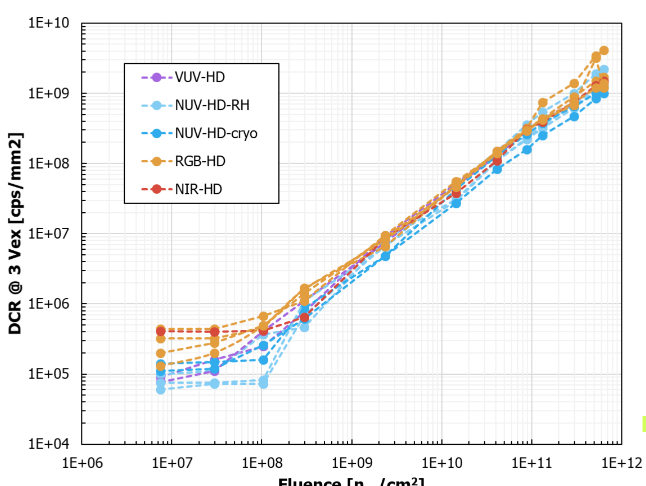
→ Use of wave-form sampling readout electronics

→ 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?



ANN]

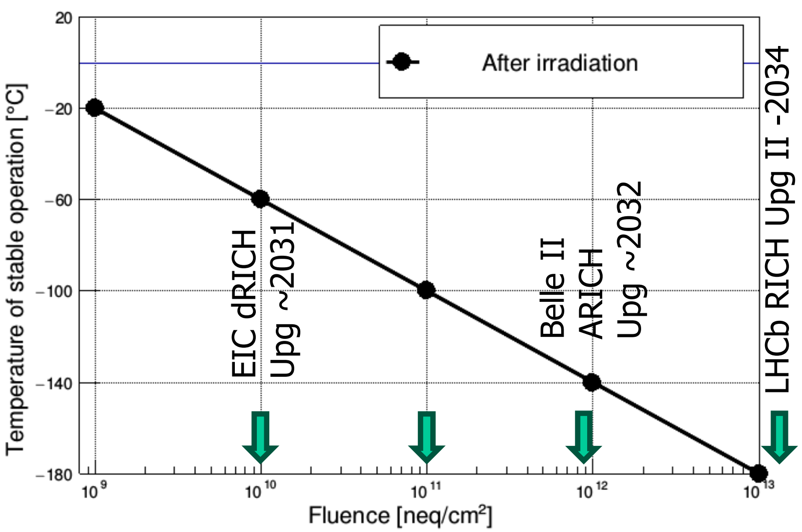
Beyond 10^7÷10^8 n_{eq}/cm^2 little correlation between the DCR before and after irradiation:

- All technologies seem to “converge” toward similar values
- Independence of bulk damage from contaminants in the SiPM starting material?
- Room temperature annealing has little effect if shorter than ~1 day

SiPMs: radiation damage, mitigation

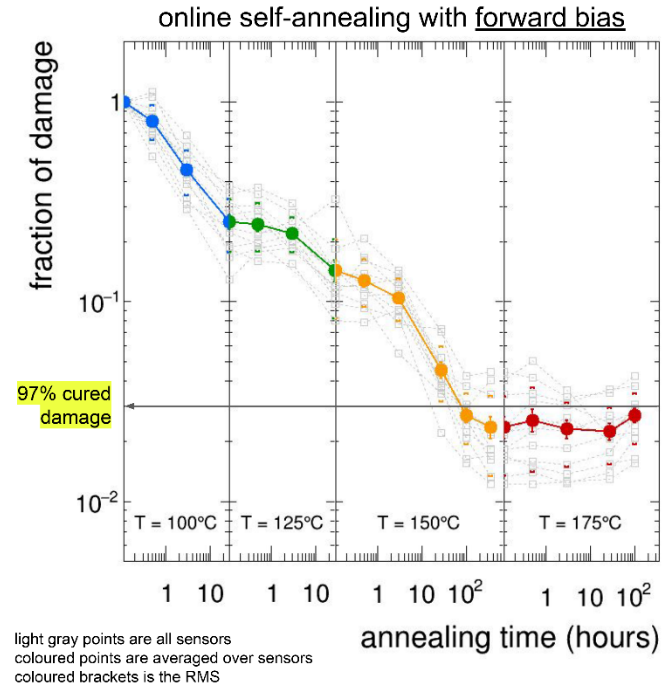
Operation of highly irradiated SiPMs for single photon detection – cooling and annealing

Cooling: Temperature at which the SiPMs are "usable" for single-photon detection, i.e. where the single photo electron peak @ 9V over-voltage is separated from the background.



D. Consuegra-Rodrigez et al., Eur. Phys. J. C 84, 970 (2024)

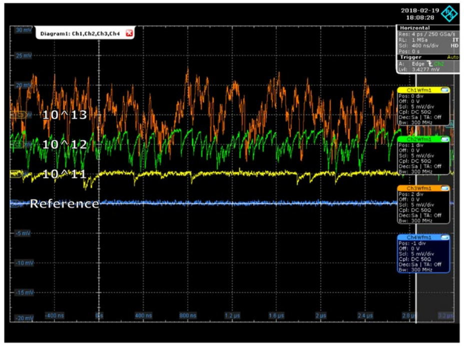
Annealing

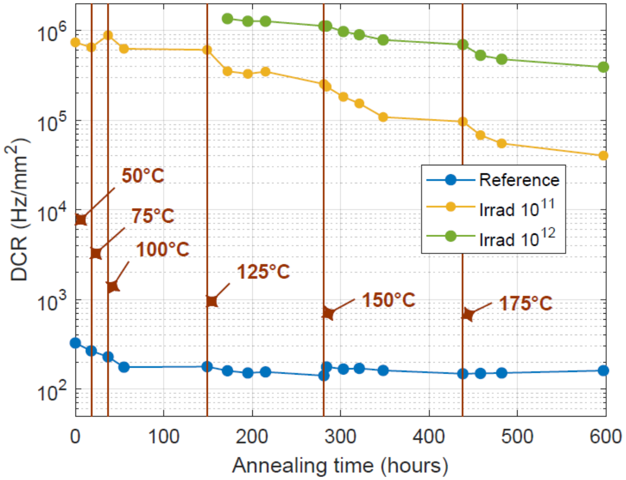


R. Preghenella, talk at PD24

SiPMs: Radiation damage, annealing at elevated temperatures

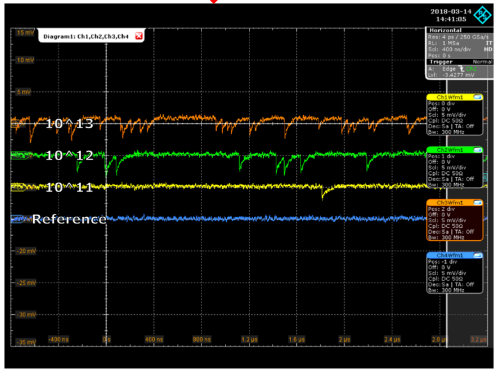
Dark counts at -30C of Hamamatsu S13360-1350CS SiPMs: non irradiated (blue) and irradiated up to 10^{11} (yellow), 10^{12} (green) and 10^{13} (orange) n_{eq}/cm^2

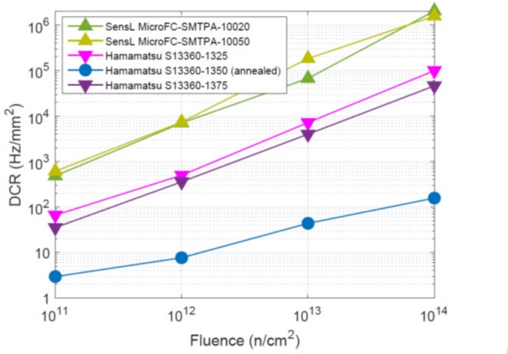




M. Calvi et al., NIMA 922 (2019) 243-249

annealing





DCR at 77 K versus neutron fluence
Blue circles: annealed sample
→ Annealing helps also at 77 K

SiPMs: radiation damage, mitigation

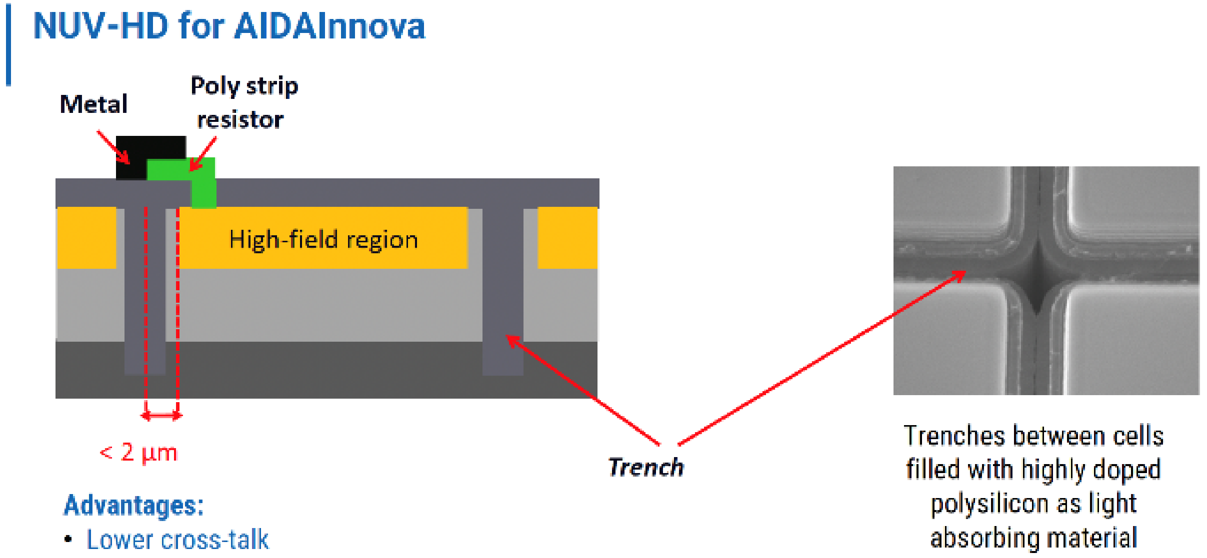
Fast & radiation hard SiPMs - enabling the use of SiPM in highly irradiated areas

Experimental structures, AidaInnova Run – exp. May 2025

Two different technologies:

- Low electric field
- Ultra Low electric field

Cell pitch: 15, 25, 40, 75um; SiPM sizes: $(0.25, 0.5,1,2,3)^2$ mm^2

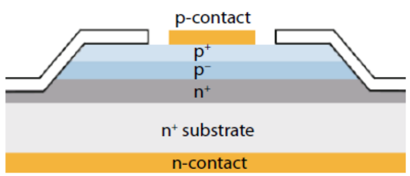


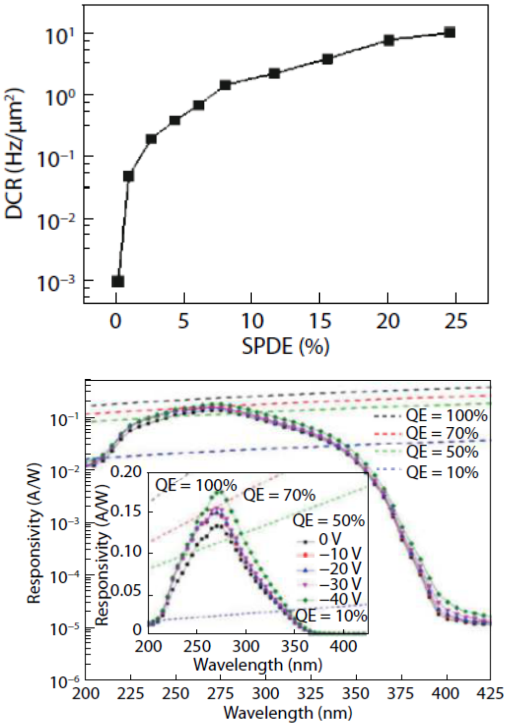
New materials

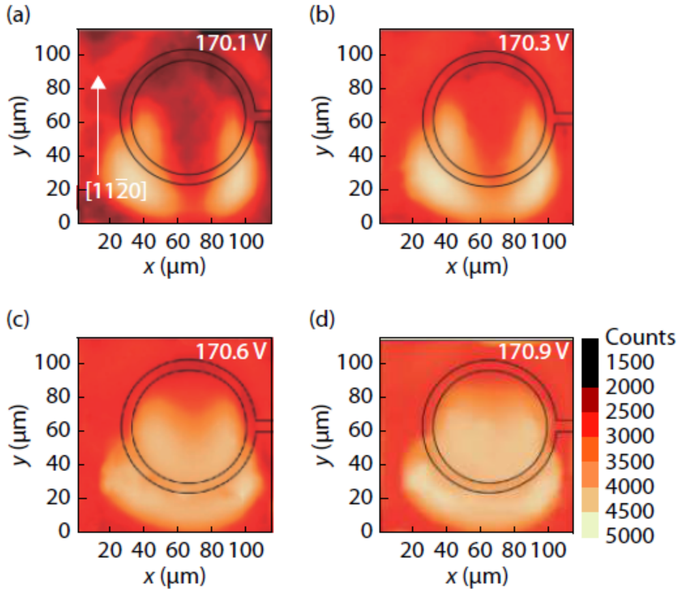
- new higher band gap materials - possibly lower DCR - higher radiation resistance, higher temperature
- (V)UV sensitive
- high dark count rate – dominated by trap assisted tunnelling

4H-SiC:

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

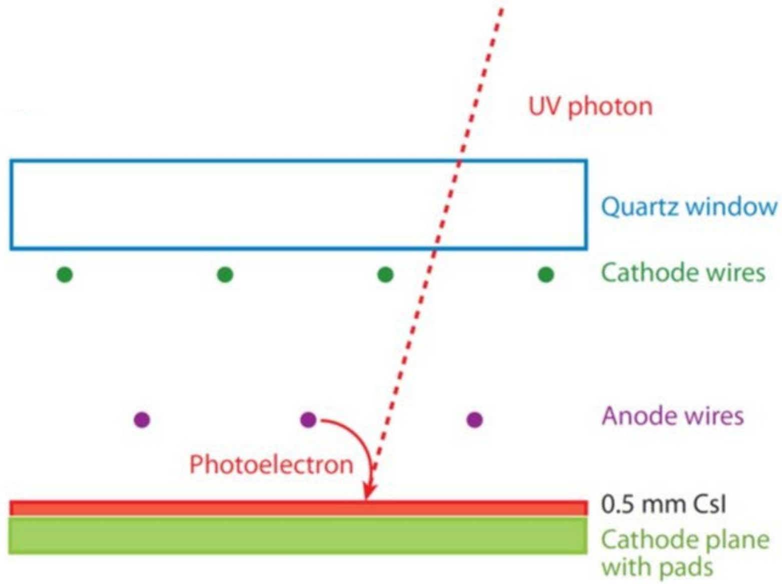




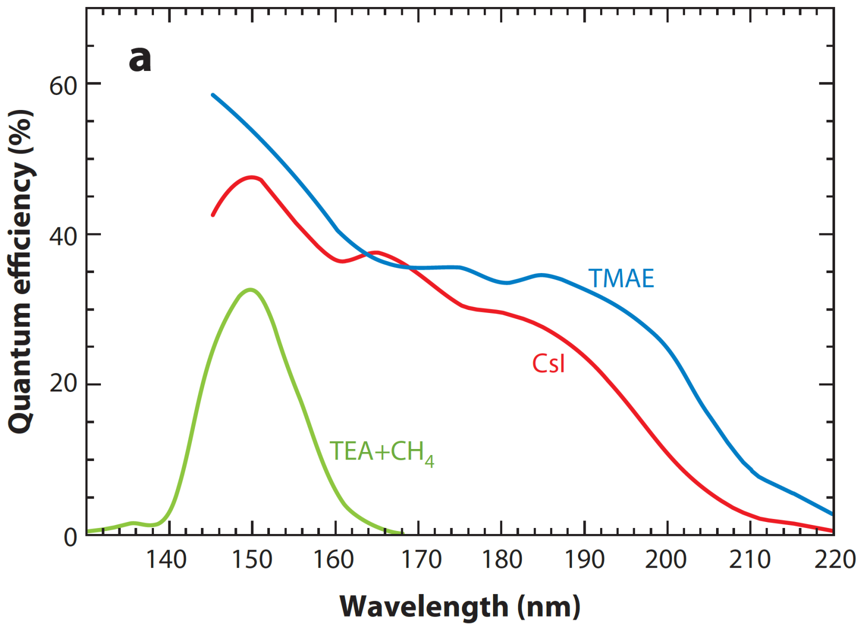


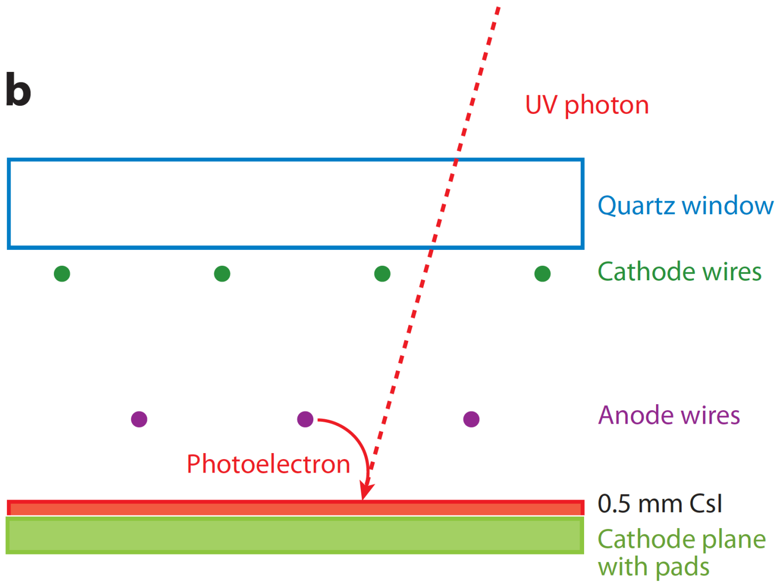
L. Su et al. J. Semicond. 40(2019)121802

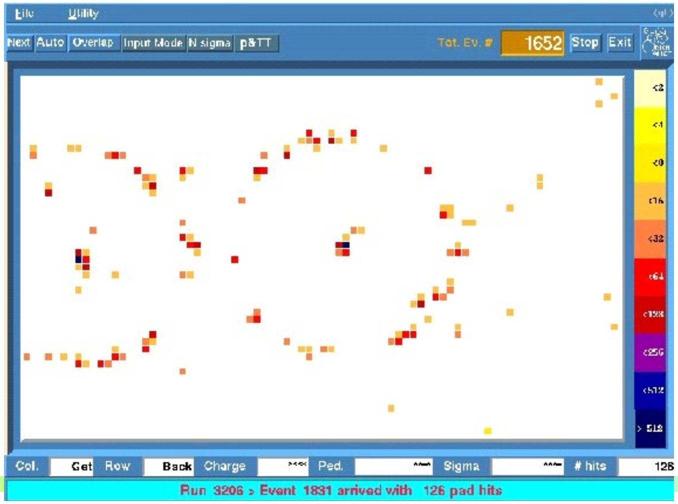
Gas-based light sensors



Gas based photon detectors







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

Large scale application: ~11 m^2 ALICE RICH

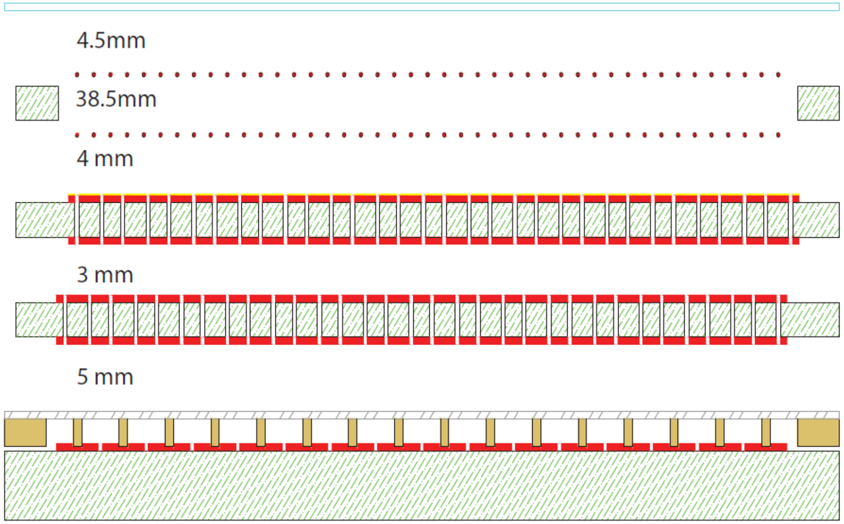
Gas based photon detectors: recent developments

Instead of MWPC:

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

•COMPASS RICH: transm. Photocathode, 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: photosensors with faster timing, wider spectral range and improved radiation tolerance.

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

A detector R&D collaboration (DRD4) was set up early in 2024 to facilitate collaboration in this area of research

Back-up slides

ECFA Detector R&D Roadmap

The ECFA Detector R&D Roadmap, developed following the 2020 European Strategy for Particle Physics, outlines a long-term vision to advance detector technologies critical for future particle physics experiments.

It emphasizes strategic planning and investment in areas like

- sensor development (gaseous, liquid, solid-state),
- photon detection,
- quantum sensing,
- calorimetry, and
- integrated electronics.

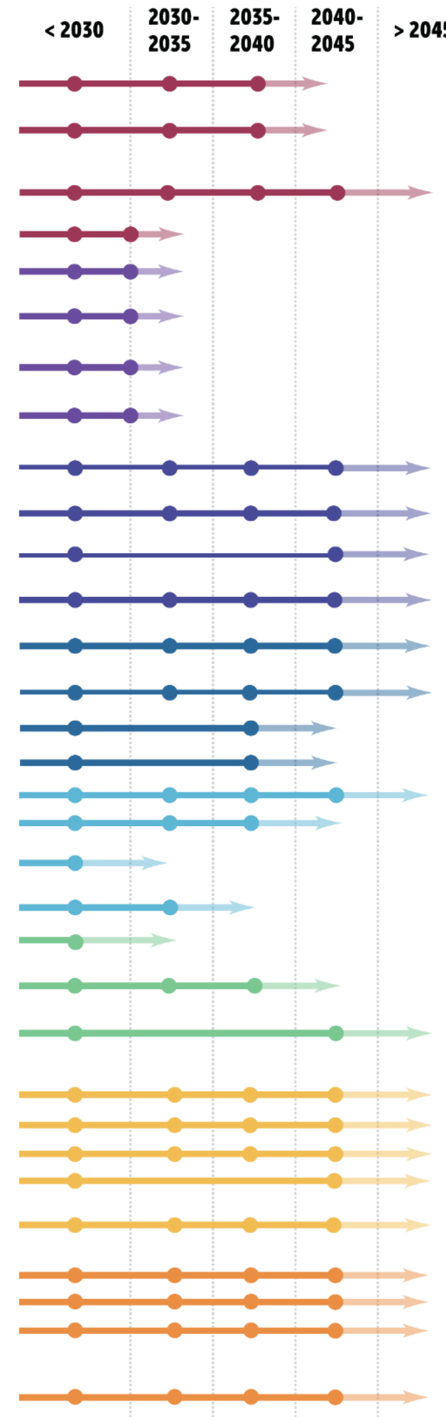
The roadmap highlights the need for coordinated European efforts, robust infrastructure, training, and industrial partnerships.

Strategic recommendations address challenges such as rising R&D costs, sustainability, and the retention of expert talent to ensure Europe remains a global leader in detector innovation.

It also provides a list of detector research and development themes - DRDTs

Detector research and development themes (DRDTs)

Theme	DRDT	Description
Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects



ECFA Detector R&D Roadmap implementation: Detector R&D (DRD) Collaborations

1. Gaseous

e.g.
time/spatial resolution;

environment friendly gases

2. Liquid

e.g.
Light/charge readout;

low background materials

3. Semiconductor

e.g.
CMOS pixel sensors;

High time resolution (10s ps)

4. PID & Photon

e.g.
spectral range of photon sensors;

Time resolution

5. Quantum

quantum sensors
- R&D, incl. beyond QFTP in conventional detectors

6. Calorimetry

e.g.
Sandwich;
noble liquid;
optical

7. Electronics

e.g.
ASICs;
FPGAs;
DAQ

8. Integration

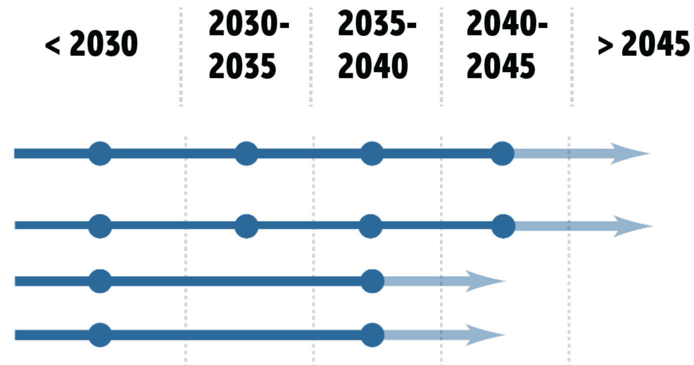
tracking detector mechanics

DRD4: photon detectors and PID

Detector R&D Themes (DRDTs)

PID and Photon

DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2	Develop photosensors for extreme environments
DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4	Develop compact high performance time-of-flight detectors

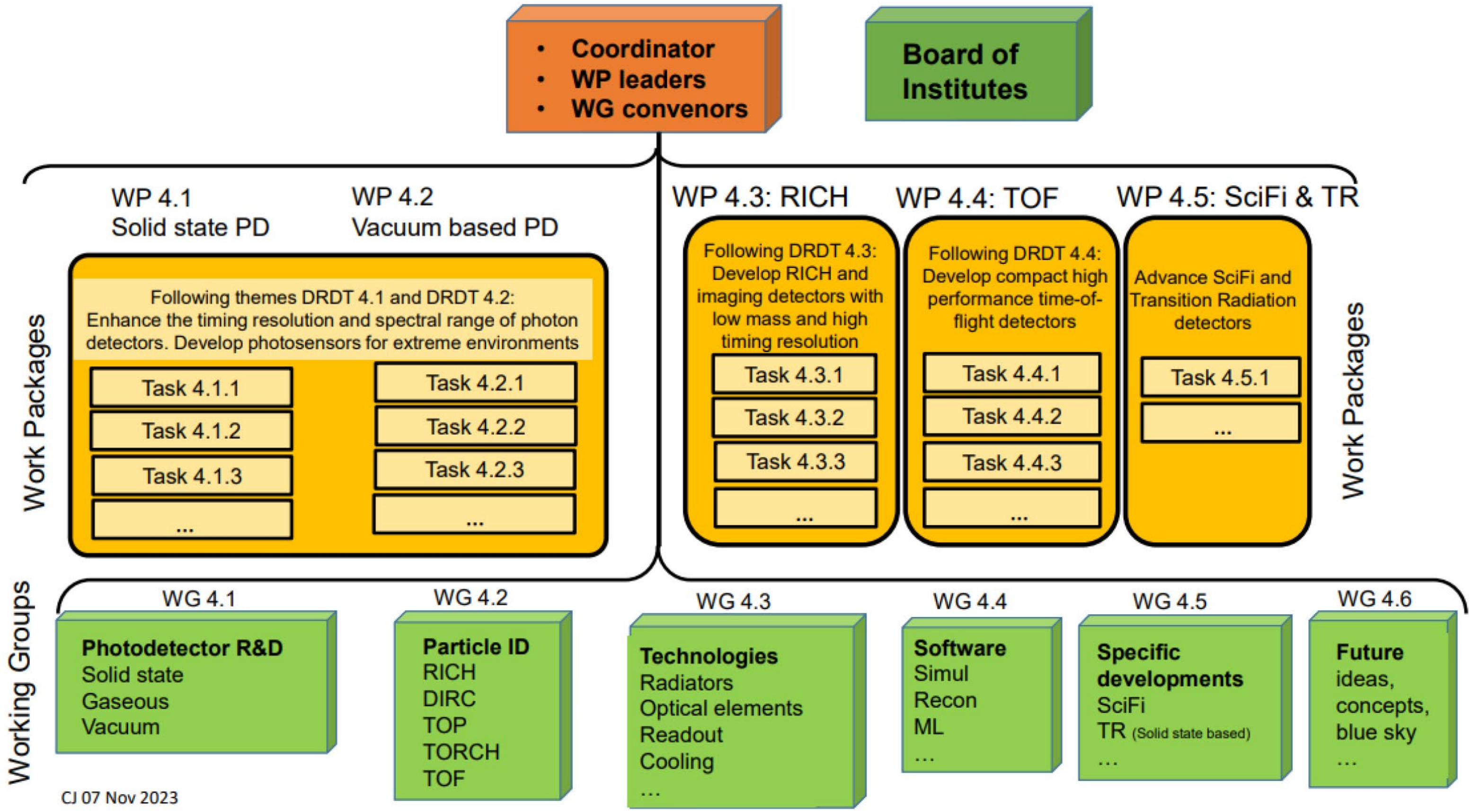


- Single-photon sensitive photodetectors (vacuum, solid state, hybrid)
- PID techniques (Cherenkov-based, Time of Flight)
- Scintillating Fiber (SciFi) tracking
- Transition Radiation (TR) using solid state X-ray detectors

DRD4 : photon detectors and PID

Organization:

- Work packages: projects
- Working groups: discussion forums



DRD4:WP4.1 Solid-State Photodetecto

- Task 1 -SSPD with new configurations and modes: Development of back-side illuminated SiPM (potential for better PDE and radiation tolerance); development of ultra-granular SiPM that integrates with the electronics by using 2.5D or 3D interconnection techniques; development of CMOS-SPAD light monolithic sensors for HEP; study of new materials for light detection

- Task 2 -Fast radiation hard SiPMs: Standardize procedures for quantification of radiation effects; irradiated SiPMs characterization in wide temperatures range (down to -200 ˚C); study of annealing; study and quantify other measures enabling the use of SiPM in highly irradiated areas (e.g. smaller SiPMs, macro-and micro-light collectors)

- Task 3 -Timing of SSPD, including readout electronics: Study and improve the timing of SiPMs; co-design of a multi-ch. readout ASIC exploiting the timing potential; integration and packaging with integrated cooling; vertical integration of SiPM arrays to FEE (better timing via reduction of interconnections' parasitic induct+capac)

DRD4:WP4.2 Vacuum-based Photodetectors

- Task 1 -New materials, coatings, longevity and rate capability studies: Develop new materials and techniques to increase MCP-PMT tube lifetime and improve rate capabilities; use new techniques with new materials to achieve high aspect ratio with small diameter for better gain, time, and spatial resolution

- Task 2 -New photocathode materials, structure and high QE VPD: Search for new materials with the required characteristics to be used as photocathodes; develop photocathodes with new structures

- Task 3 -VPD time and spatial resolution performance: Development of large area MCP-based photodetector with combined excellent timing and position resolution, including electronics integration