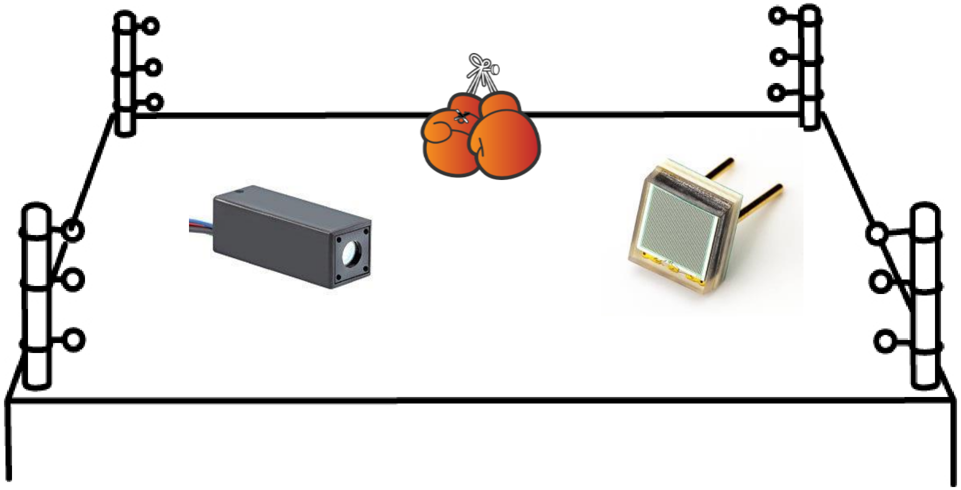
Journée thématique du réseau Photodetecteurs IN2P3

SiPM, PMT, quel photodétecteur utiliser ?



Introduction

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Véronique PUILL

Outline

Basics, properties and news concerning the:

- PMTs
- MCP-PMTs
- SiPMs

Photomultipliers

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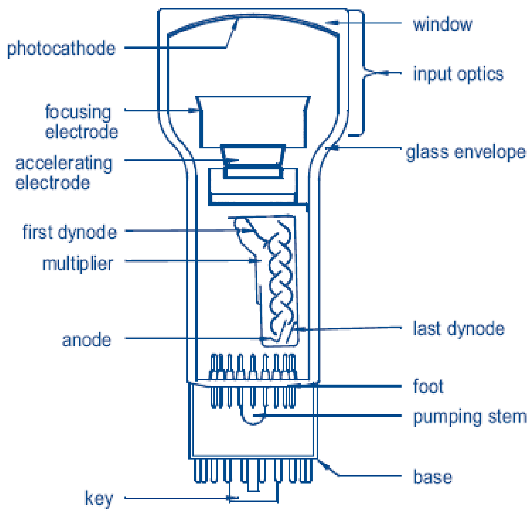
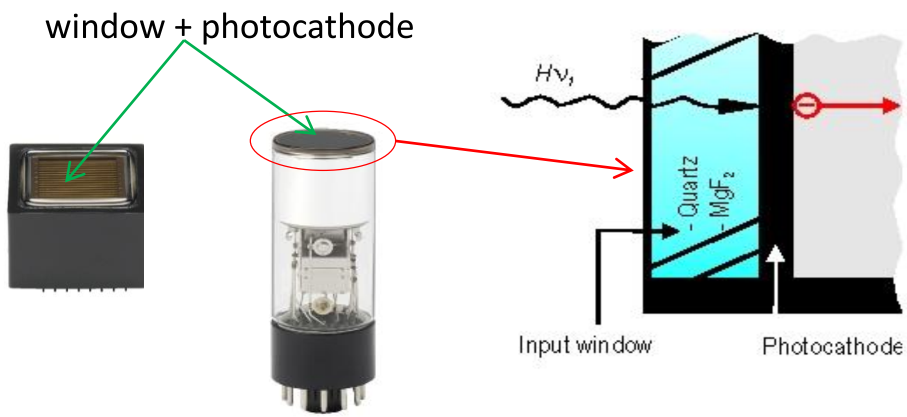
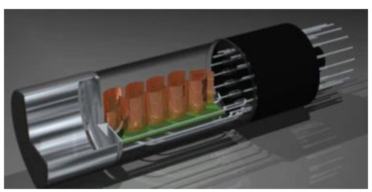
ET Enterprises
electron tubes

PMT basics







Photoelectron multiplication: secondary emission of electrons by the dynodes
The HV is supplied through a resistive voltage divider

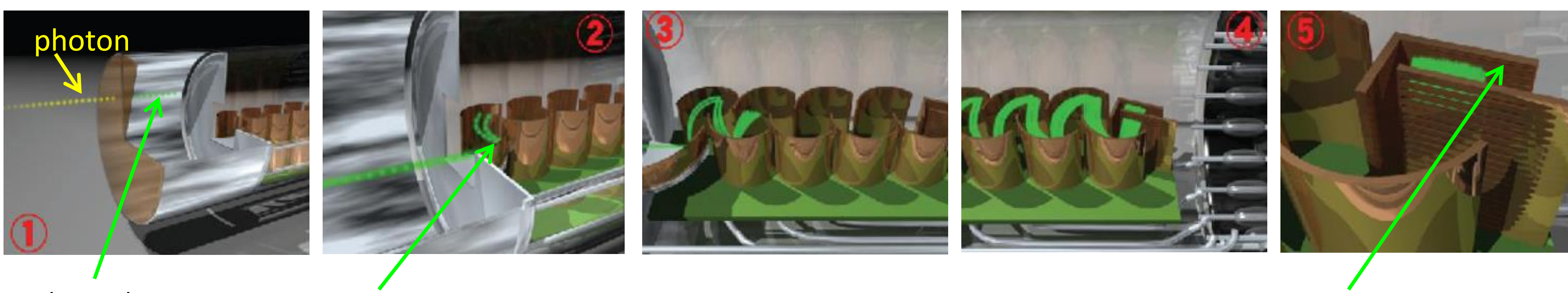
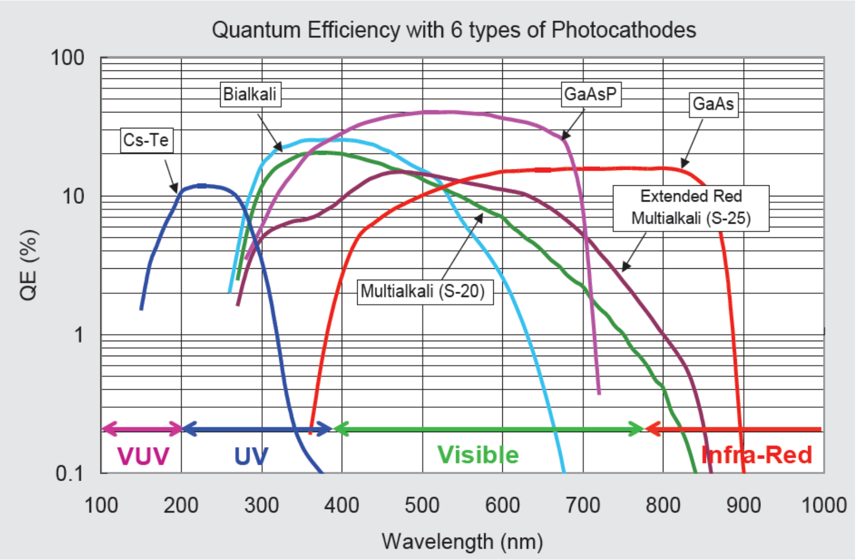
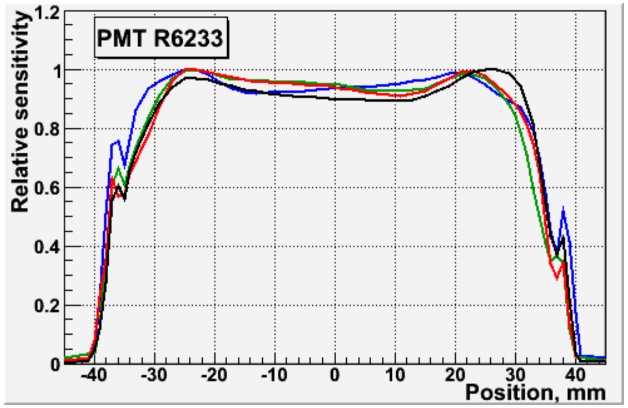


photo-electron
impact on the first dynode
multiplication by n dynodes and signal on the anode

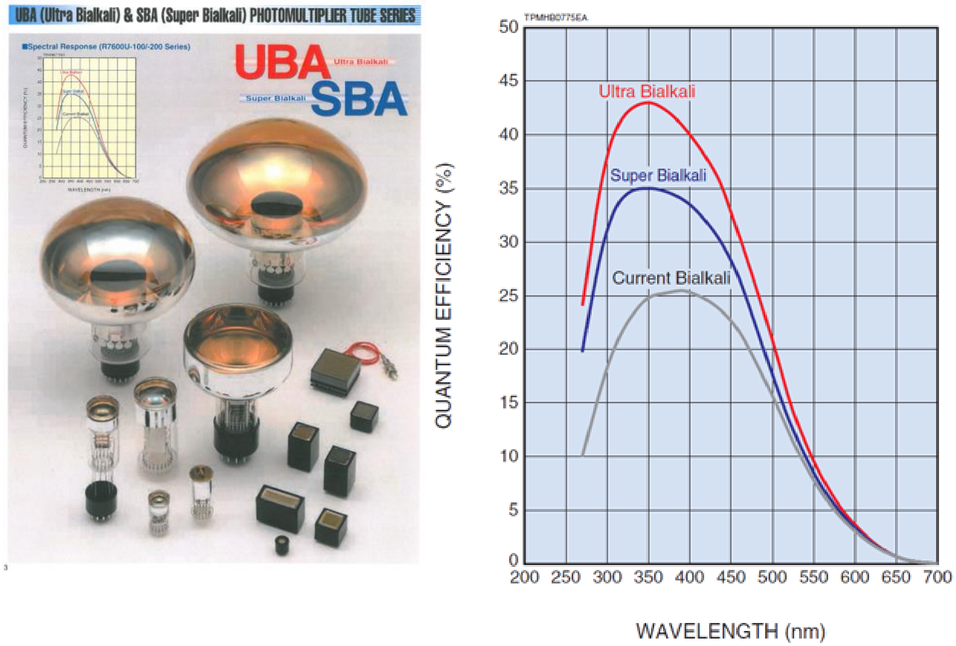
Standard Photocathodes, SBA & UBA





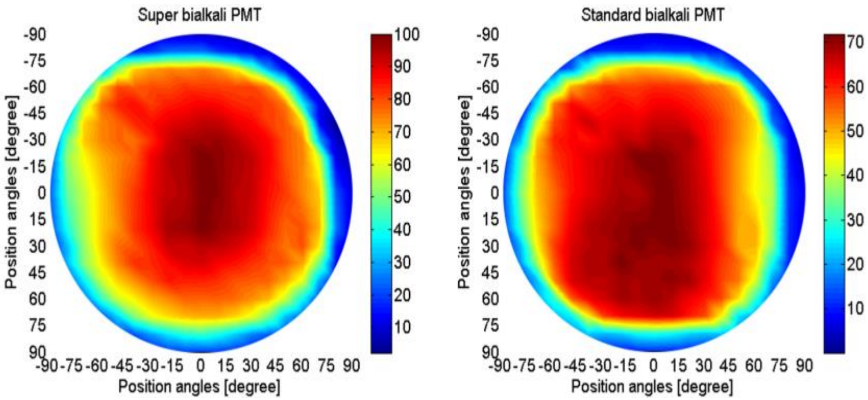
O. Kalekin, RICH 2010

Homogeneity of the photocathode deposition *and variations in collection efficiency (depends on the* PC geometry)



HAMAMATSU, PMT catalogue

Detection efficiency uniformity



E. Leonora, Photodet2012

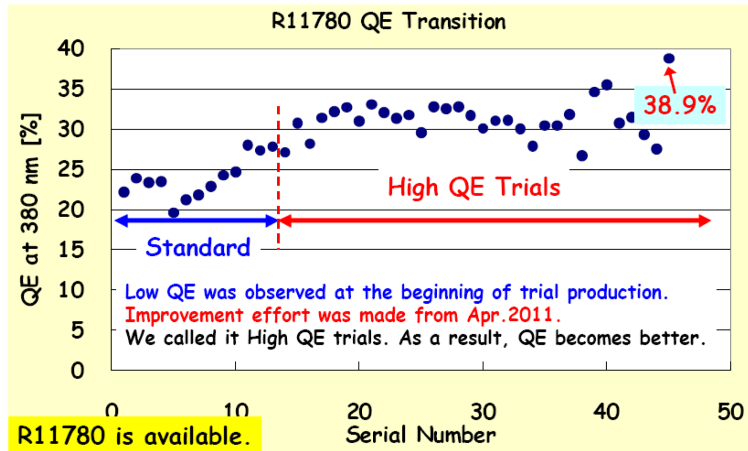
Improvement of Qε for large PMT and for UV light

Large water Cherenkov and scintillator detectors for long baseline neutrino oscillations, proton decay, supernova and solar **neutrinos experiments**

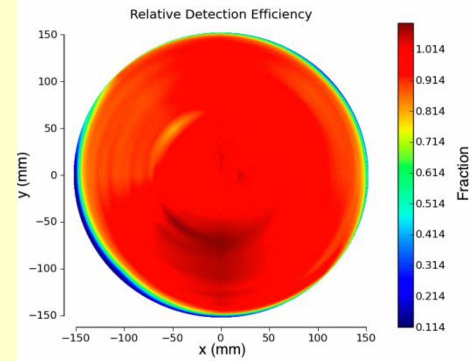
Need for PMT with:

- ✓ large-area
- ✓ high Qε in UV

R11780 (12-inch)



Y. Yoshizawa, Photodet 2012



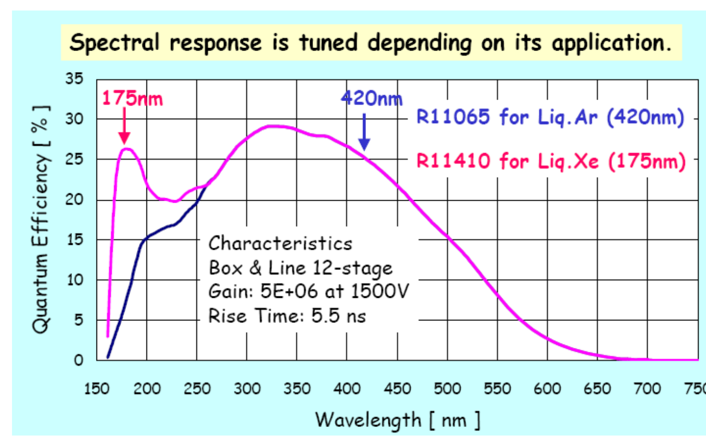
J. Brack, arXiv:1210.2765v2

Scintillation detector for **Dark Matter experiments** (scintillation light from Xe nuclear recoil resulting from the scattering of WIMPs*) - low-background detectors + proximity of the PMTs to the active scintillation region → background dominated by PMT radioactivity → need for Ultra low background PMT working at low temp

3- inch metal bulb PMT

Extremely low radioactivity (radiopure composition)

Low temp: Liquid Ar (- 186 °C)



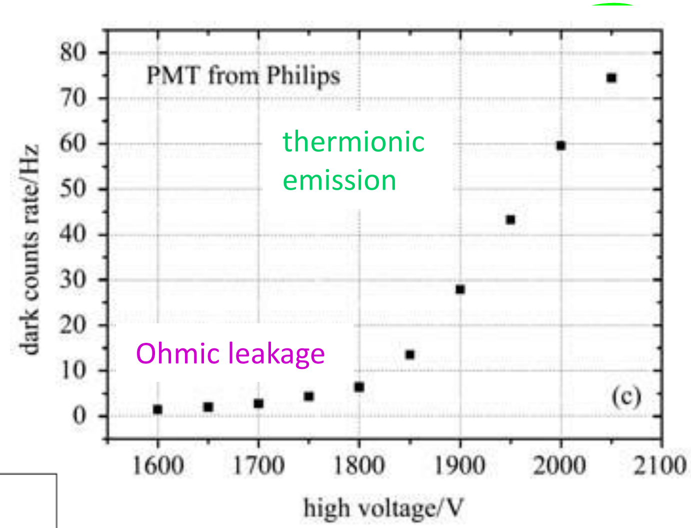
G. Fiorillo, NNN14

* WIMP: weakly Interacting Massive Particles

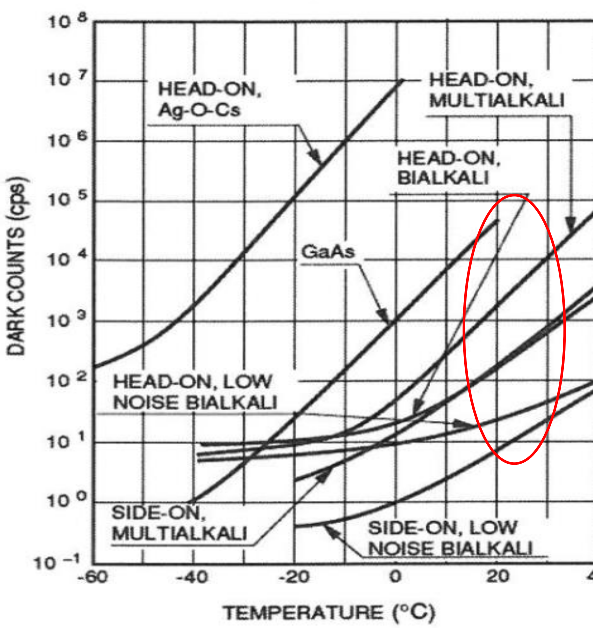
Noise of a PMT: Dark current

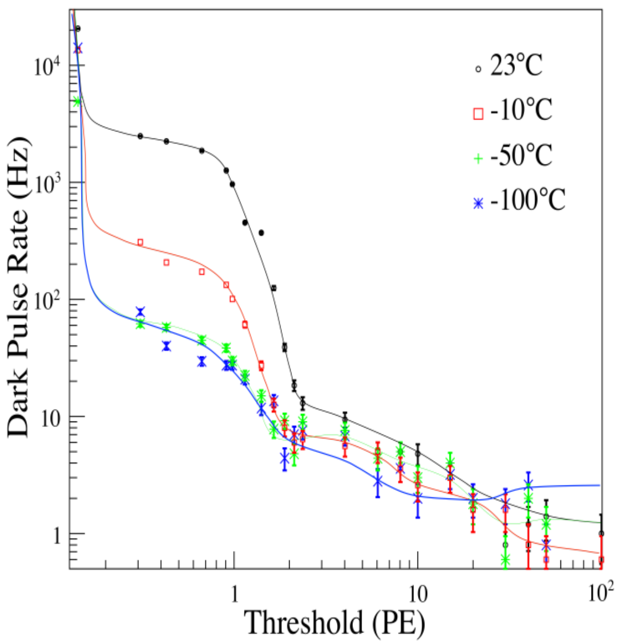
Dark current (I_d): current when photomultiplier is operated in complete darkness

- due to leakage currents between electrodes and insulating surfaces (ohmic leakage)
- depends on the cathode type, the cathode area, and the temperature (thermionic emission)
- is highest for cathodes with high sensitivity at long wavelengths (low work function)
- increases considerably if exposed to daylight



DCR of different photocathodes





I_d needs to be minimized for low intensities measurements
→ cooling

HAMAMATSU PMT book

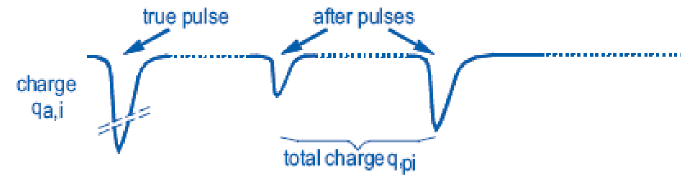
K. Lung, arXiv:1202.2628v2 [physics.ins-det], 2012

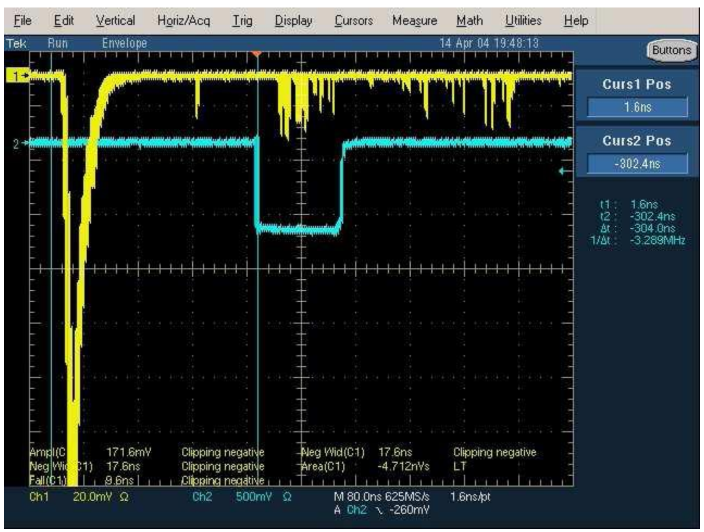
Noise of a PMT: Afterpulsing

Afterpulses: small signals, few p.e level, that appear after the main pulse

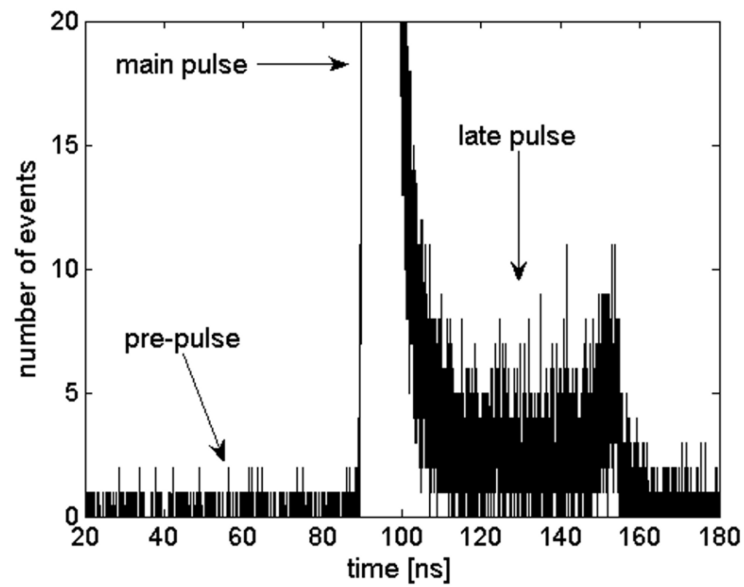
- short delay afterpulses (up to several tens of ns after the signal) caused by the elastic scattering of the electrons from the first dynode.

- long delay afterpulses(several tens of ns to several µs after the main pulse) caused by the positive ions which are generated by the ionization of residual gases





Time distributions of late pulses



E. Leonora, VLVnT09

Can be distinguished by the time interval that separates them from the true pulse → use of coincidence techniques to minimize their effect

Decrease of the after-pulse

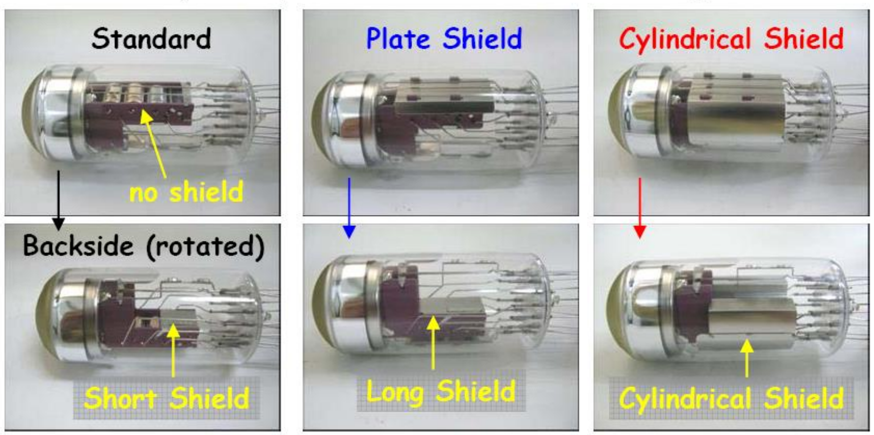
Collaboration between the PMT user and the producers → improvement of the performances

Ex: R&D in the structure of dynode chain → Lower after-pulse

	PMT	Voltage	AP/Noise
old	R9420	850V	0.20 %
new	R11920	902V	0.013 %

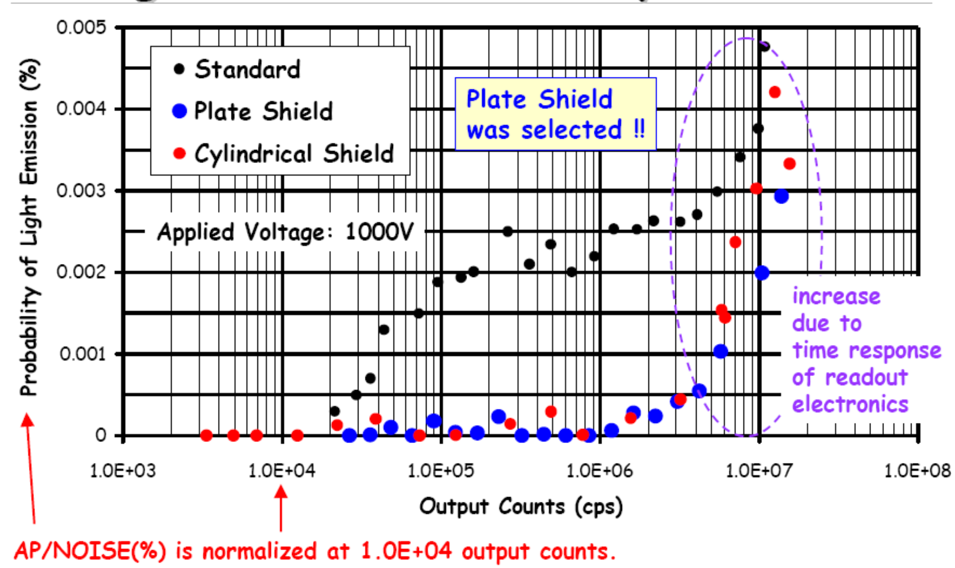
Optimazation of Dynode Shield

Dr.Mirzoyan/MPI reported that there is light emission from dynode of R11920-100. We made 2 kinds of trial tubes with different shape of dynode shield and checked the light emission.



HPK, private communication

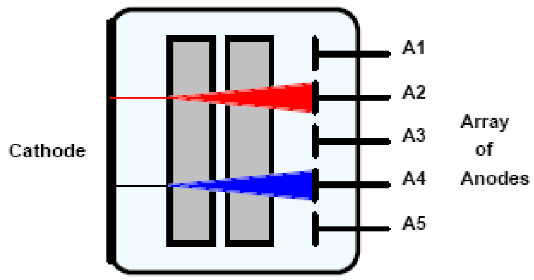
Light Emission from Dynode



20

Multi anode PMT (MaPMT)

Need of space segmentation of the light detection



metal channel dynodes + special anode configuration

avalanche confined in a narrow channel

multi-anode design

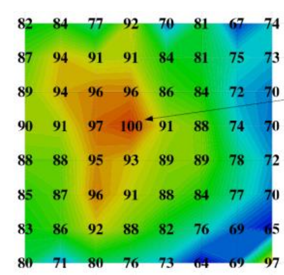
position sensitive PMT

Anode Type	Single	Single	Linear (8 ch)	Linear (16 ch)	Linear (32 ch)	Matrix (2 × 2 ch)	Matrix (4 × 4 ch)	Matrix (8 × 8 ch)
Effective Area	ϕ8 mm	18 mm × 18 mm	21.6 mm × 2.5 mm	15.8 mm × 16 mm	31.8 mm × 7 mm	18 mm × 18 mm	18.1 mm × 18.1 mm	18.1 mm × 18.1 mm
Effective Area (per channel)	—	—	2 mm × 2.5 mm	0.8 mm × 16 mm	0.8 mm × 7 mm	8.9 mm × 8.9 mm	4.2 mm × 4.2 mm	2 mm × 2 mm

- Compact
- Good timing performances
- Good immunity to magnetic field

- Cross-talk
- Non uniformity across the channels

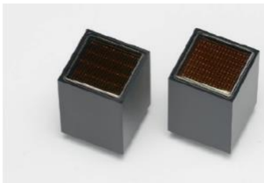
H8500 response uniformity



G. Collazuol, SuperB meeting, 2011

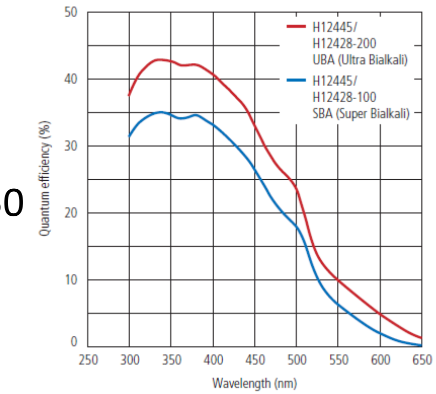
MaPMT developments

MaPMT with SBA, UBA and extended green Bialkali photocathode

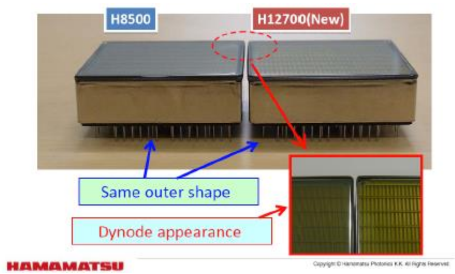


H12445-100/-200, H12428-100/-200

- Extended green bialkali PC (Qε= 14 % @ 550
- 2 x 2 → 8 x 8 multianode

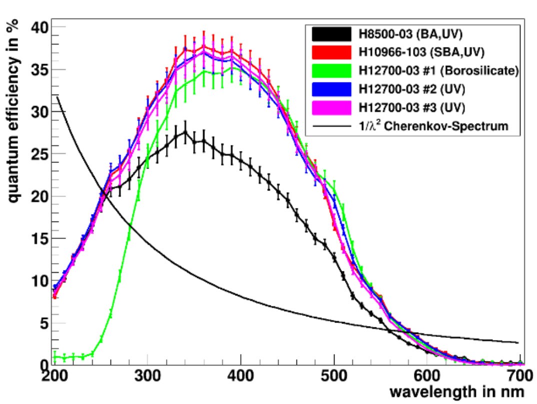


Compact packaging multianode « flat » PMTs

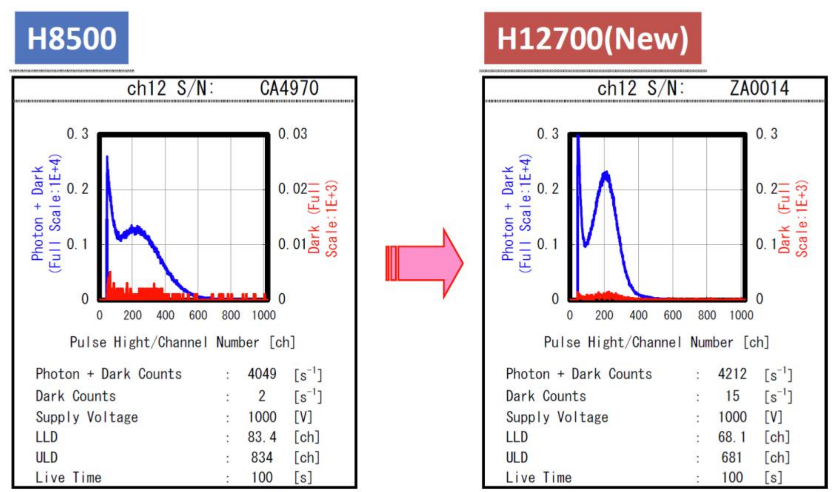


optimized dynode structure:
✓ higher collection efficiency
✓ better SPE resolution
✓ enhanced cathode sensitivity

H12700 MaPMT



C. Pauly, RICH 2013



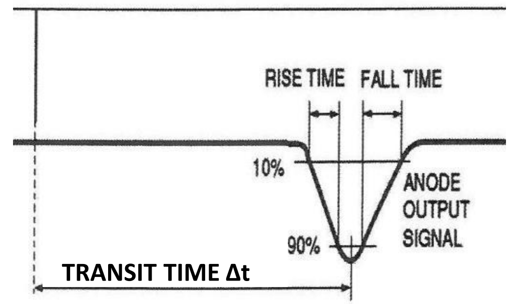
M. Contalbrigo, NDIP14

Improvement of the timing response

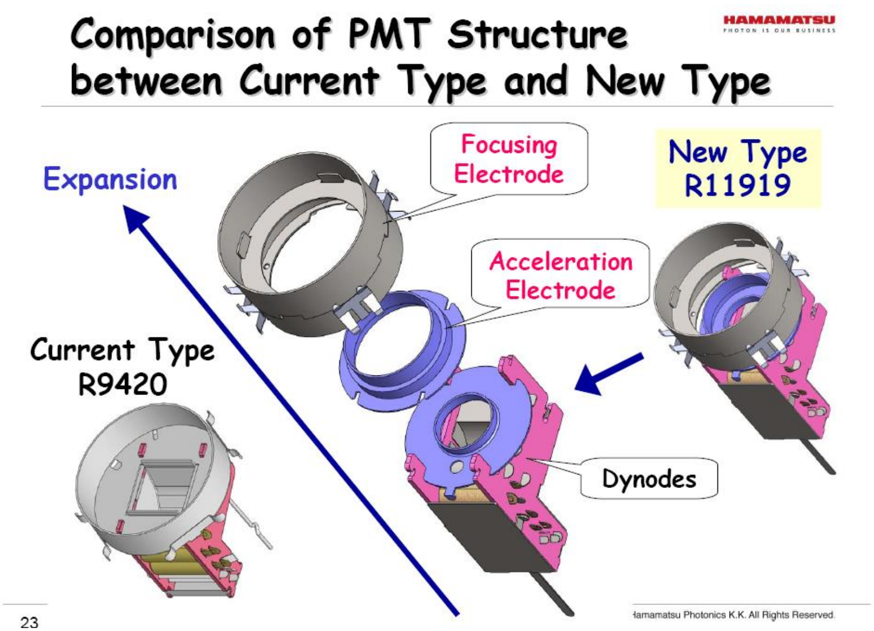
Fast time response PMTs are interesting for HEP and PET application

Need of PMTs with quite large photocathode and good TTS

R&D in the structure of the PMT: accelerating electrode



Better TTS: from 550 ps to 270 ps



HPK, private communication

R11919 / 1.5-inch FAST PMT

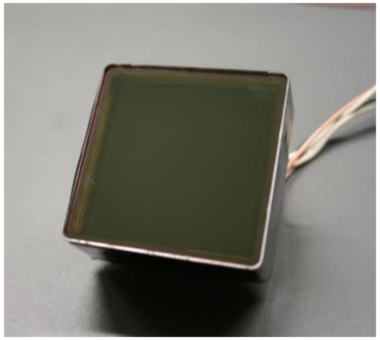
Fast Time Response with Acceleration electrode for TOF-PET and HEP experiments

Transit Time Spread = around 270 ps
(R9420 = 550 ps, R11194 = 400 ps)

Gain = 1E+06 (Gain is adjustable by request)

Cathode Blue Sensitivity = around 11
(SBA type could be available in future)

Micro-Channel Plate Photomultipliers



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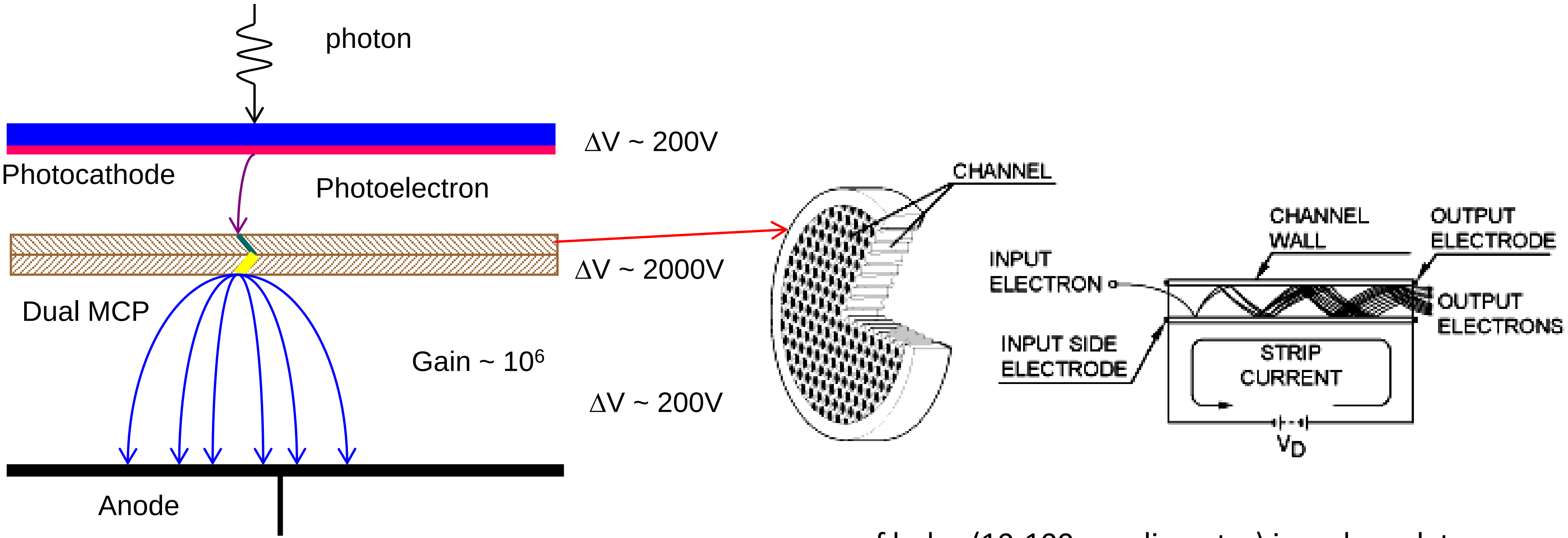
PHOTEK
ENVISAGE THE FUTURE

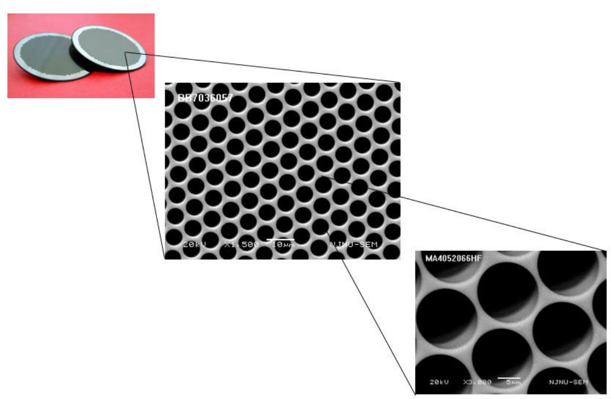
+ R&D in Research Institutes (BINP, Russia – IEHP, China – LAPP collaboration, USA -, …)

MCP-PMT basics

Photodetector multiplication chain = Micro Channel Plate

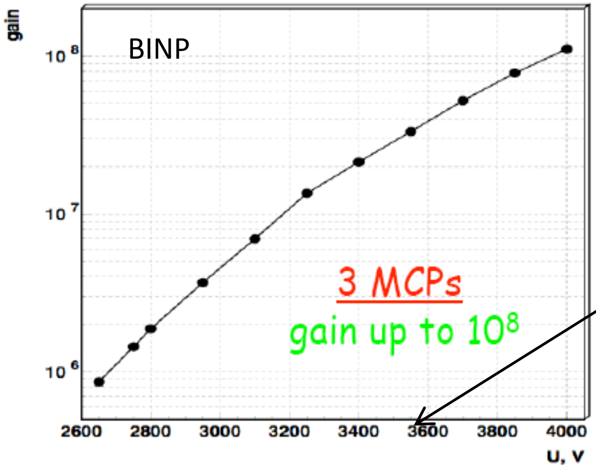


array of holes (10-100 μm diameter) in a glass plate



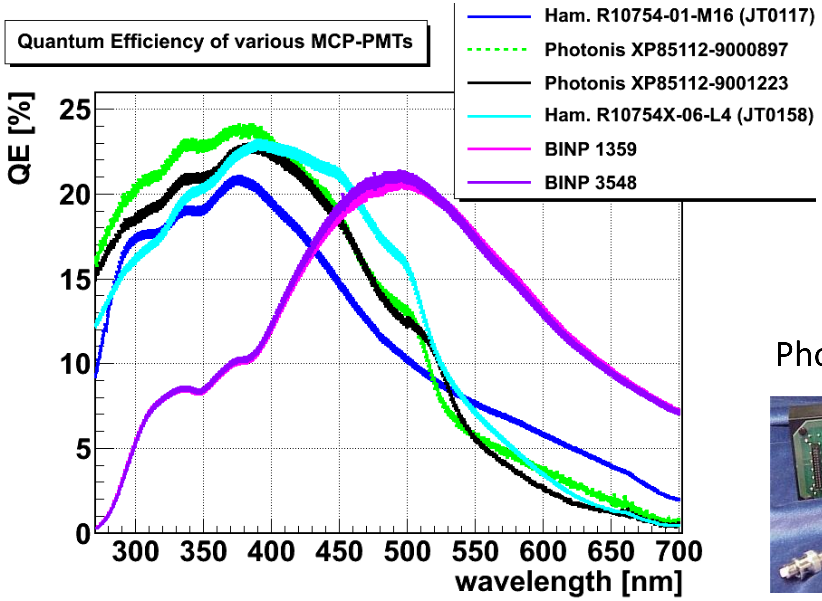
MCP-PMT gain & quantum efficiency

BINP



MCP-PMT bias voltage > PMT bias voltage

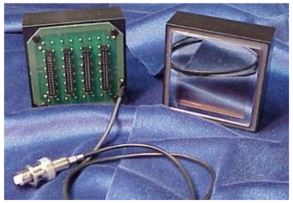
M.Barnyakov, AFAD 2013



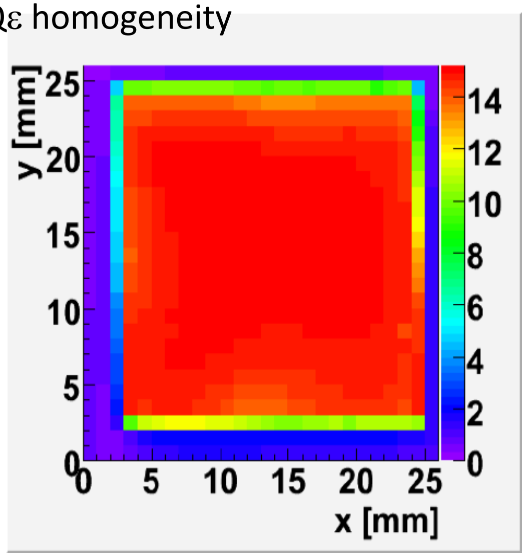
A. Lehmann, Elba Conference 2012

HAMAMATSU

Photonis BURLE



Qε homogeneity



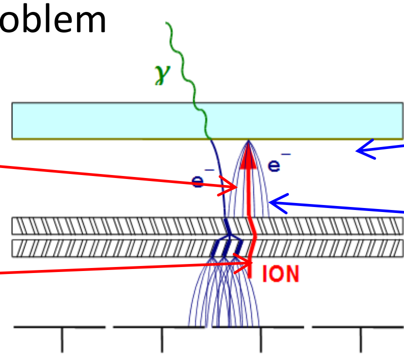
T. Inami, TIPP 2011

MCP-PMT aging

High photon rate → aging problem

2 travel back toward the photocathode

1 ionisation of atoms of residual gas

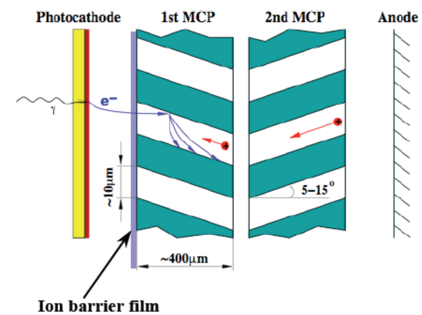


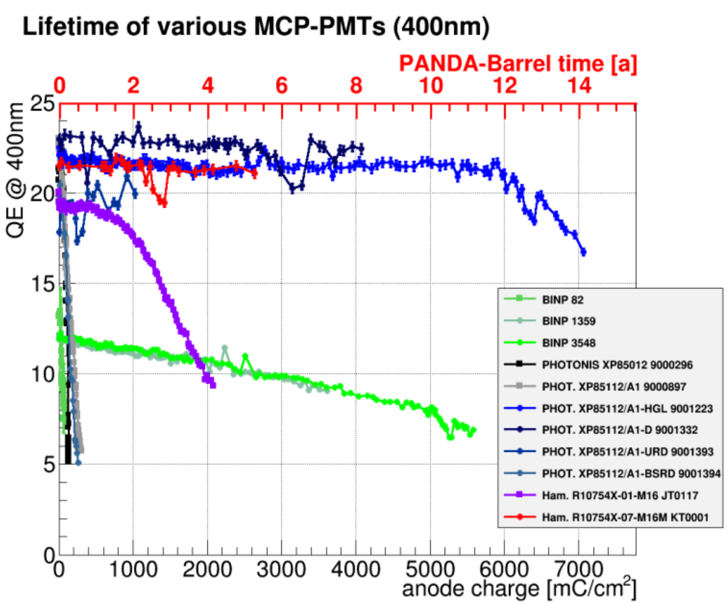
3 ion bombardment → damages the photocathode → reduces the Qε

4 production of secondary pulses

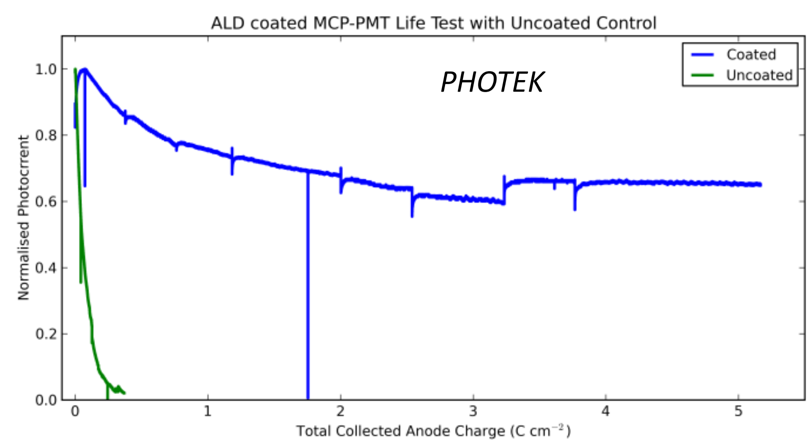
Different ways of improvement (depending on the producer):

- Protection layer on the photocathode
- Improvement of the vacuum
- Treatment of the MCP surfaces (atomic layer deposition)
- New photo cathode





F. Uhlig, NDIP14

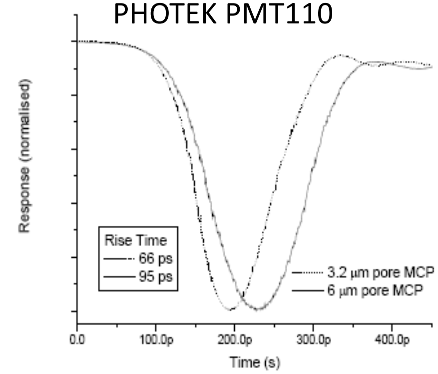


T M Conneely, PHOTEK

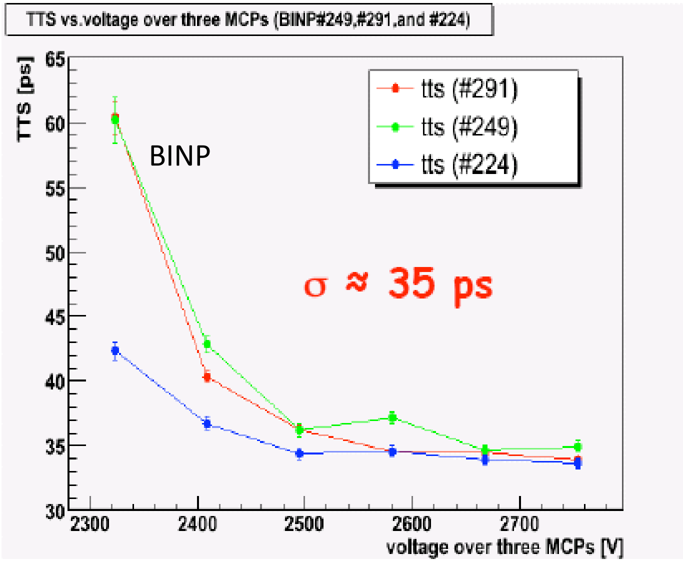
MCP-PMT time response

- high electric field between PC and MCPin and MCPout and anode → negligible effect of the angle distribution of the p.e
- e- transit time in the secondary multiplication process very short

very good TTS ≈ 30-35 ps (σ)



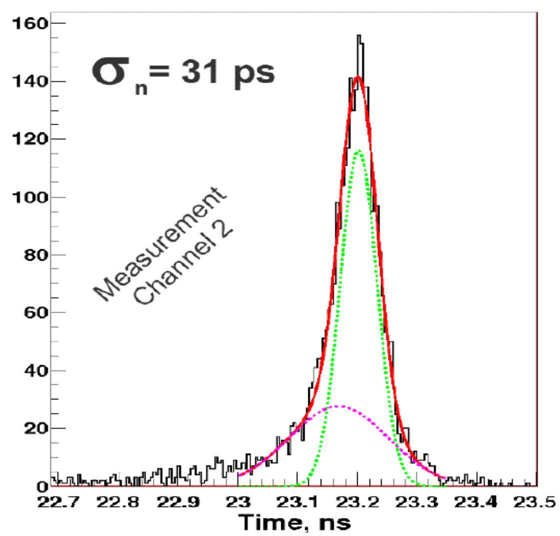
J. Milnes, PHOTEK



A. Yu. Barnyakov, NIMA 598

Single Photoelectron Timing resolution

HAMAMATSU SL10 SPTR @ 405 nm – 3.5 kV



J. Vavra, SLAC-Pub-14279

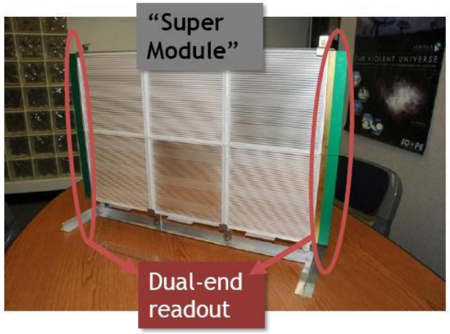
New MCP-PMT developments

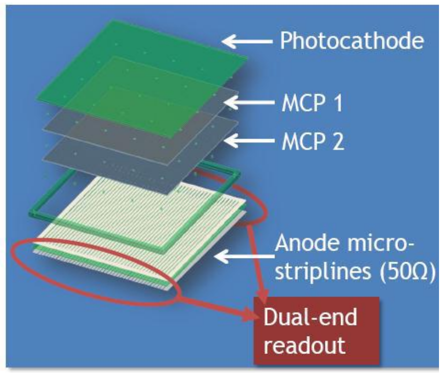
The LAPPD project

LAPPD Collaboration

The Large-Area Psec Photo-Detector Collaboration

- Development of large-area, relatively inexpensive Micro-Channel Plate (MCP) photo-detectors
  - 8” x 8” phototubes = ‘tile’ (large active area)
  - Gain >= 10^6 with two MCP plates
  - Transmission line readout – no pins!
  - Fast pulses + low TTS ~30ps





10/11/2011 ANT'11 LAPPD electronics 4

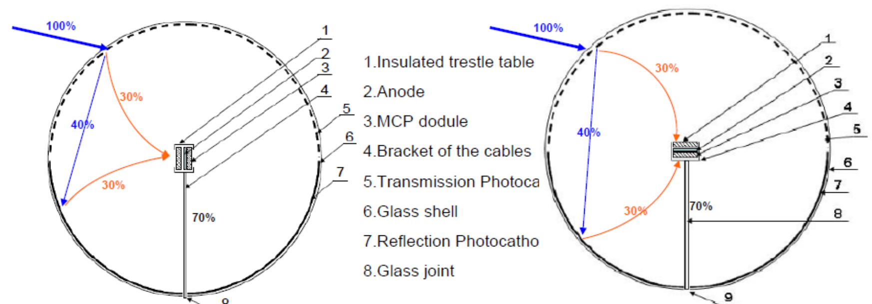
M. Sanchez, NNN14

Chinese R&D

The new design of a large area PMT

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } ~ 4π viewing angle!



Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

Collection Efficiency (CE) of MCP : 70%;

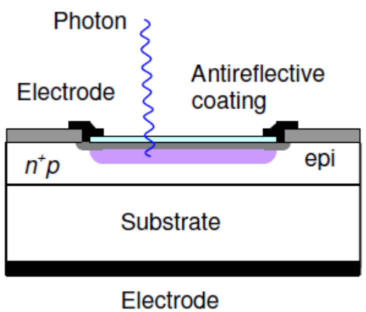
$$PD = QE_{Trans}*CE + TR_{Photo}QE_{Ref}*CE = 30\%*70\% + 40\%*30\%*70\% = 30\%$$

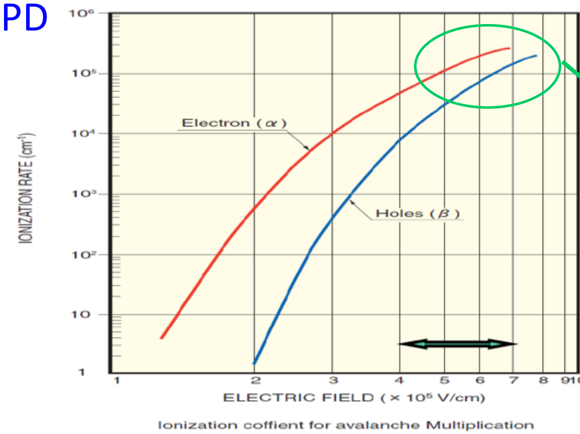
Photon Detection Efficiency: 15% → 30% ; ×~2 at least !

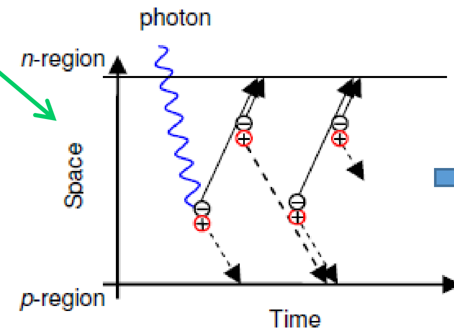
S. Quian, NDIP14

SiPM

Schematic structure of a G-M APD







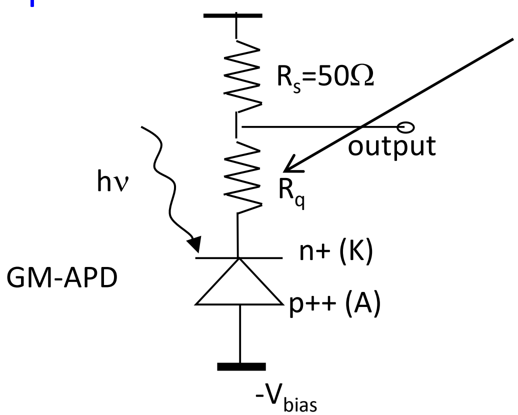
breakdown

Valeri Saveliev, ISBN 978-953-7619-76-3

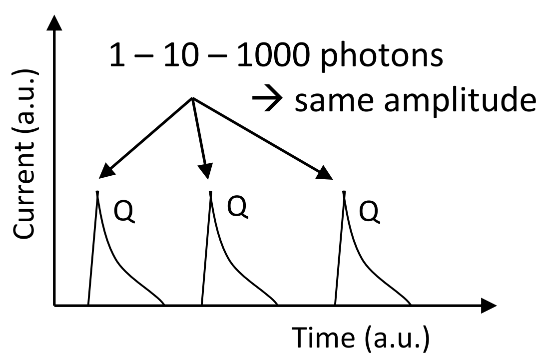
$G = 10^5 - 10^6$

both type of carriers participate in the avalanche process → creation of a self-sustaining avalanche → current rises exponentially with time and reach the breakdown condition. No internal "turn-off" → the avalanche process must be quenched by the voltage drop across a serial resistor : quenching resistor

equivalent electrical circuit

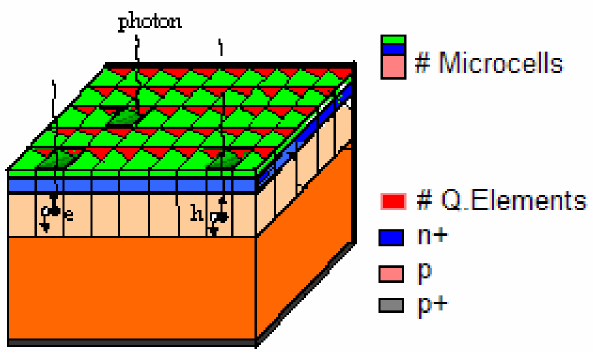


output signal

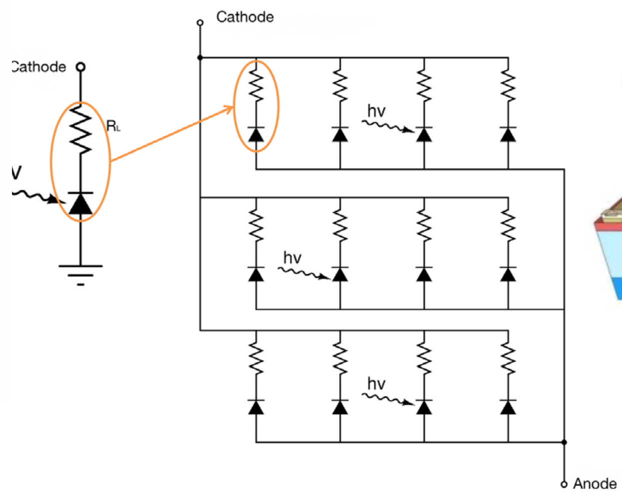


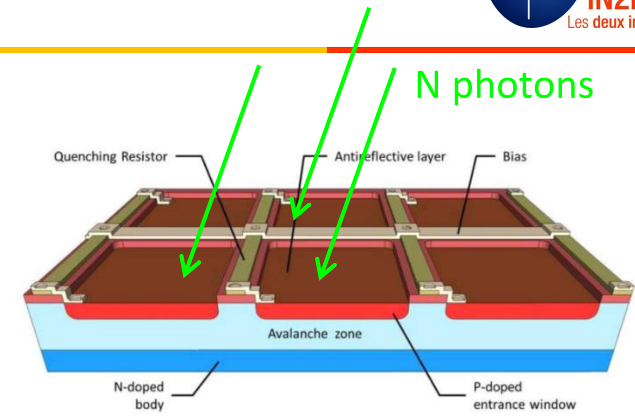
output charge is not proportional to the number of of incident photons

Structure and principle of a SiPM

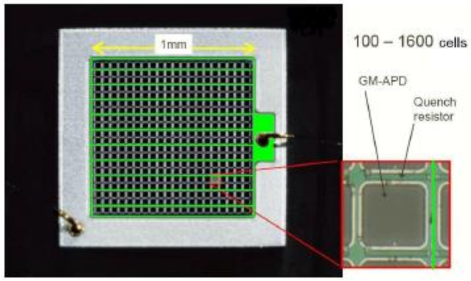


Valeri Saveliev, ISBN 978-953-7619-76-3





KETEK web site

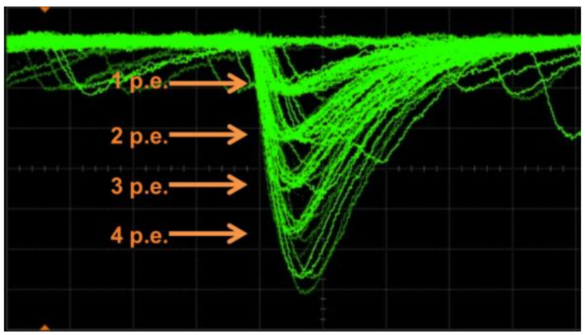


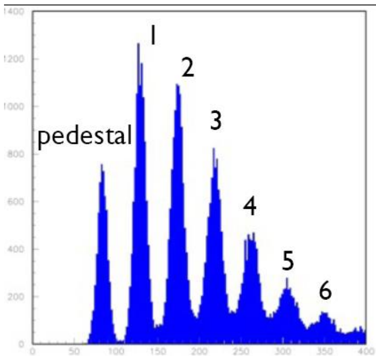
- ✓GM-APDs (cell) connected in parallel (few hundreds/mm²)
- ✓Each cell is reverse biased above breakdown
- ✓Self quenching of the Geiger breakdown by individual serial resistors

Each element is independent and gives the same signal when fired by a photon

⬇

output charge is proportional to the number of of incident photons



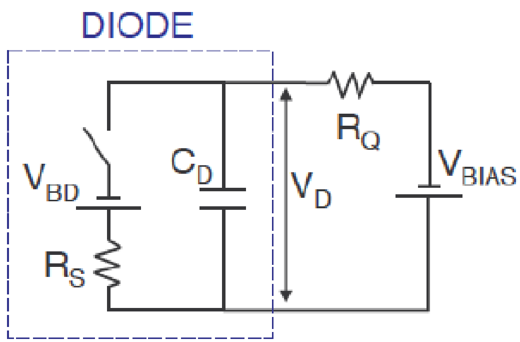


overlap display of pulse waveforms

Development of the signal in a cell

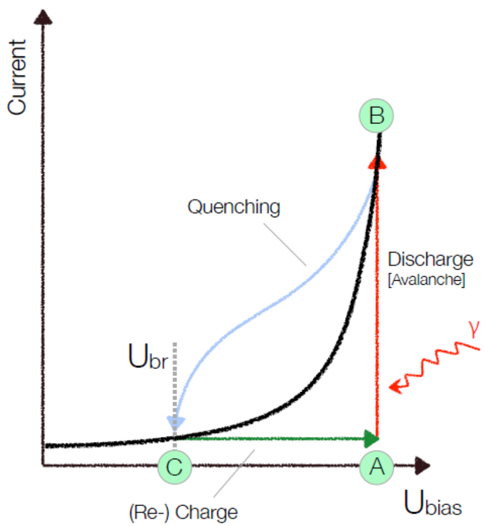
equivalent electrical circuit of a SiPM cell

G. Bisogni, RESMDD10



V_{BD} : breakdown voltage
R_Q : quenching resistance
R_S : Si subtrate serie resistance
C_D : diode capacitance
V_{BIAS} : bias voltage

Vbias > Vbd



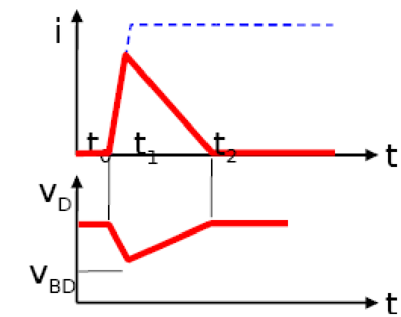
quiescient mode, switch opened
If no photon or no dark event, the current stay stable

A → B : avalanche triggered, switch closed
C_D **discharges** to V_{BD} with the time constant
$\tau = R_S \times C_D$ → asymptotic grows of the current

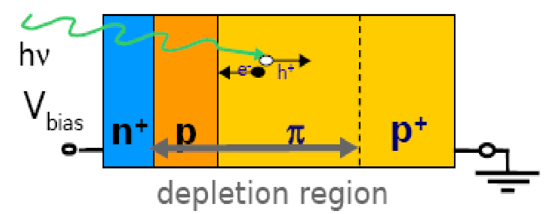
B→ C : avalanche quenched, switch open

C→ A : reset of the system
C_D **recharges** with the time constant $\tau' = R_Q \times C_D$

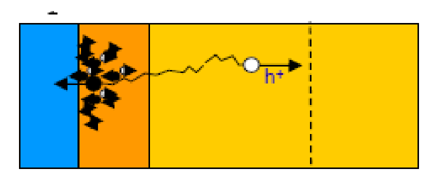
Time sequence



t=0: carrier initiates the avalanche



0<t<t1: avalanche spreading



t1<t: self-sustaining current limited by series R

G.Collazuol, LIGHT11

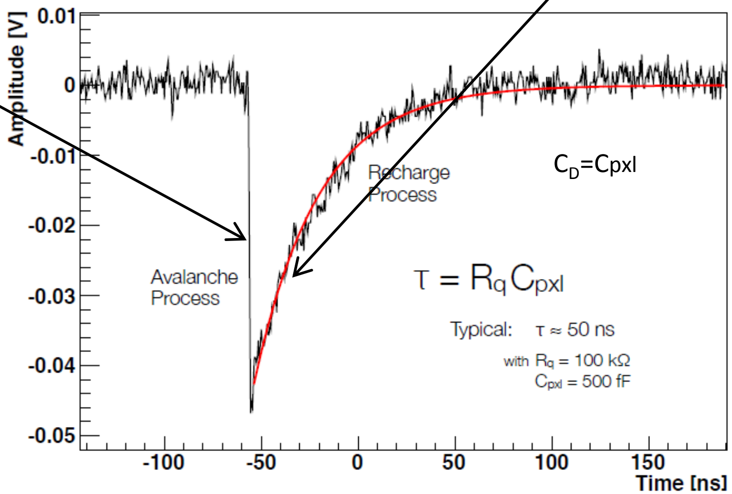
Signal pulse shape

Fast rise time: hundreds of ps

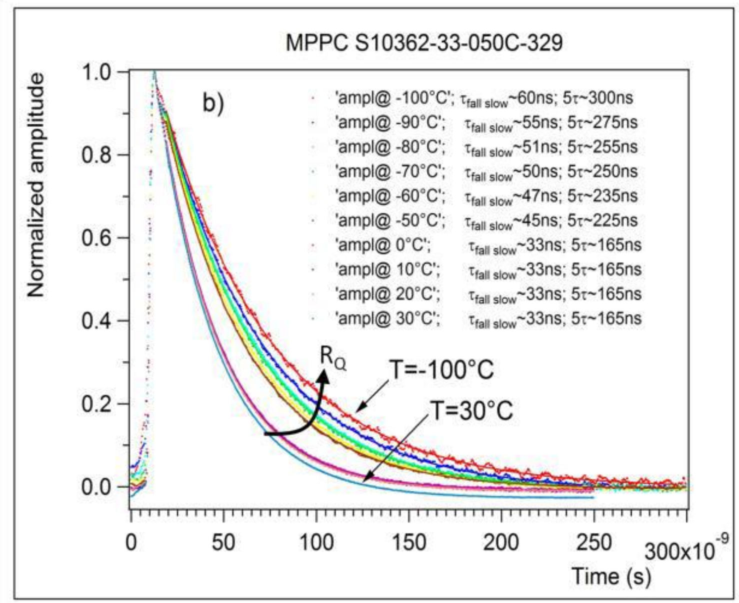
$T_R = R_S C_D$

Recovery time: tens to hundreds of ns

Time to recharge a cell after a breakdown : $\tau = R_Q C_D$



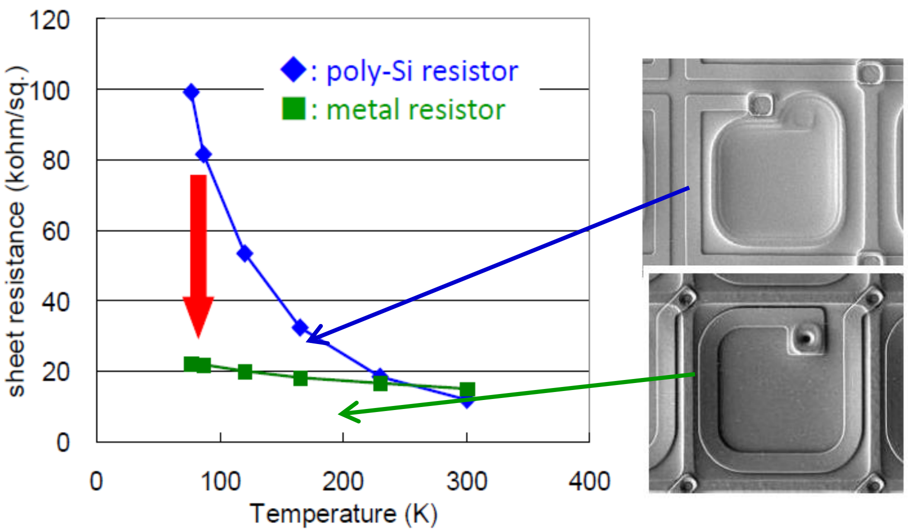
Polysilicon are temperature dependent → strong dependence of the recovery time with the temperature



Dinu, IEEE NSS 2010

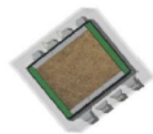
Solution: Metal Quenching Resistor (MQR)

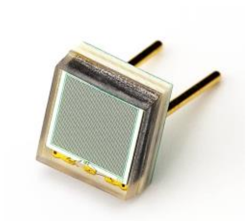
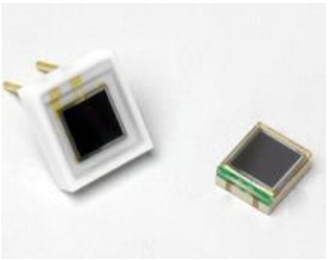
T. Nagano, IEEE NSS 2013



MQR with high transmittance → directly on the photosensitive surface → higher fill factor

What does it look like?

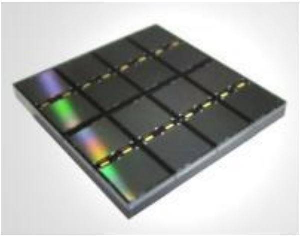
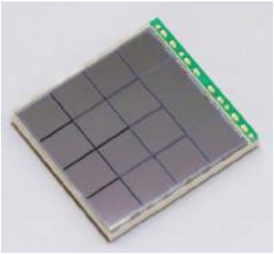



Dimensions: 1 mm² to 16 mm²

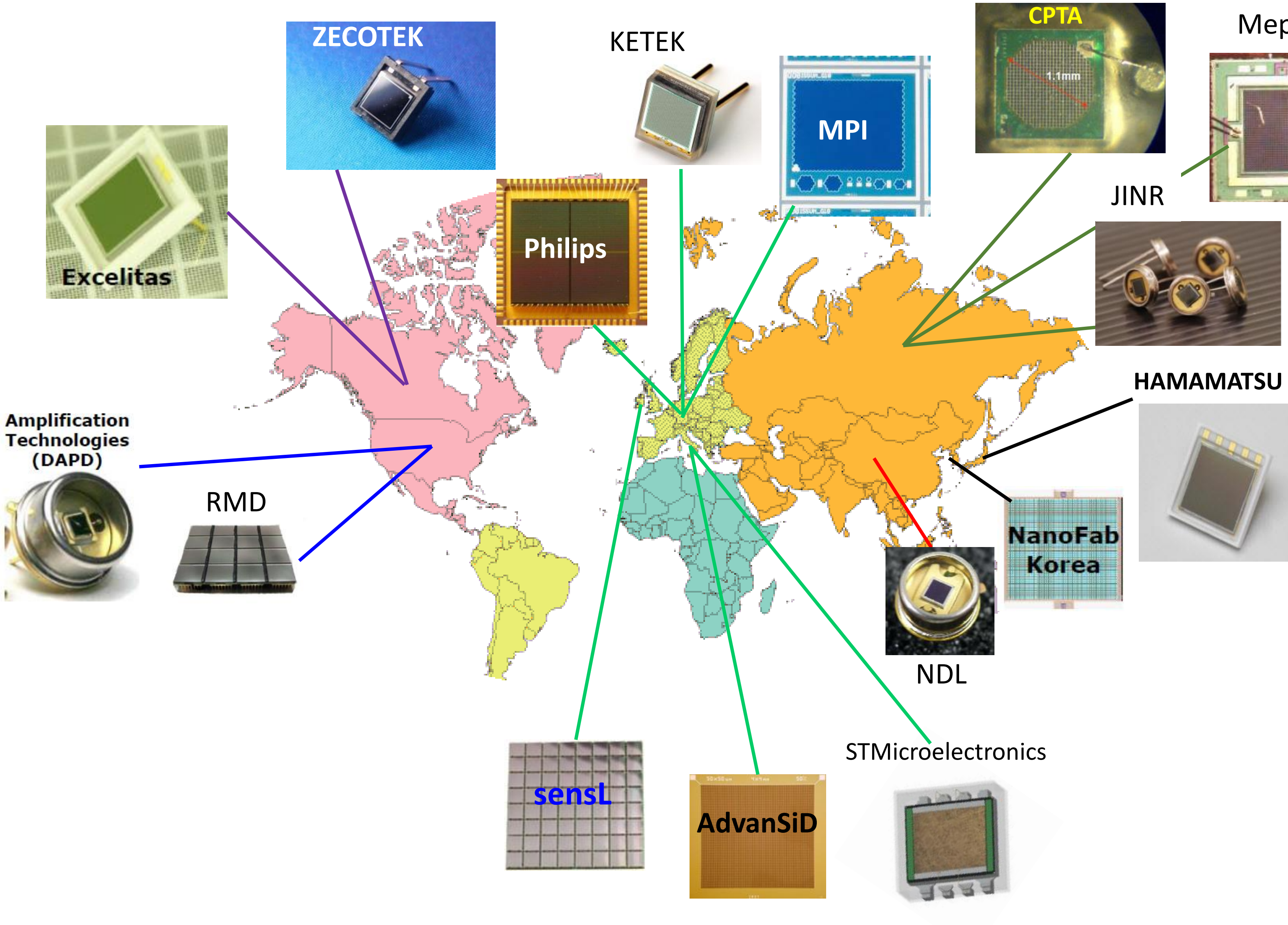
Cell size: 15 µm, 25, …, 100 µm

Matrixes: 4 to 256 channels

Packaging: metal (TO8), ceramic, plastic, with pins, surface mount type, matrix

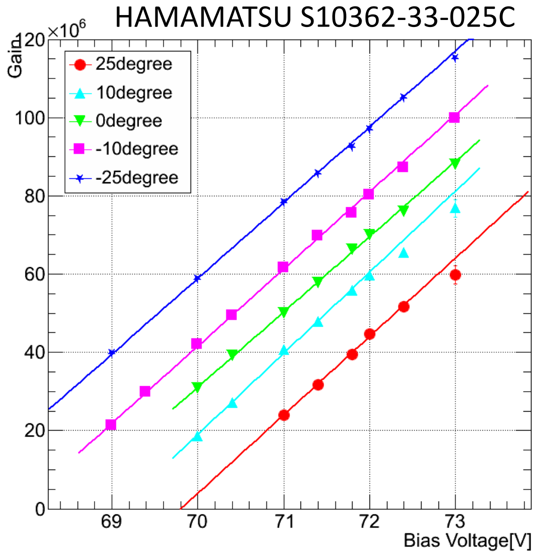
SiPM Producers in the word



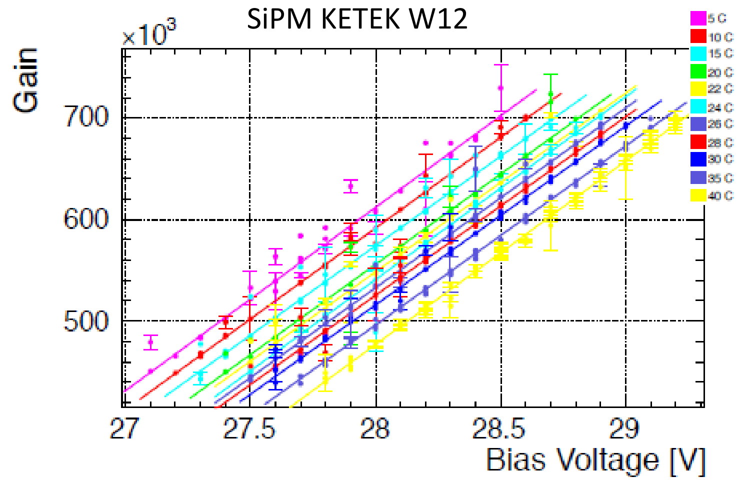
Gain of SiPM

Gain: charge developed in one cell by a primary carrier

Overvoltage $\Delta V = V_{bias} - V_{BD}$



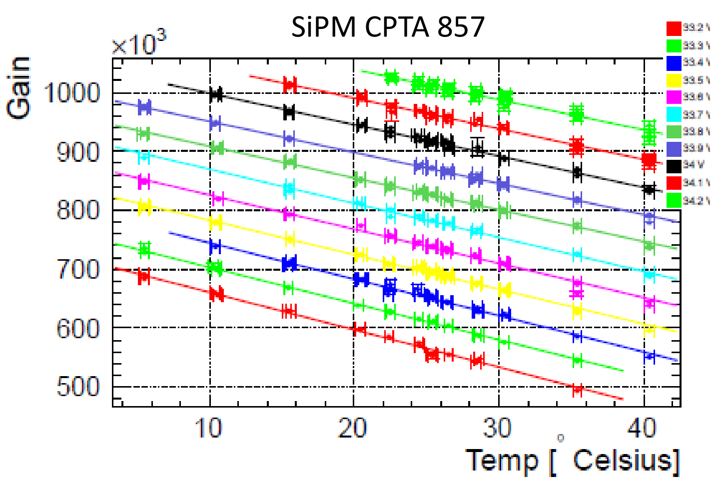
T. Okubo, ATHIC 2012



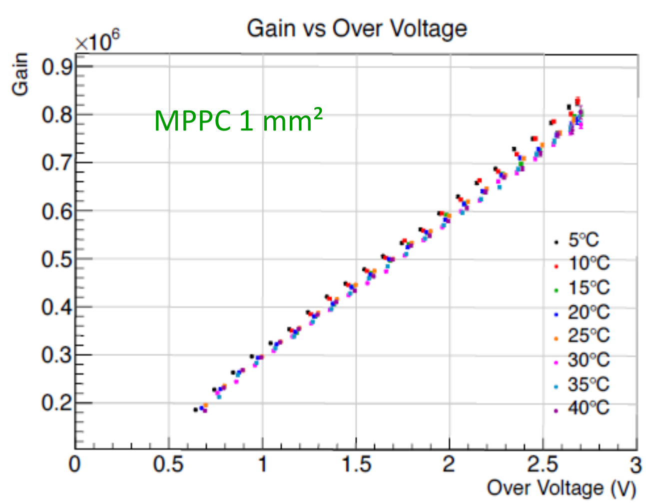
E. Van der Kraaij, AIDA 2013

10^5 < gain< 10^6

- linear increase of the gain with Vbias
- Gain independent of the temperature at fixed ΔV

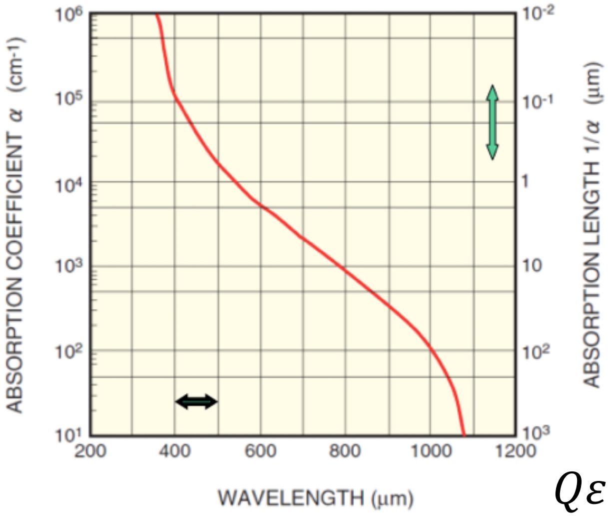


J. Cvach, arXiv:1403.8104v1]



H. Tajima, 2013 CTA SiPM meeting

Photo Detection Efficiency (PDE - Qε)



$$PDE = Q_\varepsilon \cdot P_{trig} \cdot \varepsilon_{geom}$$

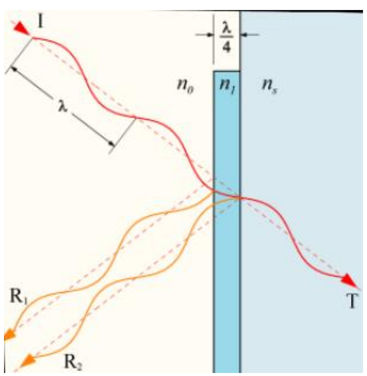
Qε: carrier Photo-generation

probability for a photon to generate a carrier that reaches the high field region in a cell

$$Q\varepsilon = (1 - R)\,\xi\,[1 - e^{-\alpha d}]$$

fraction of the photon flux absorbed in the depleted layer (sensitive region). The device should have a sufficiently large value d to maximize this factor.

effect of reflection at the surface of the device.
reflection can be reduced by the use of antireflection coatings



fraction of e-/h pairs that successfully avoid recombination at the material surface and contribute to the useful photocurrent

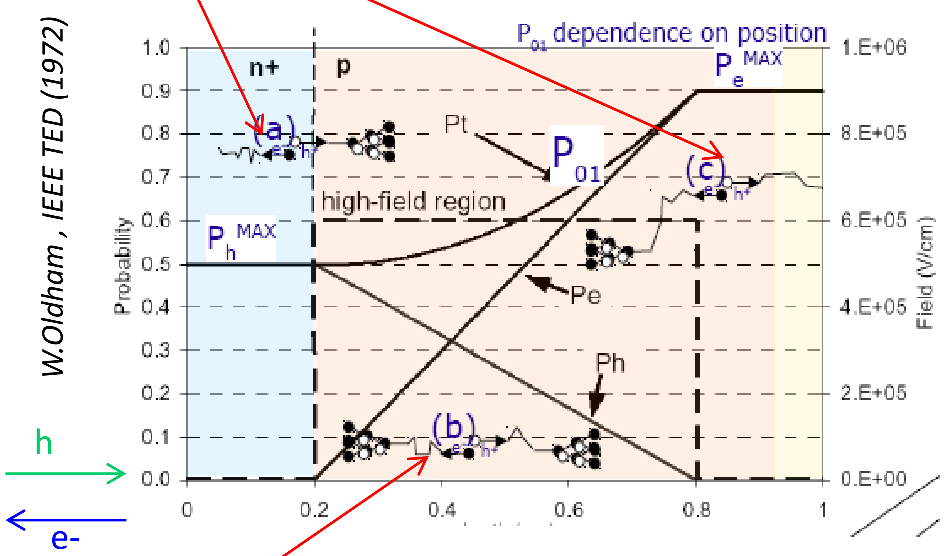
R : reflection Frenell coefficient = 0,3 for Si

$$PDE = Q_\varepsilon \cdot P_{trig} \cdot \varepsilon_{geom}$$

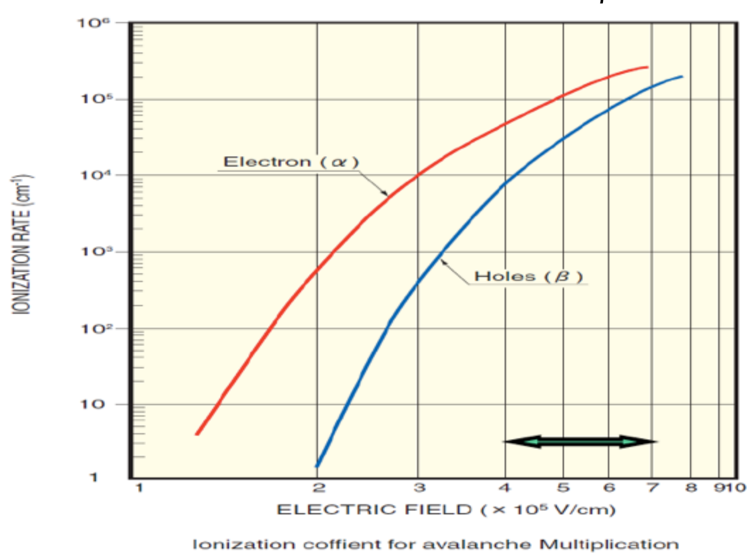
Ptrig : avalanche triggering: probability for a carrier traversing the high-field to generate the avalanche
Depends on the position where the primary e/h pair is generated

e- directly collected at the n+ electrode → only the holes contribute to the trig proba

Hole directly collected at the p+ electrode → only the e- contribute to the trig proba

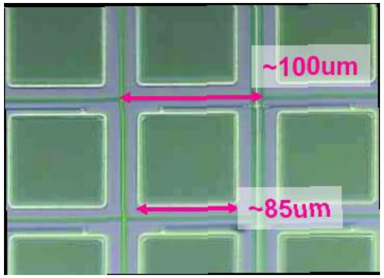


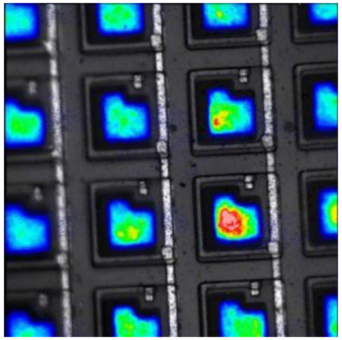
both carriers contribute to the trig proba



Ionization coefficient of e- > coeff of holes → the triggering probability is max when the charge carriers generation happens in the p side of the junction → the e- pass through the high field region

Photo Detection Efficiency (PDE - ε_{geom})

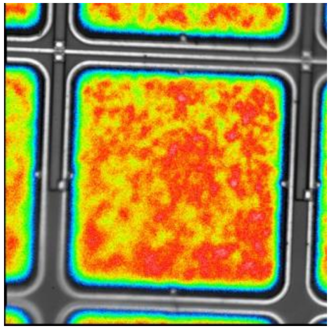


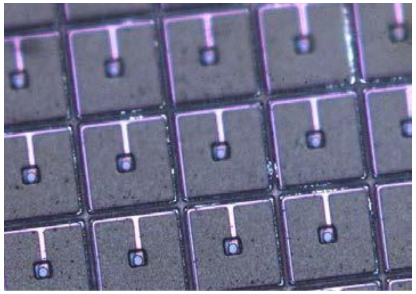


$$PDE = Q_{\varepsilon} \cdot P_{trig} \cdot \varepsilon_{geom}$$

ε_{geom} : geometrical Fill Factor

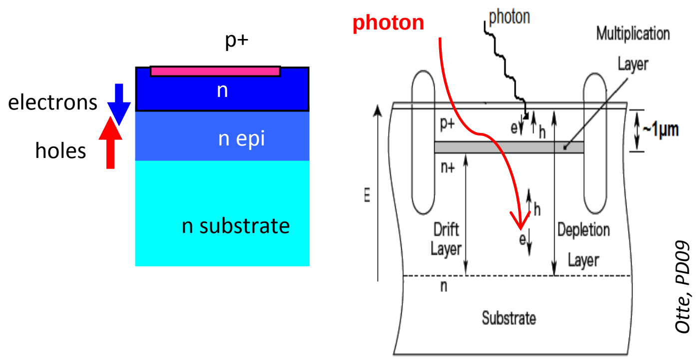
fraction of the sensitive to insensitive area. Only part of the area occupied by the cell is active and the rest is used for the quenching resistor and other connections

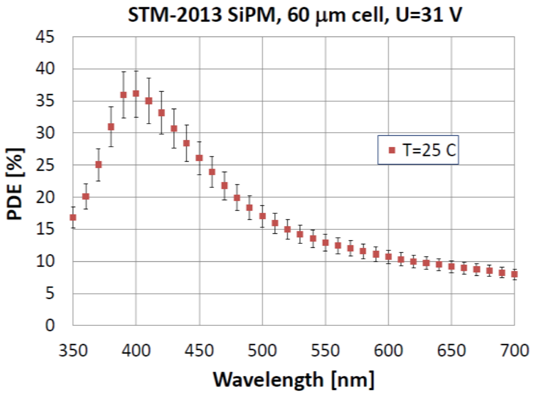


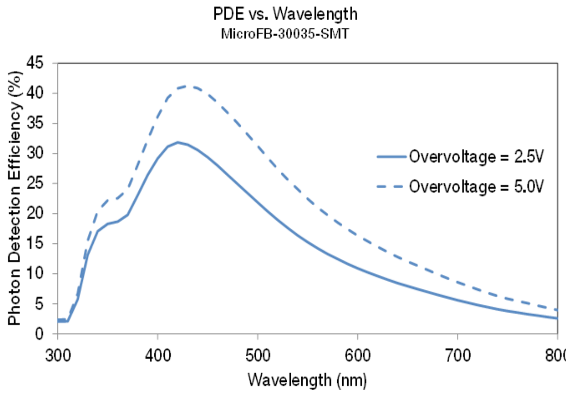


PDE of SiPMs: p-on-n structure

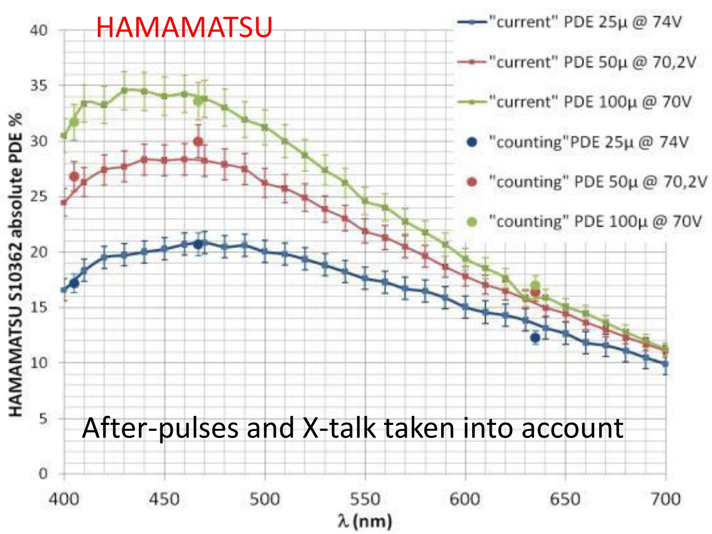
p-on-n SiPM with shallow junction exhibits higer PDE value in the blue region (e- trigger avalanches at short λ)



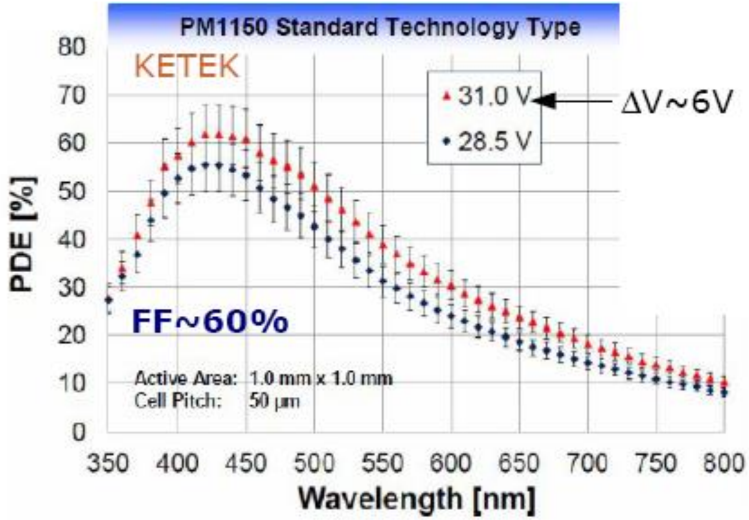




Y. Musienko, INSTR14



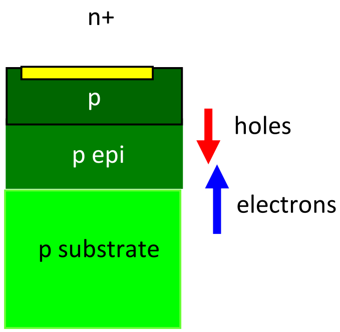
V. Chaumat, PoS (PhotoDet 2012) 058

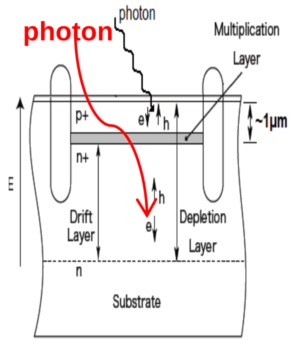


F.Wiest – AIDA 2012

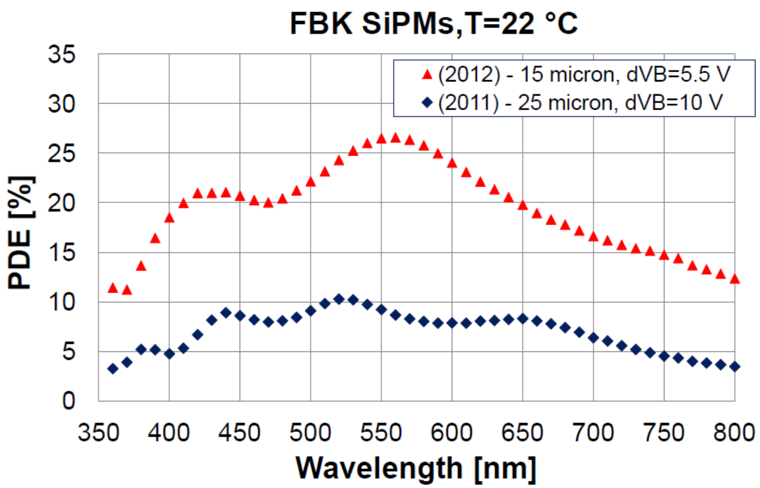
PDE in the blue region : 35 – 60 %

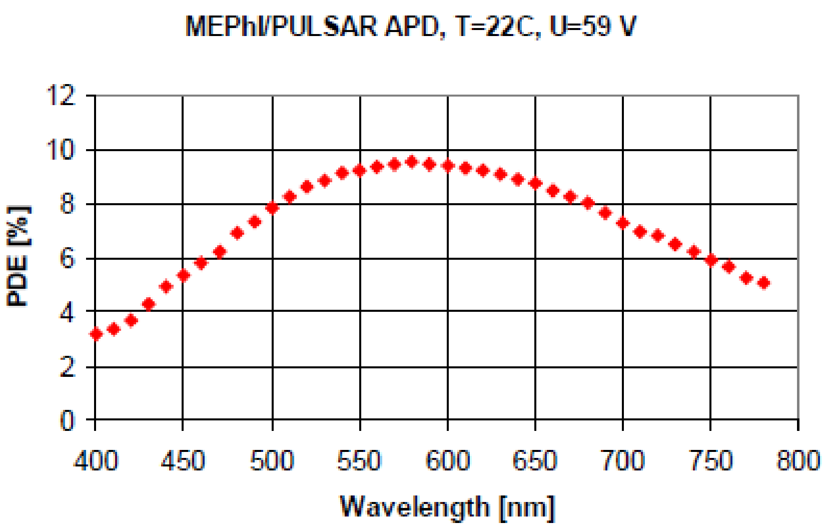
n-on-p SiPM with larger depletion depth have higher sensitivity in the red



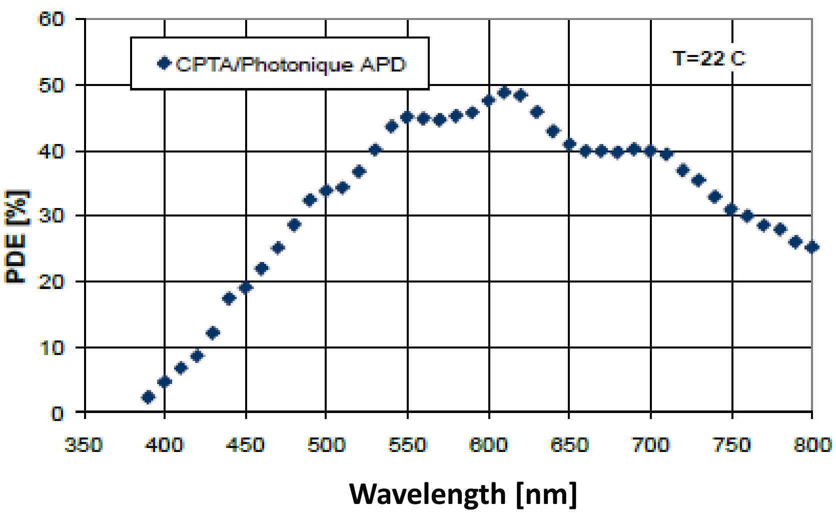


Otte, PD09





Y. Musienko, INSTR14

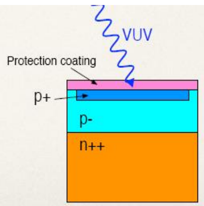


PDE in the green region : 25 – 50 %

VUV SiPMs

Almost no detection of the UV light → limitation of the suitability of SiPMs for Noble-gas detectors

PDE for VUV is ≈ 0 for commercial devices because of the low transmission for VUV of the sensitive layer due to:



- protection coating (epoxy resin/silicon rubber)
- insensitive layer (p+ contact layer with ~zero field)
- absorption length in Si for VUV photon: ~5nm
- high reflectivity for VUV on Si surface

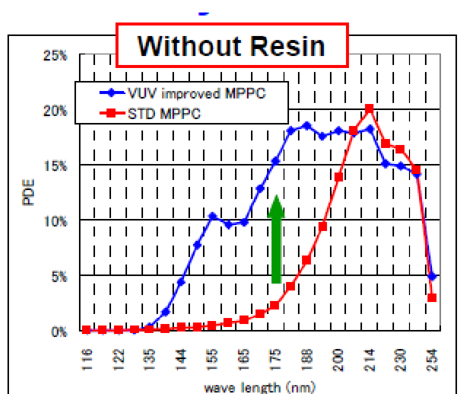
→ **Possible solutions:**

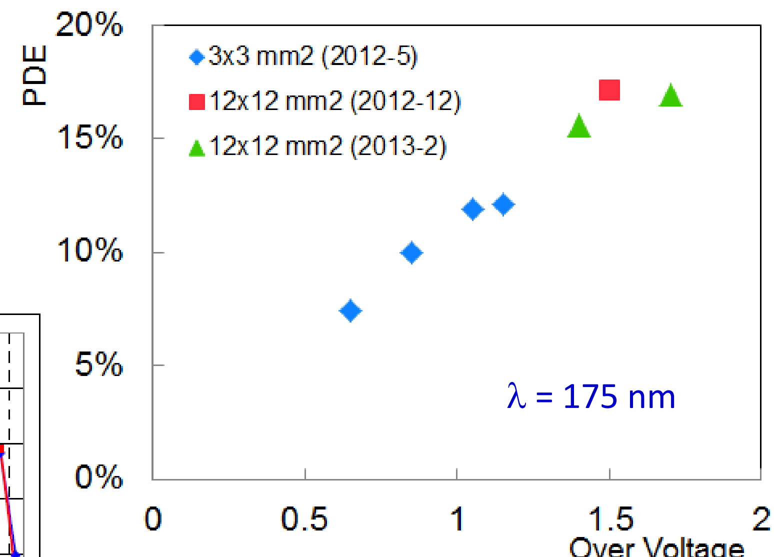
- Remove protection coating
- Thinner p+ contact layer
- Optimize reflection/refractive index on sensor surface

HAMAMATSU

UV-enhanced MPPC under development (collaboration between Hamamatsu, ICEPP and KEK) : removal of the protection coating and optimization of the MPPC parameters → currently sensor size: 12×12mm² (cell size = 50 µm)

- PDE (175 nm) = 17 % (best sample)
- Gain ≈ 10^6 @ 165 K
- DCR = 0 @ 165 K
- decay time ≈ 30 -60 ns





D. Kaneko at al, IEEE NSS 2013 Proceedings

NUV SiPMs

FBK NUV-SiPM (Near-UV SiPM)

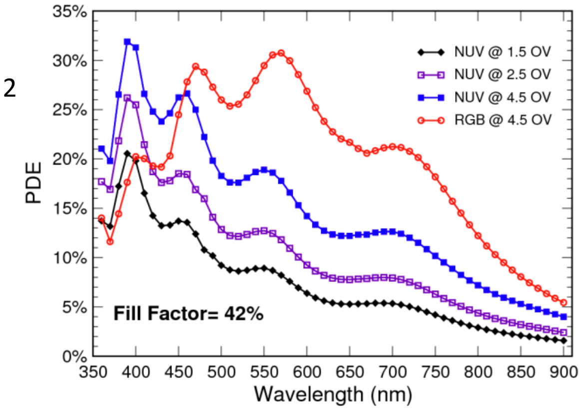
$1 \times 1 mm^2$ $50 \times 50 \mu m^2$ cell

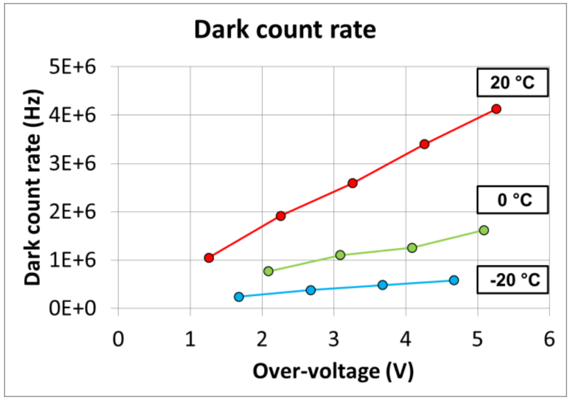
Designs available: 1x1, 2x2, 3x3, 4x4mm^2

Results (FBK measurements):

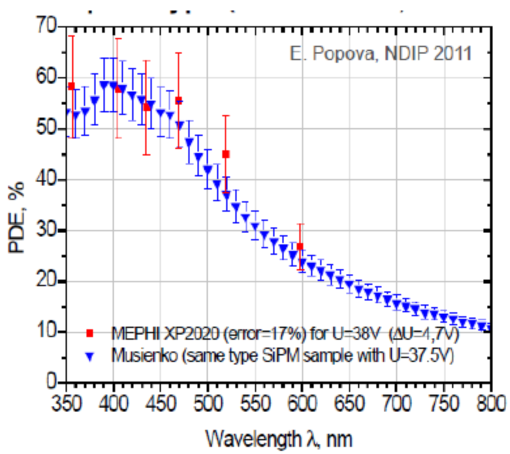
✤ PDE (350 nm) = 20 %

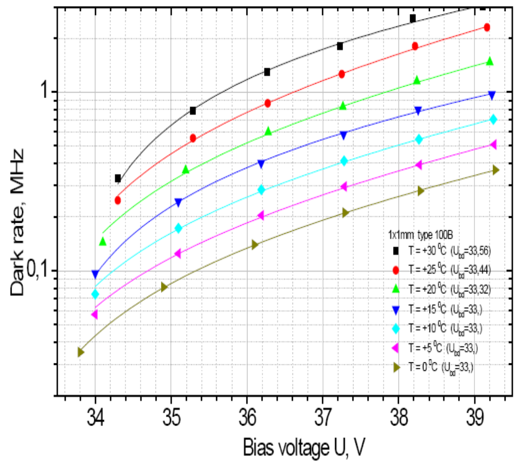
✤ DCR = 4 MHz @ 20°C (ΔV = 5V)





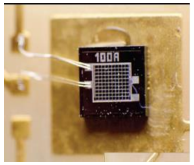
A. Ferri, NIMA 718 (2013)





E. Popova, NDIP2011

Excelitas

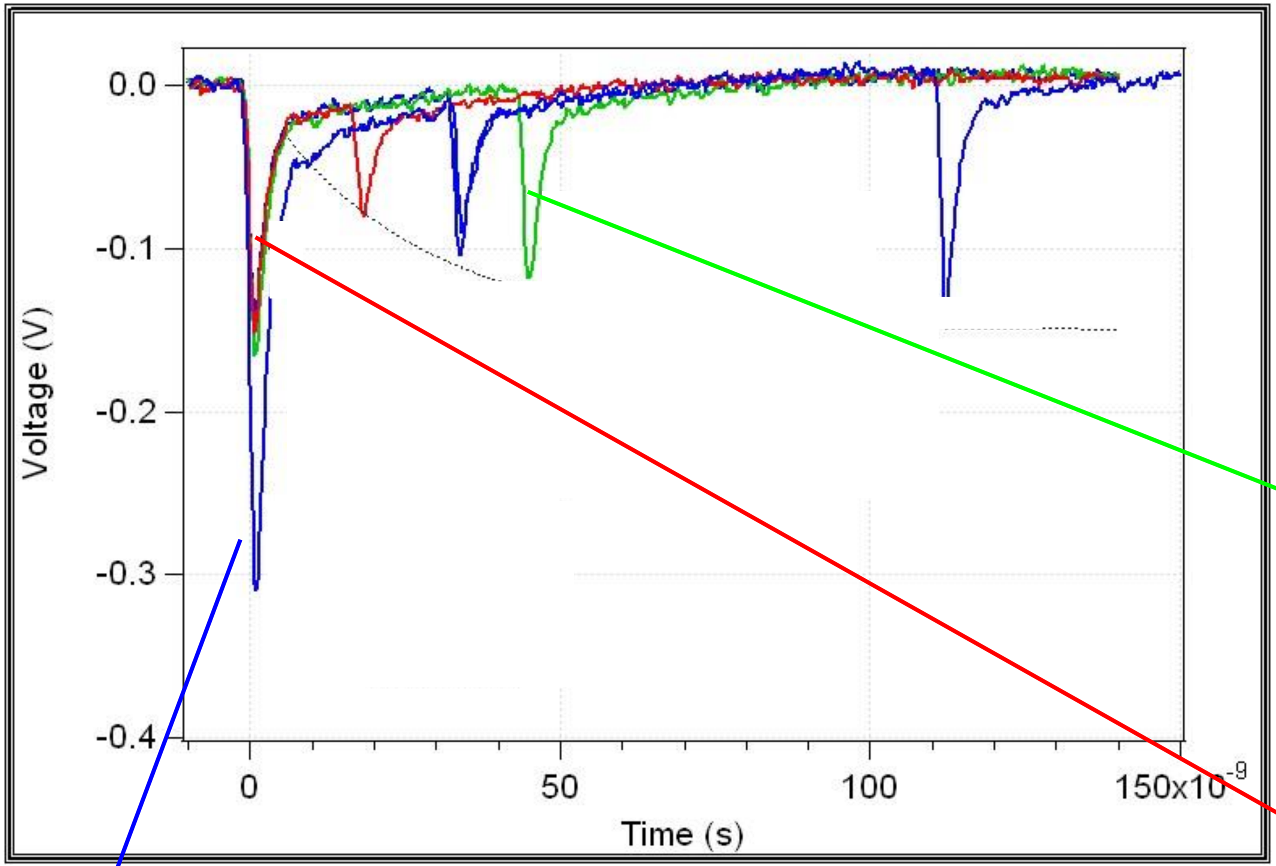


Collaboration between Excelitas, MEPHI and MPI : 1×1 mm^2 (cell size = 100 µm)

✤ PDE (350 nm) = 50 %

✤ DCR = 800 kHz @ 20 °C (ΔV = 4V)

Noise sources of a SiPM



After-pulses

carriers trapped during the avalanche can produce delayed secondary pulses

Dark counts

pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

Cross-talk : amplitude = 2 p.e

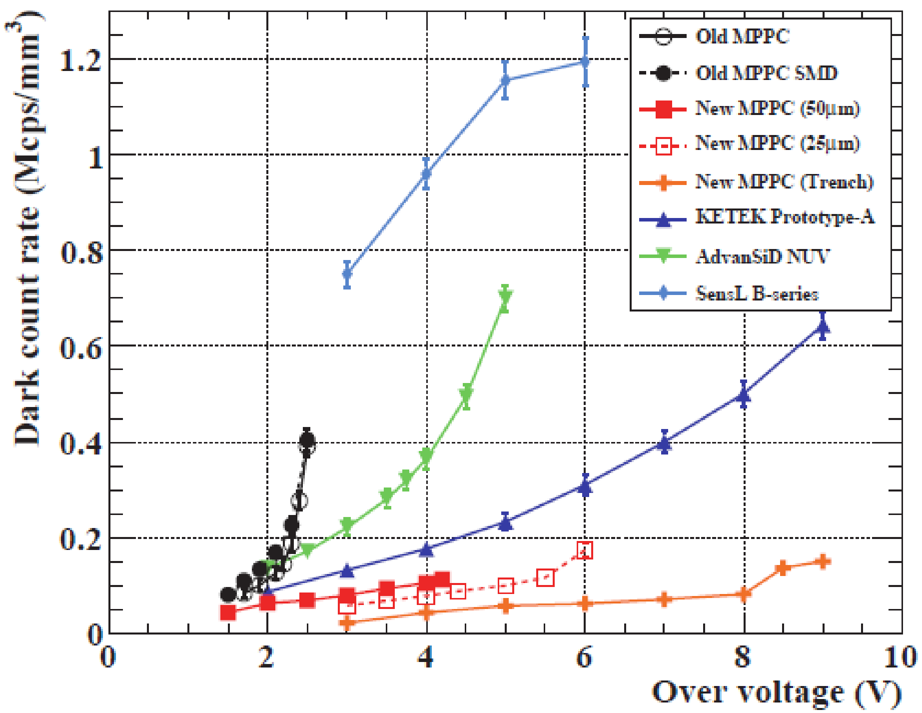
avalanche in one cell → proba that a photon triggers another avalanche in a neighboring cell without delay

Dark Count rate (DCR)

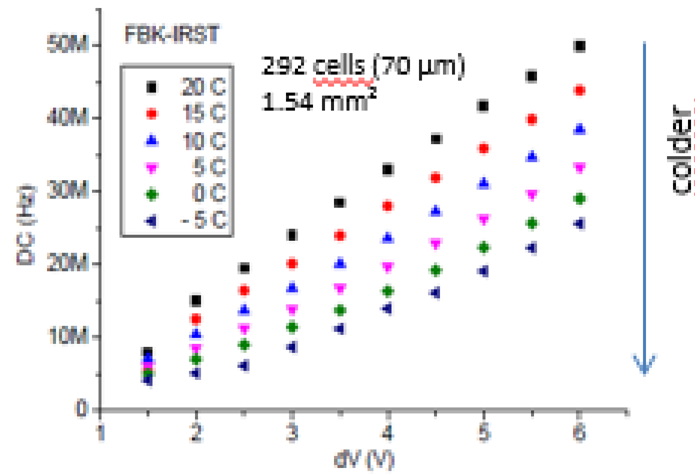
Average frequency of the thermally generated avalanches breakdown process that result in a current pulse indistinguishable from a pulse produced by the detection of a photon.

Few 100kHz/mm² < DCR < 1 MHz/mm² till 2013

DCR of most recent devices ≈ few 10 kHz/mm²



Y.Uchiyama et al, IEEE NSS 2013



O. Starodubtsev, PoS 2012

Best way to decrease the Dark Count rate:

✓ operate the SiPM at lower voltage

✓ cooling (factor ≈ 2 reduction of the dark counts every 8°C)

After-pulses

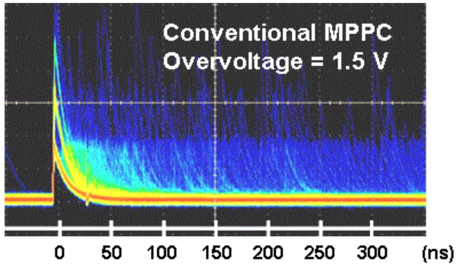
Breakdown → production of a large number of charge carriers → some of them are trapped in deep trap levels created by impurities (Iron, Gold) and defects (point, dislocation)

These carriers may be released at some time and trigger a new breakdown avalanche event : afterpulse (described in term of probability)

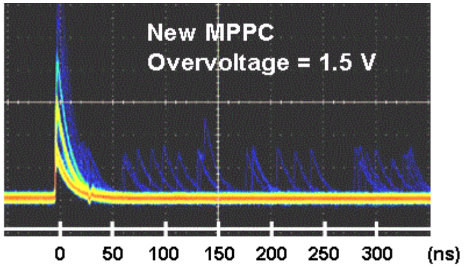
↓

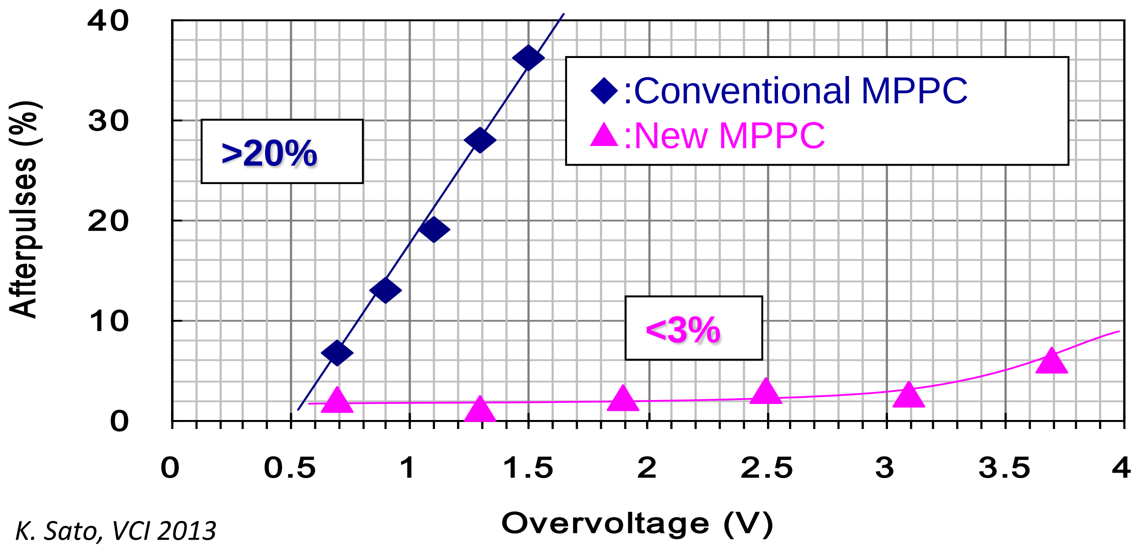
Minimization of the amount of impurities in the avalanche region employing pure Si wafers and new process conditions.

before



after



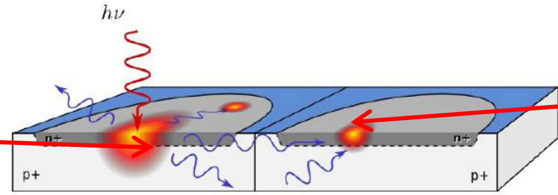


After-pulse proba < 10 % for most of the SiPMs on the market

K. Sato, VCI 2013

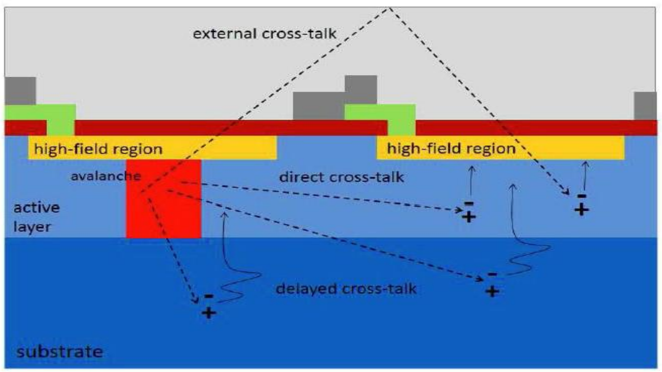
Cross-talk

avalanche in one cell probability than 1 carrier emits ≈ 3.10^{-5} photons with E > 1.12 eV

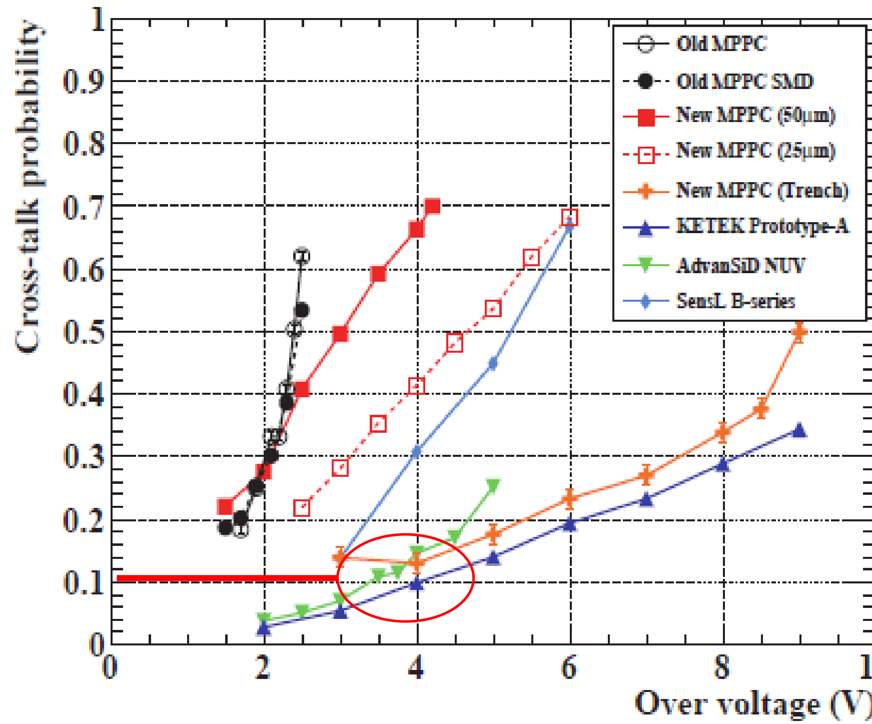


these photons (≈ 30 for a gain of 10^6) can trigger another avalanche in a neighboring cell without delay

A. Lacaita, et al., IEEE Trans. Electron Devices ED-40 (1993) 577

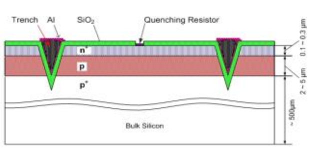


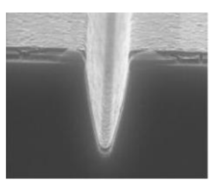
A. Ferri, IPRD13



Y.Uchiyama et al, IEEE NSS 2013

One solution to decrease the CR is to improve the optical isolation between the cells: etching trenches filled with opaque material



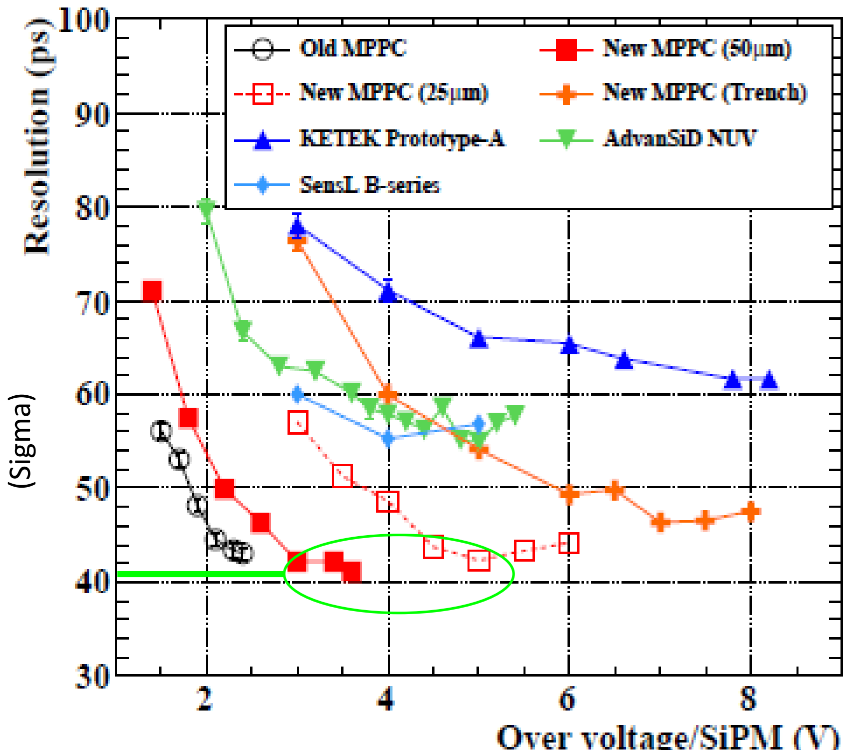


D. McNally, G-APD workshop (2009)

less than 15 % of crosstalk for low overvoltage which is at least a factor 2 better than with the old geometries

Timing resolution

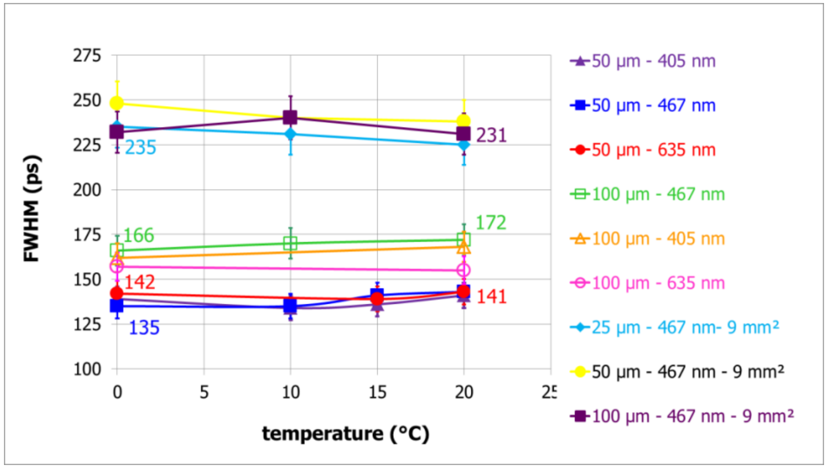
active layer is very thin (few µm) + breakdown development is very fast + big signal amplitude → very good timing properties even for single photons can be expected



P.W Cattaneo, arXiv:1402.1404v1

40 ps < SPTR (σ) < 60 ps

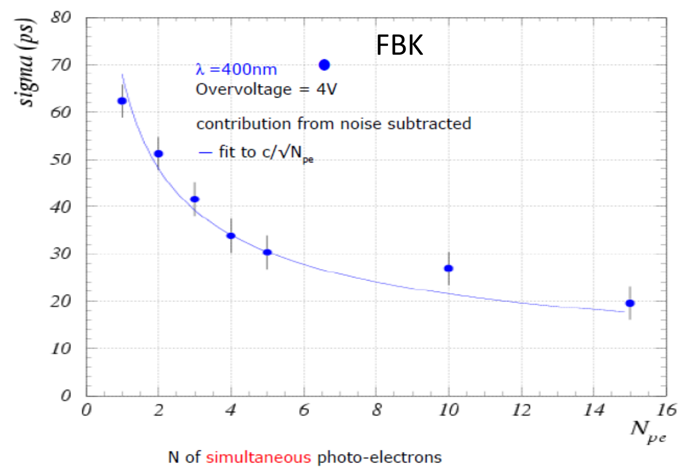
No variation of the SPTR with the temperature



V. Puill, NIMA 695, 2012

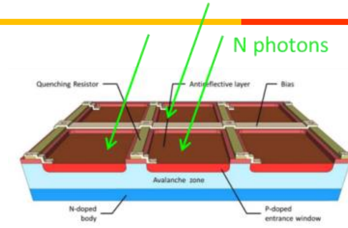
Timing resolution as a function of the incident number of photons

G. Collazuol, NIMA 581 (2007)



Dynamic range and linearity

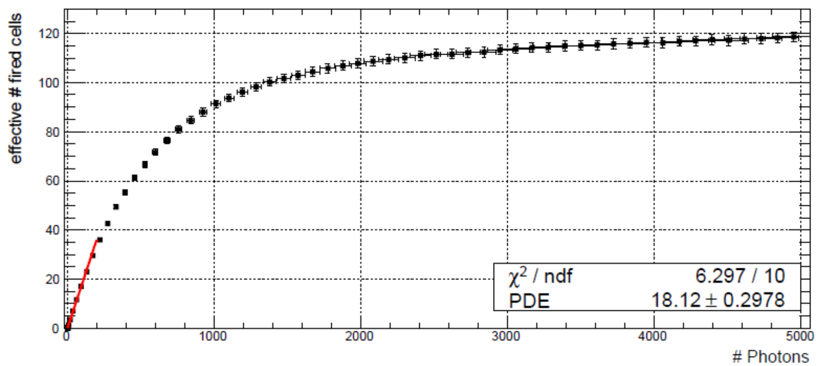
2 or more photons in 1 cell look exactly like 1 single photon



KETEK web site

Output signal: proportional to the number of fired cells as long as N_{photon} x PDE << N_{total}

SiPM response as a function of the number of instantaneous incident photons



T. Kowalew Thesis

$$A \approx N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

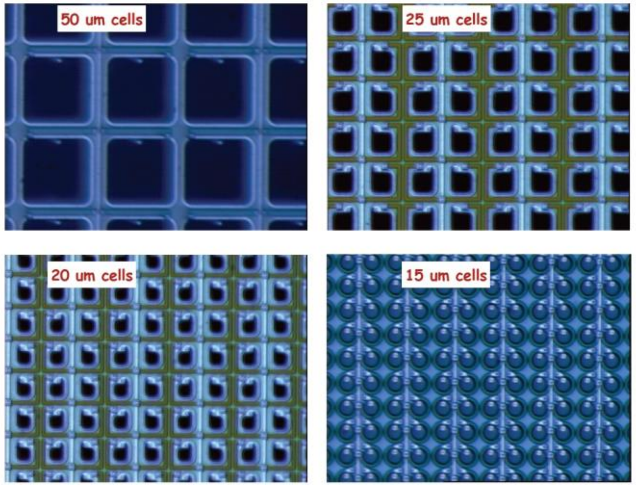
$N_{firedcells}$: number of excited cells
N_{total}: total number of cells
N_{photon}: number of incident photons in a pulse

The saturation is a limiting factor for the use of SiPM where large dynamic range of signal (5000 – 10000 photons/pulse) has to be detected (calorimetry)

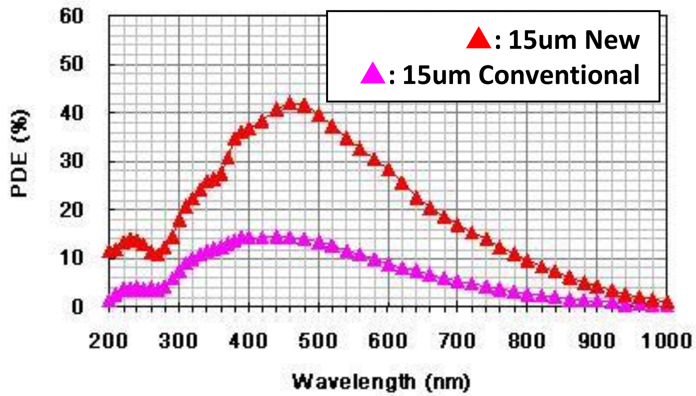
Solution to the saturation: large number of cells

high density SiPM : device with more than 1000 cells/mm² + short recovery time

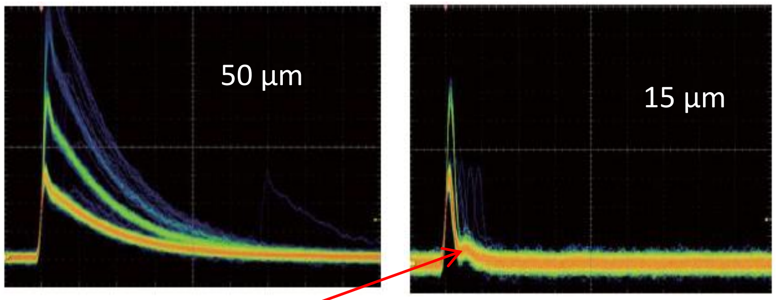
HAMAMATSU

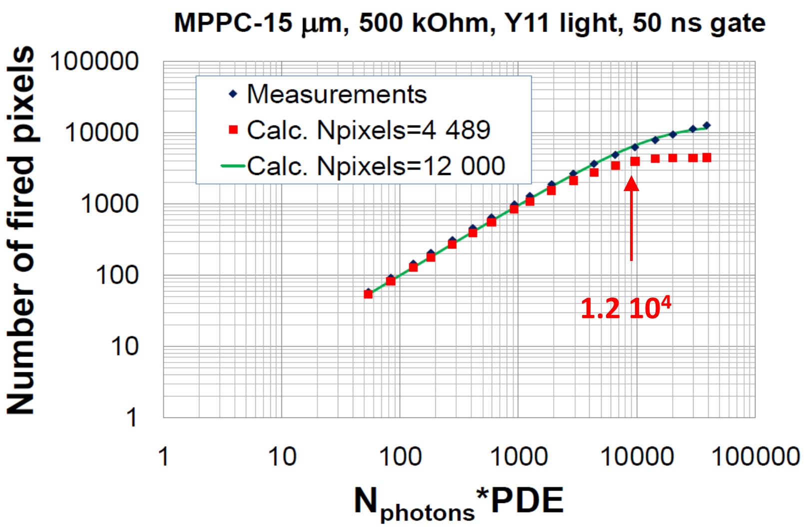


1 mm²
4489 cells
cell size : 15 µm
gain = 2×10^5



HPK, private communication





Y. Musienko, NDIP-2011

fast cell recovery time (~4ns) → the linearity for Y11 (WLS fiber) light of 4489 cells/mm² MPPC corresponds to a SiPM with ~ 12000 cells/mm²

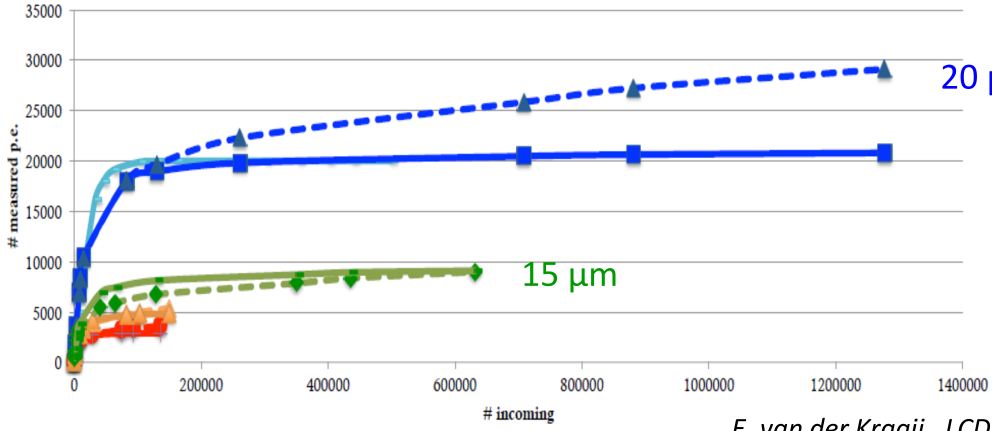
Solution to the saturation: large number of cells

high density SiPM : device with more than 1000 cells/mm²

KETEK

MP15 V6 W8:
1.2x1.2 mm²
Cell size = 15 µm
12800 cells

MP20 V4 W12:
3x3 mm²
Cell size = 20 µm
22500 cells



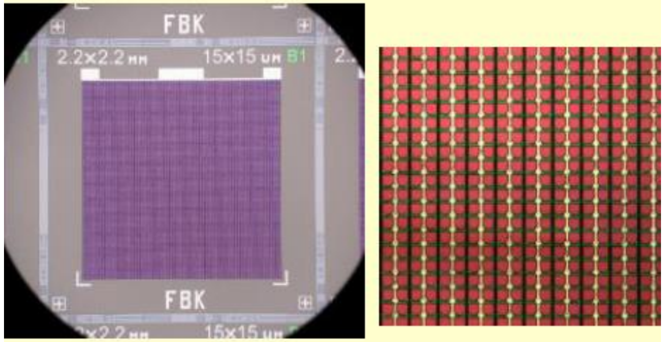
E. van der Kraaij, LCD ECAL meeting 2014

FBK

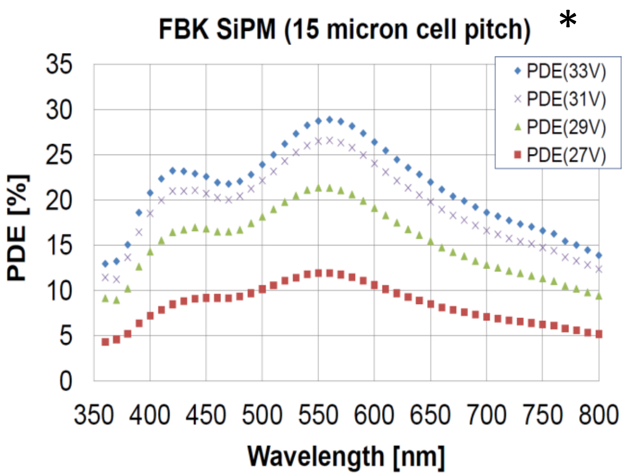
RGB-SiPM-HD

2.2 x 2.2 mm²
gain = 8x10⁵
DCR = 2MHz/mm²
recovery time = 9 ns

Active area: **2.2x2.2 mm²**
cell size: **15x15 µm²**
cells: ~ 21300
Fill factor = 48%



A. Ferri

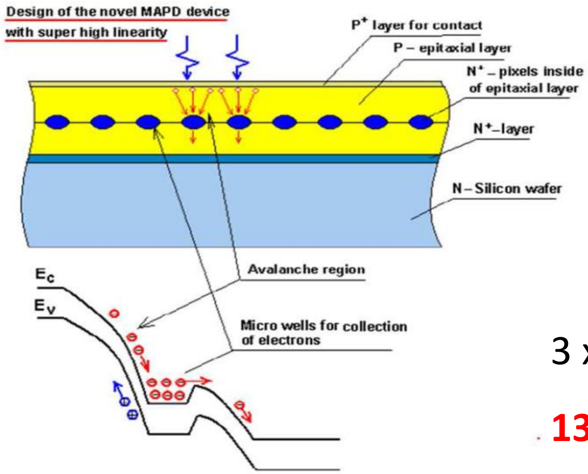


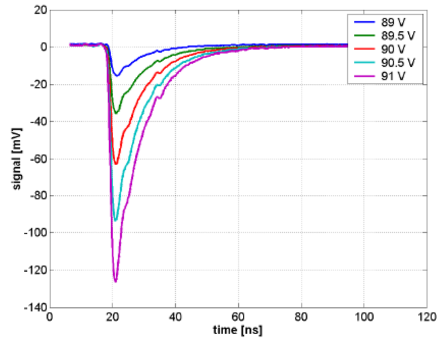
** measurements by Y.Musienko @ CERN*

Solution to the saturation: very large number of cells

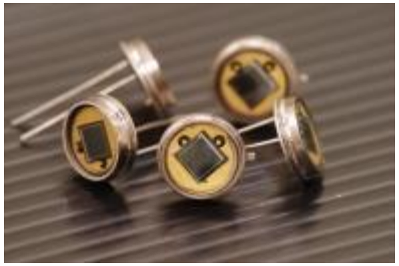
ZECOTEK MAPD-3N

Special design: both the matrix of avalanche regions and the individual quenching elements are created inside the Si substrate with a special distribution of the inner electric field





A. Rychter, Proc. of SPIE Vol. 8454

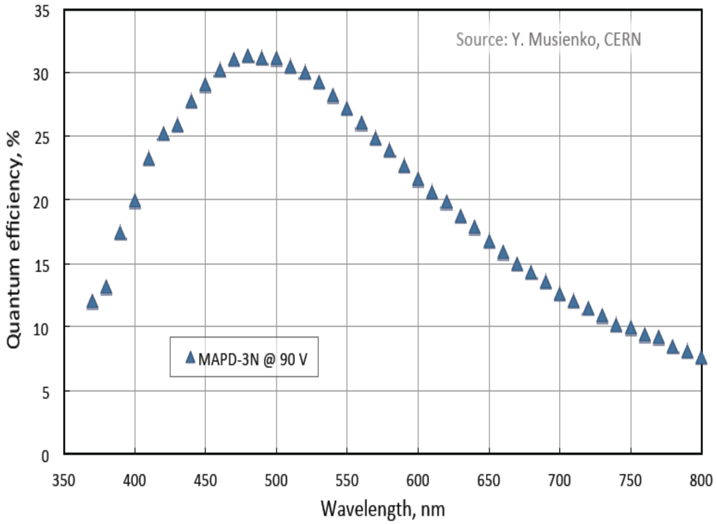


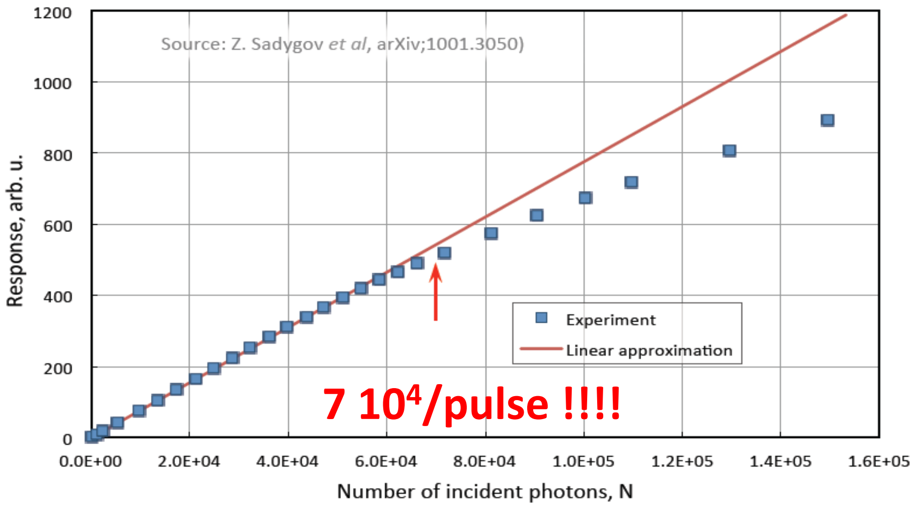
3×3 mm^2

1350000 cells (15000/mm^2)

gain = 10^5

slow cell recovery time : 80 ns





Radiation-hardness of SiPMs

protons / neutrons

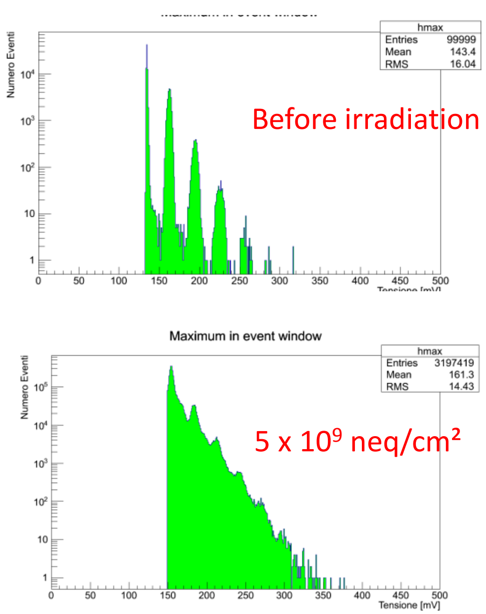
bulk damages caused by lattice defects

γ-rays, X-rays

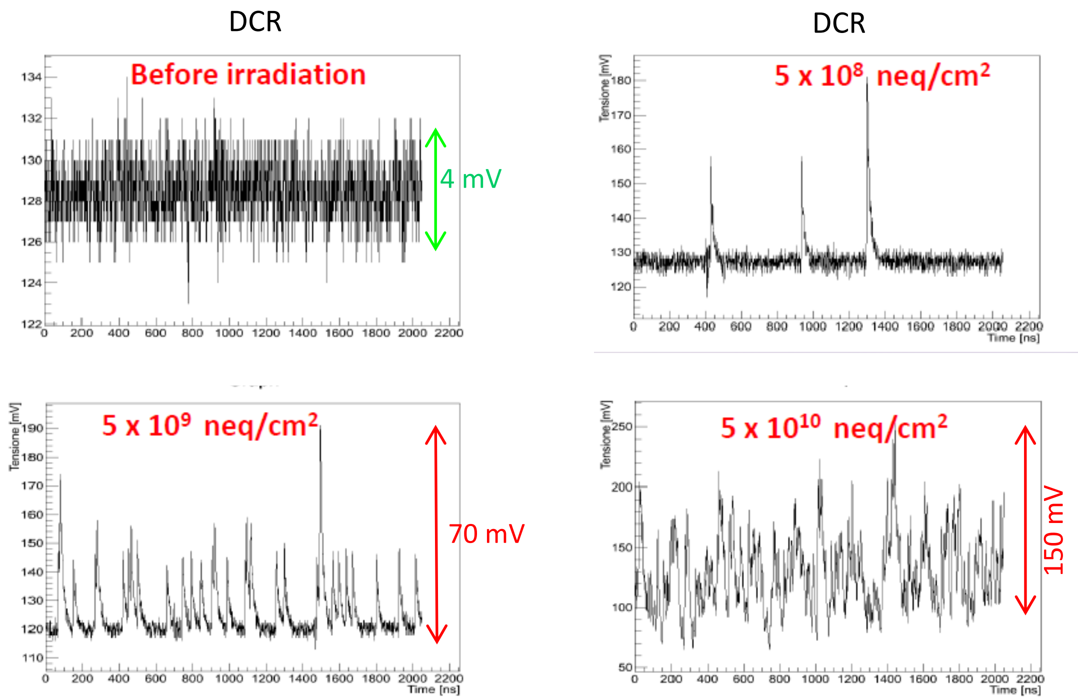
creation of trapped charges near the Si-insulator interface

- increase of the dark current and the DCR
- change of the breakdown voltage
- change of the gain and PDE dependence as a function of bias voltage

→ high dark noise → large size cells (we need them for high PDE!!) are permanently fired → significant drop of the SiPM PDE and gain → SiPM has low PDE, gain and it is useless as a photodetector for the calorimetry… (Y. Musienko, NDIP14)



W. Baldini, TIPP 2014

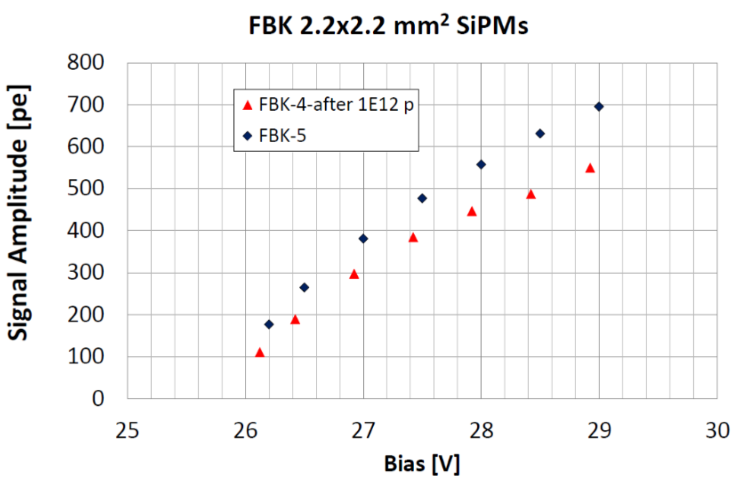


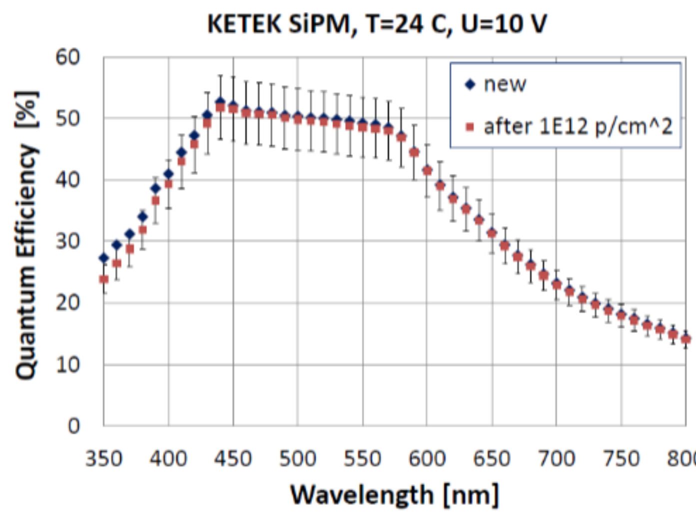
Wander Baldini, TIPP 2014

Good resistance to neutron irradiation

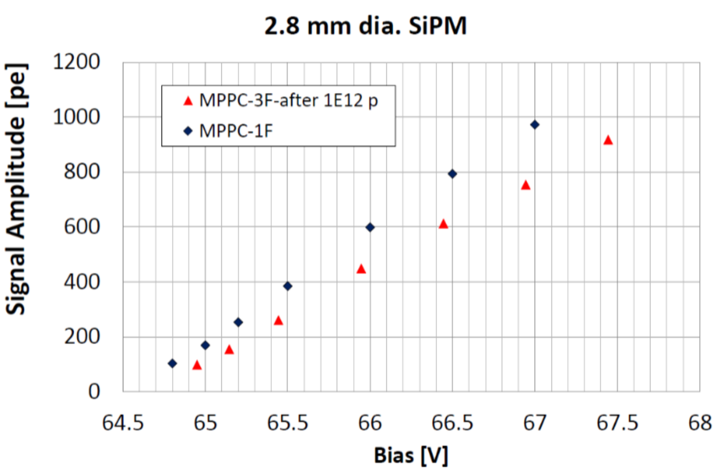
HAMAMATSU , FBK, NDL, ZECOTEK, KETEK developed devices with improved radiation hardness

HAMAMATSU, KETEK and FBK SiPMs **survive 10^{12} n/cm² 1 MeV equivalent neutron flux** (it was 10^8 n/cm² 3 years ago)





Y. Musienko, NDIP 2014

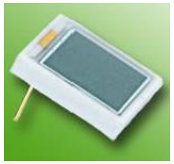


At high neutron fluence a decrease of the Gain*PDE is observe → can be recovered by bias voltage increase.

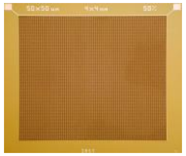
Large SiPMs

Large SiPMs: large sensitive area but high DCR …

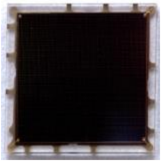
Excelitas C30742-66



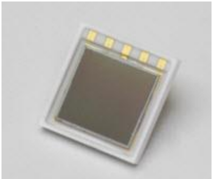
ASD-SiPM4S



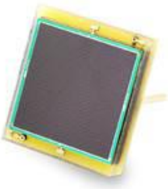
sensL C-series



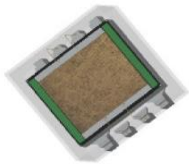
HAMAMATSU S10985



KETEK PM6060



STMicroelectronics



Producer	Reference	Area (mm^2)	PDE max @ 25 °C *	Dark Count Rate max (Hz) @ 25°C *	Gain *
EXCELITAS	C30742	6 x 6	30% @ 420 nm	$10\ .10^6$	$1.5\ 10^6$
FBK - AdvanSiD	ASD-SiPM4S	4 x 4	30% @ 480 nm	$9.5\ 10^7$	$4.8\ 10^6$
HAMAMATSU	S10985-50C	6 x 6	50% @ 440 nm (includes afterpulses & crosstalk)	10.10^6	$7.5\ 10^5$
SensL	C-series	6 x 6	40 % @ 420 nm	$4.5\ 10^6$ (21 °C)	$3\ 10^6$
KETEK	PM6060	6 x 6	40% @ 420 nm	18.10^6	10^7
STMicrolectronics	SPM35AN	3,5 x 3,5	16% @ 420 nm	$7.5\ 10^6$	$3.2\ 10^6$

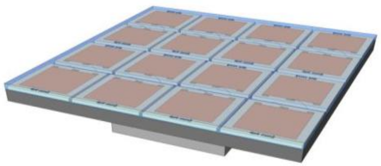
** datasheet data*

Matrixes: SiPMs discrete arrays

Segmentation of the light detection + need of larger active area → SiPM matrix

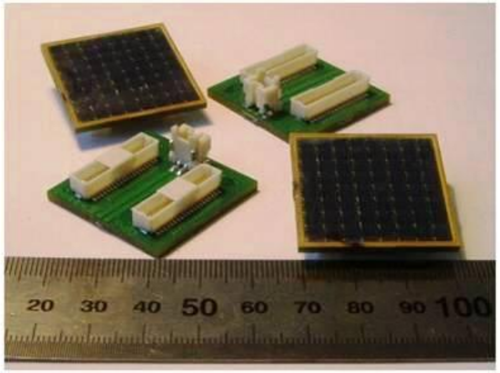
FBK

ASD-SiPM4S-P-4×4T-50



4x4 channels
1 channel = 4x4 mm²
6400 cells (50 x 50 µm²) /channel

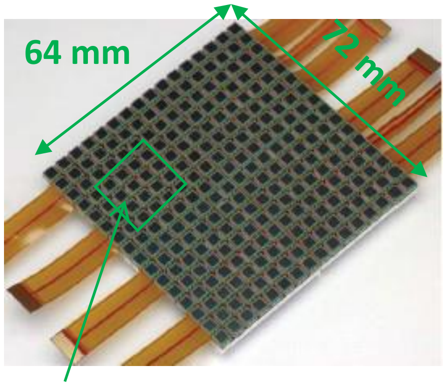
Zecotek



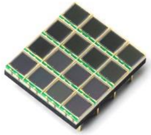
8x8 channels
1 channel = 3x3 mm²
15000 cells /channel

HAMAMATSU

S11834-3388DF



S11064-025

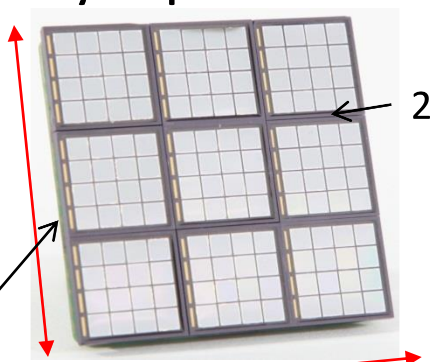


4x4 channels
1 channel= 3 x 3 mm²
14400 cells (25 x 25 µm²) /channel

SiPMs discrete arrays

Sensl

ArraySL-4p9-30035



2.72 mm

48 mm

46 mm

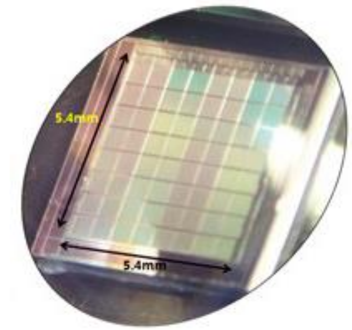
SL-4-30035-CER

4x4 channels
1 channel= 3 x 3 mm²
4774 cells (35 x 35 µm²) /channel

ArrayB-600XX-64P

8x8 channels
1 channel= 6 x 6 mm²
18980 cells /channel
new surface mount package

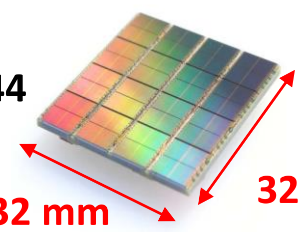
Sungkyunkwan University (Korea)



8x8 channels
1 channel= 0.5 x 0.5 mm²
1024 cells (32 x 32 µm²)/channel

Philips Digital Photon Counting

DLS-6400-22-44



32 mm

32 mm

8x8 channels
1 channel = 3.9 x 3.2 mm²
6396 cells (59 x 32 µm²) /channel
Electronics embedded

Evolution of the matrix: packaging and technology

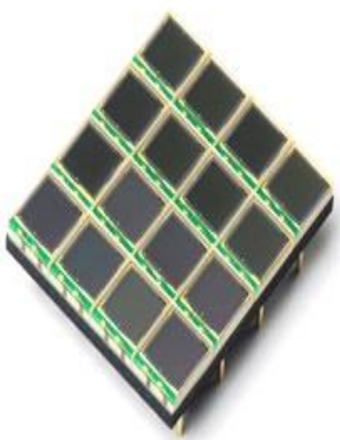
Requirements for the SiPM matrixes:

- improvement of the spatial resolution and PDE
- simplification of the assembly for the building of detectors with large surface and large active area

✓ Important efforts on the packaging: matrix tileable on almost all their sides + small dead space between them

✓ Development of monolithic SiPM matrices: all the channels are on the same substrate → small dead spaces, simplification of the assembly

Discrete Array



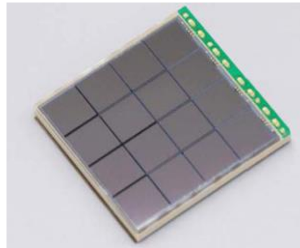
Monolithic Array

3-side buttable Tiling

SiPMs monolithic arrays

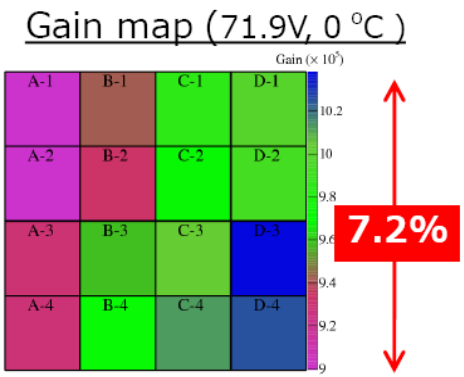
HAMAMATSU

4x4 channels
1 channel = 3x3 mm²
3600 cells (50x50 µm²)/channel



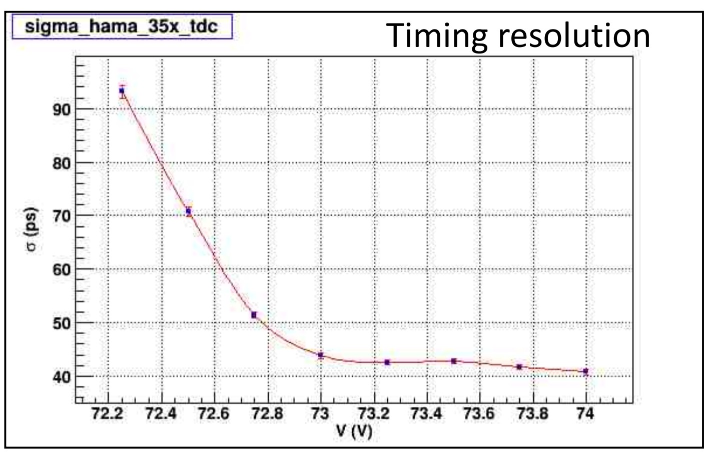
S11828-3344

Kato et al, NIMA 638 (2011) 83–91



ave. gain = 9.7×10^5

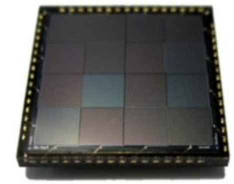
3 sides tileable
1 cathode – 16 anodes

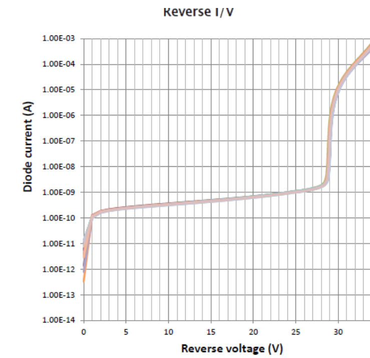


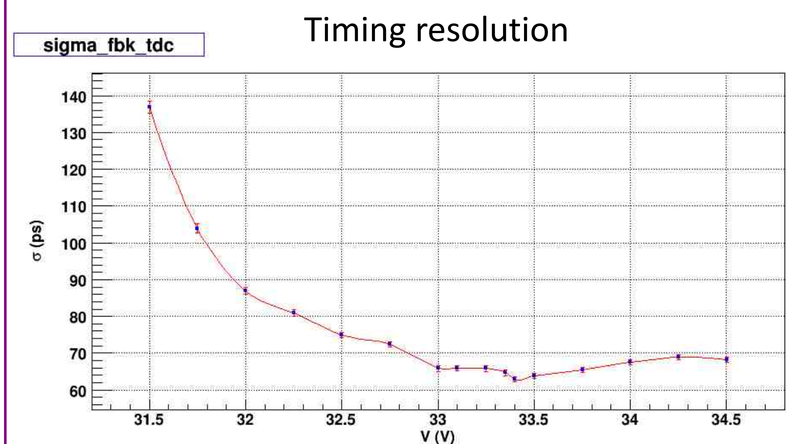
M. Bonesini, IPRD13

FBK - AdvanSiD

ASD-SiPM3S-P-4x4A

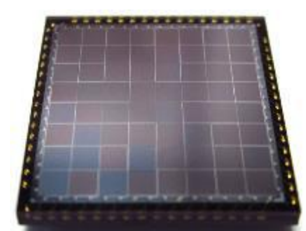






M. Bonesini, IPRD13

ASD-RGB1.5S-P-8x8A



8 x 8 channels

4 sides tileable

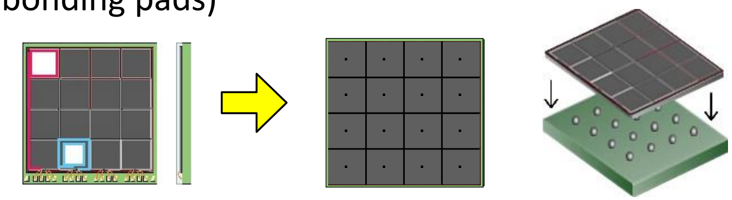
Discret array with TSV technology

HAMAMATSU development: another way to improve the fill factor and therefore the PDE

Through Silicon Via Technology: each anode is connected by the shortest distance possible to the substrate

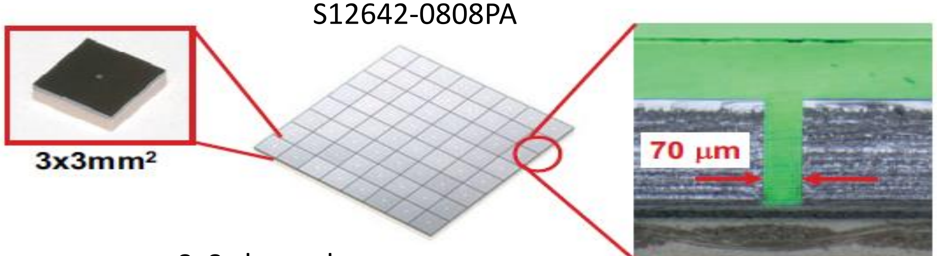
with wire bonding (traces to the bonding pads)

with TSV (No traces)



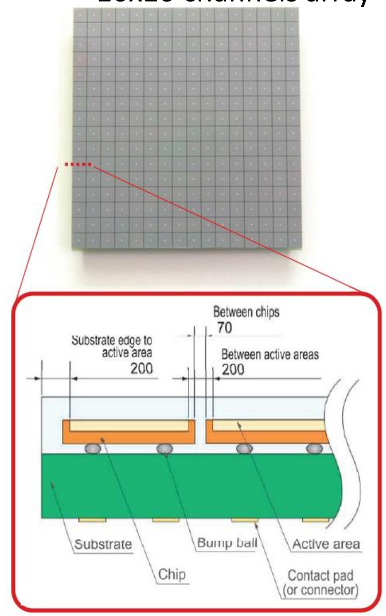
+ high precision assembly → Discrete Array like monolithic array !

S12642-0808PA



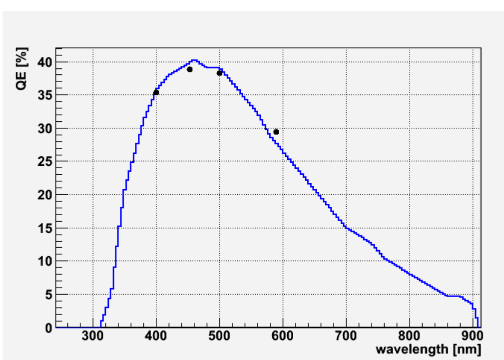
8x8 channels array

16x16 channels array



K. Sato, IEEE NSS 2013

➜ 4 side tileable configuration with very narrow gap between neighboring active areas (200 µm) equivalent to the gap in traditional monolithic type devices

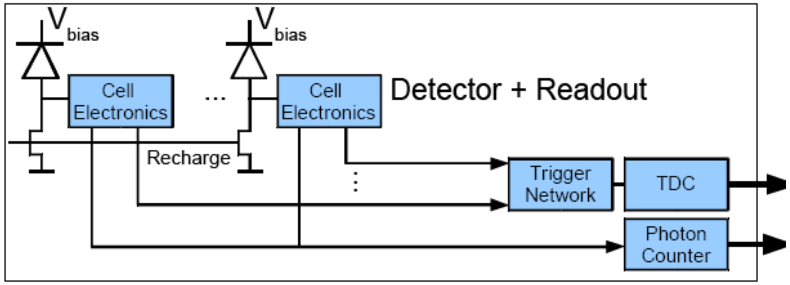


N. Otte, NDIP14

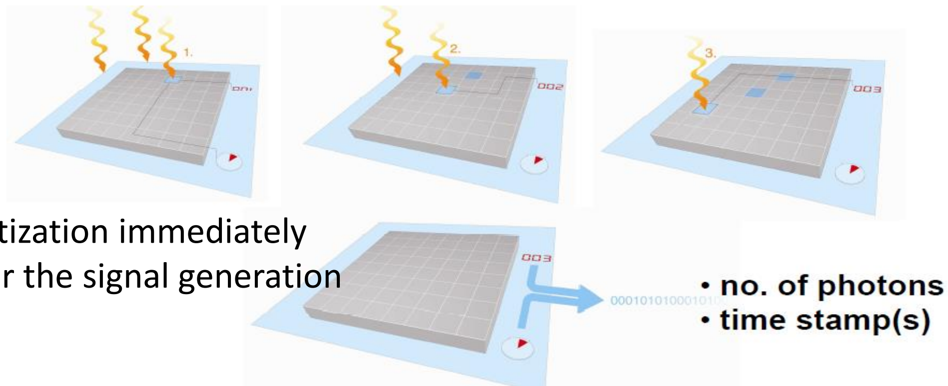
The Digital SiPM by Philips

Array of G-APDs integrated in a standard CMOS process. The signal from each cell is digitized and the information is processed on chip:

- time of first fired cell is measured
- number of fired cells is counted
- active control is used to recharge fired cells

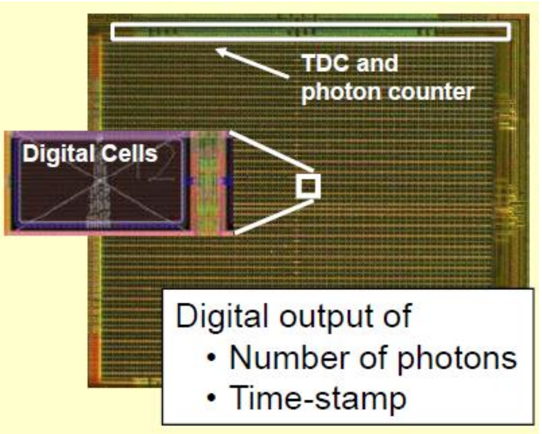


York Hämisch, TIPP 2011

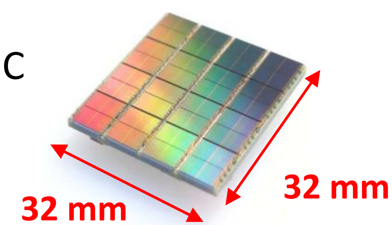


digitization immediately after the signal generation

digital sum of the detected photons



Example of a matrix of DPC



DLS-6400-22-44

8x8 channels

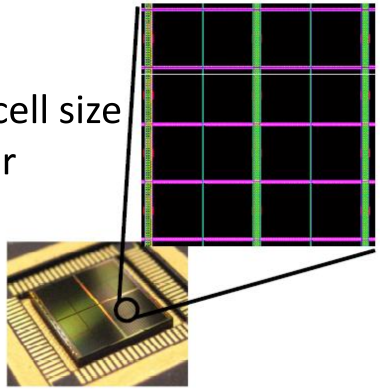
1 channel = 3.9 x 3.2 mm²l

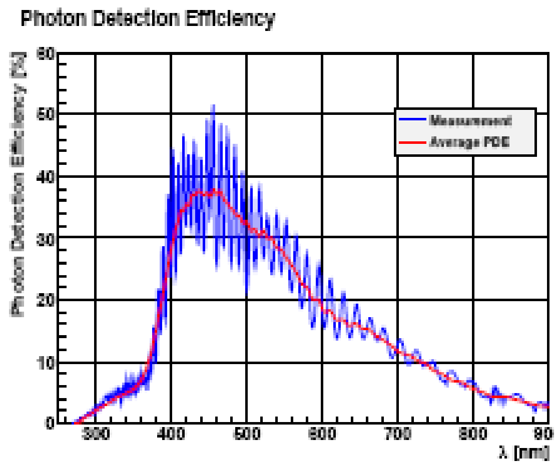
Electronics embedded

Early Designs in 2005

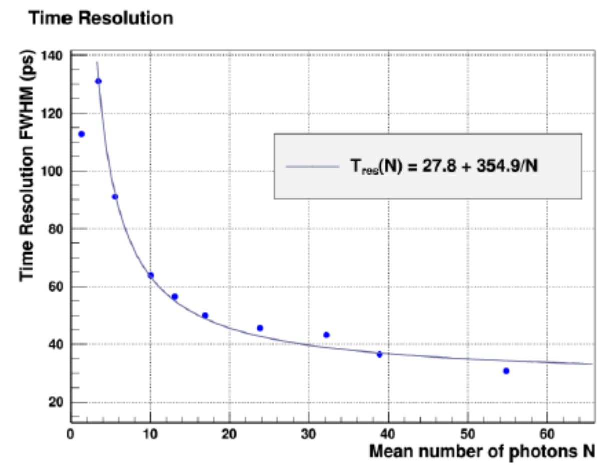
DLS-3200-22-44

- 3200 cells
- 59 x 64 μm² cell size
- 78% fill-factor





T. Frach, 2012 JINST 7 C01112



T. Frach, Hereaus seminar 2013

- *afterpulsing ~ 18% (20 °C)*
- *DCR = 200 kHz/mm² (20 °C)*
- *temperature sensitivity ~ 0.33 %/°C*
- *timing resolution (SPTR) = 140 ps (FWHM)*
- *recovery time : 5 – 40 ns*

Radiation hardness ?

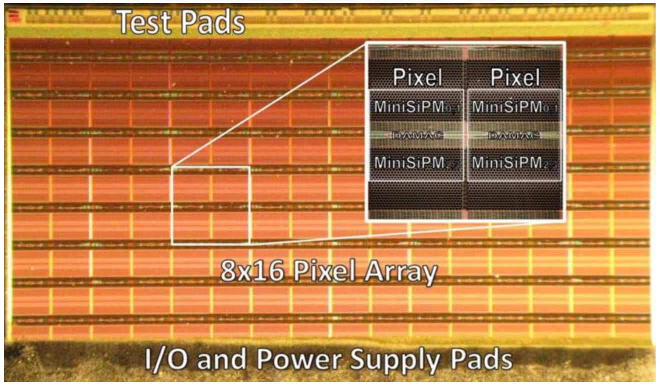
→ still working for 10^{11} n/cm² (producer communication)

Drawback:

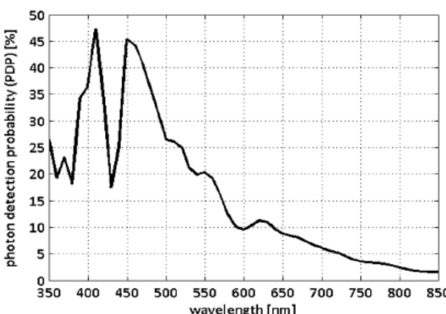
➢ requires a dedicated readout provided by Philips

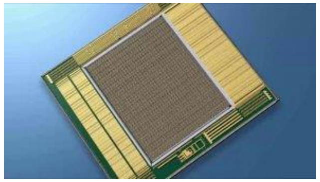
Digital SiPM: other developments

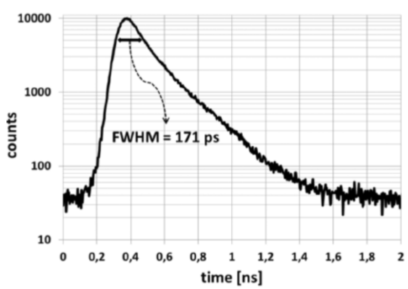
FBK – ST micro – Edimburg University



L. H. C. Braga, IEEE Journal of solid state circuit vol. 49, 2014.

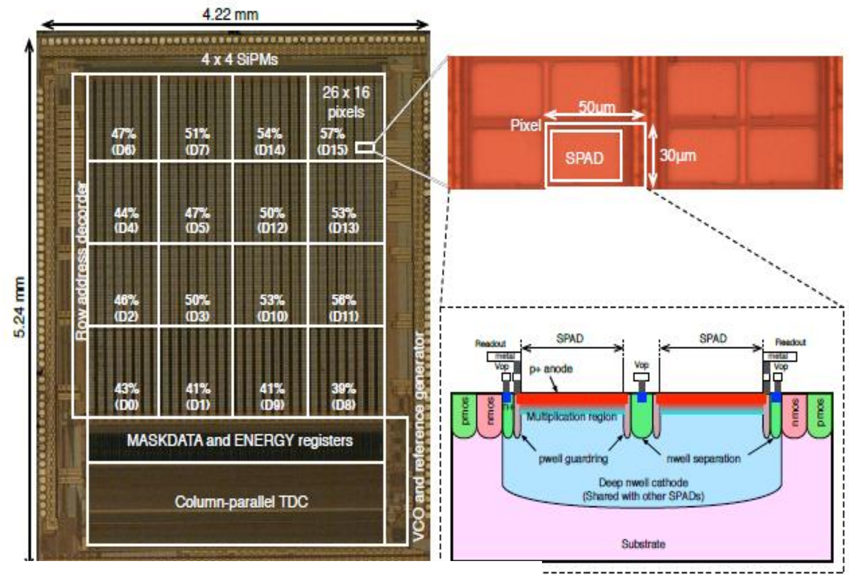


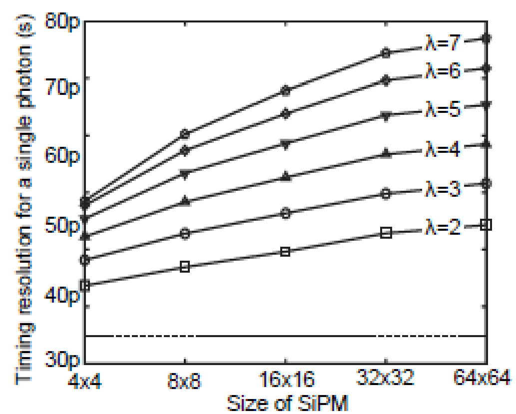




Faculty of Electrical Engineering, TU Delft

Area of the chip: 22.1 mm2 with a sensitive area of 3.2 x 3.2 mm²





S. Mandai, 2013 JINST P05024

Conclusion

Summary of the photodetectors characteristics

	😊 (max value)	😢
PMT	▪ High gain (10^6) with 1000 – 2000 V ▪ Low noise ▪ High quantum efficiency (30 % in blue) ▪ Large area (> 10000 mm²) ▪ Large number of configurations ▪ Commercial products since 70 years	▪ Non linearity ▪ Non response uniformity ▪ Affected by magnetic field ▪ Fragility ▪ Only 2 producers on the market !!
MCP-PMT	➢ High gain (10^7- 10^8) ➢ High quantum efficiency ➢ Very good timing properties (SPTR = 30 ps)	➢ Fragility ➢ Cost
SiPM	• High gain (10^5-10^6) with low voltage (< 100 V) • Single photo detection • Good timing resolution (SPTR = 40 ps) • Insensitivity to magnetic field (up to 7 T) • High photon detection efficiency (50 % in blue) • Mechanically robust • A lot of R&D and different producers • Low cost mass production possible (ex: T2K)	• High dark count rate @ room temperature for large device (≥ 9 mm²) • High temperature dependence of the breakdown voltage, the gain • Small devices • Few geometrical configurations available

Documentary sources and for more explanations

Lectures and Revues :

- **IEEE NSS 2012:** Vacuum based photodetector, **Katsushi Arisaka**
- **PhotoDet 2012 workshop**, LAL Orsay: The SiPM Physics and Technology - a Review , ***Gianmaria Collazuol***
- **Summer School INFIERI 2013, *Oxford:*** Intelligent PMTs versus SiPMs***, Véronique Puill***
- **RICH 2013**: Status and Perspectives of Solid State Photo-Detector***, Gianmaria Collazuol***
- **NDIP14*:*** MCPs and Vacuum Detectors Review***, Thierry. Gys***

Reference articles:

- **Photomultipliers** from S.Donati
- **Silicon Photomultiplier - New Era of Photon Detection** from Valeri Saveliev
- **Advances in solid state photon detectors** from D. Renker and E. Lorenz
- **Silicon Photo Multipliers Detectors Operating in Geiger Regime: an Unlimited Device for Future Applications** from G. Barbarino, R. de Asmundis, G.a De Rosa, C. M Mollo, S. Russo and D. Vivolo

Books:

- **Hamamatsu PMT Handbook**
- **Burle PMT book**

Articles and presentations:

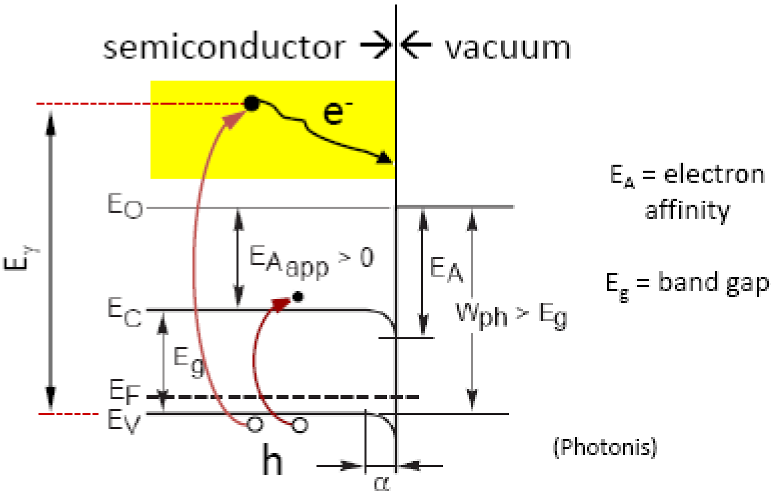
All quoted under the figures and plots of this presentation (my apologies if I forgot some of them)

The End

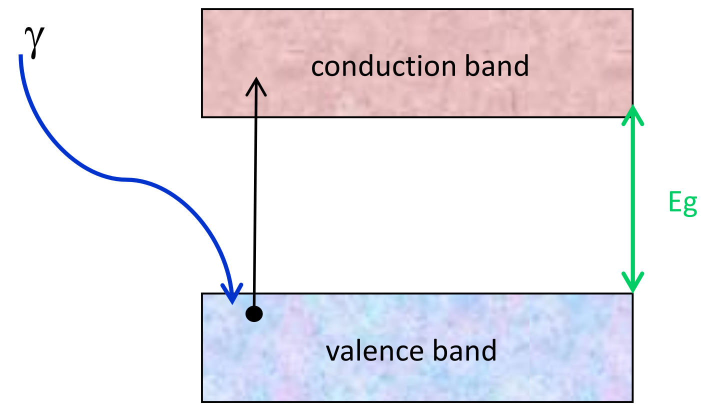
Thanks for your attention

Véronique PUILL

in vacuum devices



in semiconductor devices



1 or 3 steps process:

Step 1: Absorption of the photon (γ) in the material and generation of electrons. If $E_\gamma > E_g$, electrons are lifted to conduction band

→ for Si-photodetector this leads to a photocurrent: internal photoelectric effect

→ for vacuum device (PMT, MCP-PMT, …), 2 more steps are needed to detect a signal: external photoelectric effect

Step 2: diffusion of the electrons through the material toward the boundary to vacuum. The escape depth L depends on the material.

Step 3: electrons with sufficient excess energy (larger energy than the work function) reaching the surface escape from it

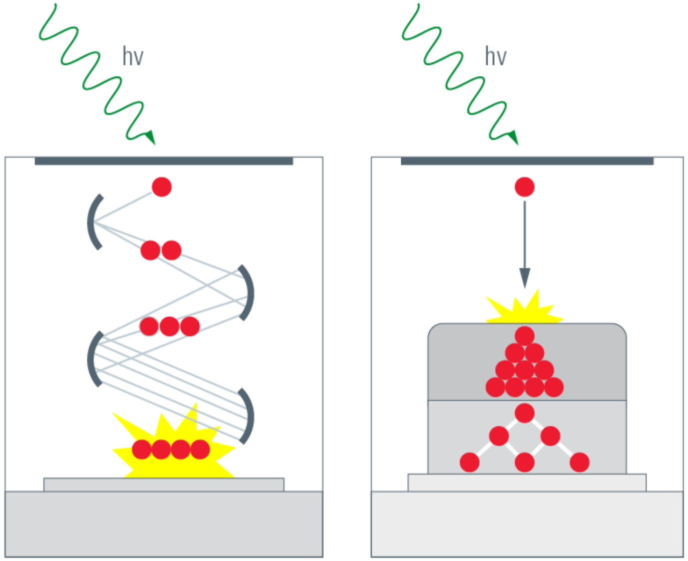
Step 2: the Photoelectron collection

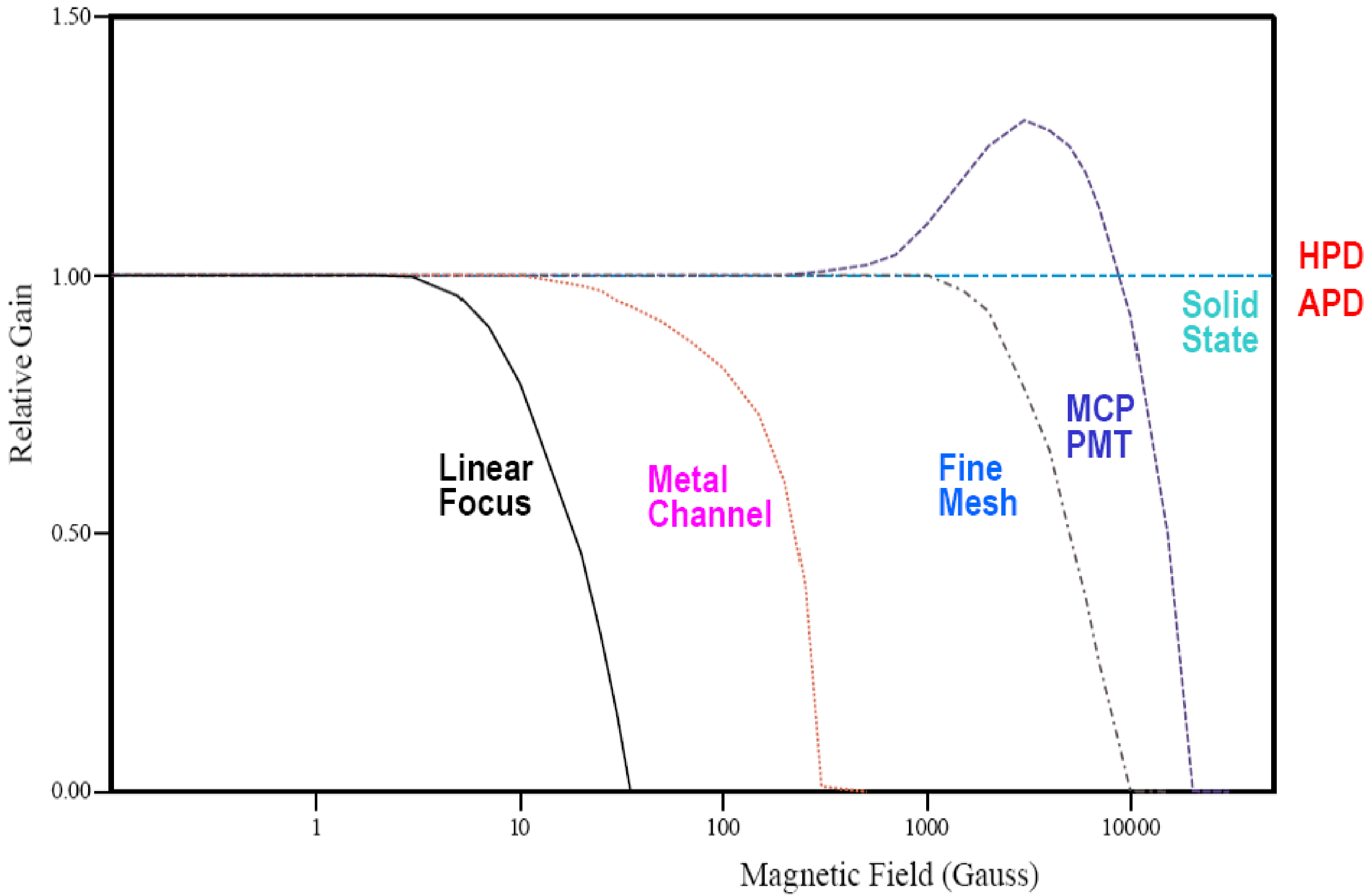
Once created, the photo-electrons (vacuum devices) or electron/hole pair (Si photodetector) can be lost (absorption, recombination)

Need of a good **collection efficiency (C_E)**: probability to transfer the primary p.e or e/h to the amplification region or readout channel

Step 3: the signal multiplication

The primary photo-electron or electron/hole pair is amplified (photodetector with **internal gain**)

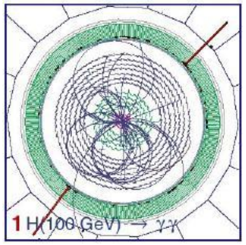



1.50
1.00
0.50
0.00
Relative Gain
1
10
100
1000
10000
Magnetic Field (Gauss)
Linear Focus
Metal Channel
Fine Mesh
MCP PMT
Solid State
HPD
APD

Operation of PMT and MCP-PMT in magnetic field

★ earth magnetic field = 30-60 mT

$\vec{B}$ ⇨



curves the trajectory of charges particles ⇨ separate the particles ⇨ easier analysis

⇨ reduce the detector size ⇨ reduce the detector price

PMT

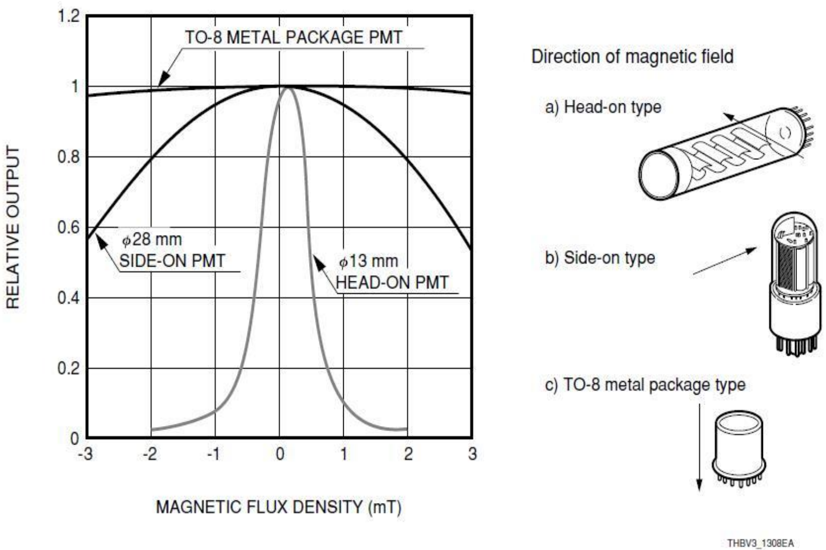


Figure 13-8: Magnetic characteristics of typical photomultiplier tubes

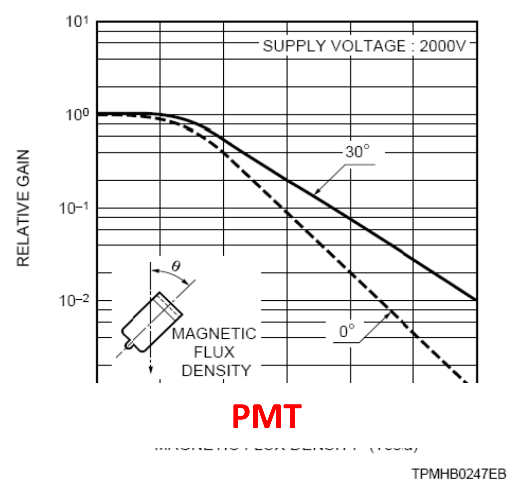
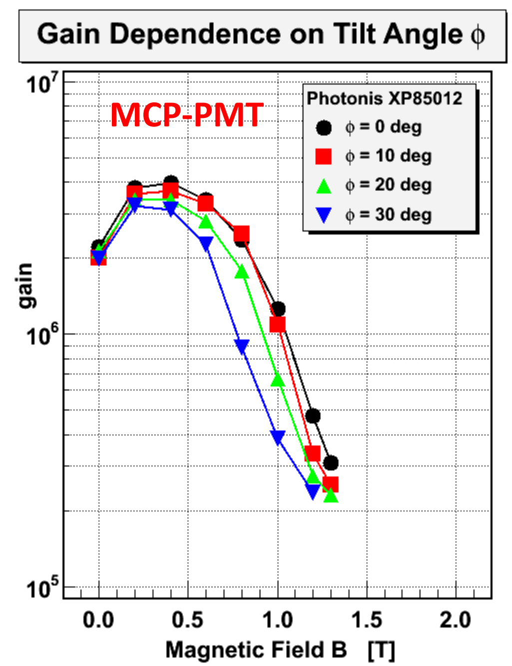


Figure 6-25: Gain vs. magnetic flux density

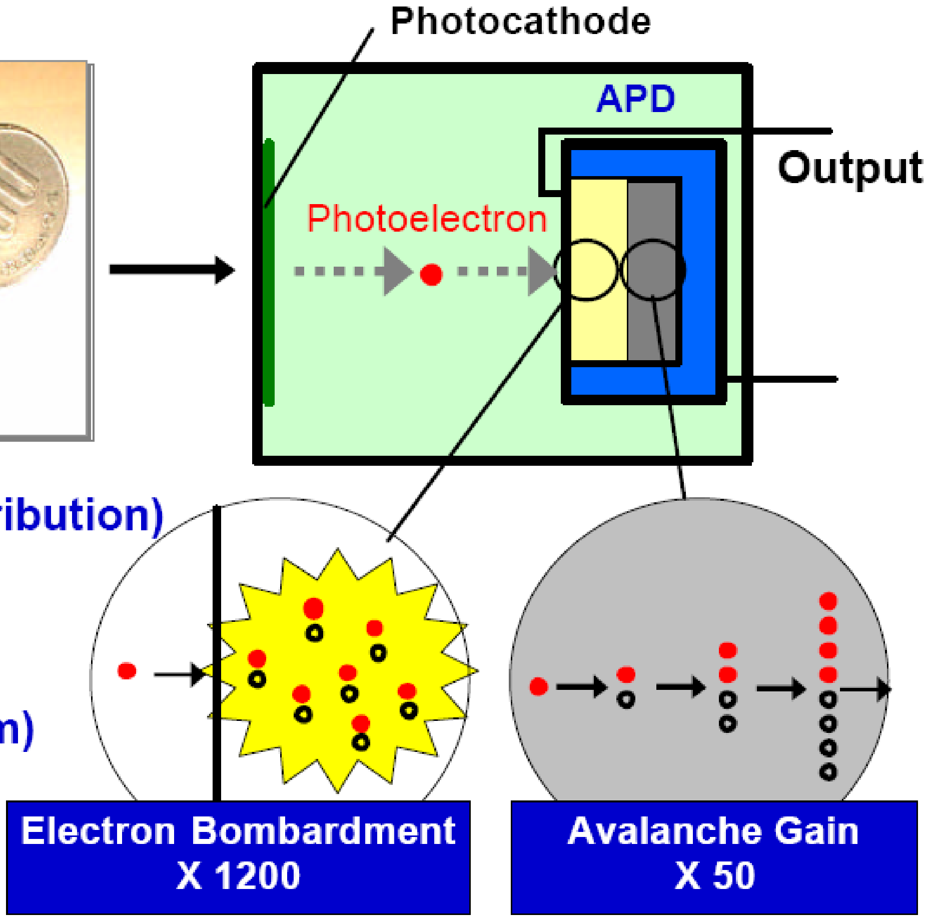
HAMAMATSU PMT book



Albert Lehmann RICH 2010

PMT very sensitive to magnetic field → shielding required (µ metal)

HPD

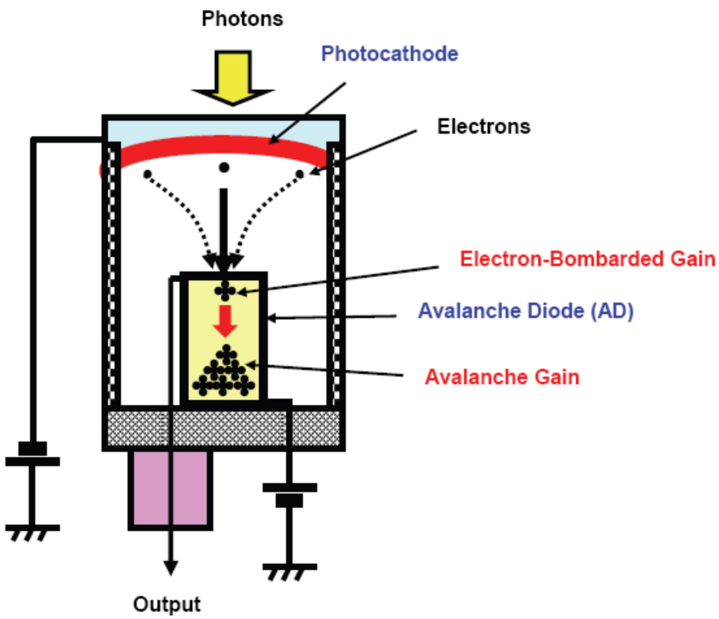


Good PHD (Pulse Height Distribution)
Good Uniformity
Immunity to Magnetic Field
Fast Time Response
Compact (16mm in dia x 16mm)

<Photocathode>
Multi-Alkali, GaAsP, GaAs

Combination of EB and avalanche gain

HPD



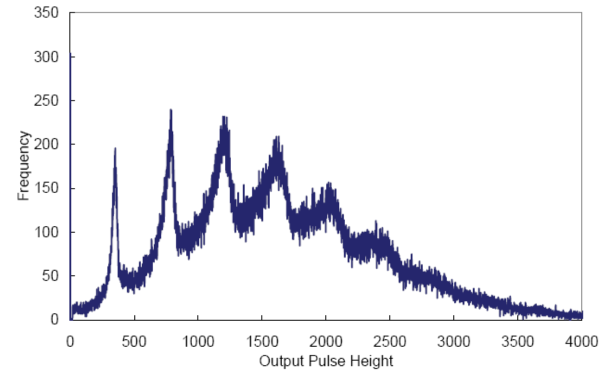
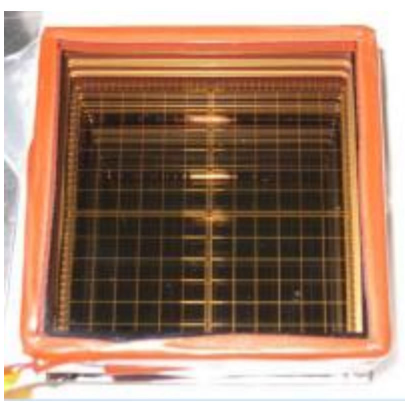
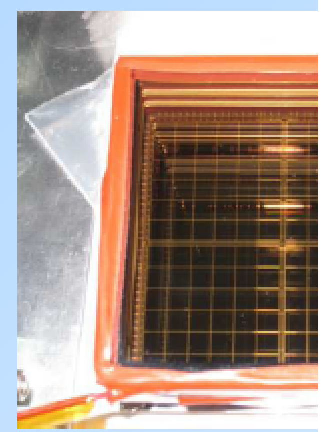


Figure 13: The pulse height spectrum for multi photons clearly shows peaks corresponding up to 6 photoelectrons.

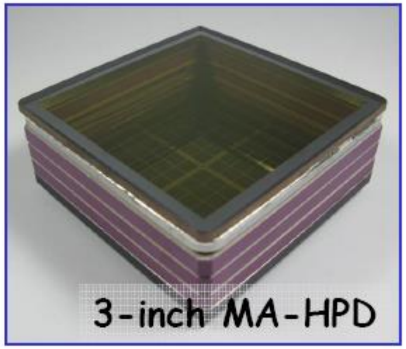


Belle II aerogel RICH HAPD

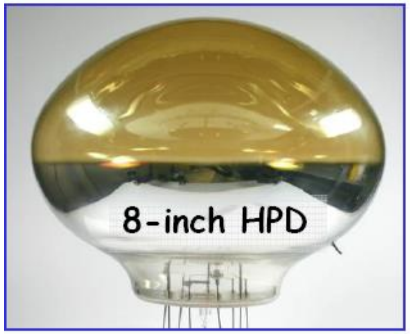
- proximity focusing configuration → operation in magnetic field
- HV ~8kV, gain ~100k (2000x50)
- 144 channels
- ~ 65% effective area
- tested up to 1000 Gy and 10^{12} n(1MeV)/cm^2
- Belle + Hamamatsu



R&D on HPD

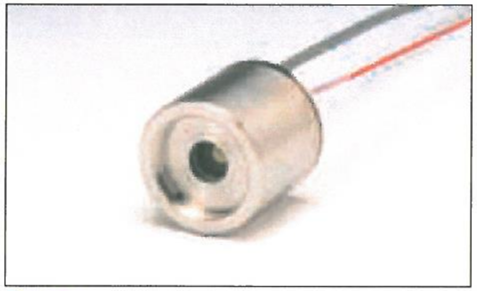


RICH/Belle upgrade



Water Tank Detector

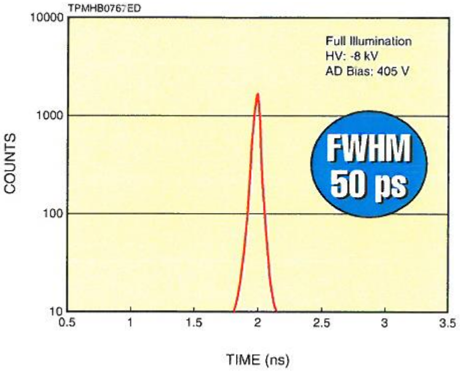
The HPD (Hybrid Photodetector) utilizes the "electron bombardment" method in which photoelectrons are accelerated in a strong electric field to directly strike an avalanche diode (AD) in a vacuum tube. This mechanism achieves excellent quality of amplification.
Using a new AD with very low capacitance, we have developed a compact HPD with an excellent time resolution.



R10467U series

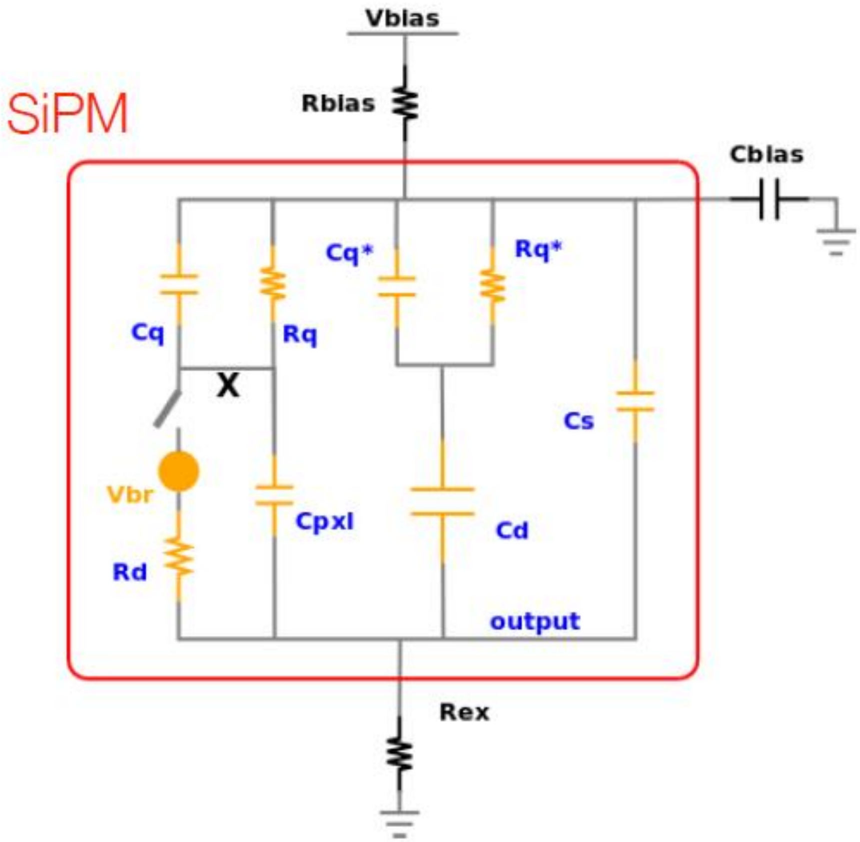
Parameter		R10467U-06	R10467U-40	R10467U-50	Unit
Spectral Response		220 to 650	300 to 720	380 to 890	nm
Photocathode	Material	Bialkali	GaAsP	GaAs	—
	Effective Area	$\phi 6$	$\phi 3$		mm
Quantum Efficiency		28 ①	45 ②	14 ③	%
Gain ④		1.2×10^5			—
Rise Time		400			ps
T.T.S. (Transit Time Spread) ⑤ (FWHM)		50	90	130	ps

① At 350 nm ② At 500 nm ③ At 800 nm
④ At the photocathode voltage of –8 kV and the AD bias voltage of Vb –10 V
⑤ At the single photon state and full illumination on the photocathode, specified as FWHM (Full Width at Half Maximum). These values include the jitter of the electronics of about 30 ps

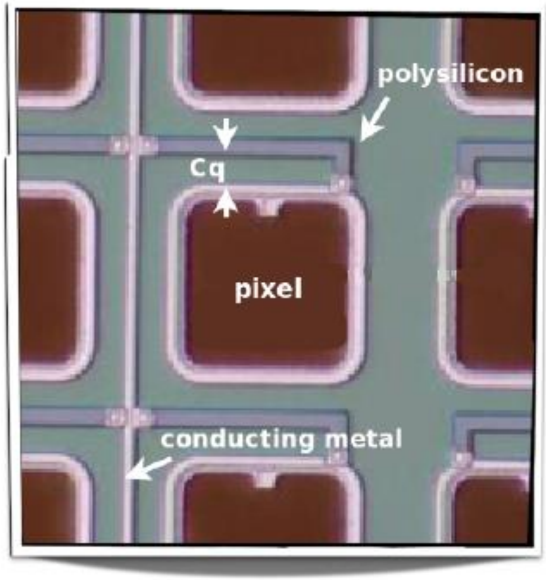


SiPM – Electrical Model

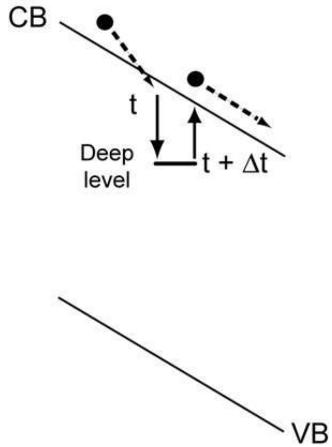
[source: W. Shen]



C_{pxl}	Pixel capacitance
C_q	Parasitic capacitance
C_d	Capacitance of inactive pixels
C_s	Stray capacitance
R_q	Quench resistor
R_d	Space charge resistance



After-pulses



Breakdown → production of a large number of charge carriers → some of them are trapped in deep trap levels

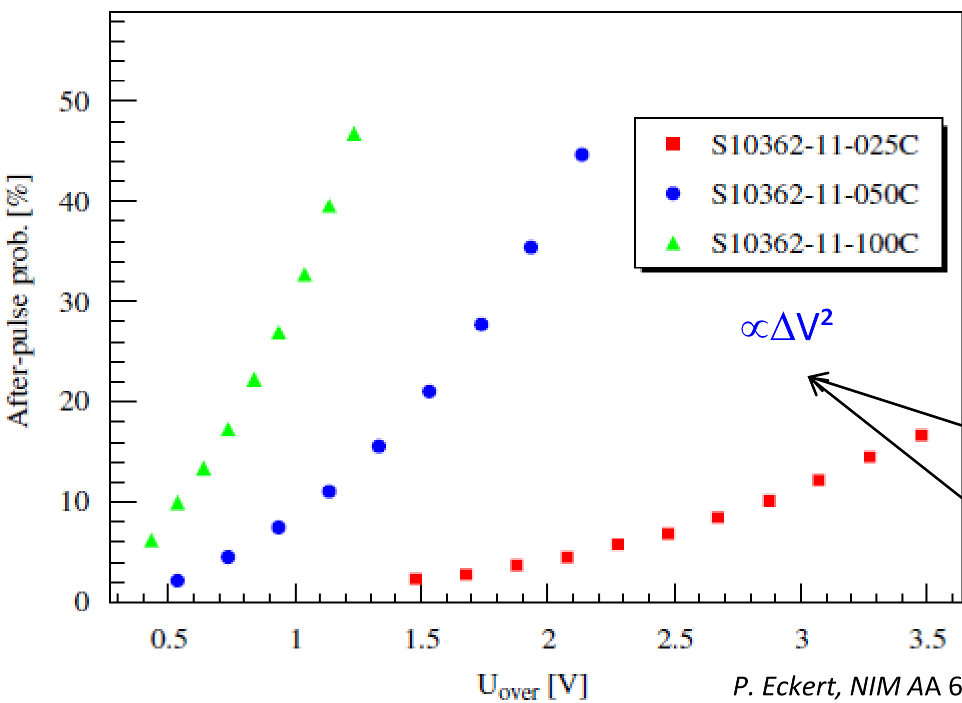
These carriers may be released at some time and trigger a new breakdown avalanche event : afterpulse (described in term of probability)

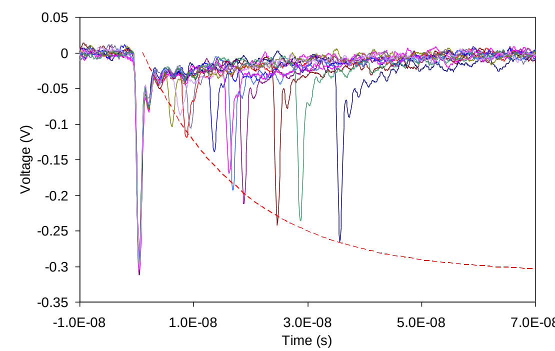
$$P_{afterpulse}(t) = P_{trig} \times P_{capture} \frac{e^{-t/\tau}}{\tau}$$

$P_{capture}$: trap capture proba

P_{trig}: avalanche triggering proba

τ: trap lifetime





P. Eckert, NIM AA 620 (2010)

Number of carriers produced in the avalanche ∝ ΔV

Triggering proba ∝ ΔV

SiPM Annealing

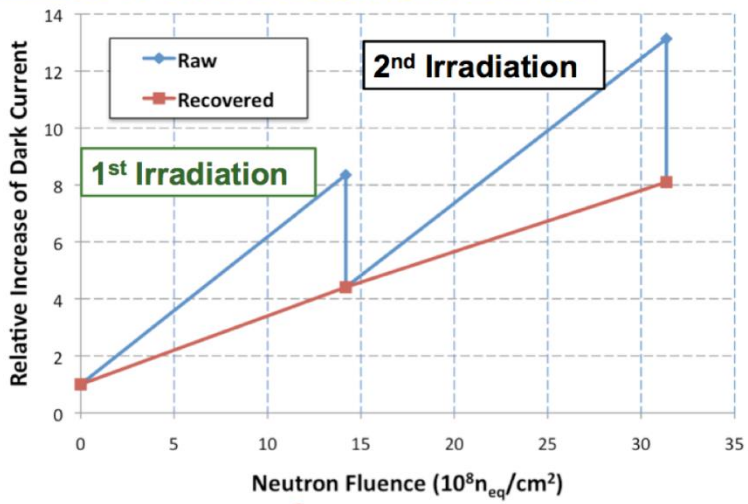
Proposal to Test Improved Radiation Tolerant Silicon Photomultipliers
F. Barbosa, J. McKisson, J. McKisson, Y. Qiang, E. Smith, D. Weisenberger, C. Zorn
Jefferson Laboratory

How to Extend the Lifetime?

SiPMs cooled to 5°C during the beam → reduction of the dark noise by a factor 3 and minimization of the effects of neutron irradiation

Beam down period : SiPMs heated to ~40°C (post-irradiation annealing) → bring the noise down to a residual level

SiPM Neutron Radiation Test

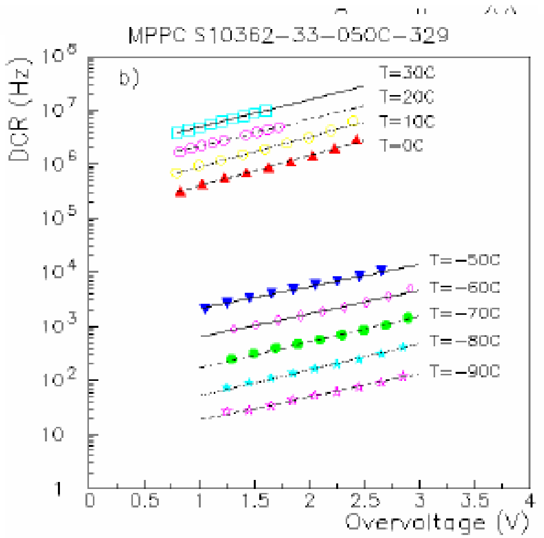


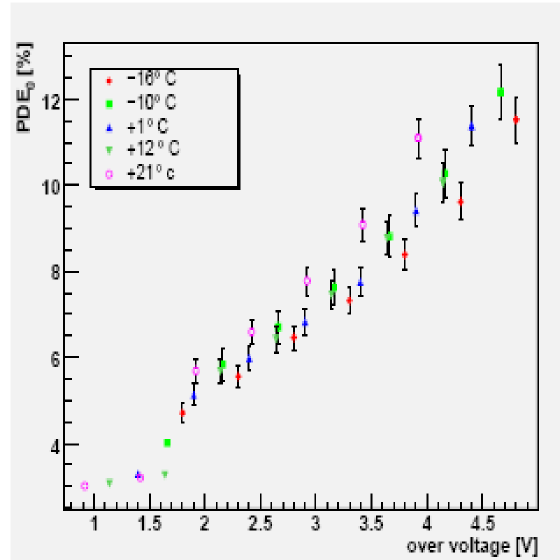
Neutron Fluence with 10^8 g/s on LH_2 Target with 1/3 efficiency
-> $3x10^8$ n_{eq}/cm^2/year

At 25°C, annealing requires at least 5 days

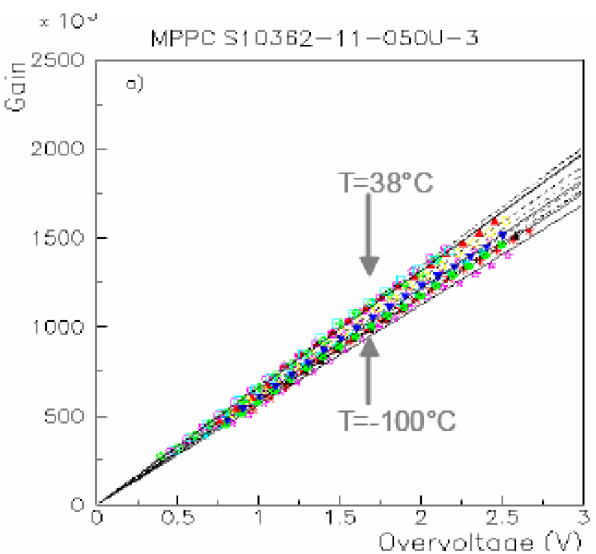
Heating to above 40°C can reduce the annealing time to less than 24 hours

Variations of SiPMs with temperature





M. Ramilli



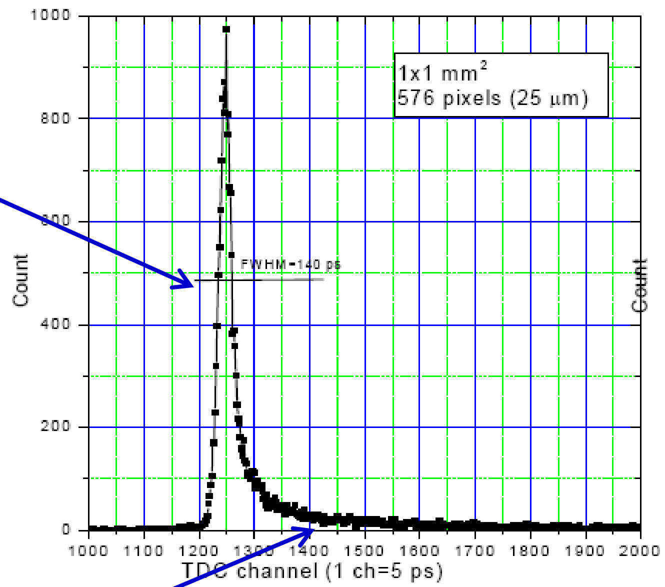
no temperature dependence of the PDE

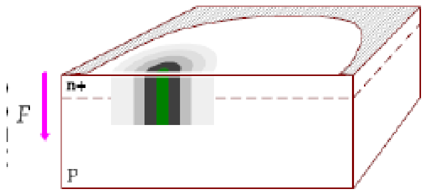
Dinu, IEEE NSS 2010

Time response of SiPMs

Two components :

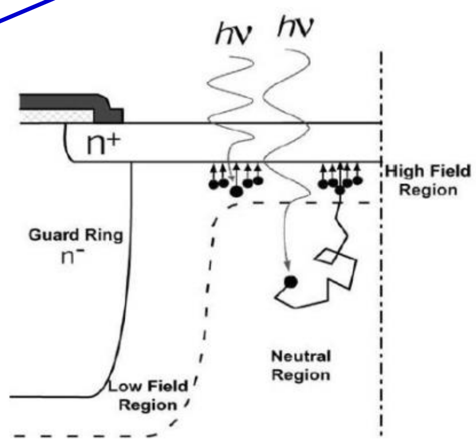
fast component of Gaussian shape with 50 ps< σ < 150ps
The fluctuation are due to the variance of the transverse diffusion speed and the variance of transverse position of photo-generation.





Transverse multiplication

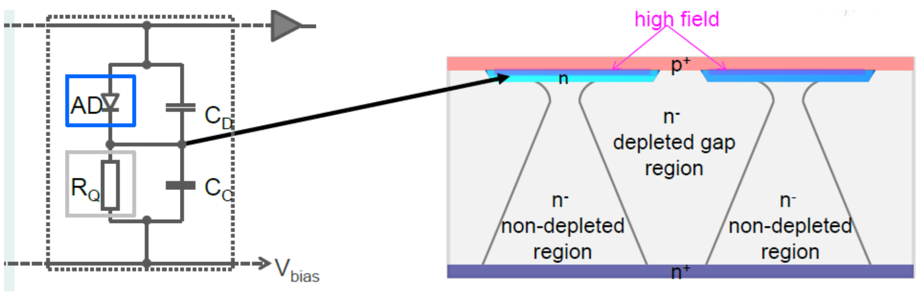
slow component: minor non Gaussian tail
with time scale of several ns due to minority carriers, photo-generated in the neutral regions beneath the depletion layer that reach the junction by diffusion.



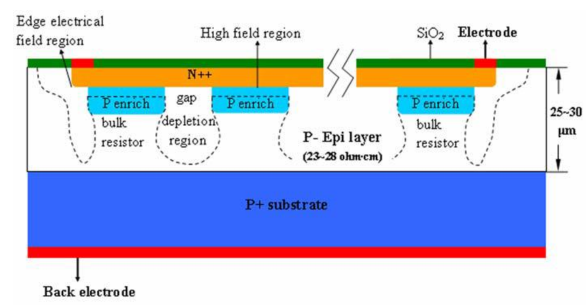
SiPMs with bulk integrated resistors

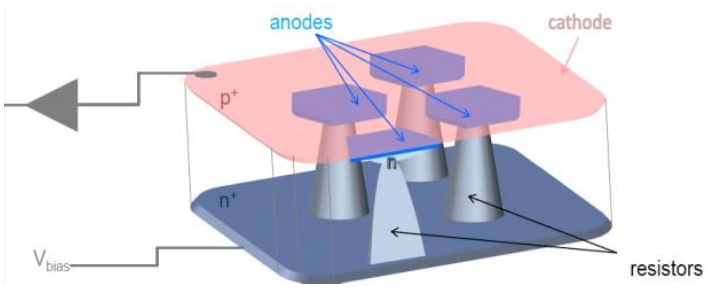
The quenching resistors are formed in the Si bulk rather than on the surface of the device

MPI



NDL





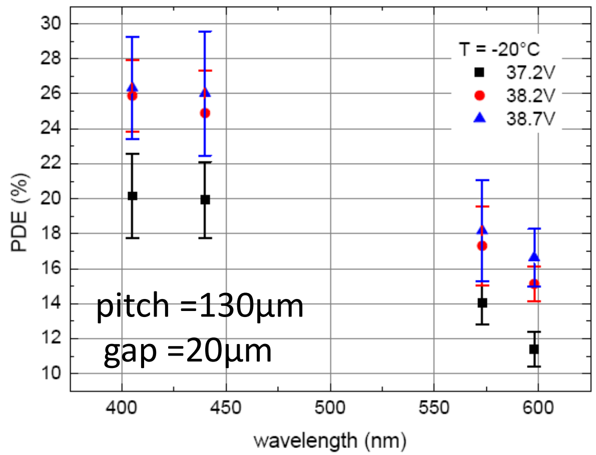
Advantages

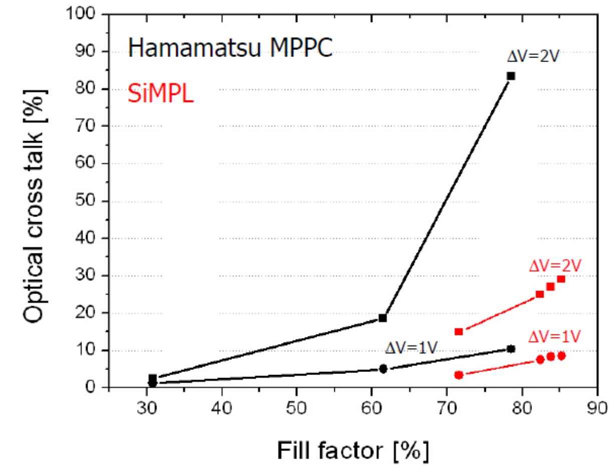
- simple fabrication process
- no obstacles in entrance window
- possible high geometrical fill-factor
- possibility of antireflective coating
- possible high cell density

SiPMs with bulk integrated resistors

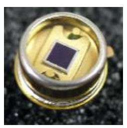
MPI

- Pitch : 100 – 160 µm
- Gap : 5 – 20 µm
- Gain = 2 – 10x10^{6}
- Cross-talk= 15 – 30 % (-20°C)
- DCR= 10 MHz/mm² (25 °C)
- PDE (440 nm) = 26 % (-20°C)



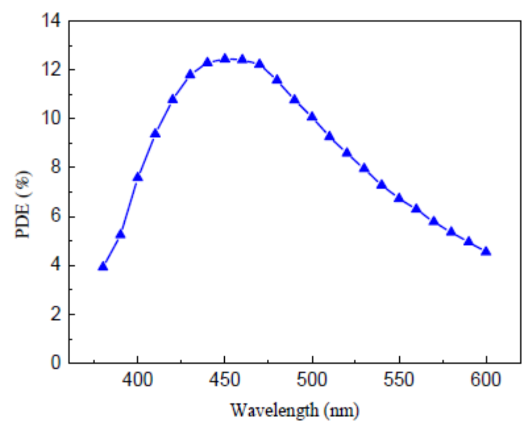


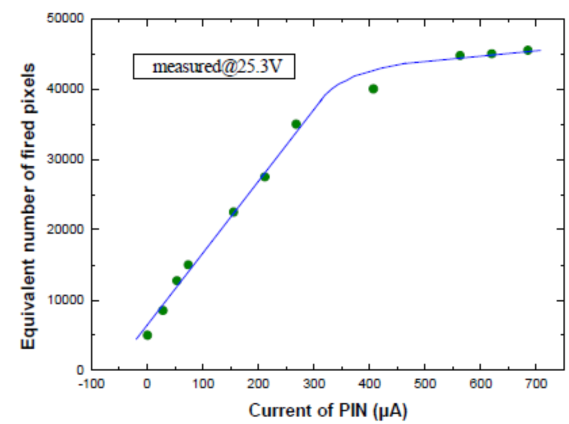
C. Jendrysik, NIM A 718 (2013)



NDL

- 2.2 × 2.2 mm² cell size : 42 µm
- 43400 cells
- DCR = 8 MHz/mm² (21 °C)
- Gain = 2 10^{5} (21 °C)
- PDE (460 nm) = 12 %
- recovery time : 5.8 ns





C. Li, IEEE NSS 2013

Promising results

R&D on going at MPI and NDL to improve the structure and the performances

SiPMs for Calorimeters : CALICE AHCAL

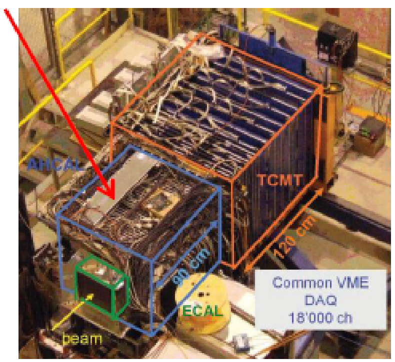
High granularity hadronic calorimeter optimised for the Particle Flow measurement of multi-jets final state at the ILC

Photodetector requirements:

- insensitive to magnetic field (~ 4T)
- good sensitivity in blue-green
- cheap (10 millions channels)

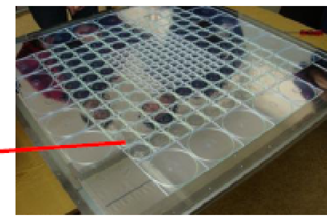
studied SiPMs : MePHI/PULSAR, CPTA

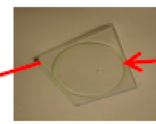
HCAL prototype (from 2007 to 2011)

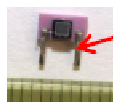


38 layers - ~ 7600 SiPMs from MePHI/PULSAR

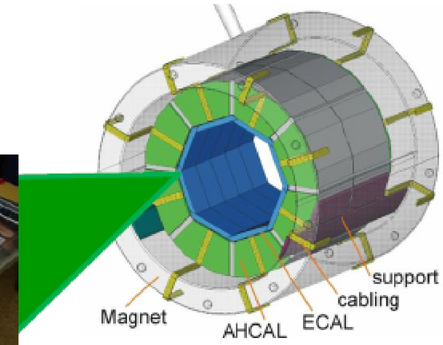
scintillator tiles





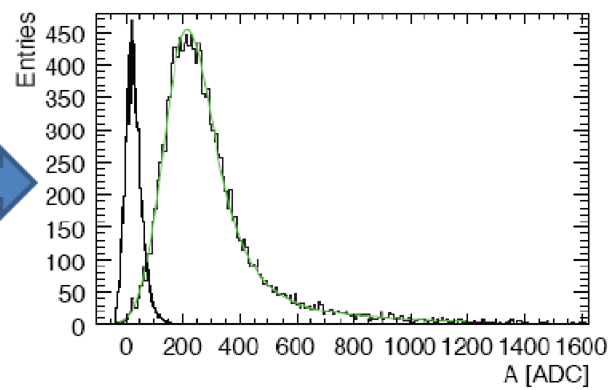


MePHI/PULSAR SiPM



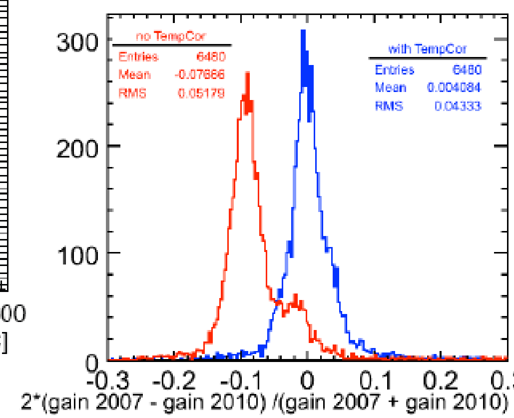
Michal Tesař, PhotoDet2012

HCAL test beams at SPS H8



MIP distribution of muons

CALICE Collaboration, 2010 JINST 5 P05004



S. Lu, LCWS11

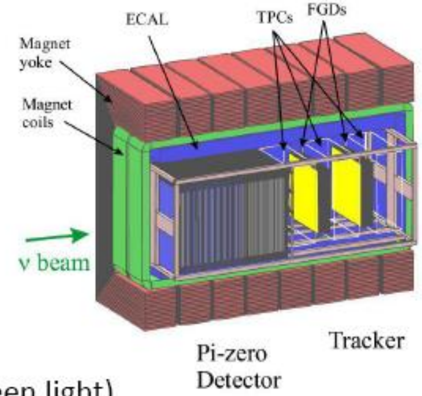
temperature dependance (variation of PDE x Gain : 3.7%/°C %)→ correction of response variations

Ongoing activity : engineering prototype is now under construction with SiPM from CPTA

SiPMs for neutrino oscillation experiment: T2K

Far detector : Super Kamiokande

ND280 : near detector complex - neutrino beam flux and spectrum measurements



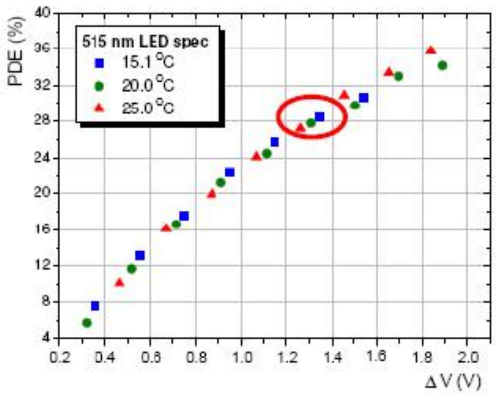
HAMAMATSU MPPC customized device

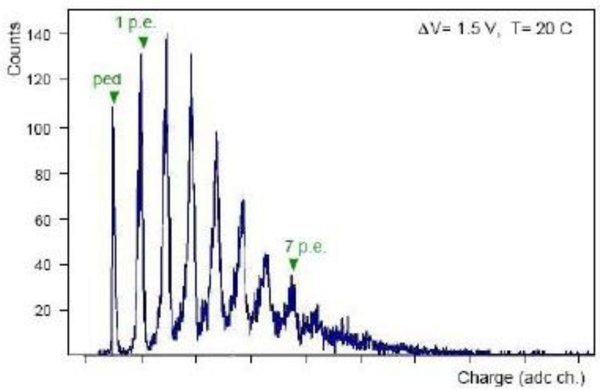
1.3 x 1.3 mm²

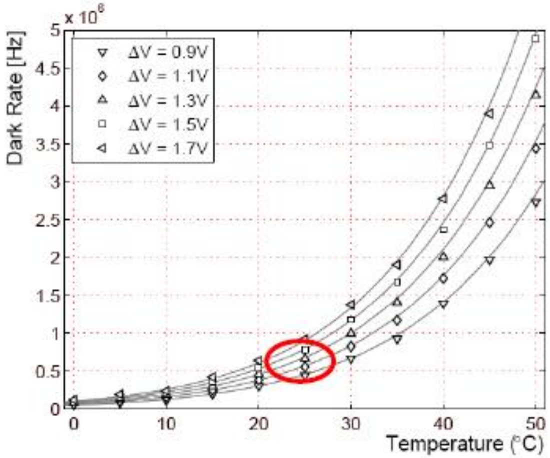
667 cells (50 x 50 µm²)

Photodetector requirements:

- insensitive to magnetic field
- coupling with a scintillator + WLS fiber (PDE > 20 % for green light)
- DCR < 1 MHz
- compact







A. Vacheret, arXiv:1101.1996

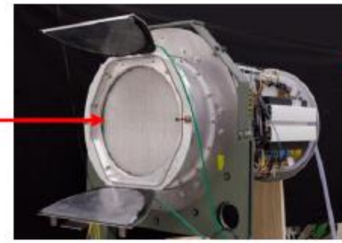
55996 MPPC tested : only 0,16 % rejected

SiPMs for Cherenkov light detection (IACT)

FACT: First G-APD Cherenkov Telescope

MPPC S10362-33-50C coupled to a cone light concentrator

1440 channels



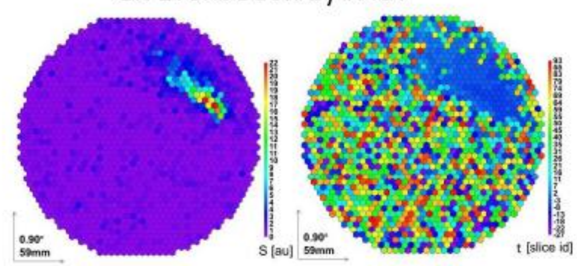
Th. Krähenbühl, Photodet 2012

Photodetector requirements:

- PDE > 20 % for blue light
- ability to detect single photons
- stable
- robust
- compact

problem with the SiPM V_{BD} temperature dependance
→regulation of the bias voltage with a feedback system

an Event Seen by FACT



P. Vogler, TWEPP 2012

First operation on the night of October 11, 2011

After one year of routine operation:

- no indication of any problem or ageing in any SiPM
- temperature as well as ambient-light dependence of SiPM well under control
- operation under very different ambient conditions shows no problem