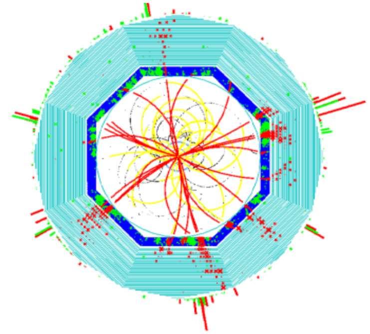
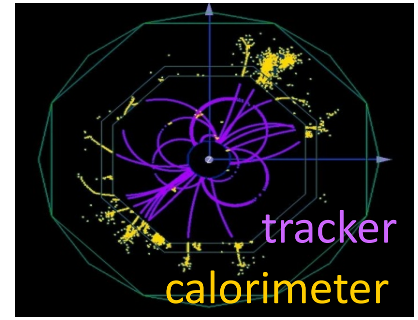
Intelligent PMTs versus SiPMs

Véronique PUILL

Light is detected in …

… High Energy Physics





Calorimetry: readout of organic and inorganic scintillators, lead glass, scint. or quartz fibres

→visible light
→10s to 10000s of photons

PMT

HPD

Particle Identification Detection of Cherenkov light

SiPM

→UV/blue light
→single photons

MCP-PMT

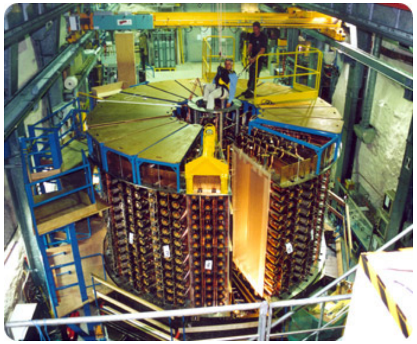
Tracking: readout of scintillating fibers

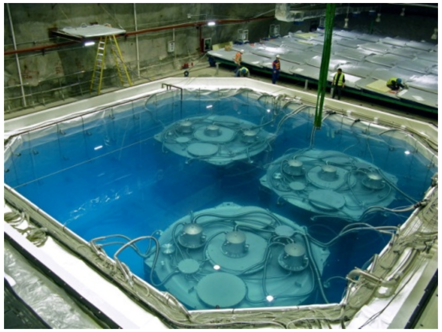
→ visible light
→few photons

APD

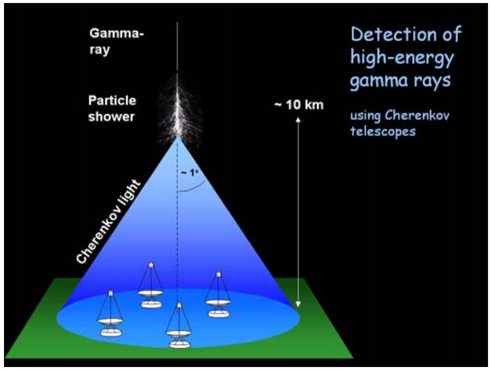
Light is detected in …

… **Neutrino Experiments**

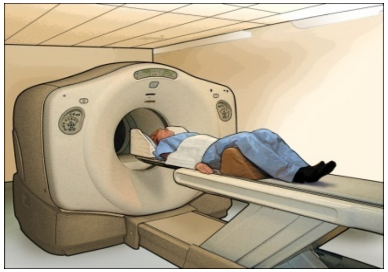


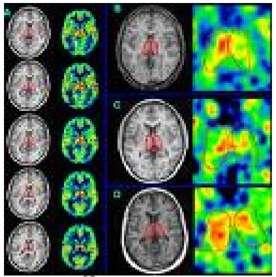


… **Astrophysics** : IACT (imaging Atmospheric Cherenkov Telescopes)



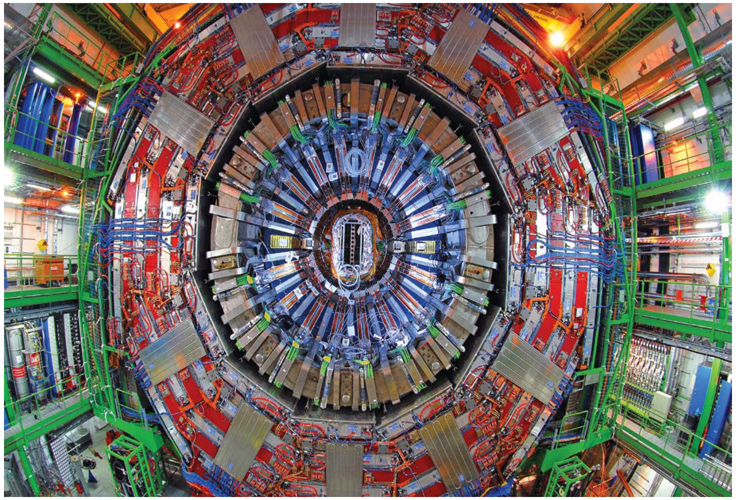
…. **Medical systems** : imagery, cancer treatment, ..

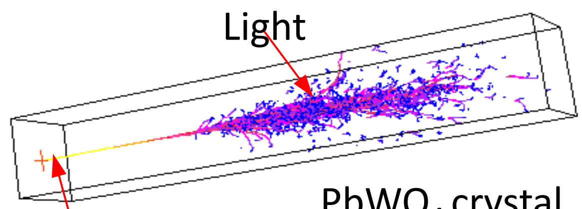


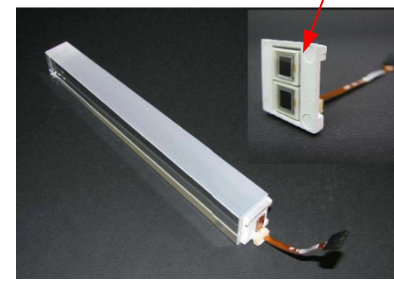


Calorimetry

Example: CMS ECAL

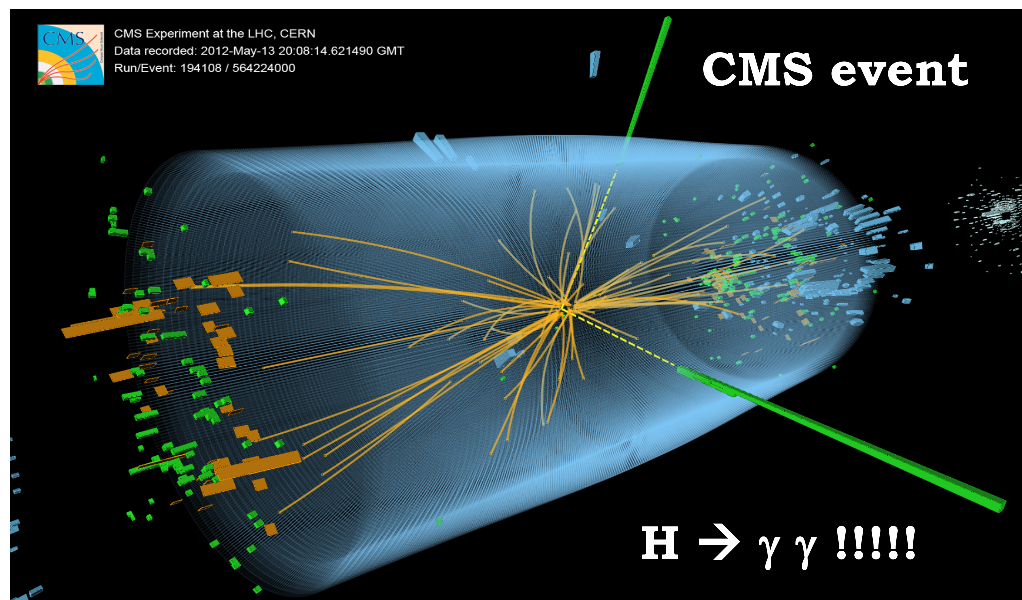






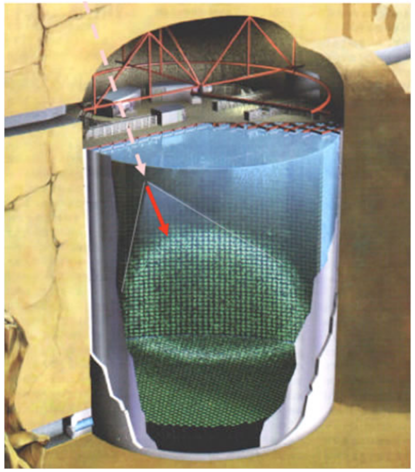
impact of e- or γ comming from electromagnetic showers

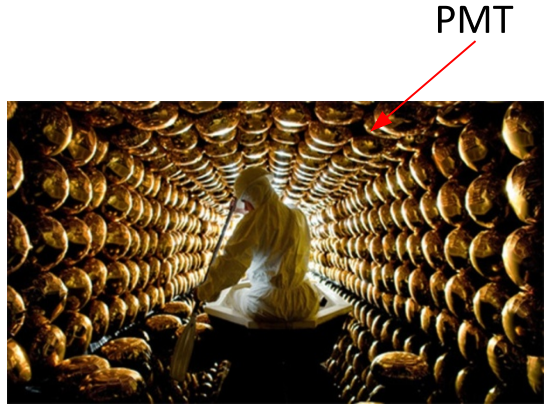
80000 channels



Neutrino Experiments

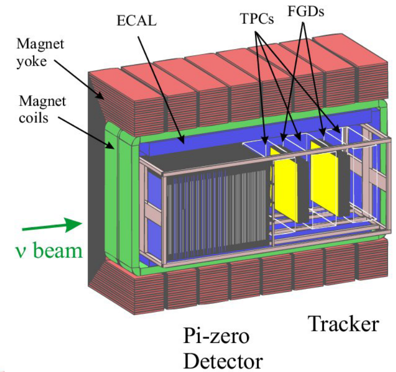
Super Kamiokande





T2K: Tokai-to-Kamioka

2nd generation long baseline neutrino oscillation experiment

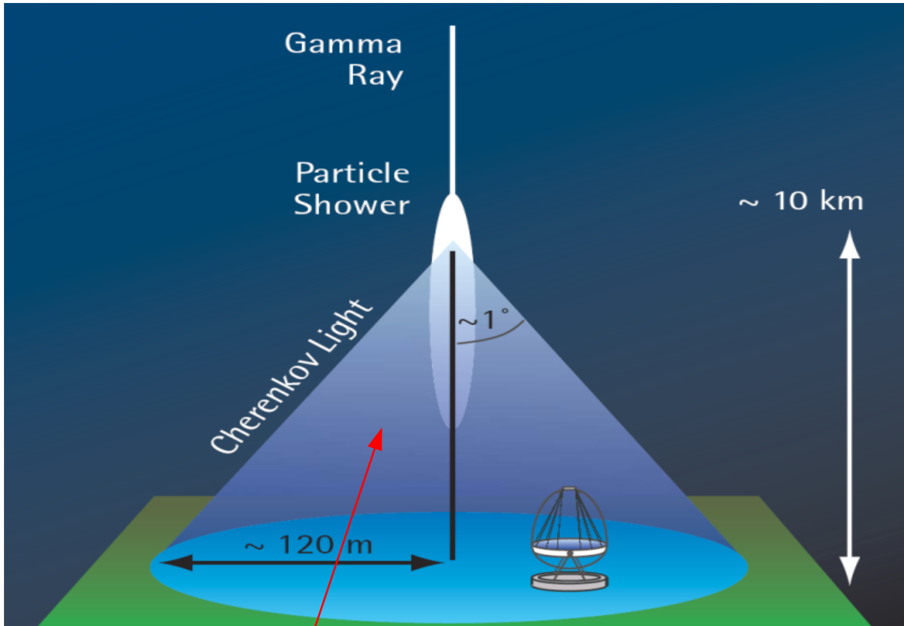


60000 channels

SiPM

Imaging Atmospheric Cherenkov Telescopes

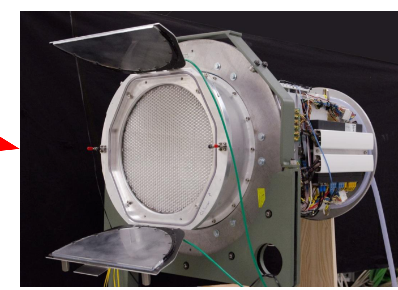
Detection of the very faint light flashes from air showers induced by cosmic rays



Cherenkov light detection

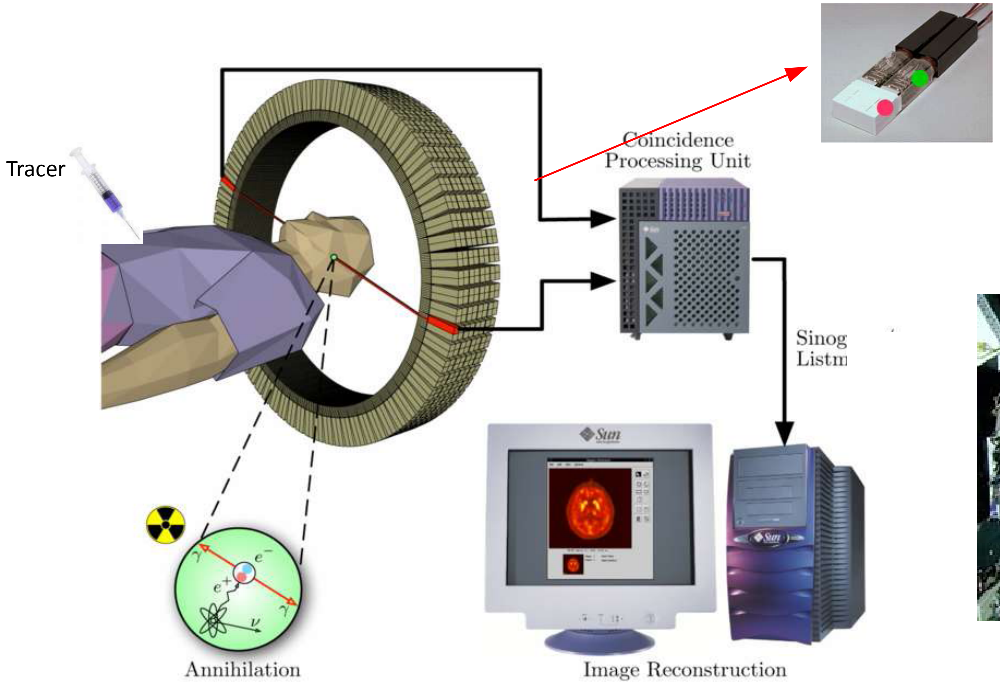
1500 – 2000 channels/camera

PMT or SiPM



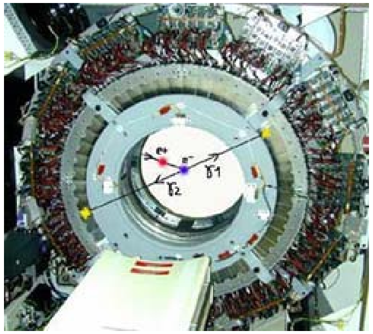
Medical applications

PET



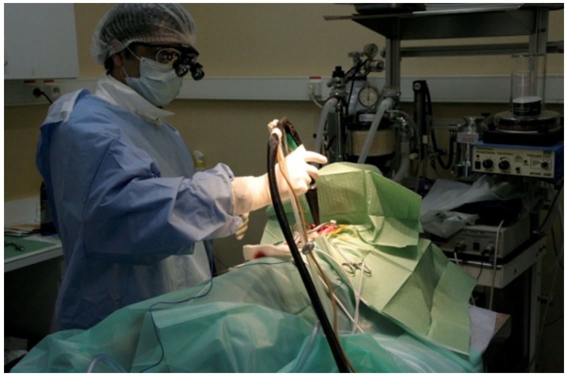
(E = 511 keV)

PMT or SiPM



Radio-isotopic probes

PMT or SiPM

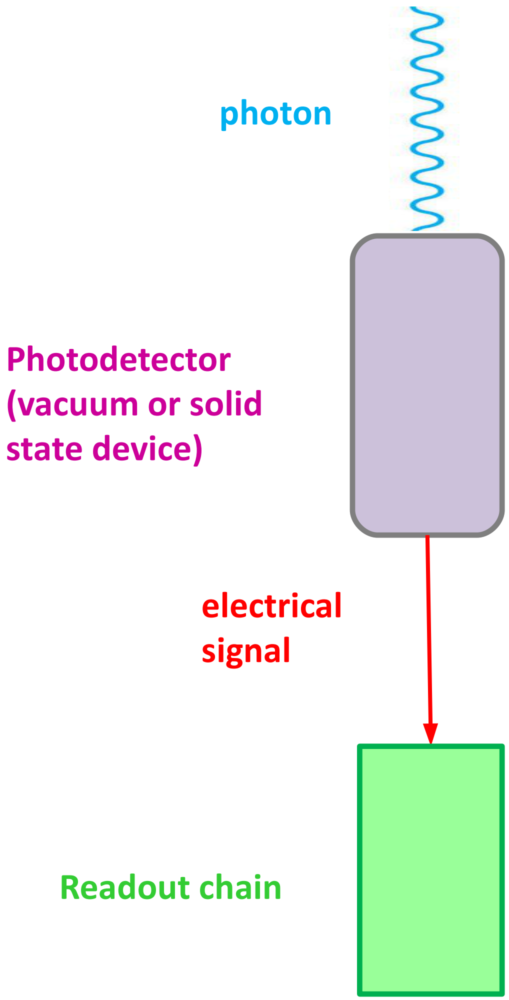


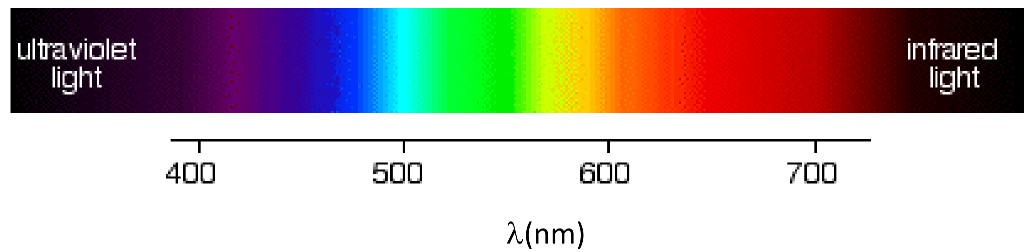
Outline

- Basic principle of the Photodetection
- Key parameters of the Photodetectors
- The Vacuum photodetectors
- The Silicon photodetectors

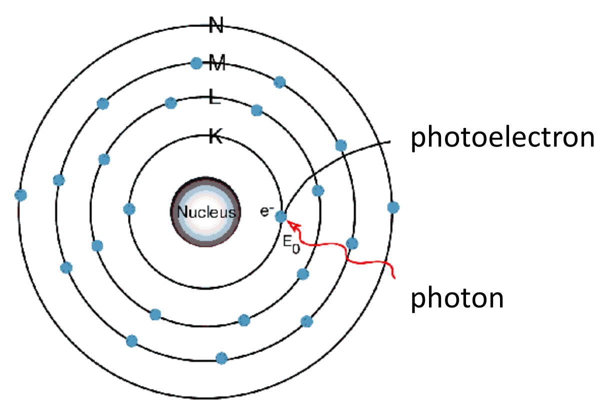
Basic principle of the Photodetection

Goal of the Photodetection: convert Photons into a detectable electrical signal





1. Photoconversion: photoelectric effect

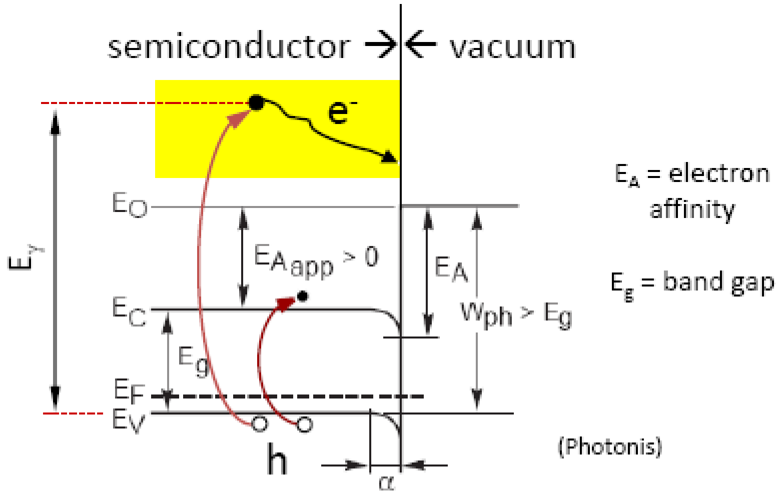


2. Photo-electron collection

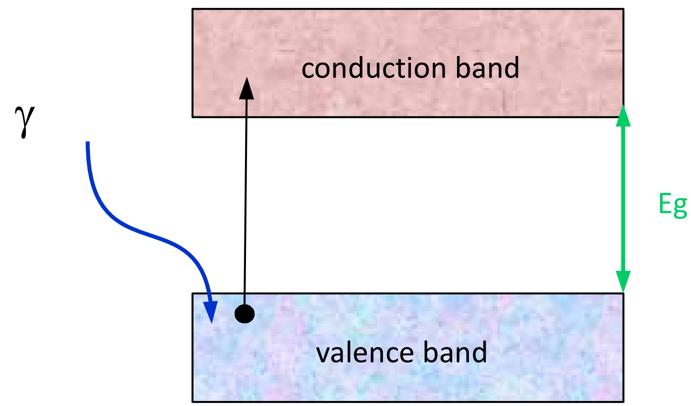
3. Signal multiplication

Step 1 : the Photoconversion

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

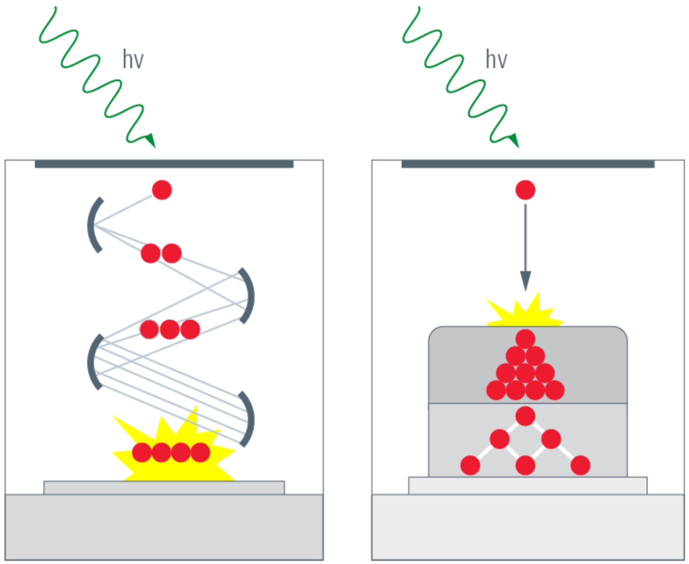
Step 2: the Photoelectron collection

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**)

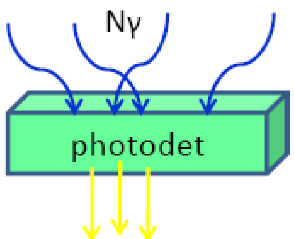


Key parameters of the photodetectors

- Sensitivity
- Noise
- Gain
- Linearity
- Time response

Sensitivity

Probability that the incident photon (Nγ) generates a photoelectron (Npe)

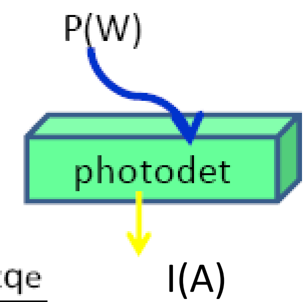


Quantum efficiency

Sensitivity x Gain x Npe

$$Q\varepsilon[\%] = \frac{N_{pe}}{N_{\gamma}}$$

Radiant sensitivity



$$S[mA/W] \approx \frac{Q\varepsilon[\%] x \lambda[nm] x qe}{hxc} = \frac{Q\varepsilon[\%] x \lambda[nm]}{124}$$

Photo detection efficiency : combined probability to produce a photoelectron and to detect it

$PDE[\%] = Q\varepsilon\,[\%] \times C_E\,[\%]$ for a PMT

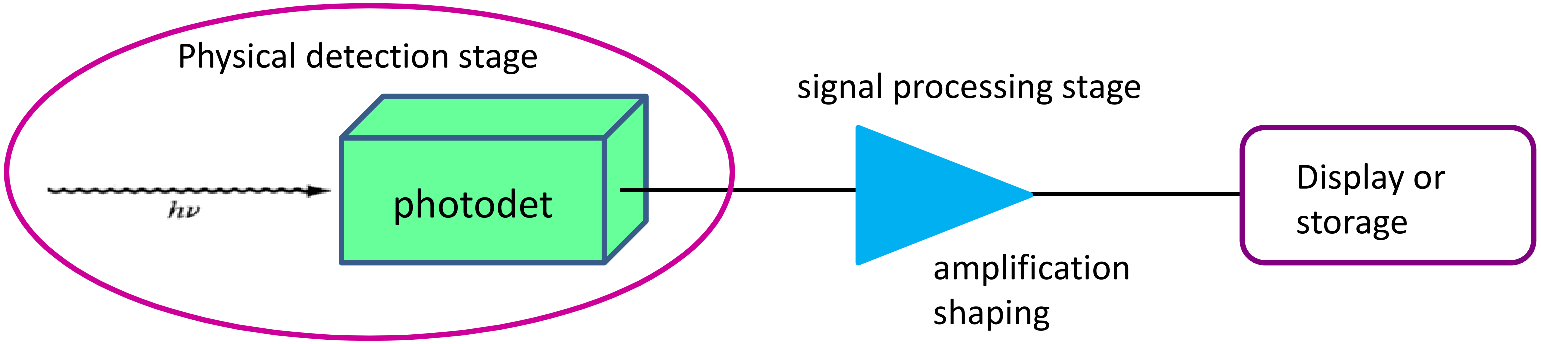
C_E: collection efficiency

$PDE\,[\%] = \mathcal{E}geom\,[\%] \times Q\varepsilon[\%] \times Ptrig\,[\%]$ for a SiPM

$\mathcal{E}geom$: geometrical factor

Ptrig: triggering probability

Principal noises associated with photodetectors :



Shot noise:

statistical nature of the production and collection of photo-generated electrons upon optical illumination (the statistics follow a Poisson process)

Dark current noise:

the current that continues to flow through the bias circuit in the absence of the light :

- **bulk dark current** due to thermally generated charges
- **surface dark current** due to surface defects

The dark noise depends a lot on the threshold → not a big issue when we want to detect hundreds or thousands of photons but in the case of very weak incident flux ….

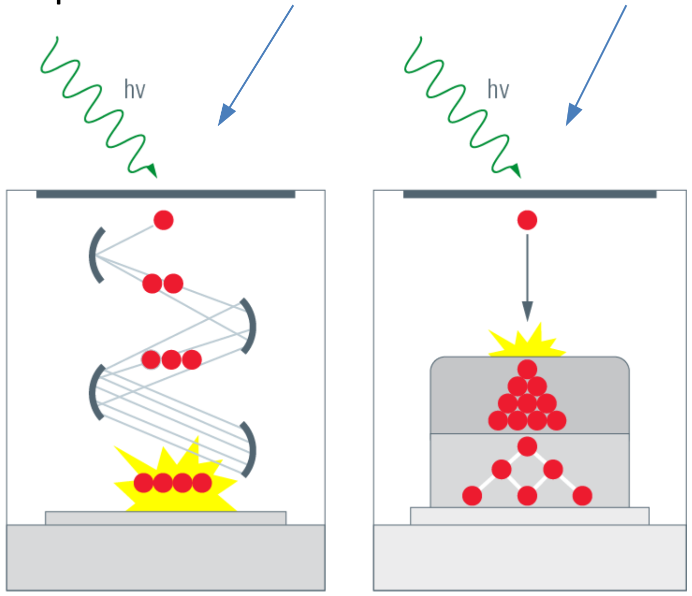
Gain and signal fluctuations

The photodetector output current fluctuates.
The noise in this signal arises from 2 sources:

- randomness in the photon arrivals
- randomness in the carrier multiplication process

The statistical fluctuation of the avalanche multiplication which widen the response of a photodetector to a given photon signal beyond what would be expected from simple photoelectron statistics (Poisson) is characterized by the **excess noise factor ENF**

Gain process in a PMT and in an APD or SiPM



M: gain of the photodetector

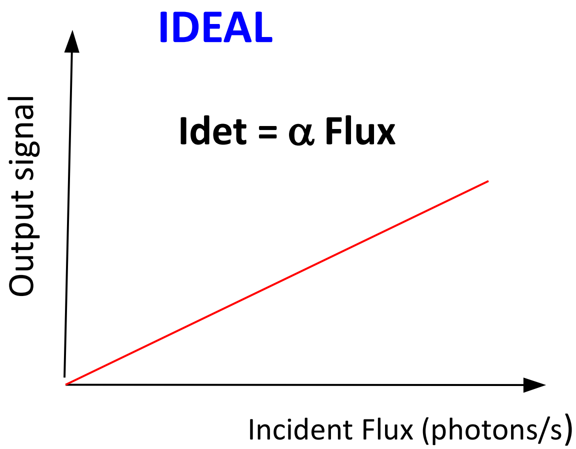
$$ENF = 1 + \frac{\sigma_M^2}{M^2}$$

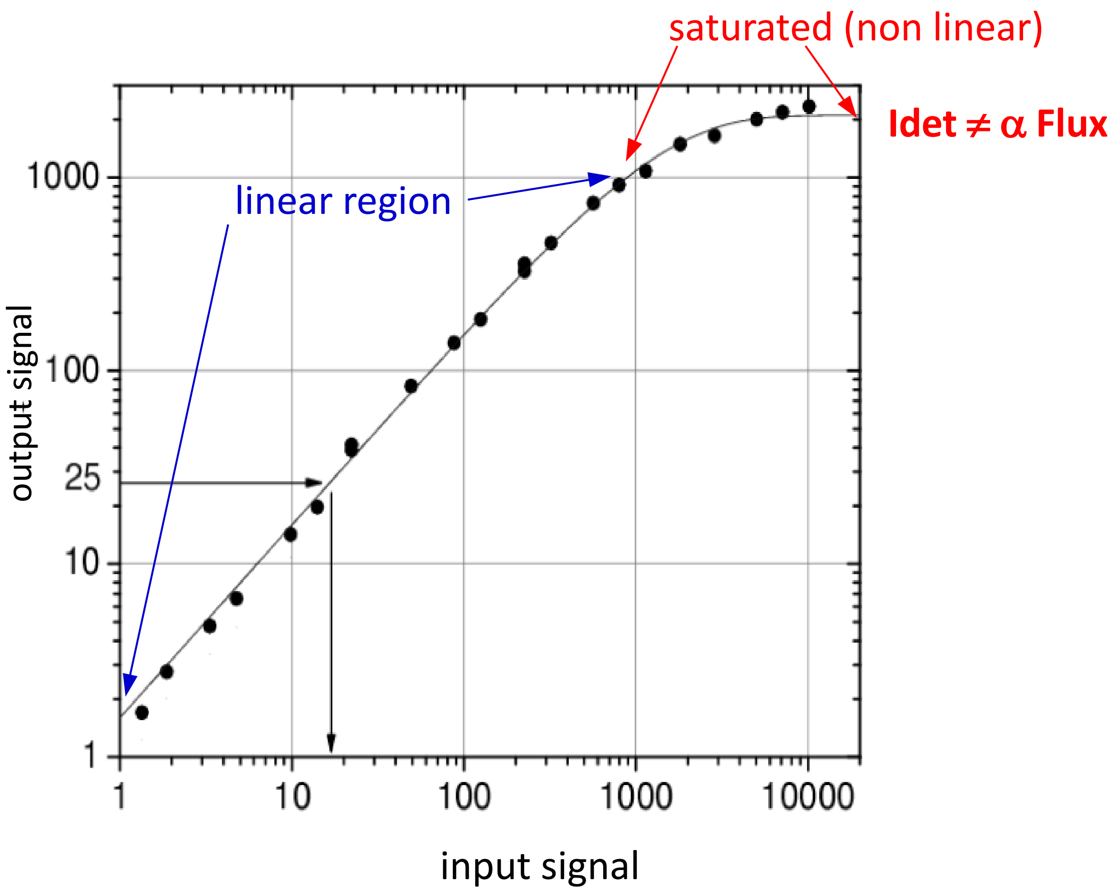
ENF

- impacts the photon counting capability for low light measurements
- deteriorates the stochastic term in the energy resolution of a calorimeter

Linearity

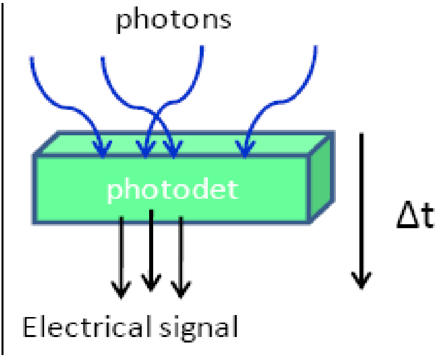
Ideally, the photocurrent response of the photodetector is linear with incident radiation over a wide range. Any variation in responsivity with incident radiation represents a variation in the linearity of the detector

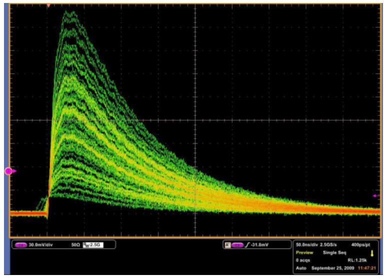


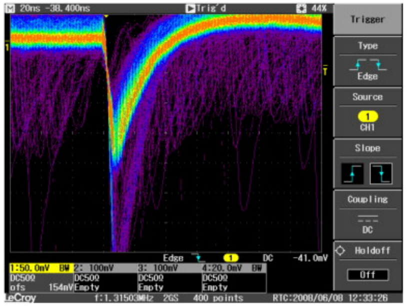


Saturation: issue for the measurement of large number of photons (calorimeter)

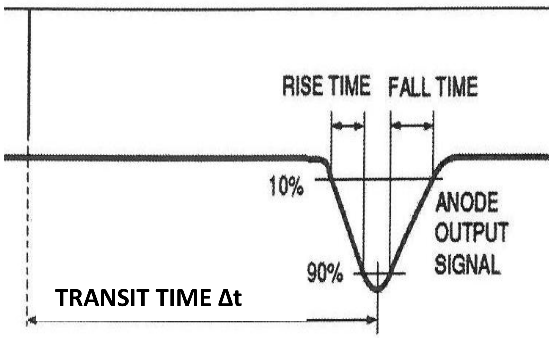
Time response







★ light travels 300 µm in 1 ps



Timing parameters of the signal:

- Rise time, fall time (or decay time)
- Duration
- Transit time (Δt): time between the arrival of the photon and the electrical signal
- Transit time spread (TTS): transit time variation between different events ➡ timing resolution

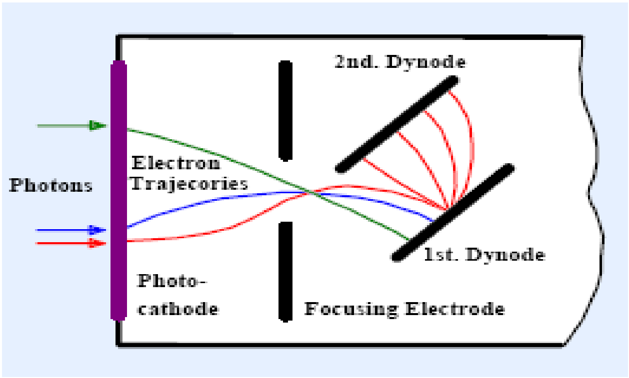


Fig. 13: Different electron trajectories cause different transit times in a PMT

Important photodetectors parameters

Photodetectors parameters

- Photon Detection Efficiency ●
- Dark noise rate ●
- Correlated noise ●
- Timing capability ●
- Signal shape ●
- Gain ●
- Radiation hardness ●
- Geometry ●
- Temperature dependence ●
- Packaging ●

System requirements

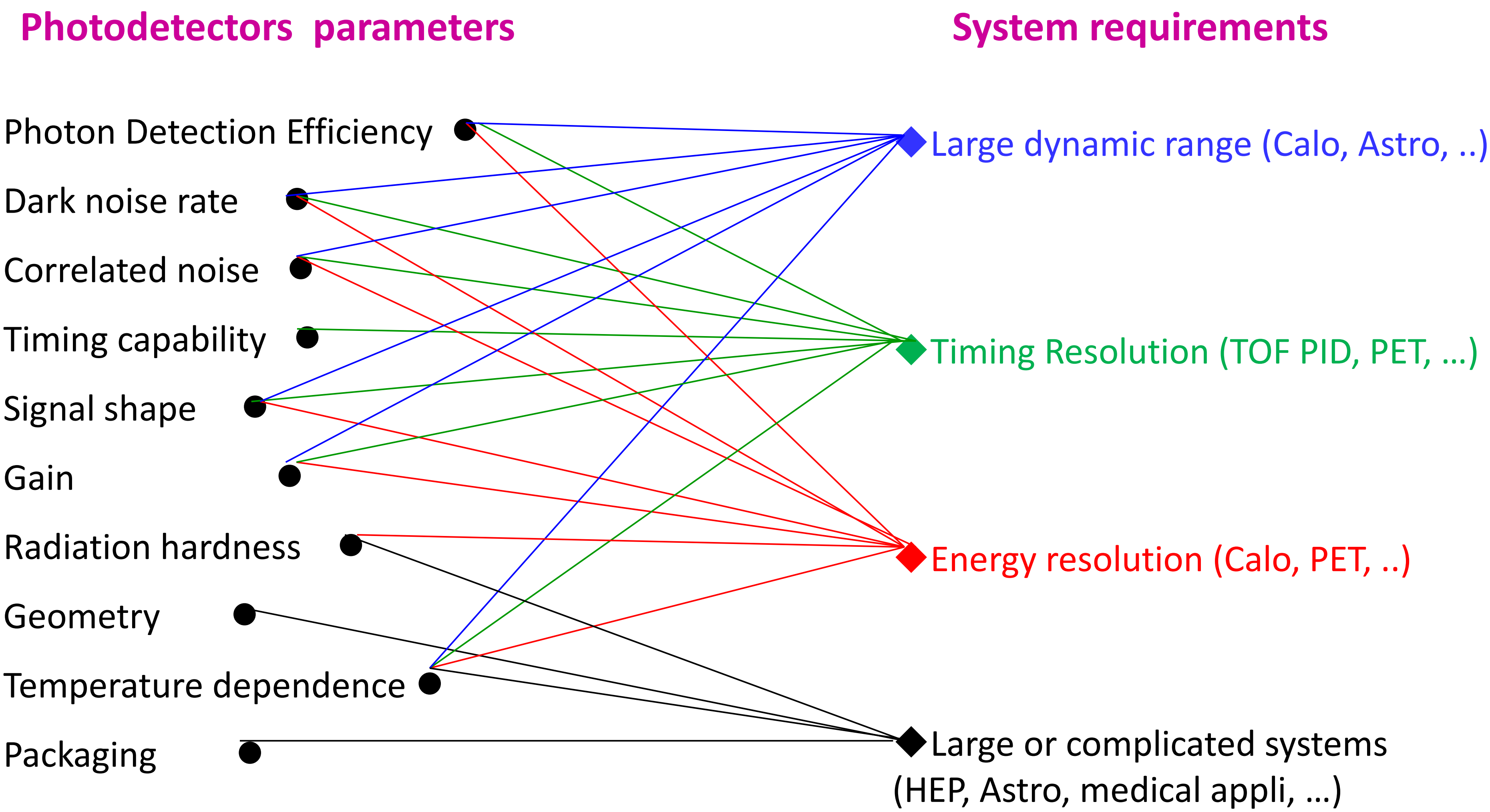
◆Large dynamic range (Calo, Astro, ..)

◆Timing Resolution (TOF PID, PET, ...)

◆Energy resolution (Calo, PET, ..)

◆Large or complicated systems (HEP, Astro, medical appli, ...)

Important photodetectors parameters



Vacuum Photodetectors

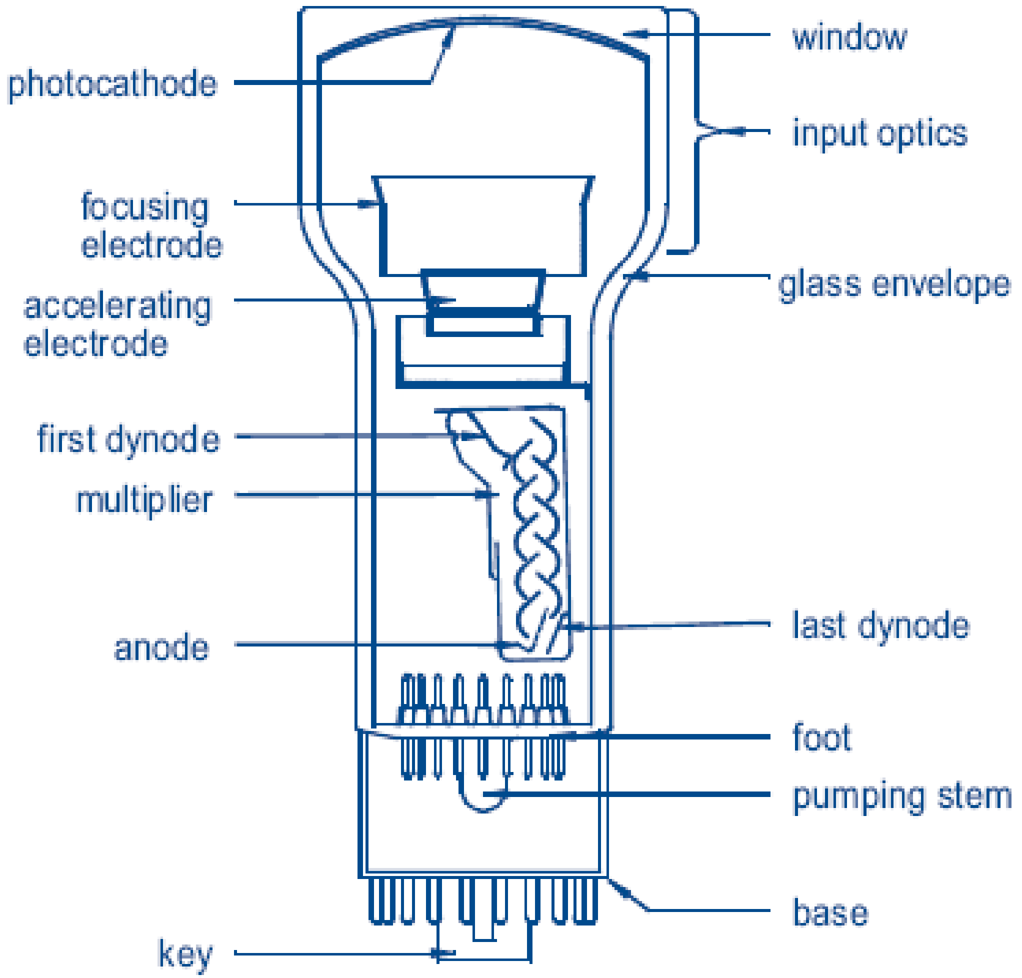
- Photomultipliers
- Micro Channel Plate Photomultipliers

Photomultipliers

HAMAMATSU
PHOTON IS OUR BUSINESS

ET Enterprises
electron tubes

Photomultiplier structure

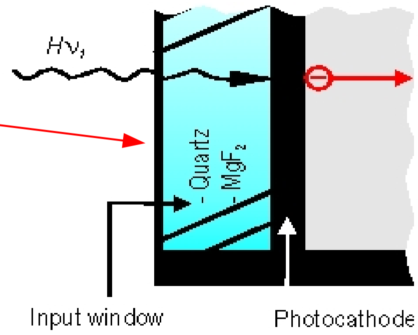


PHOTONIS PMT book

R976

Photoconversion in the PMT: crossing of the window

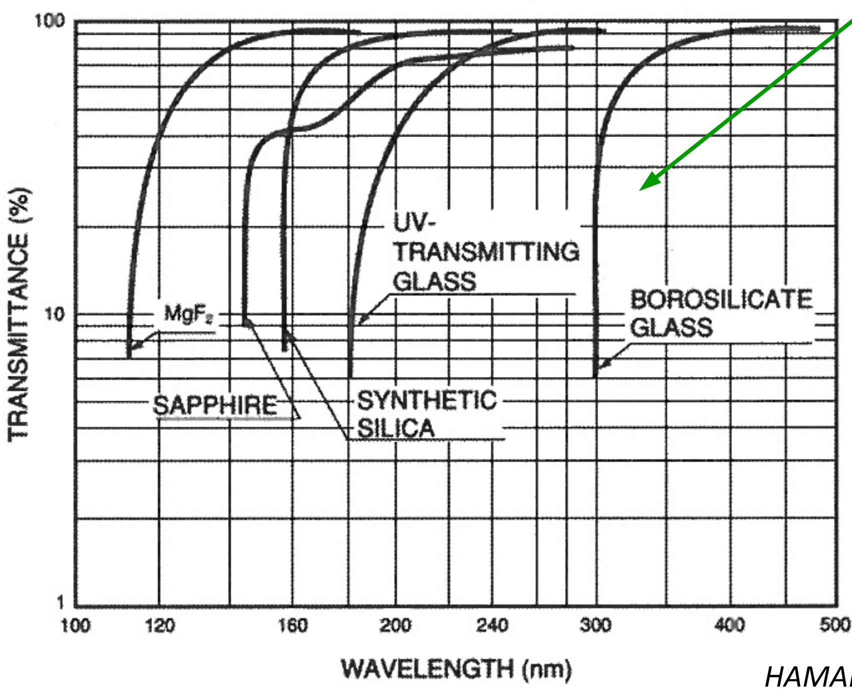
window + photocathode

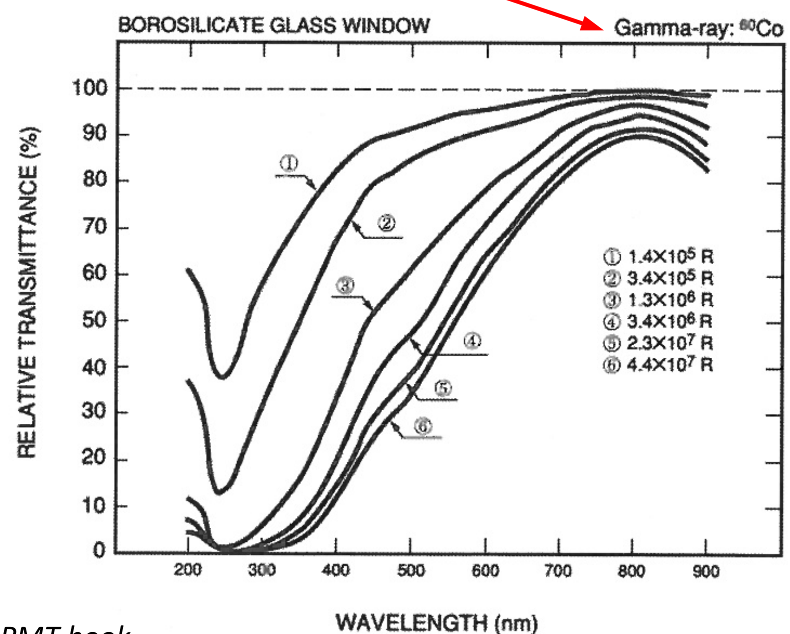


glass envelopes for PMTs

The choice of the window depends on the wavelength of the light we want to detect but also on the radioactive environment.

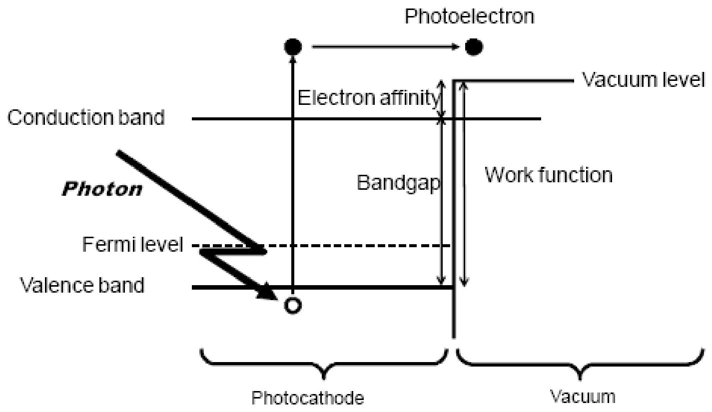
Transmittance of different material for the window





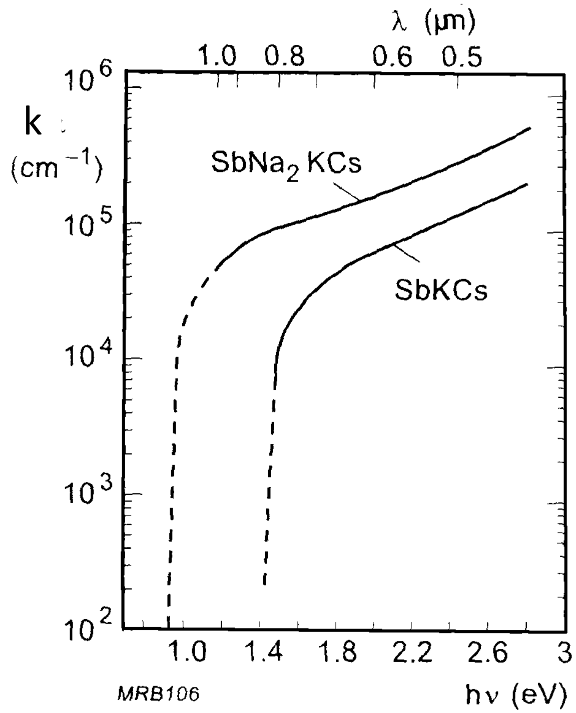
HAMAMATSU PMT book

Band model for alkali photocathode



1. photon absorption and generation of an e-/hole
2. pair diffusion of the e- to the surface
3. emission of the e- in the vacuum

Light absorption in photocathode



Quantum efficiency Qε

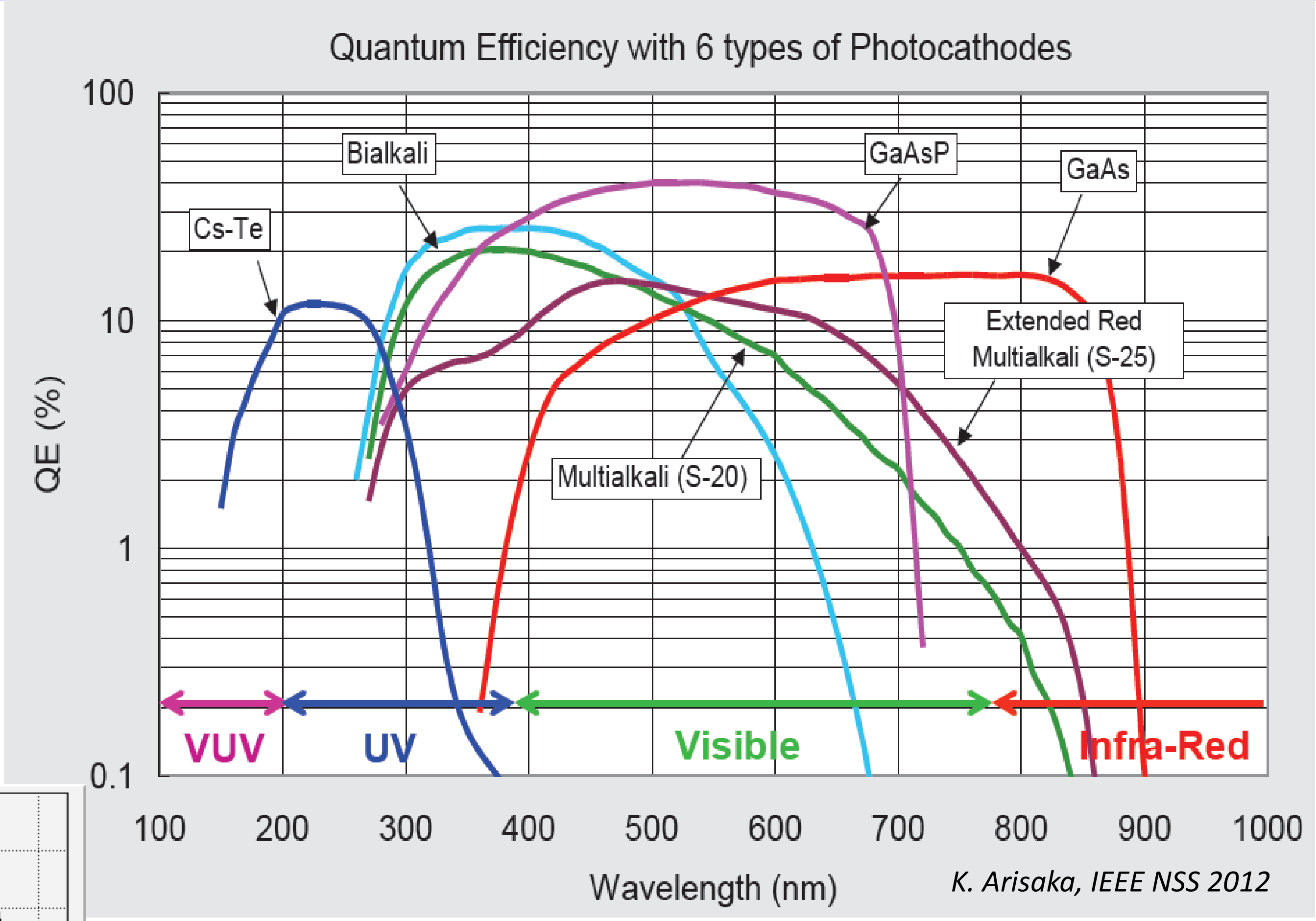
$$Q_\varepsilon = (1-R)\frac{P_v}{k}\times\left(\frac{1}{1+1/kL}\right)\times P_s$$

- R : reflexion coefficient
- Pv: exitation proba to vacuum level
- k: full absorption coefficient
- L: p.e mean escape length
- Pe: extraction proba to the PC surface

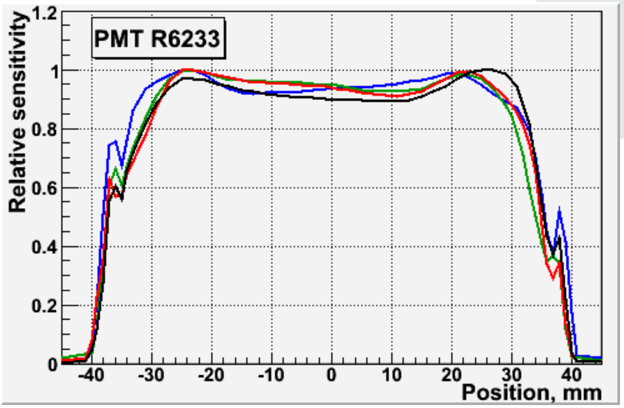
Photocathode materials and Qε of PMT

Photocathode materials:

- alkali metals (Sb, K, Rb, Cs)
- compound semiconductors (GaAsP, GaAs, InGaAs)



K. Arisaka, IEEE NSS 2012



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

O. Kalekin, RICH 2010

New Photocathodes: SBA & UBA

$$Q\varepsilon = (1-R)\,\frac{P_v}{k}\times\left(\frac{1}{1+1/kL}\right)\times P_s$$

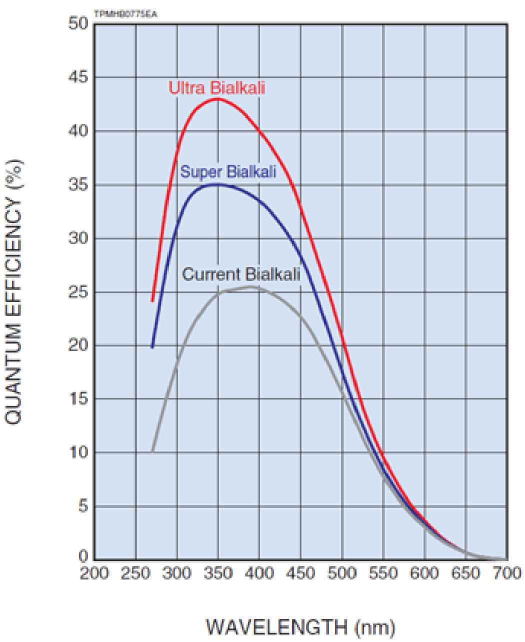
reflexion loss — $(1-R)$

excitation efficiency — $\frac{P_v}{k}$

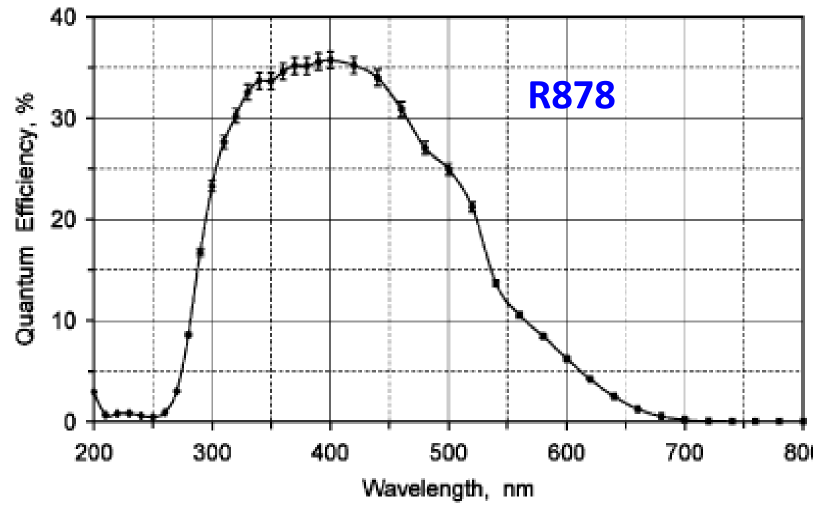
loss in the PC — $\left(\frac{1}{1+1/kL}\right)$

extraction efficiency — P_s

reduction of the losses → SBA
enhancement of the efficiencies → UBA

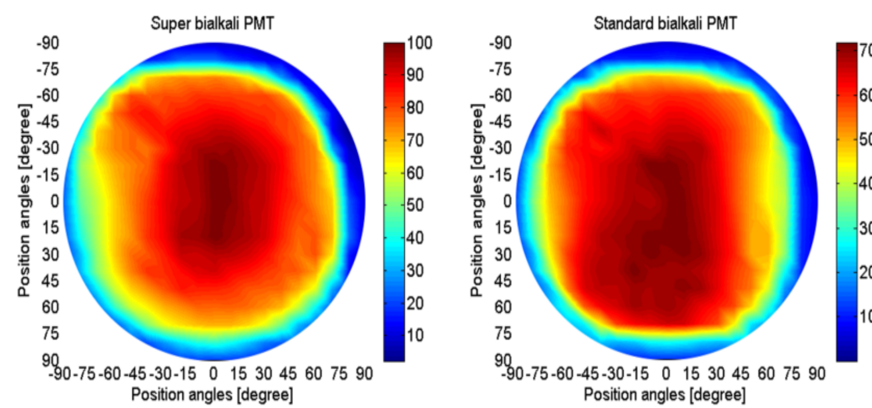


HAMAMATSU, PMT catalogue



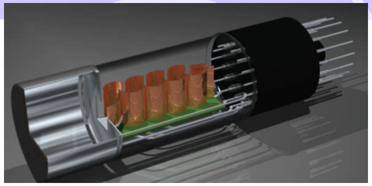
R. Mirzoyan NIMA 567 (2006) 230–232

Detection efficiency uniformity



E. Leonora, Photodet2012

Gain of the PMT



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

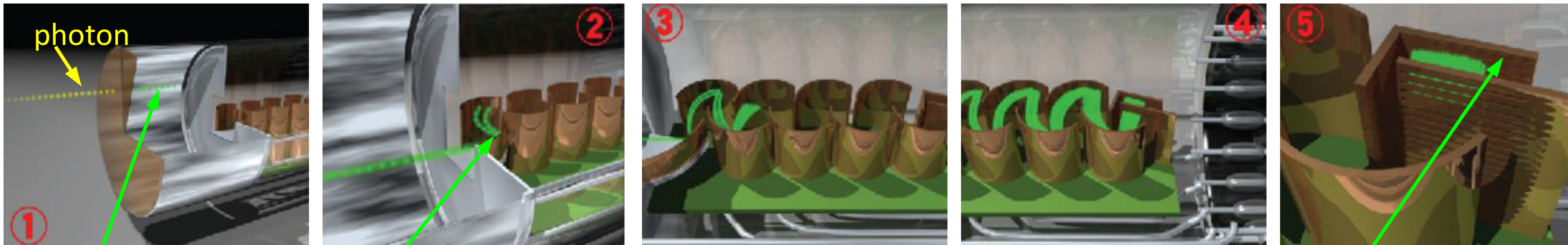
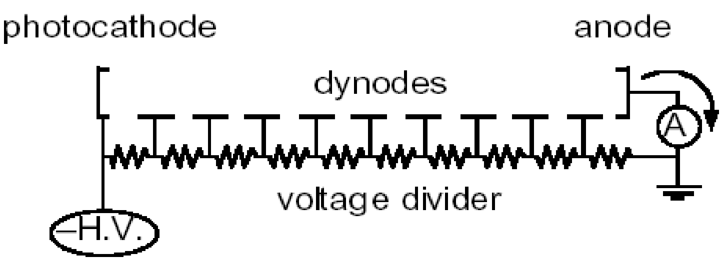
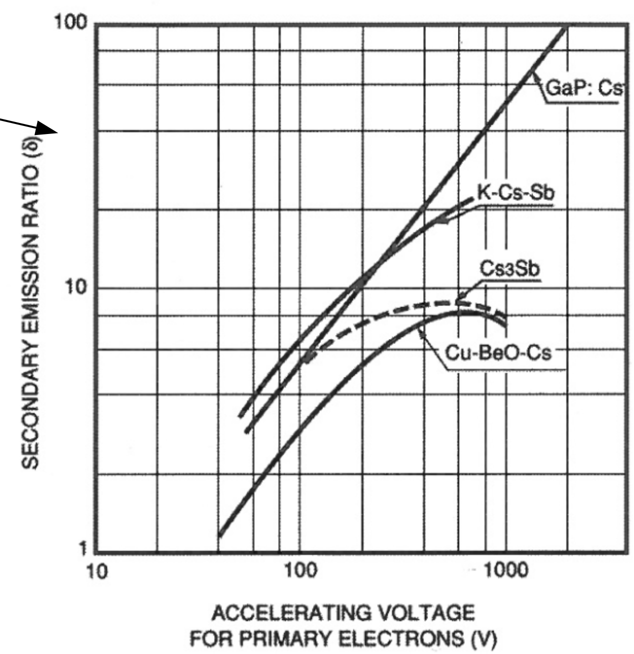


photo-electron

impact on the first dynode (multiplication coeff : δ_1)

multiplication by n dynodes and signal on the anode





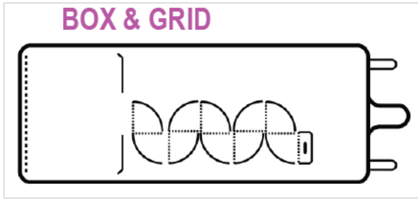
The gain of the PMT depends on the emission coefficient of the dynode (and on the bias voltage) and of their number:

$$G = \delta_1 \times \delta_2 \times \delta_3 \times . . . \times \delta_n$$

$10^5 < G < 10^6$
For $800 < HV < 2000$ V

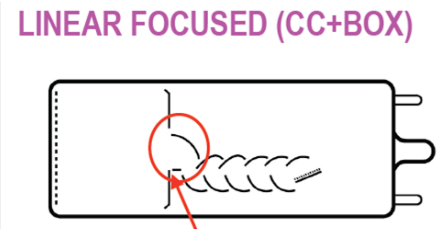
Example of dynodes configurations

Large variety of dynode types available



large collection area on the first dynode

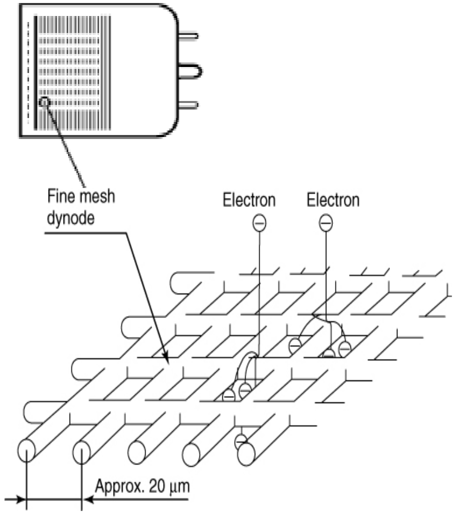
→ Good detection efficiency (good CE)
→ Slow time response



focus of the e- path

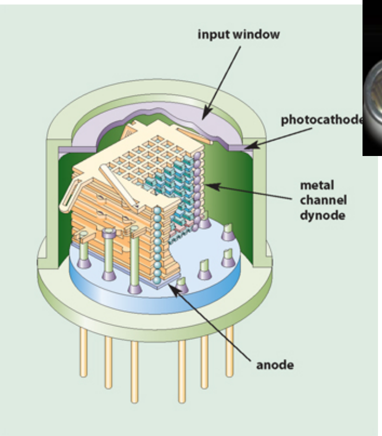
→ Good output linearity
→ Fast time response

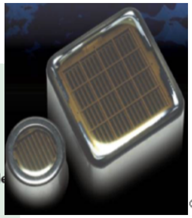
Fine Mesh

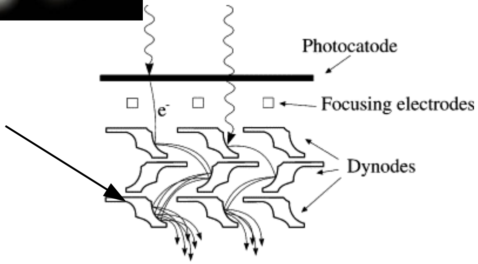


Good output linearity
High immunity to magnetic fields

Metal channel





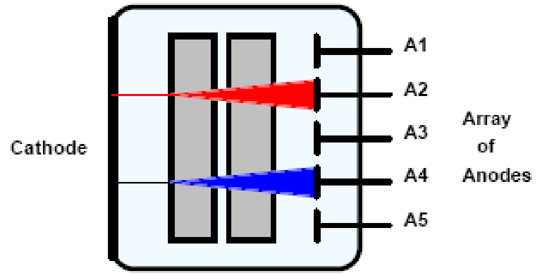


thin dynodes produces by micromachinning and precisly stacked

→ compact
→ Fast time response

Multi anode PMT (MaPMT)

Need of space segmentation of the light detection



metal channel dynodes + special anode configuration

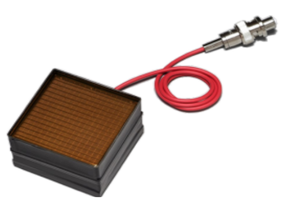
avalanche confined in a narrow channel

multi-anode design

position sensitive PMT

HAMAMATSU PMT book

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

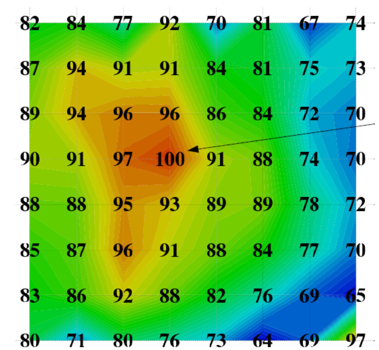


H8500 (8 x 8)

R7600 (8x8)

R11265 (8x8)

H8500 response uniformity



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

•

•Cross-talk
•Non uniformity across the channels

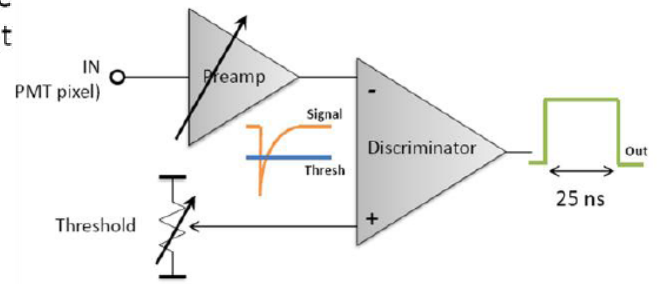
G. Collazuol, SuperB meeting, 2011

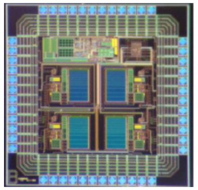
Example of ASICs for MaPMTs

CLARO

The CLARO-CMOS is the first prototype of an ASIC for single photon counting with photomultipliers, designed to readout multi-anode PMTs in the upgraded LHCb RICH.

- Each channel has a preamplifier (with settable gain) and a discriminator (with settable threshold)
- This prototype has 4 channels
- No dead time at 40 MHz hit rate
- Power consumption below 1 mW/channel

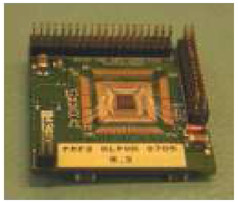


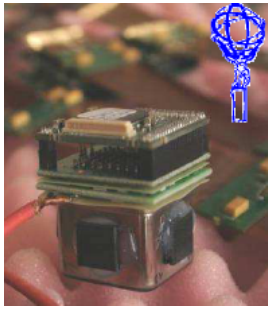


G. Collazuol, SuperB meeting, 2011

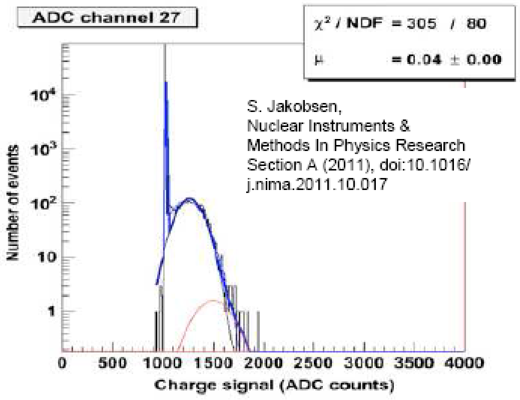
MAROC (Multi Anode Read-Out Chip)

Readout of the MaPMT 64 channels of the ATLAS luminometer





64 channel inputs:
Variable gain current preamps (8 bits/ch.)
- 64 trigger outputs + 2 OR outputs
- 1 mux. analog charge output
- 1 digitized charge output (8, 10 or 12 bits ADC)
- Trigger efficiency= 5fC
- Variable slow shaper (20-100 ns)
- 10 bits DAC as threshold



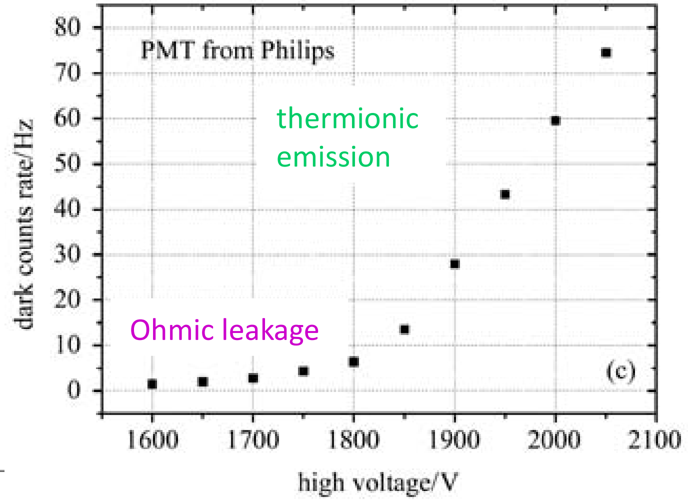
Charge spectrum of one MAPMT channel illuminated by a LED at low light level.

S. Conforti, PhotoDet 2012

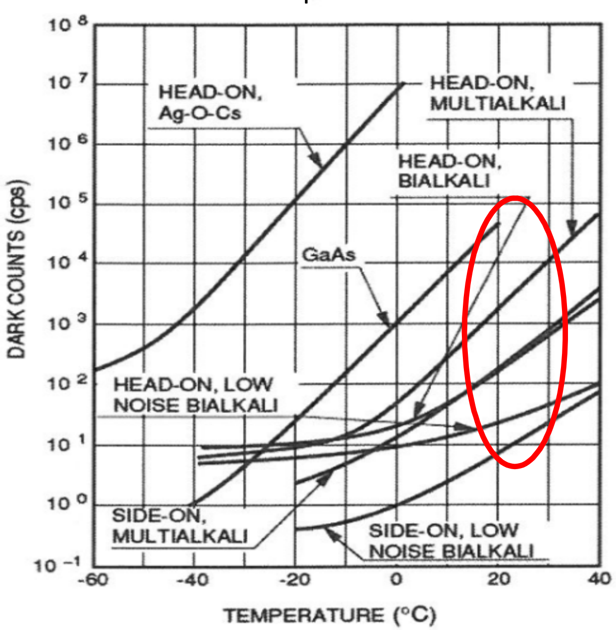
Noise of a PMT: Dark current

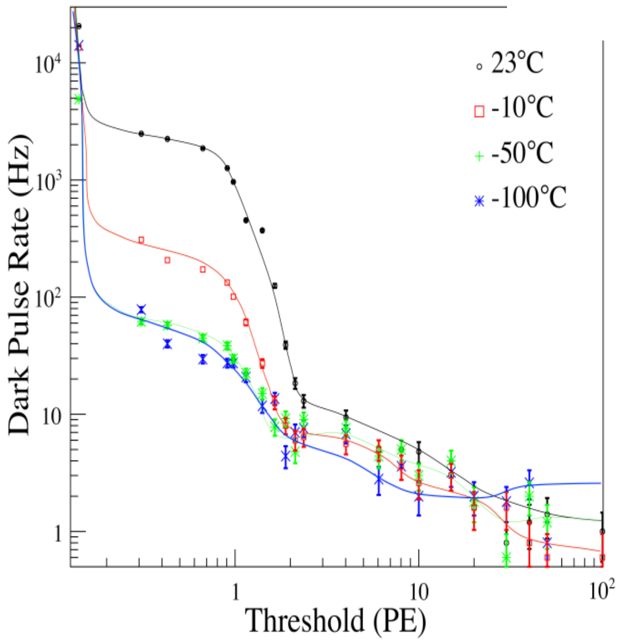
Dark current (I_d): current when photomultiplier is operated in complete darkness

- 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

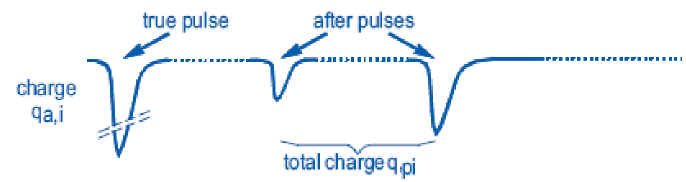
HAMAMATSU PMT book

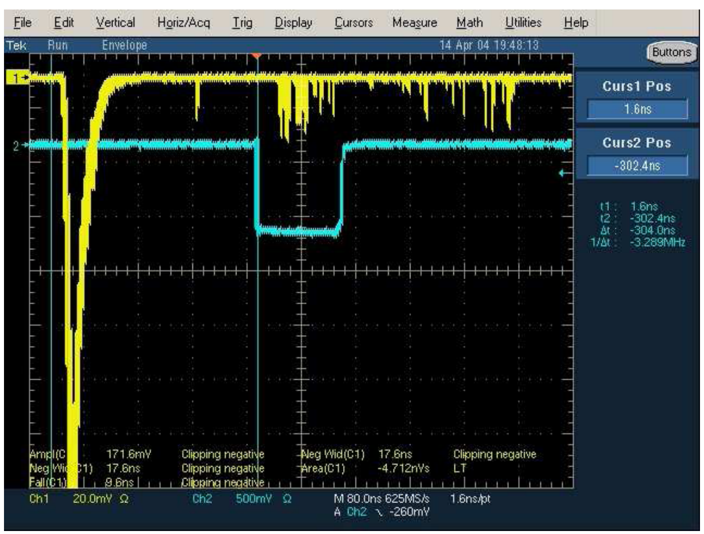
K. Lung, arXiv:1202.2628v2 [physics.ins-det], 2012

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

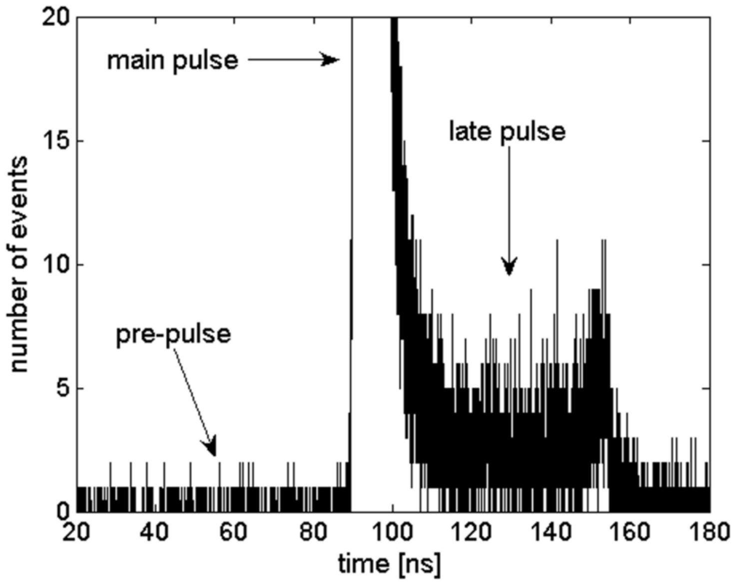
- short delay afterpulses (up to several tens of ns after the signal) caused by the elastic scattering of the electrons from the first dynode.

- 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

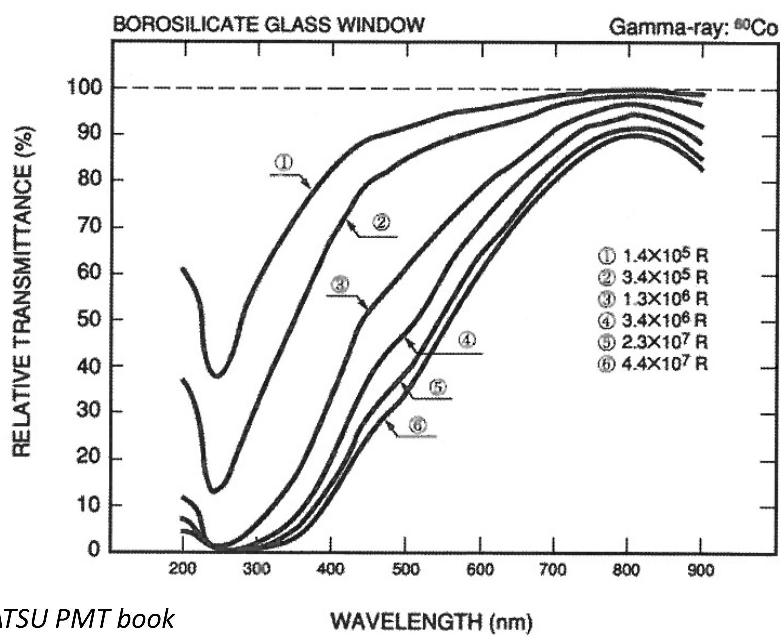
Can be distinguished by the time interval that separates them from the true pulse → use of coincidence techniques to minimize their effect

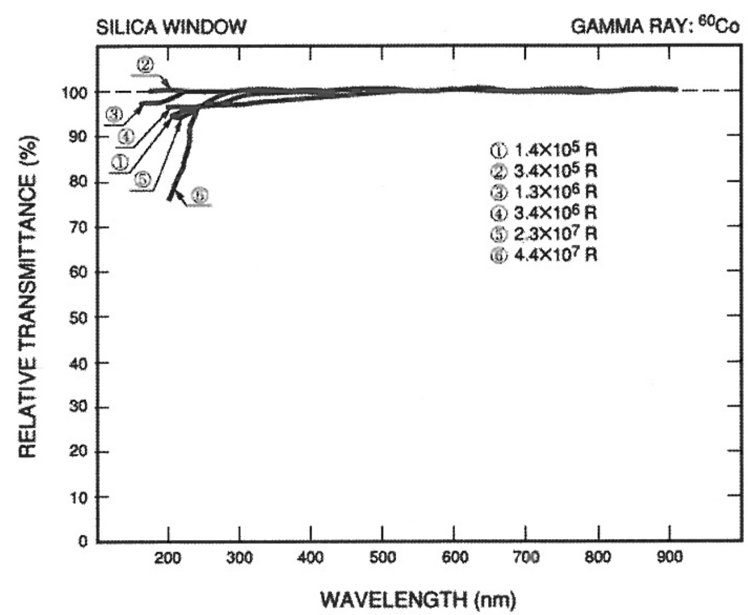
HEP Detector near accelerator (LHC, ILC) : very hostile environment for PMT

Damages caused by:

- ionizing radiation: energy deposited by particles in the detector material (the unit of absorbed dose is Gray (Gy) ==> 1 Gy = 1 J/kg = 100 rad) and by photons from electromagnetic showers
- neutrons created in hadronic shower, also in the forward shielding of the detectors and in beam collimators

➢ important deterioration of the window transmittance (Borossilicate glass)
➢ no effect for visible light with Silica window



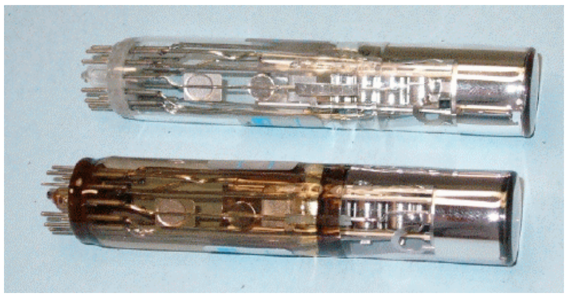


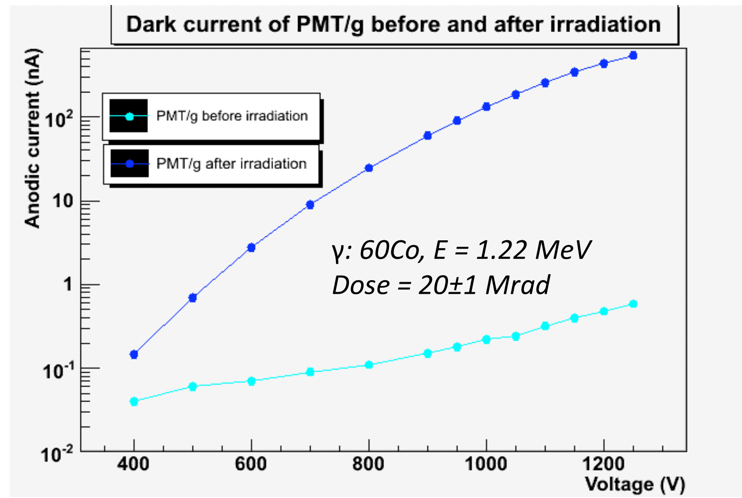
HAMAMATSU PMT book

Radiation tolerance of PMTs

➢increase of the dark current (scintillation of the glass window)

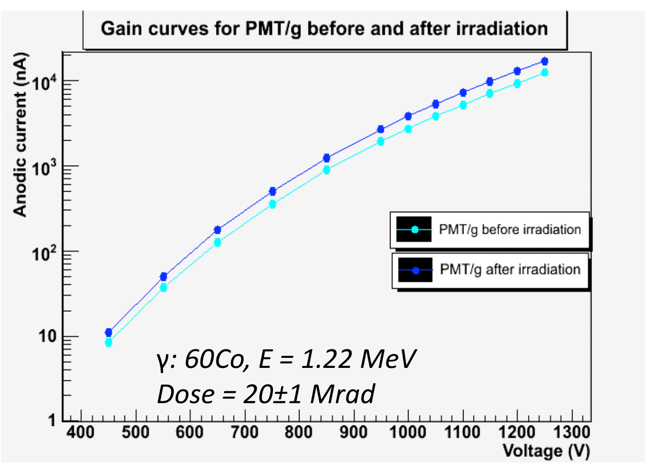
Dark current of PMT R762

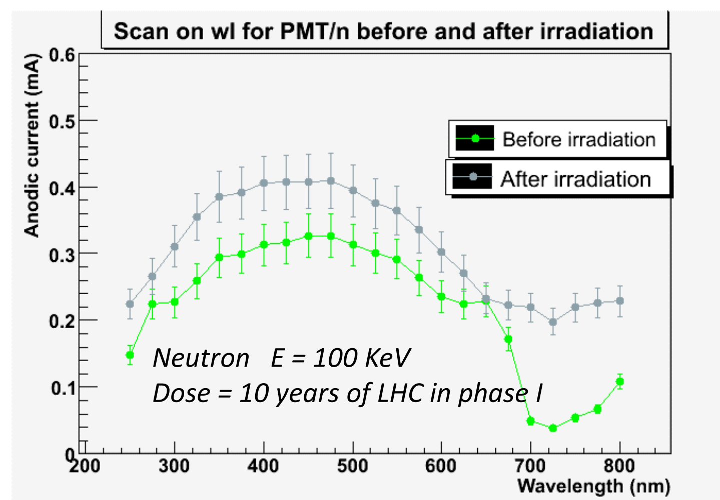




A. Sbrizzi LUCID in ATLAS

➢no important change of the gain and quantum efficiency





Progress in PMT development

80 years of existence and still in R&D !

some examples …

Improvement of Qε for large PMT and for UV light

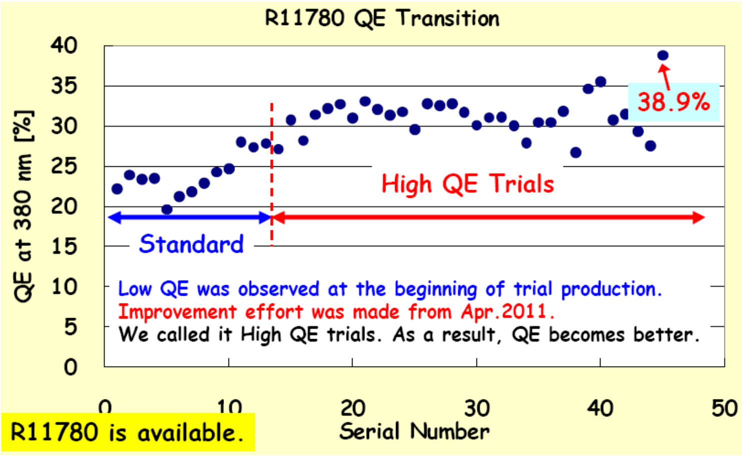
Large water Cherenkov and scintillator detectors for long baseline neutrino oscillations, proton decay, supernova and solar **neutrinos experiments**

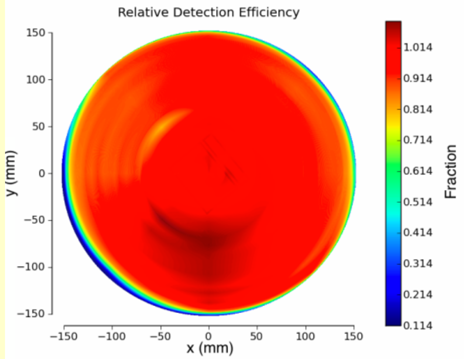
Need for PMT with:

- ✓large-area
- ✓high Qε in UV

R11780 (12-inch)

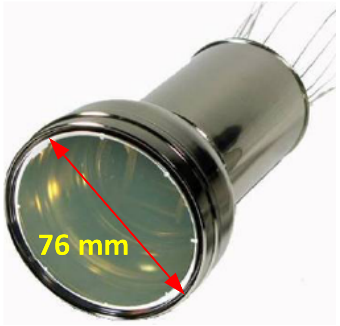
Y. Yoshizawa, Photodet 2012





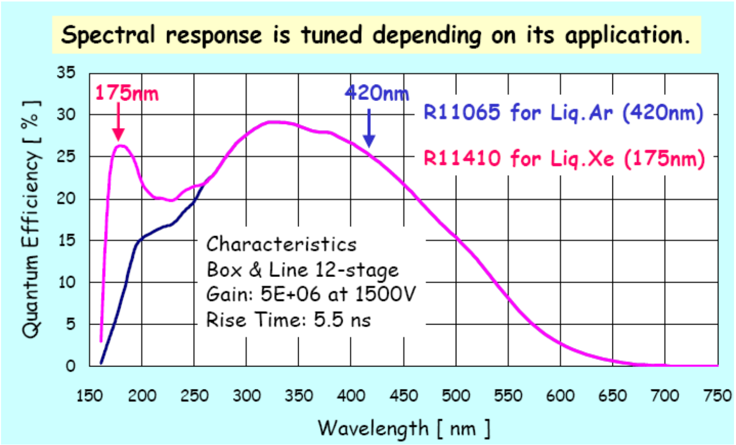
J. Brack, arXiv:1210.2765v2

Scintillation detector for **Dark Matter experiments** (scintillation light from Xe nuclear recoil resulting from the scattering of WIMPs*)→ need for Ultra low background PMT working at low temp



3- inch metal bulb PMT

Extremely low radioactivity
Low temp: Liquid Ar(- 186 °C)

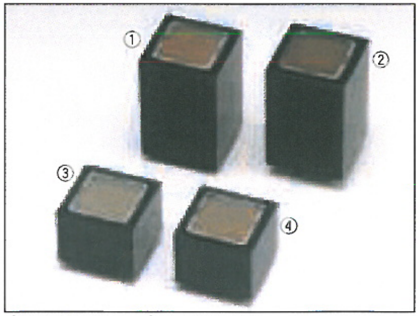


Y. Yoshizawa, Photodet 2012

* WIMP: weakly Interacting Massive Particles

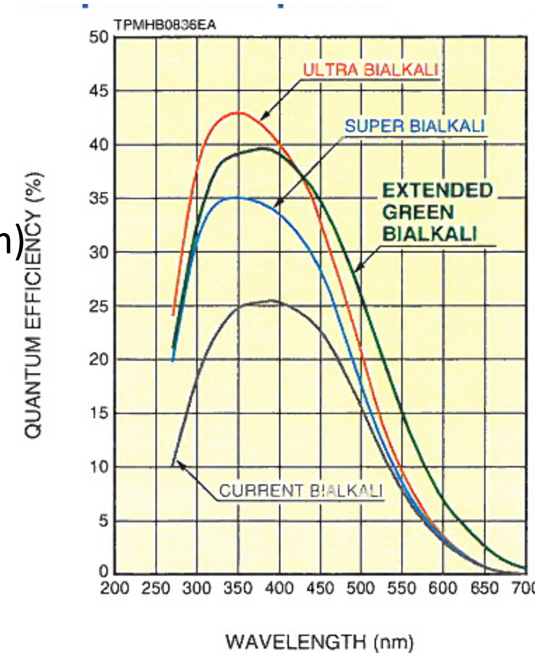
Latest MaPMT developments

PMT with extended green Bialkali photocathode



①H8711-300 ②H7546B-300
③R7600U-300 ④R7600U-300-M4

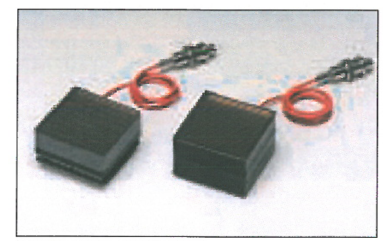
- Extended green bialkali PC (Qε= 14 % @ 550 nm)
- 2 x 2 multianode
- 4 x 4 multianode
- 8 x 8 multianode

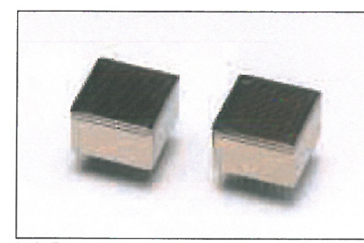


Compact packaging multianode PMTs

Parameter	H8500C②, H8500D②	H9500 ②	NEW R11265-100-M16/M64	Unit
Spectral Response	300 to 650		300 to 650	nm
Transit Time Spread (FWHM)	0.4		0.34 / 0.35	ns
Anode Type	Matrix		Matrix	—
	8 × 8	16 × 16	4 × 4 / 8 × 8	—
Effective Area	49 × 49		23 × 23	mm
Effective Area Ratio ①	89		77	%

① (Effective Area) / (External Size) ② UV type is also available. Suffix: -03, 185 nm to 650 nm


Left: H8500C, Right: H9500


Left: R11265-100-M16, Right: R11265-100-M64

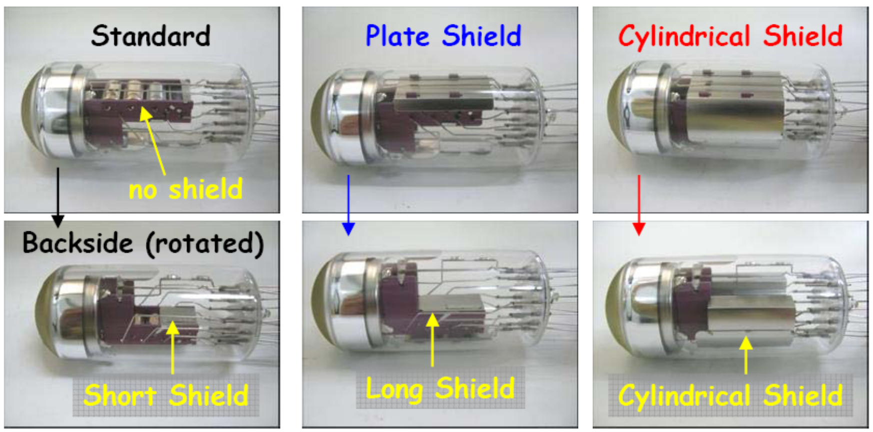
HPK, private communication

Decrease of the after-pulse

R&D in the structure of the PMT (dynode) → Lower after-pulse %

Optimazation of Dynode Shield

Dr.Mirzoyan/MPT 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.

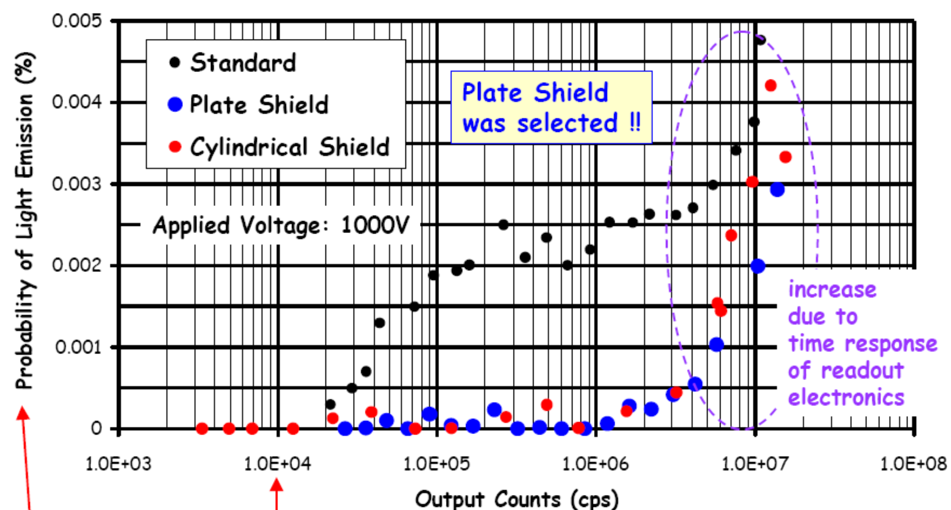


HPK, private communication

Producers and Physicists work together to increase the PMT quality

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

Light Emission from Dynode



AP/NOISE(%) is normalized at 1.0E+04 output counts.

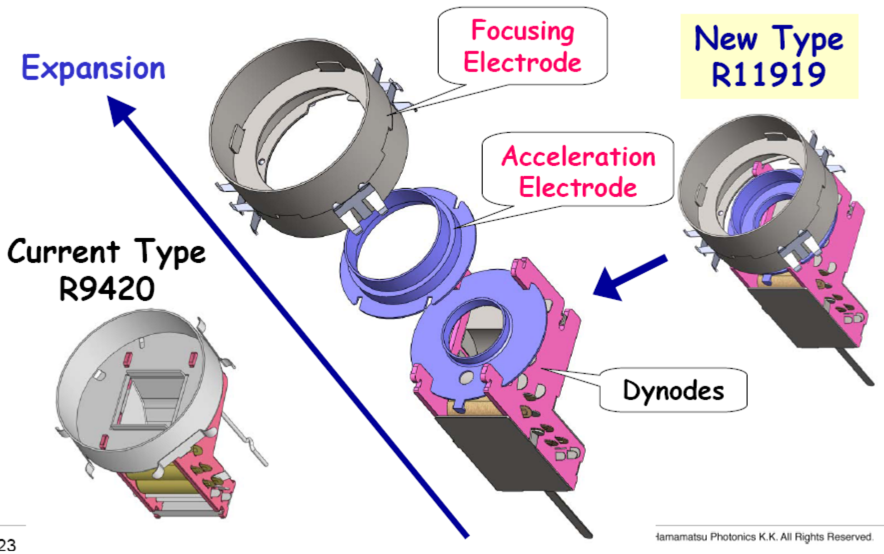
20

R&D in the structure of the PMT (electrode)

Better TTS

HAMAMATSU
PHOTON IS OUR BUSINESS

Comparison of PMT Structure between Current Type and New Type

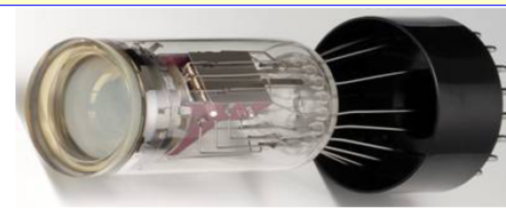


23 Hamamatsu Photonics K.K. All Rights Reserved.

HPK, private communication

R11919 / 1.5-inch FAST PMT

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

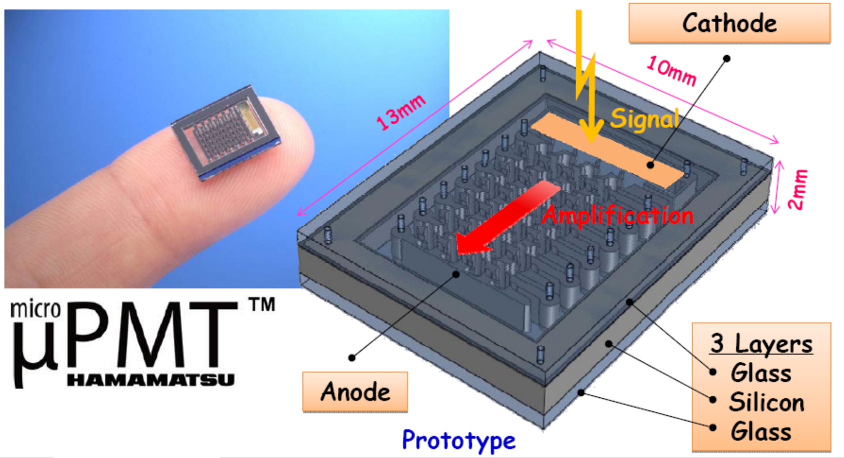


Transit Time Spread = around 270 ps
(R9420 = 550 ps, R11194 = 400 ps)

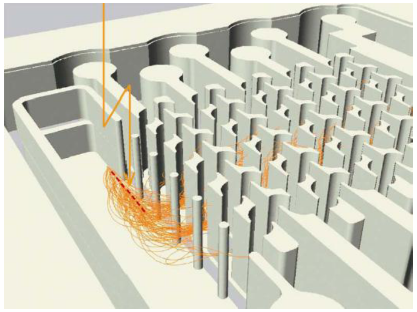
Gain = 1E+06 (Gain is adjustable by request)

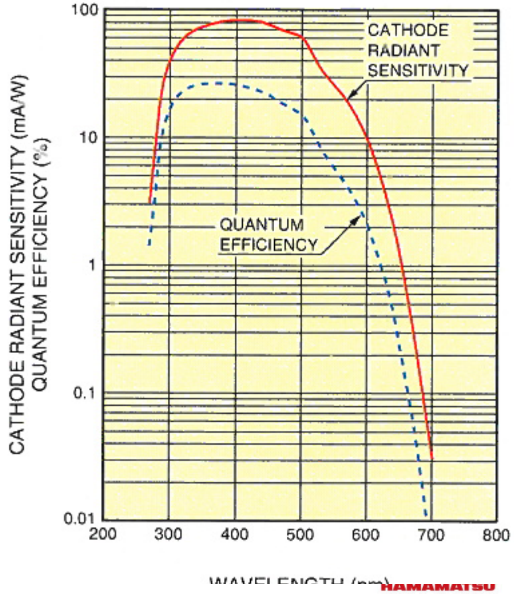
Cathode Blue Sensitivity = around 11
(SBA type could be available in future)

Micro PMT



Silicon PMT





HAMAMATSU

Technologies for Micro-PMT

Unification of Key technologies

Semiconductor Processing → Advanced Simulation → Vacuum Sealing → Vacuum Processing → **Photon Sensor with New Concept**

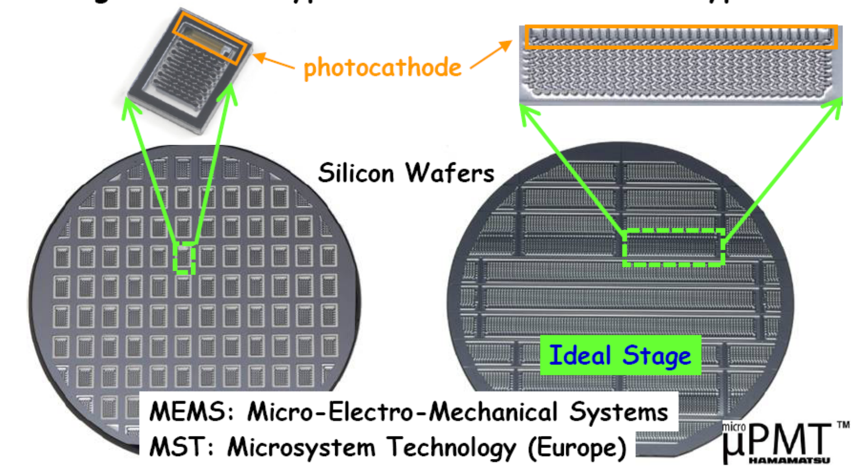
Main characteristics
Effective Area: 3.5 mm x 1 mm
Quantum Efficiency: 26 % at peak
Gain (with 12-stage): 1E+06 at ~1000V
Rise Time: around 1.2 ns
Single Photon Counting Ability

Prototype

Sample (with assembly) is available.

HAMAMATSU

Micro-PMTs come from Si Wafers !!

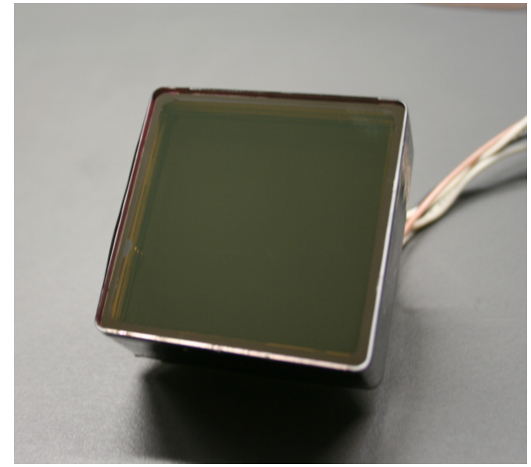


[37] *HPK, private communication*

Micro-Channel Plate Photomultipliers

BURLE

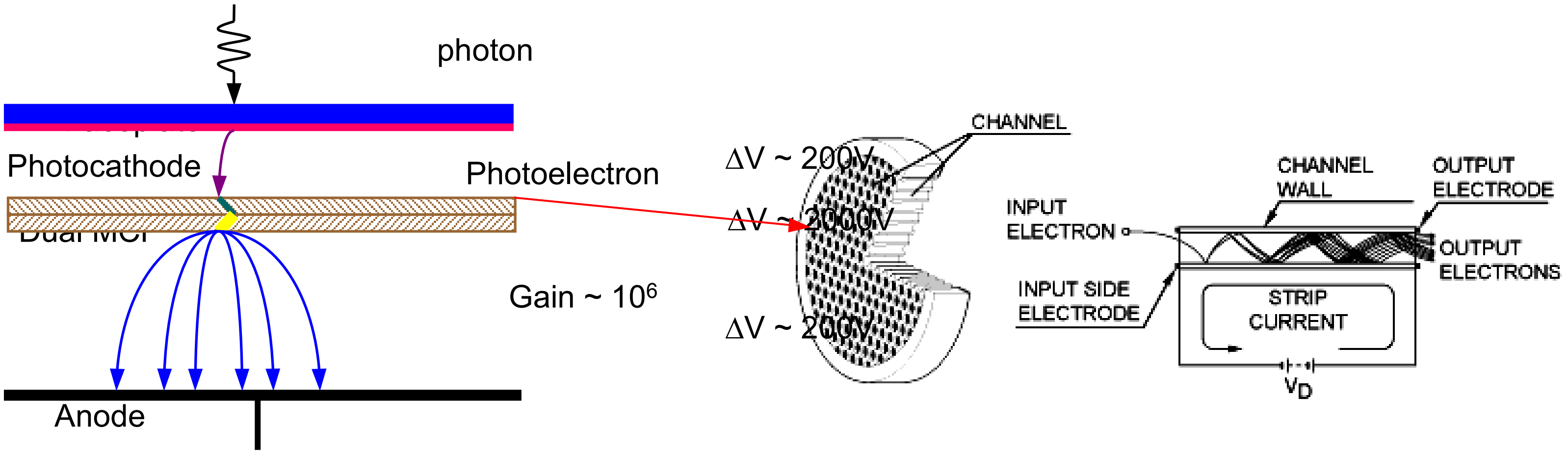
PHOTEK
ENVISAGE THE FUTURE



HAMAMATSU
PHOTON IS OUR BUSINESS

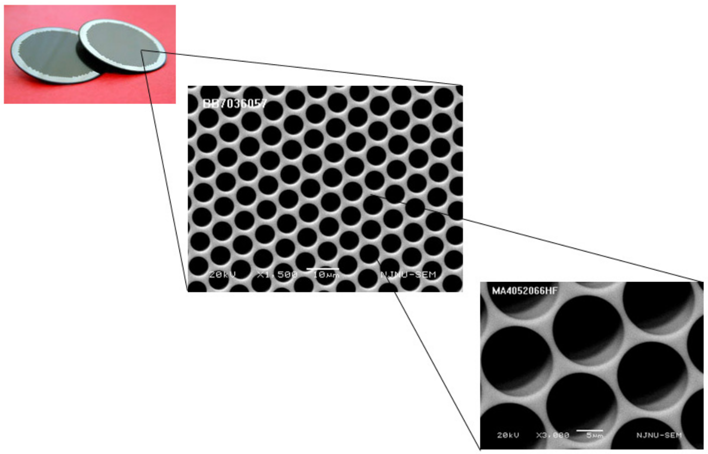
R&D in Research Institutes (BINP, Russia – IEHP, China – LAPP collaboration, USA -, …)

Photodetector multiplication chain = Micro Channel Plate



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

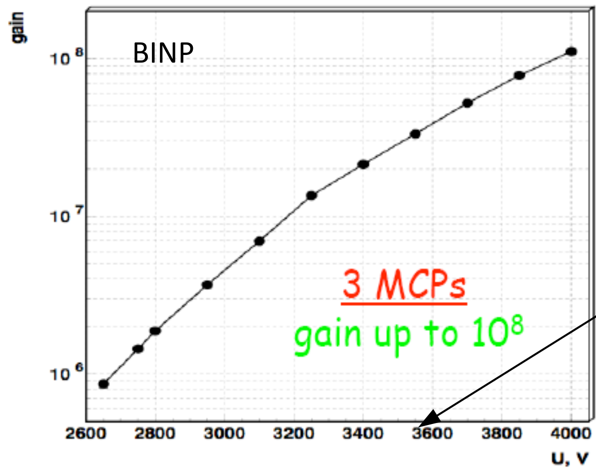
- high gain: → 10^7 with 3 MCP stages
  → single photon sensitivity
- very fast time response:
  → signal rise time = 0.3 – 1.0 ns
  → TTS < 50 ps
- quantum efficiency comparable to that of standard PMT
- multi-anode available



- lifetime (QE drops)
- price

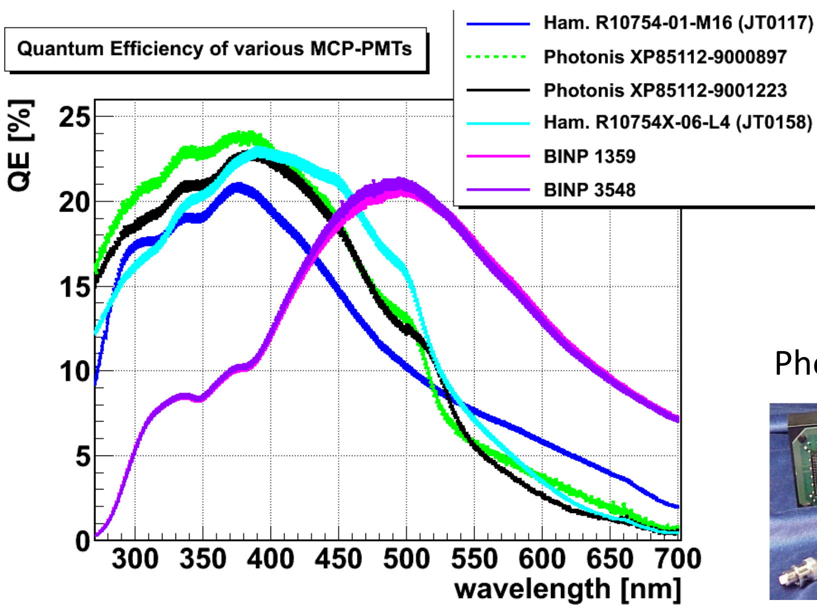
MCP-PMT gain & quantum efficiency

BINP

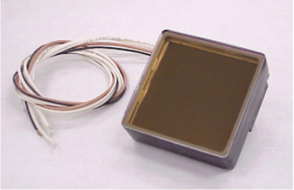


M.Barnyakov, AFAD 2013

MCP-PMT bias voltage > PMT bias voltage

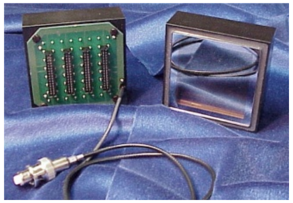


A. Lehmann, Elba Conference 2012

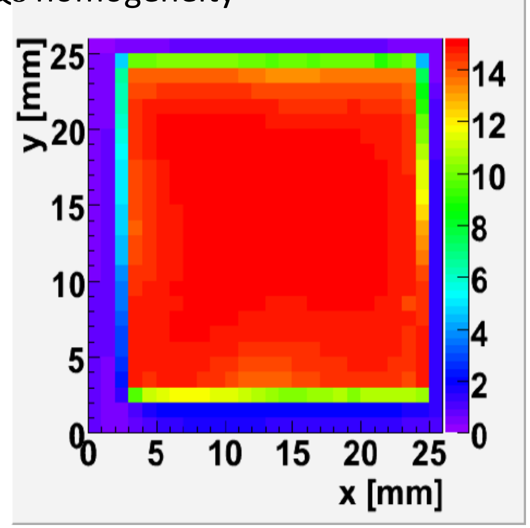


HAMAMATSU

Photonis BURLE



Qε homogeneity



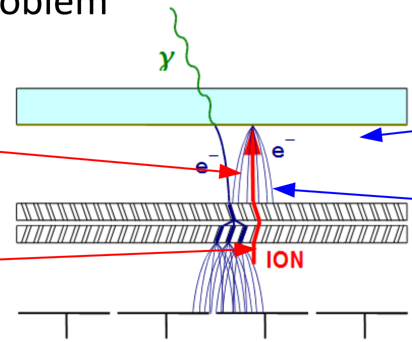
T. Inami, TIPP 2011

MCP-PMT aging

High photon rate → aging problem

2 travel back toward the photocathode

1 ionisation of atoms of residual gas

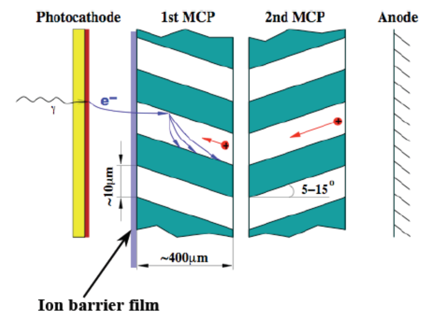


3 ion bombardment → damages the photocathode → reduces the Qε

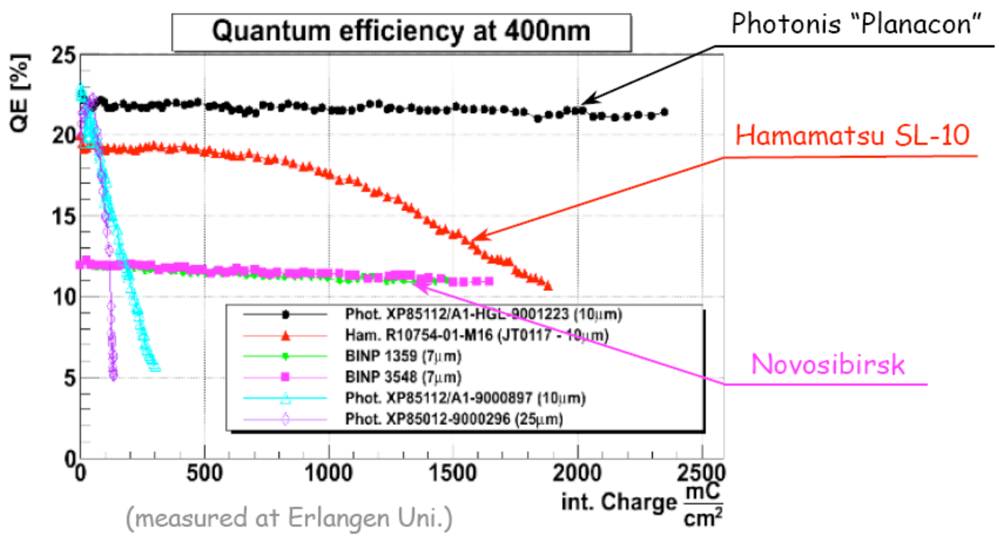
4 production of secondary pulses

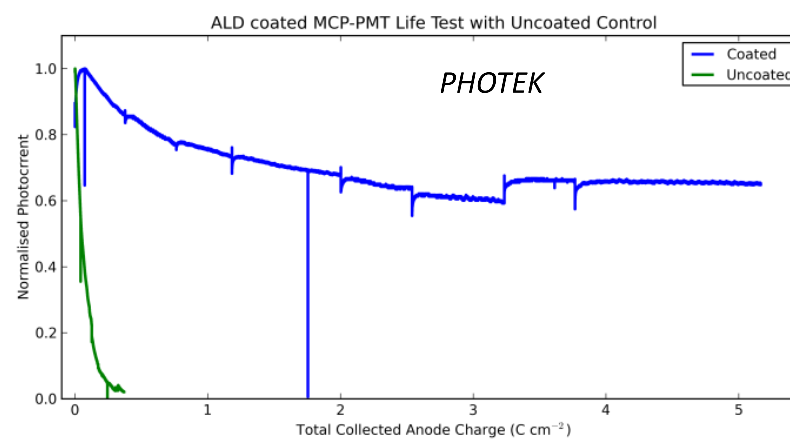
Different ways of improvement (depending on the producer):

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



A. Lehmann, Elba Conference 2012





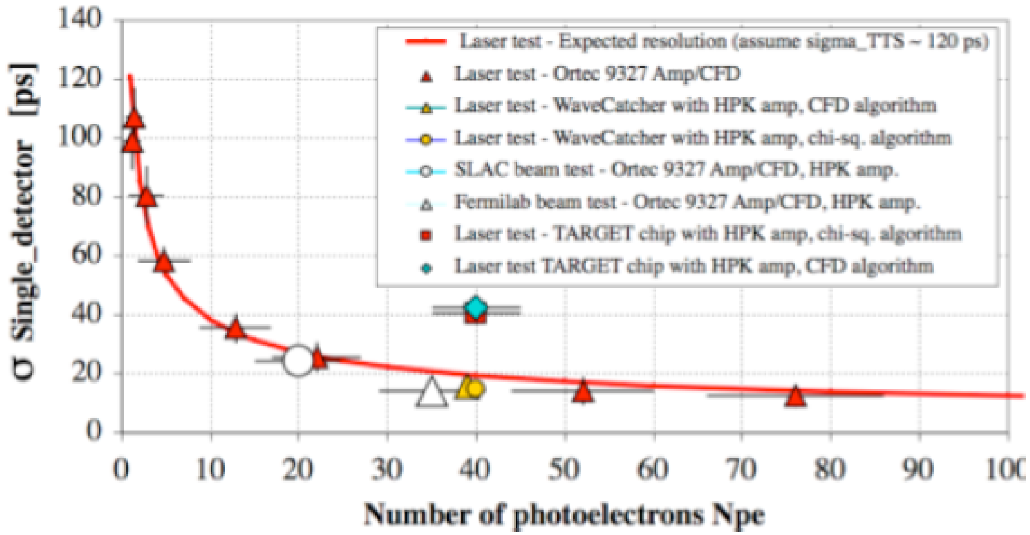
T M Conneely, PHOTEK

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

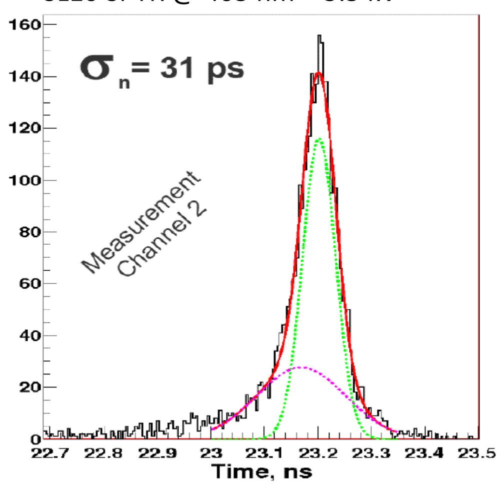
→ very good TTS



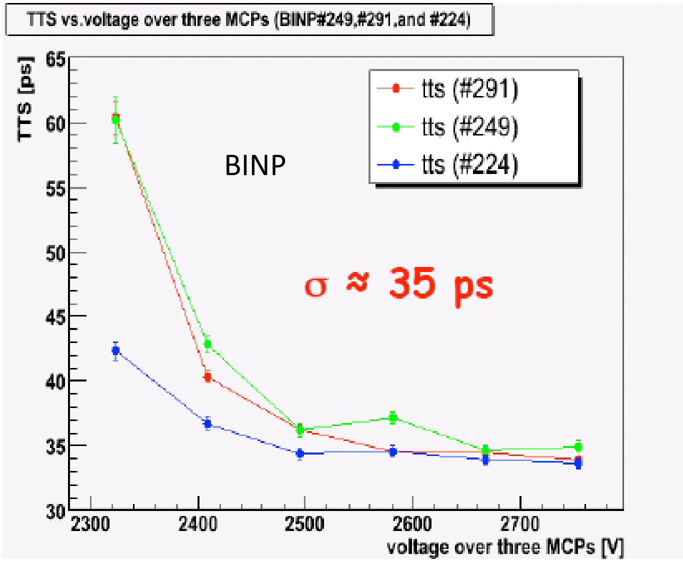
J. Vavra, SLAC-Pub-14279

Single Photoelectron Timing resolution

SL10 SPTR @ 405 nm – 3.5 kV



L. Burmistrov, LAL

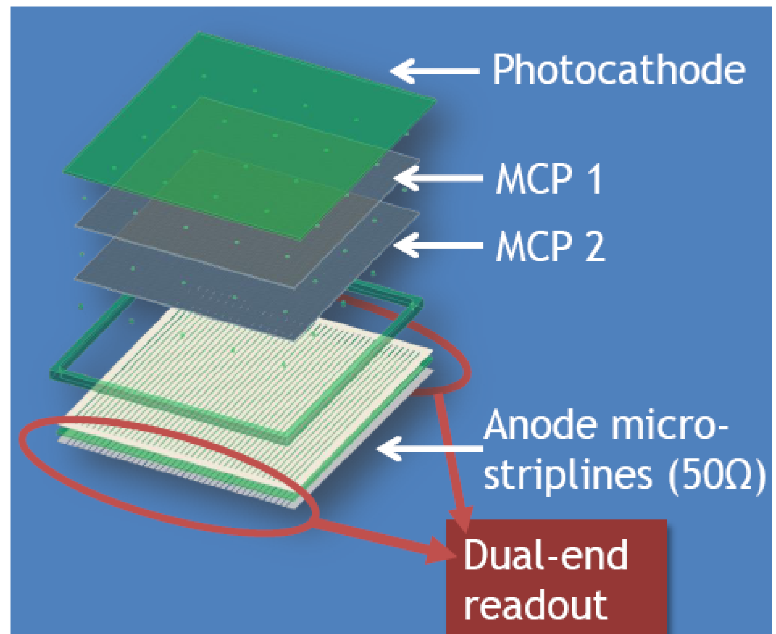


A. Yu. Barnyakov, NIMA 598

LAPPD Collaboration

The LAPPD project

- 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



New MCP-PMT developments

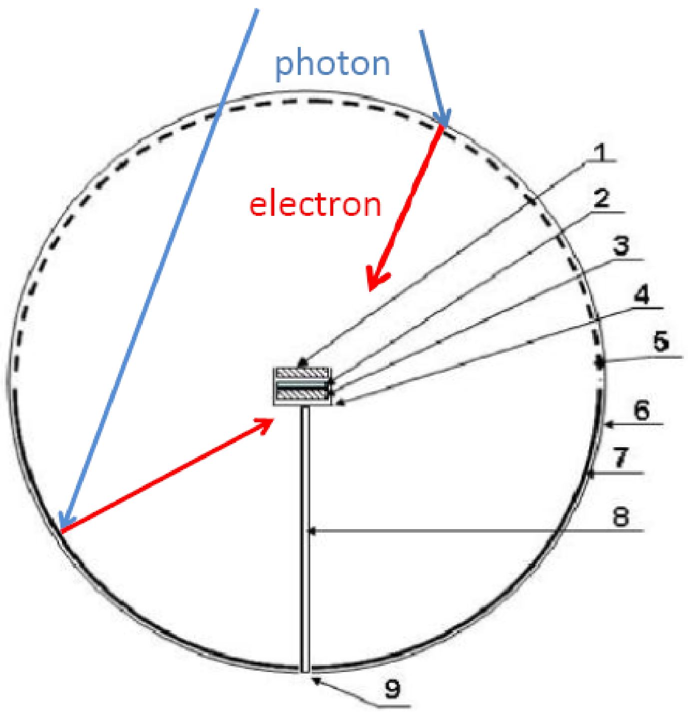
中国科学院高能物理研究所
Institute of High Energy Physics, CAS

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 reflective photocathode (back hemisphere) } ~ 4π viewing angle!!

- Quantum Efficiency:
  - Transmission photocathode: 20%
  - Reflection photocathode: 40%
- MCP Collection Efficiency: 60%



1. up MCP
2. anode
3. down MCP
4. insulated trestle table
5. transmission photocathode
6. glass shell
7. reflection photocathode
8. bracket of the cables
9. glass joint

➢Total Photon Detection Efficiency: ~30%

Photon Detection Efficiency: 14% → 30% ; ×~2 at least !

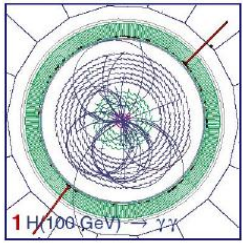
2012/6/13 PhotoDet 2012

Y. Heng, PhotoDet 2012

Operation of PMT and MCP-PMT in magnetic field

★ earth magnetic field = 30-60 mT

B



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

→ reduce the detector size → reduce the detector price

PMT

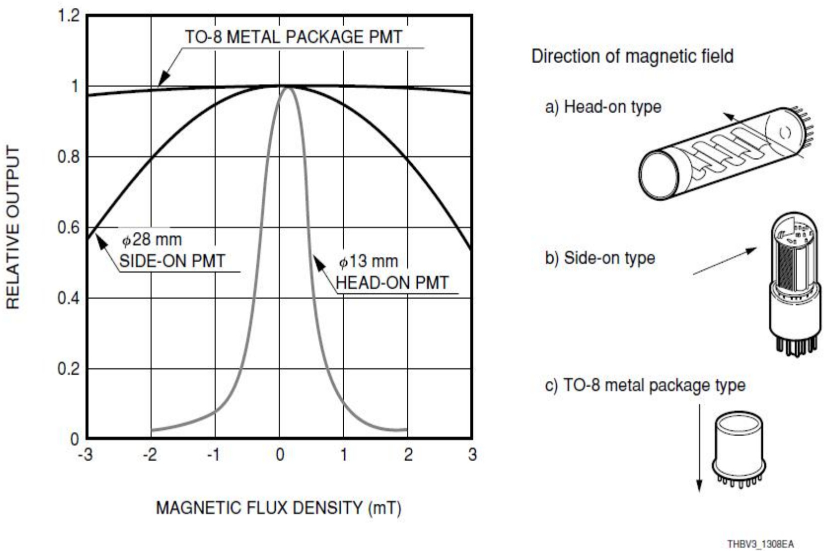


Figure 13-8: Magnetic characteristics of typical photomultiplier tubes

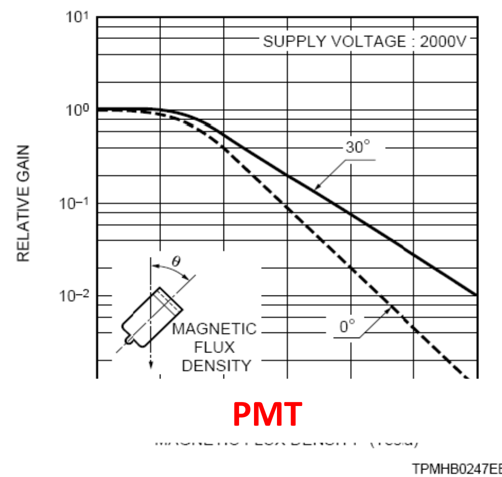
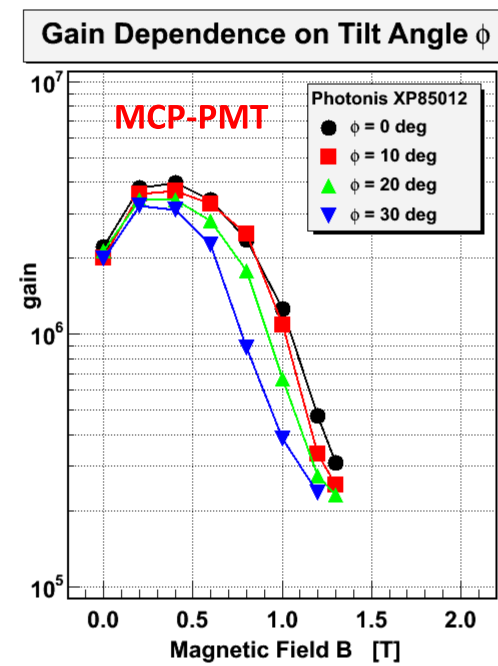


Figure 6-25: Gain vs. magnetic flux density

HAMAMATSU PMT book

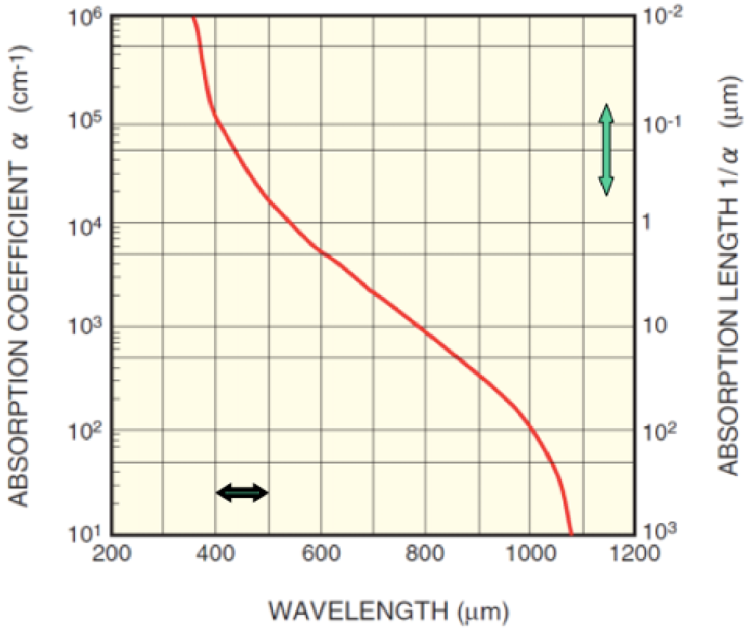


Albert Lehmann RICH 2010

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

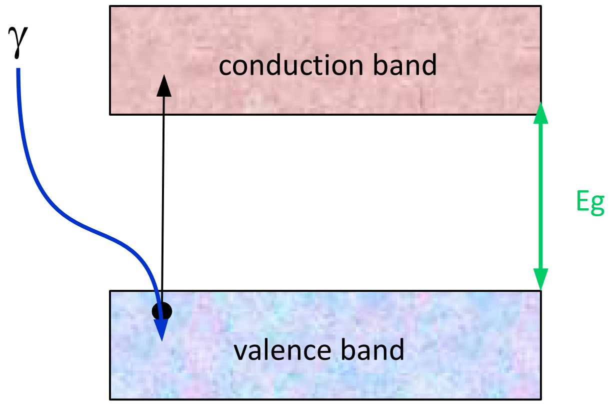
Silicon Photo Multiplier

Internal photoelectric effect in Si



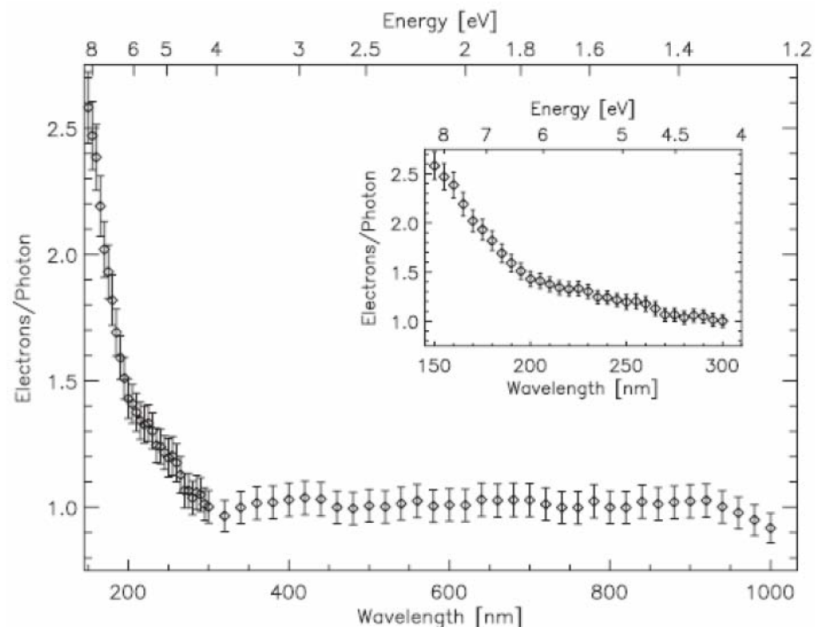
Beer-Lambert law $I(\lambda, z) = I(\lambda)e^{-\alpha(\lambda)z}$

I(λ) : initial photon flux
I(λ,z) : photon flux on the distance z from SiPM surface
α(λ): optical absorption coefficient
z : penetrated thickness in Si

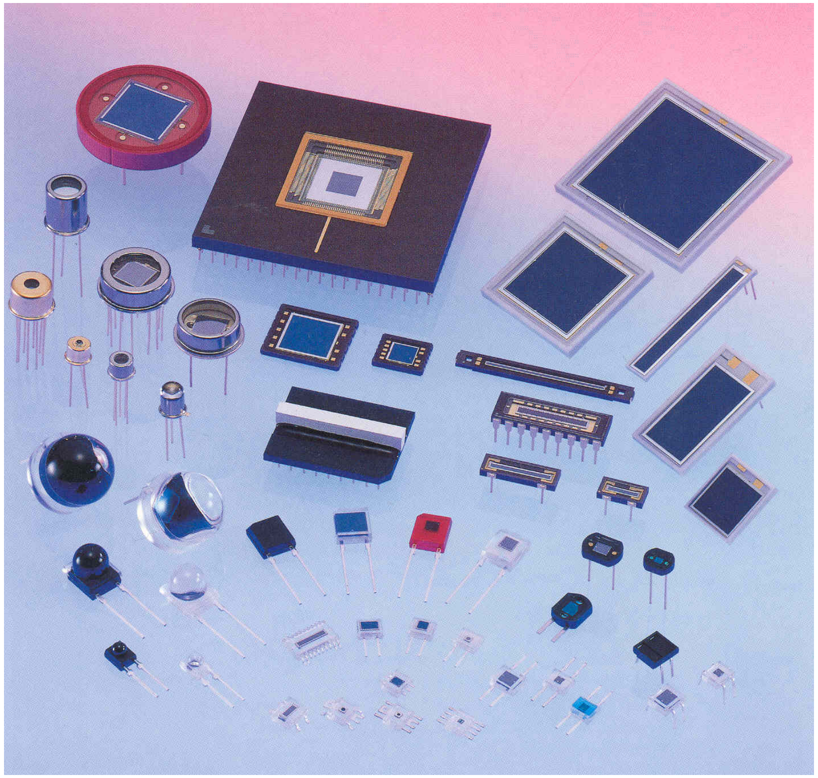


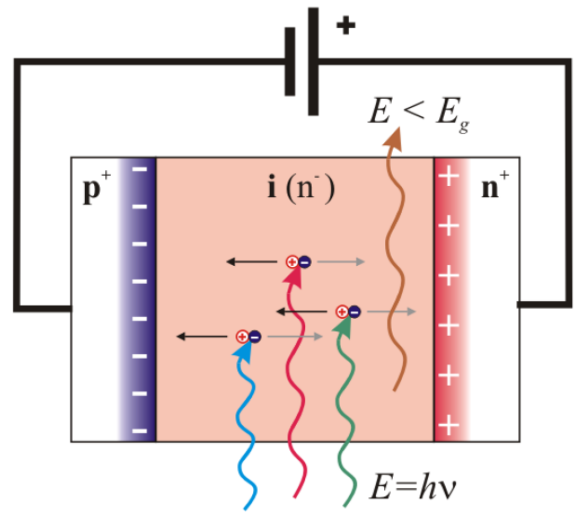
Band gap (T=300K) = 1.12 eV (~1100 nm)

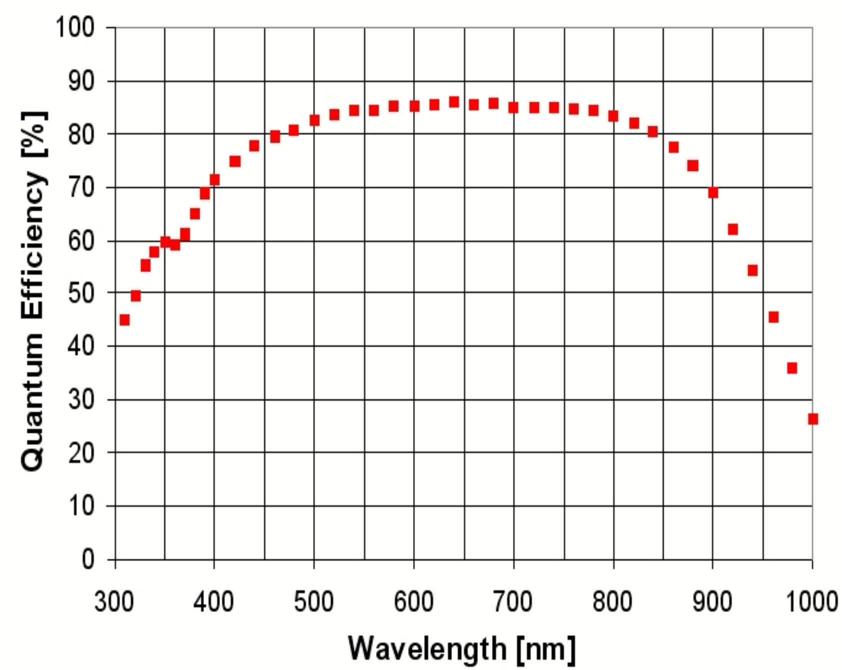
Number of electron / incident photon as a function of λ



The Pin photodiode

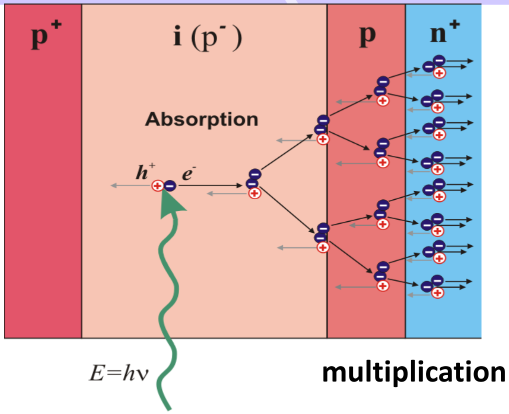




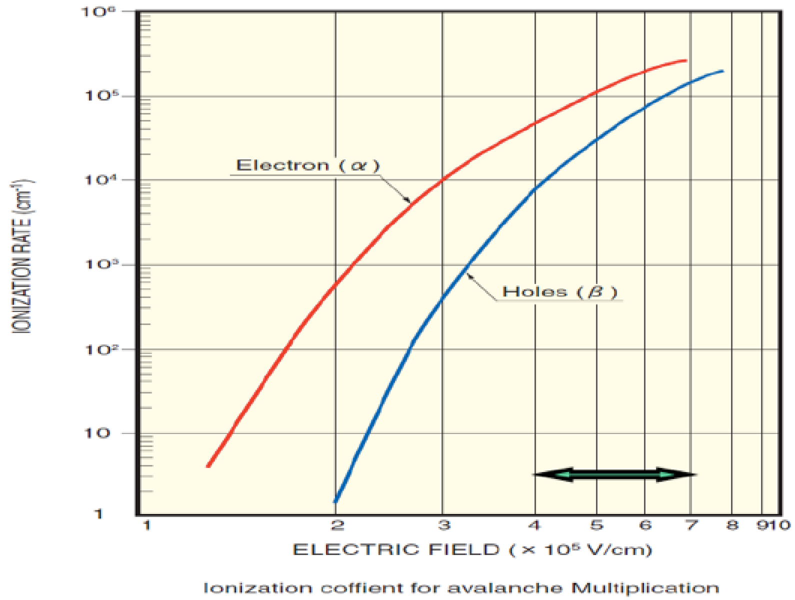


- p layer very thin (< 1 µm)
- high QE (80% @ 700nm)
- Gain = 1

The Avalanche Photodiode

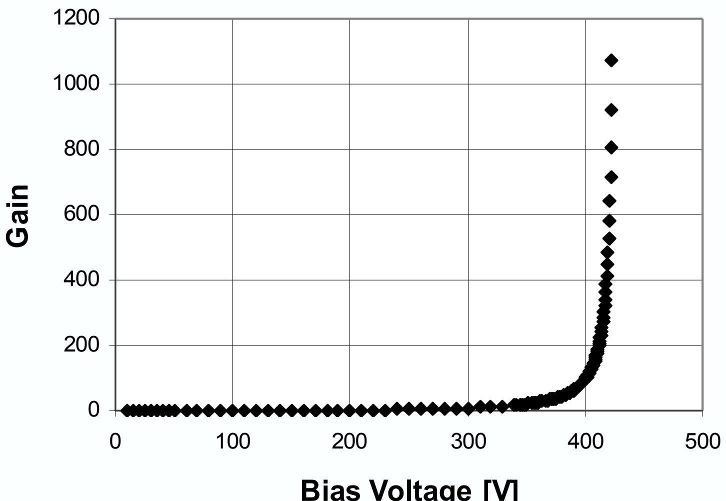


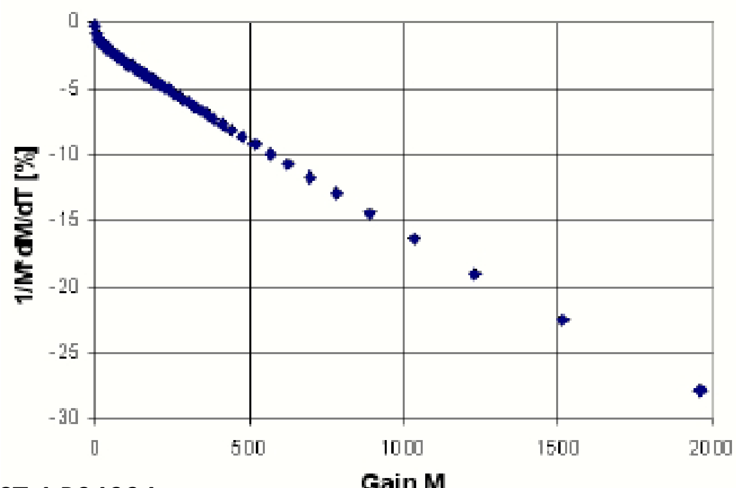
Ionization coefficients α for electrons and β for holes



Bias voltage : few 100 V

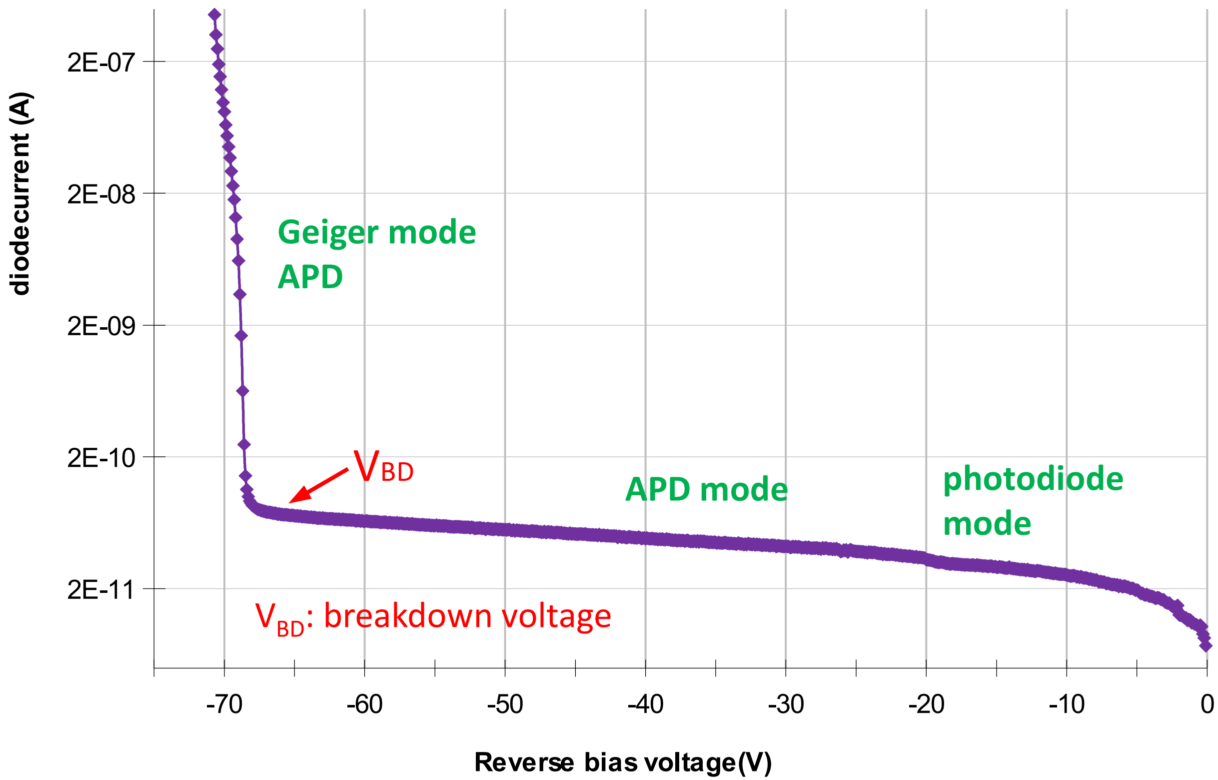
- high QE (80% @ 700nm)
- Gain = 50 – 100
- high variation with temp. and bias voltage : ΔG = 3.1%/V and -2.4 %/K



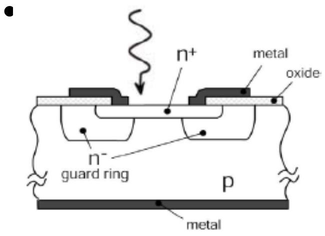


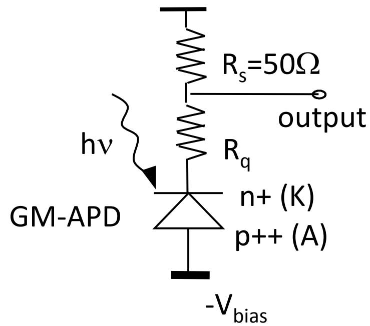
D. Renker, 2009 JINST 4 P04004

From PIN photodiode to Geiger mode APD



Geiger mode -APD

- $V_{bias} > V_{BD}$
- G ⇨ ∞
- single photon level
- 

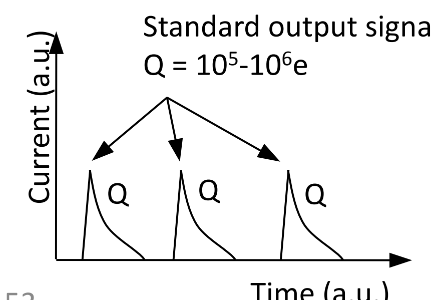


Photodiode

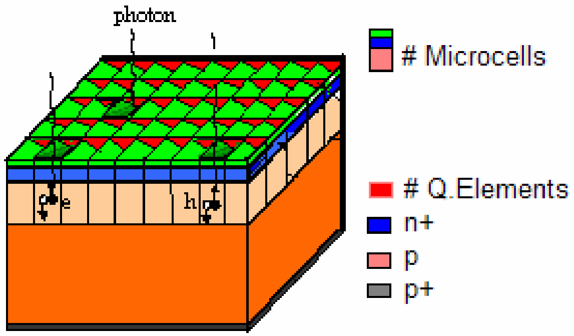
- $0 < V_{bias} < V_{APD}$ (few volts)
- G = 1
- Operate at high light level
  (few hundreds of photons)

APD

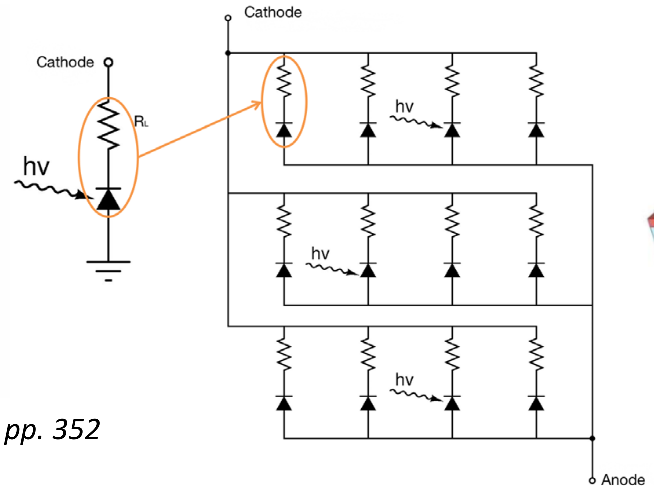
- $V_{APD} < V_{bias} < V_{BD}$
- G = M (50 - 100)
- Linear-mode operation

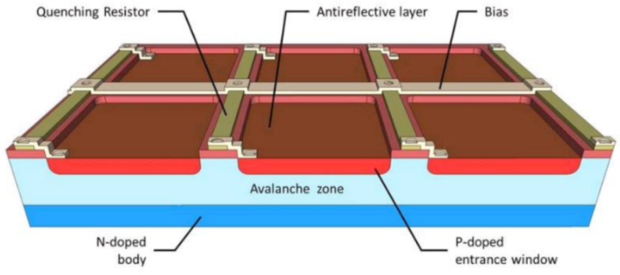


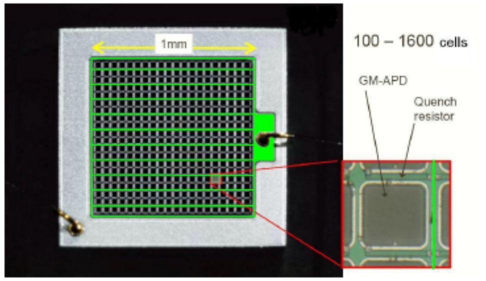
Structure and principle of a SiPM



Valeri Saveliev, ISBN 978-953-7619-76-3, pp. 352





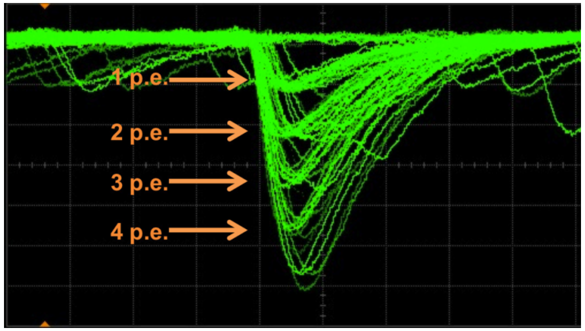


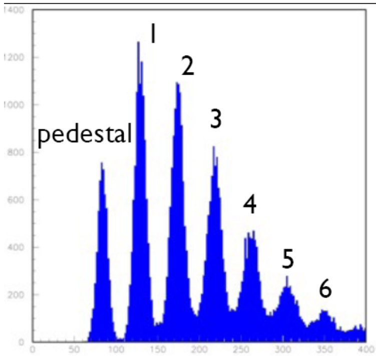
- ✓GM-APDs (pixel) connected in parallel (few hundreds/mm²)
- ✓Each cell is reverse biased above breakdown
- ✓Self quenching of the Geiger breakdown by individual serial resistors

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

⇩

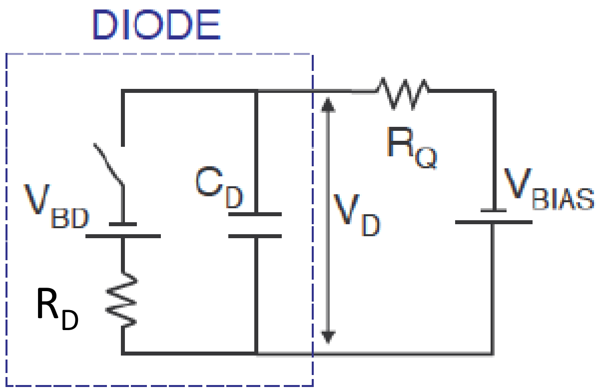
output charge is proportional to the number of of incident photons



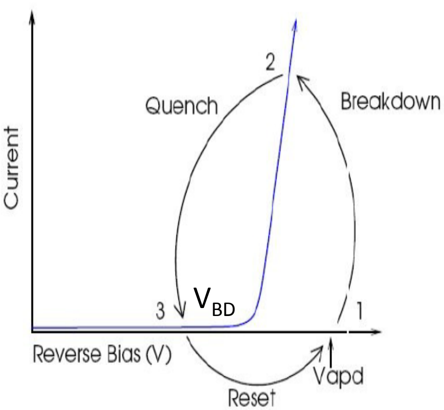


Development of the signal

G. Bisogni, RESMDD10



VBD : breakdown voltage
R_Q : quenching resistance
R_D : diode resistance
C_D : diode capacitance
V_{BIAS} : bias voltage

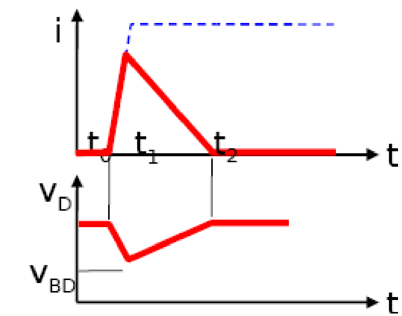


1 → 2: avalanche triggered, switch closed
C_D discharges to V_{BD} with the time constant $\tau = R_D \times C_D$
asymptotic grows of the current

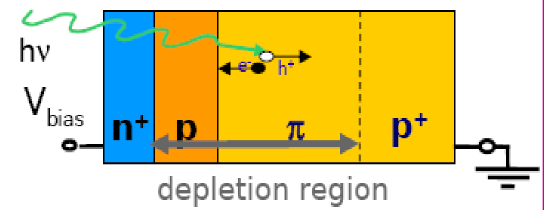
2 → 3 : avalanche quenched, switch open
capacitance charged until no current flowing with the time constant $\tau' = R_Q \times C_D$

3→ 1 : reset of the system. The carrier traversing the high-field region triggers the avalanche

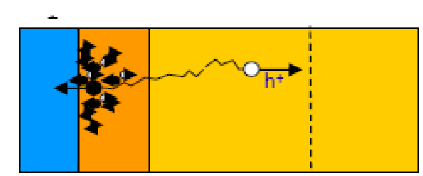
Time sequence



t=0: carrier initiates the avalanche



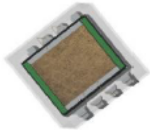
0<t<t1: avalanche spreading

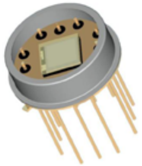


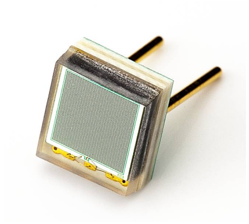
t1<t: self-sustaining current limited by series R

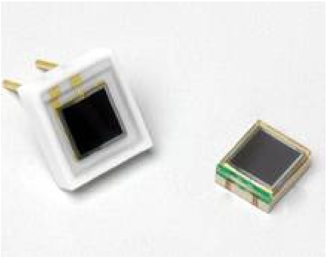
G.Collazuol, LIGHT11

What does it look like?







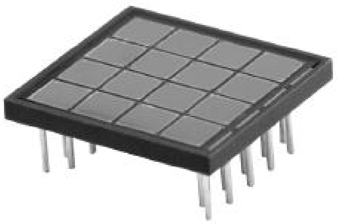


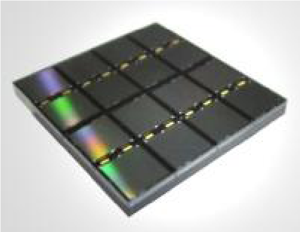
Dimensions: 1 mm² to 16 mm²

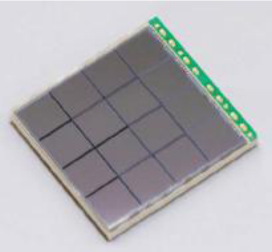
Matrixes: 4 to 256 channels

Pixel size: 15 µm, 25, …, 100 µm

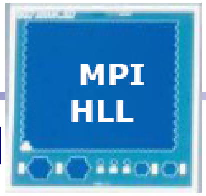
Packaging: metal (TO8), ceramic, plastic, with pins, surface mount type, matrix (wire bonding, TSV (Through Silicon Via)

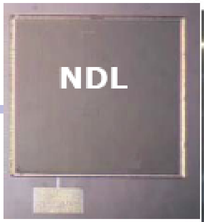


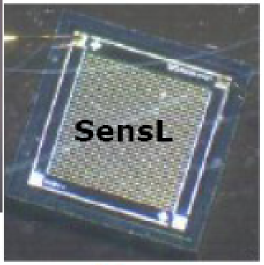




Producers of SiPMs

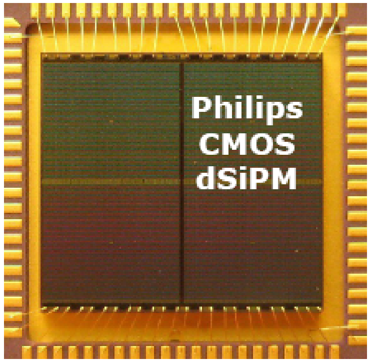


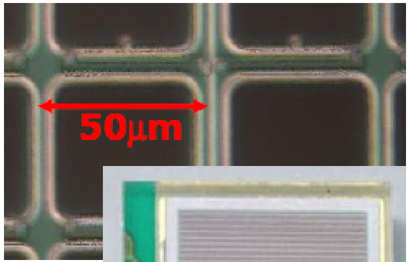


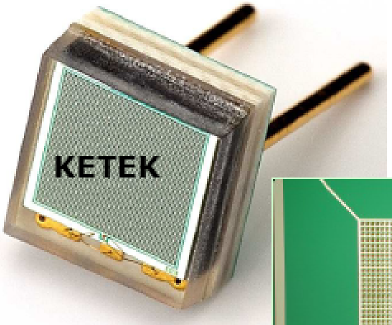


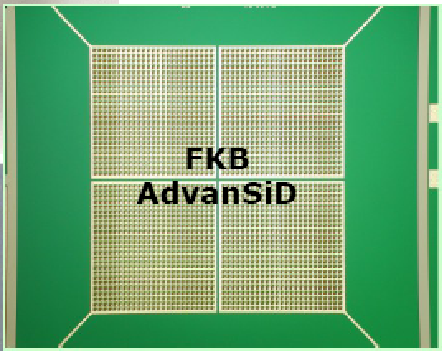
Many institutes/companies are involved in SiPM development/production:

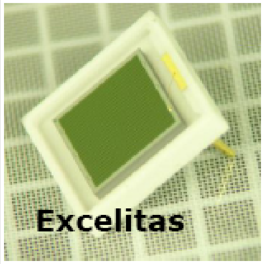
- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek,** Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, Munich, Germany
- **RMD**, Boston, USA
- **Philips**, Aachen, Germany
- **Excelitas** tech. (formerly Perkin-Elmer)
- **KETEK**, Munich, Germany
- **National Nano Fab Center**, Korea
- **Novel Device Laboratory** (**NDL**), Bejing, China
- **E2V**
- **CSEM**



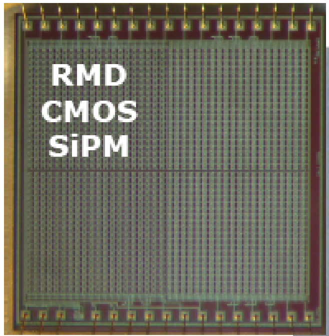


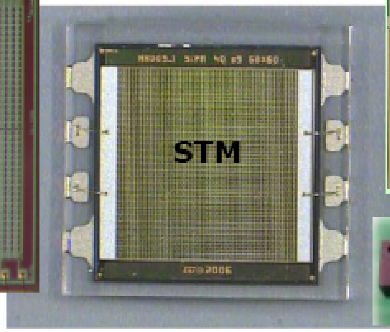






Amplification Technologies (DAPD)



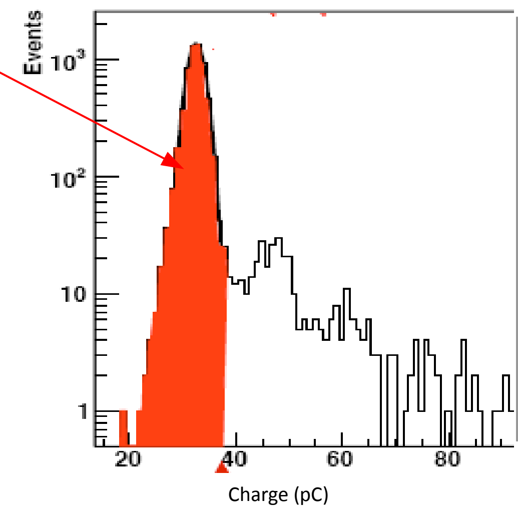
G.Collazuol - PhotoDet 2012

many names like Silicon PM (SiPM), Geiger APD (G-APD), Metal Resistive layer Semiconductor (MRS-APD), Multi Photon Pixel Counter (MPPC), SiPM, SPM,… **SiPM is by now the most used name**

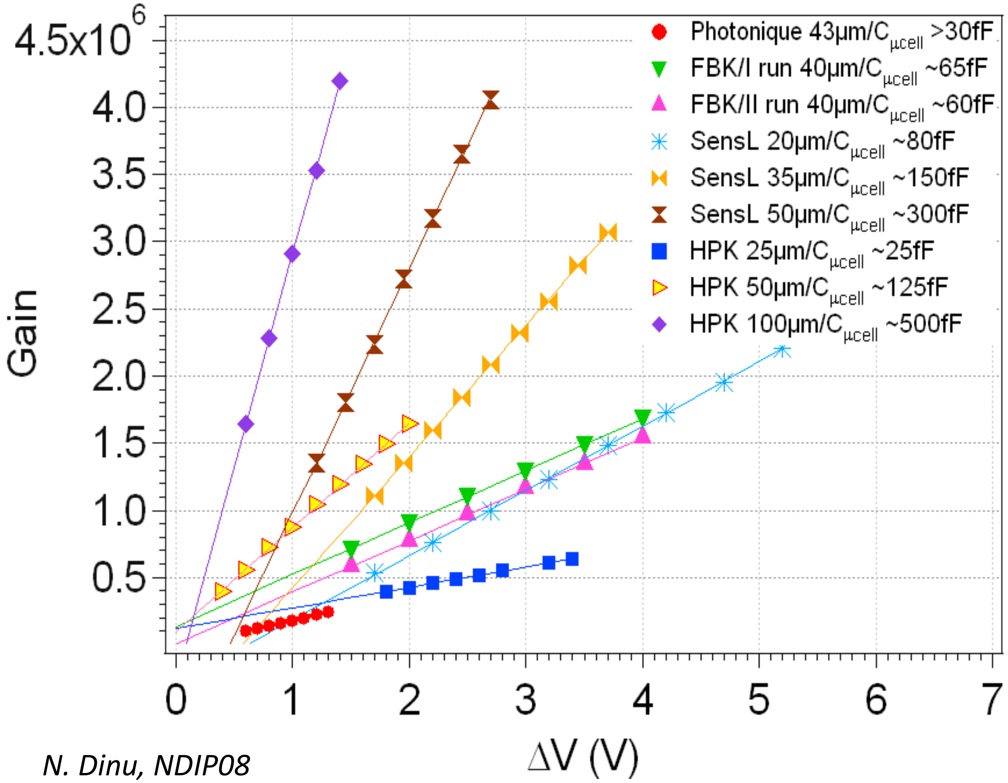
Gain of a SiPM

Defined as the charge developed in one pixel by a primary carrier

$$Gain = \frac{Q_{pixel}}{e} = \frac{C_{pixel} \times (V_{bias} - V_{BD})}{e}$$



Gain of 1 mm² SiPM (25°C)



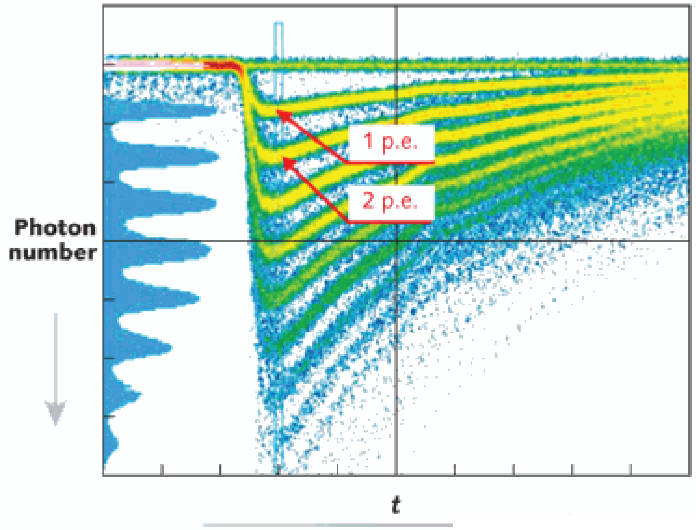
N. Dinu, NDIP08

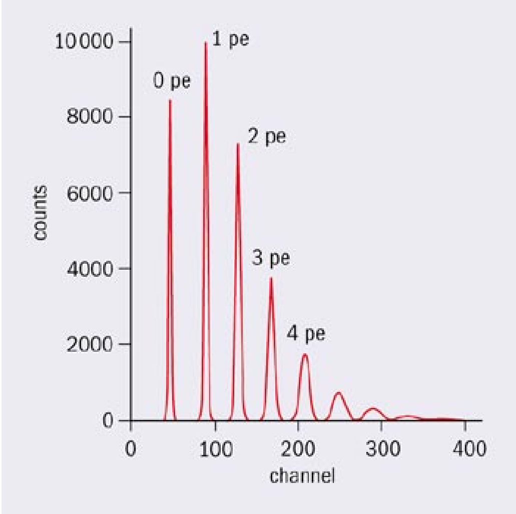
10^4 < Gain < 10^6

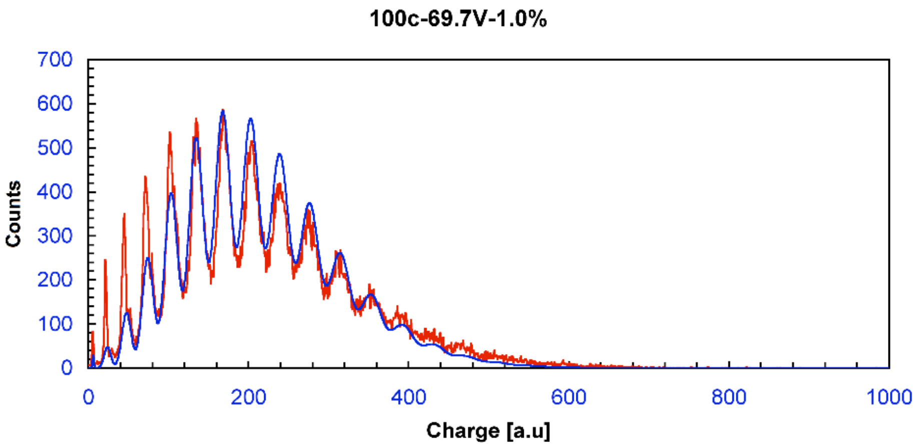
- linear increase of the gain with Vbias
- slope of the linear fit of G as a function of Vbias
  → pixel capacitance (tens to hundreds of fF)
- increase of the gain with the pixel dimensions

Single photon detection performance

The resolution of SiPM allowed very precise analysis of the detecting photon flux up to single photon

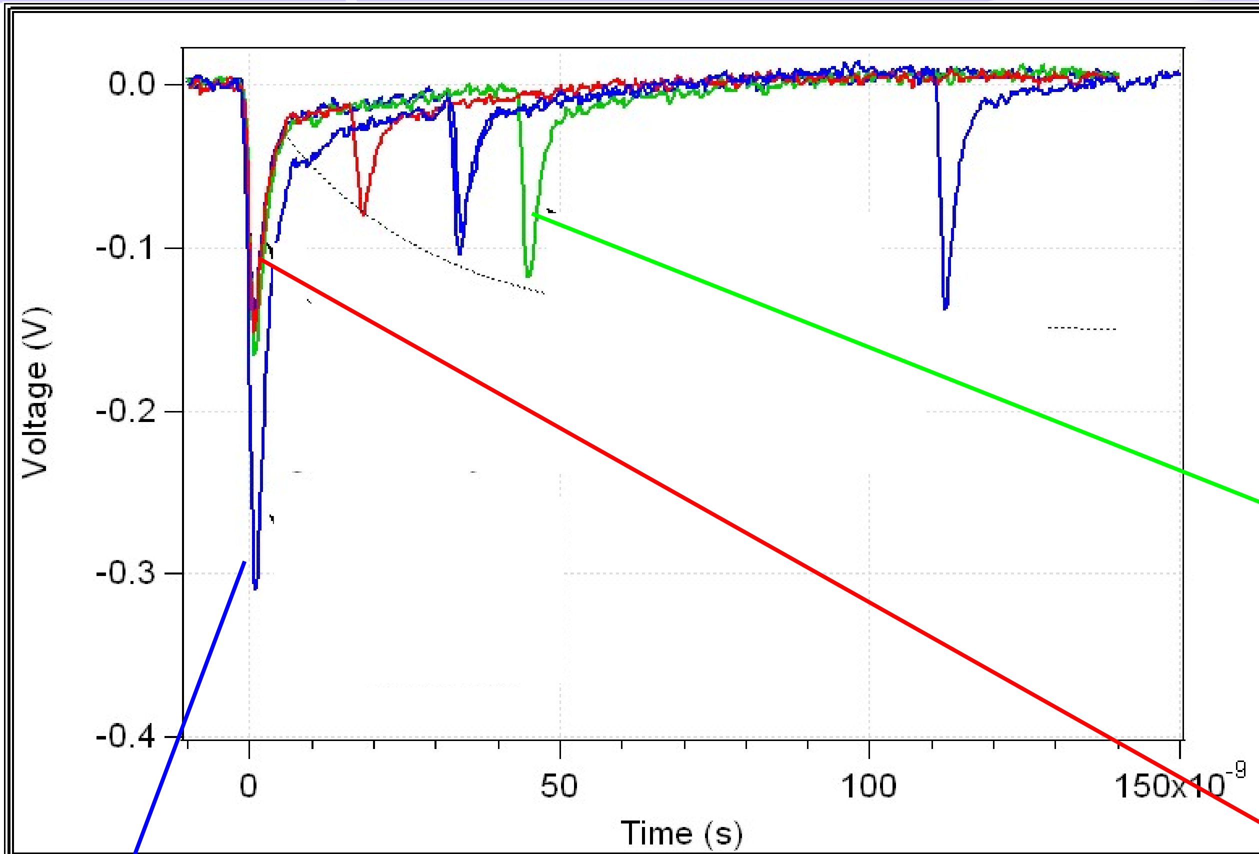






Single photons are well separated in a wide range

Noise sources of a SiPM



After-pulses

carriers trapped during the avalanche can produce delayed secondary pulses

Dark counts

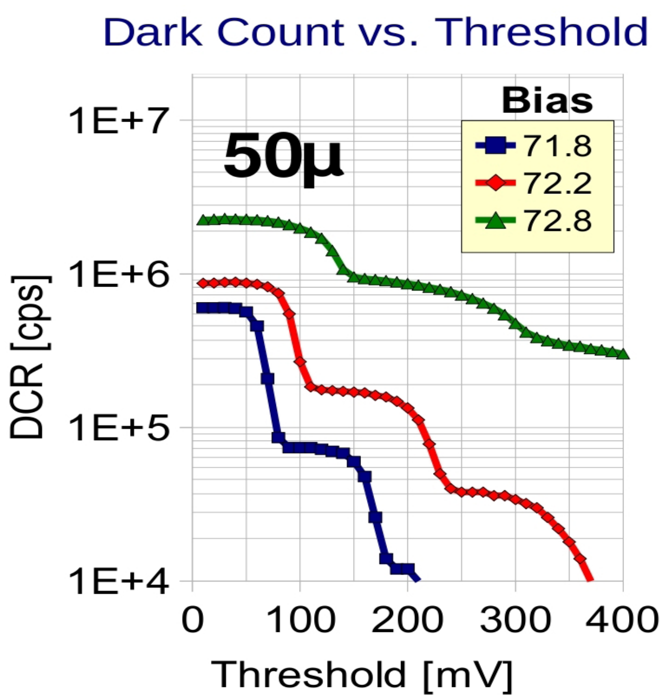
pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

Cross-talk : amplitude = 2 p.e

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

Dark Count rate (DCR)

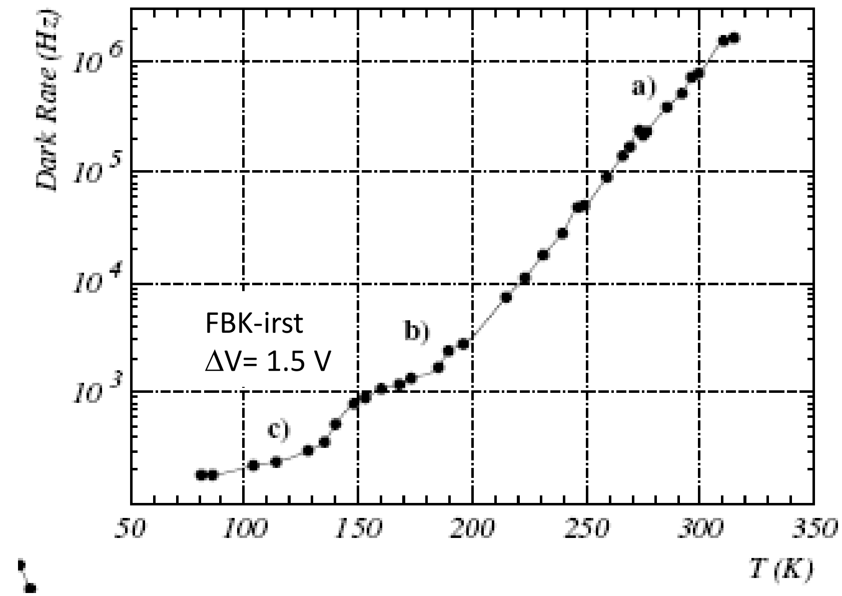
Breakdown triggered by thermaly generated carriers → dark counts with a rate of 80 kHz to several MHz /mm² at 25°C when the threshold is set to half of the one photon amplitude.



S. Gundacker, PhotoDet 2012

The dark count rate falls rapidly with increasing threshold with steps that depend on the crosstalk probability

Variation with temperature



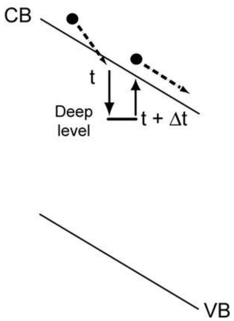
G.Collazuol, NIMA 628

Best way to decrease the Dark Count rate:

✓operate the SiPM at lower gain

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

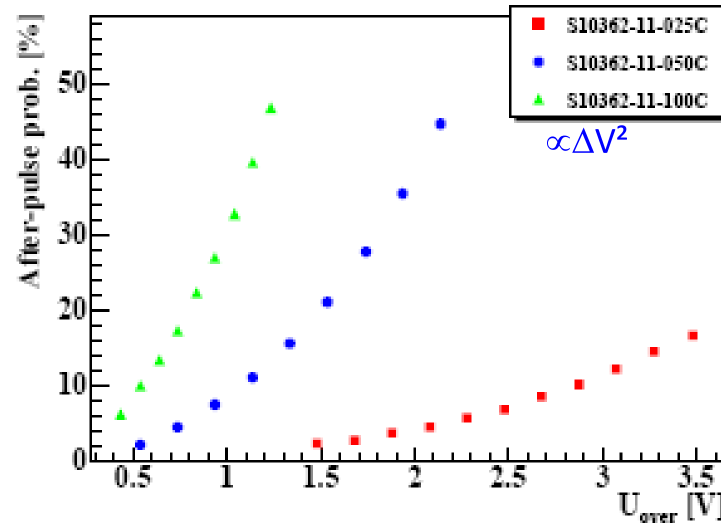
Breakdown → plasma → filling of the traps



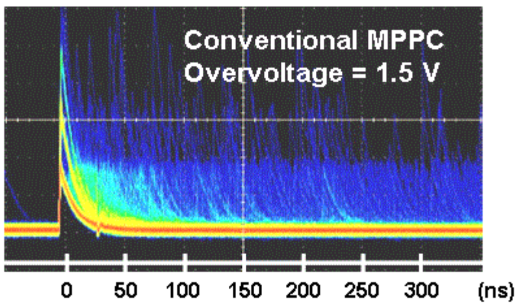
trapping + delayed release → afterpulse

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

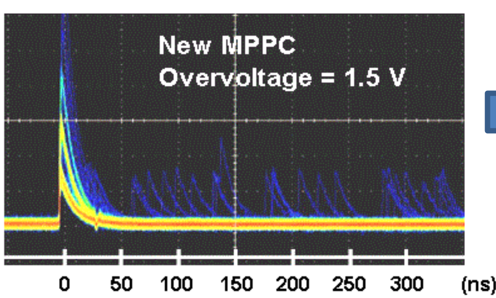
$P_{capture}$: trap capture proba
P_{trig}: avalanche triggering proba
τ: trap lifetime

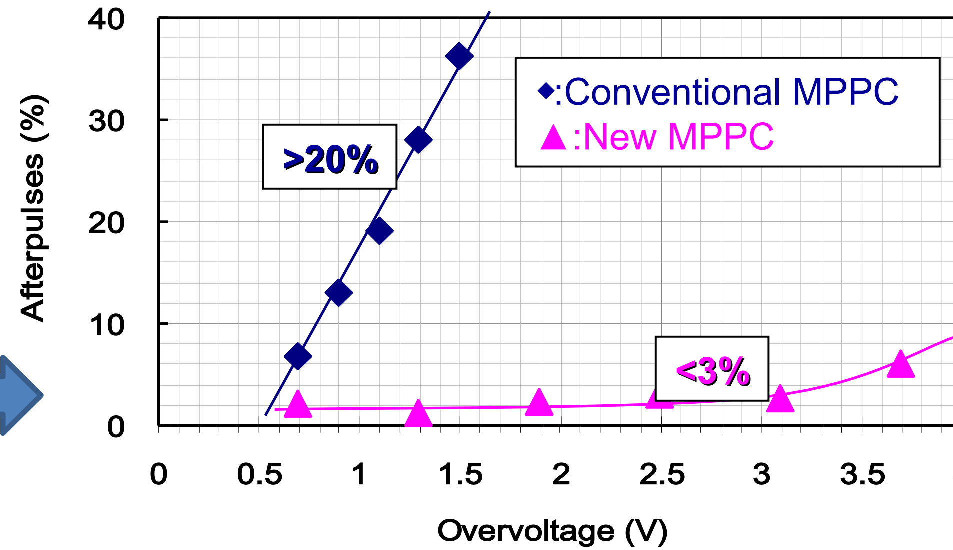


P. Eckert, arXiv:1003.6071v2



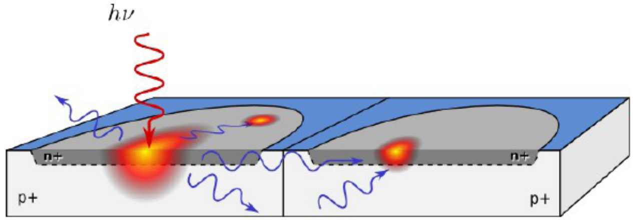
Minimization of the trap levels



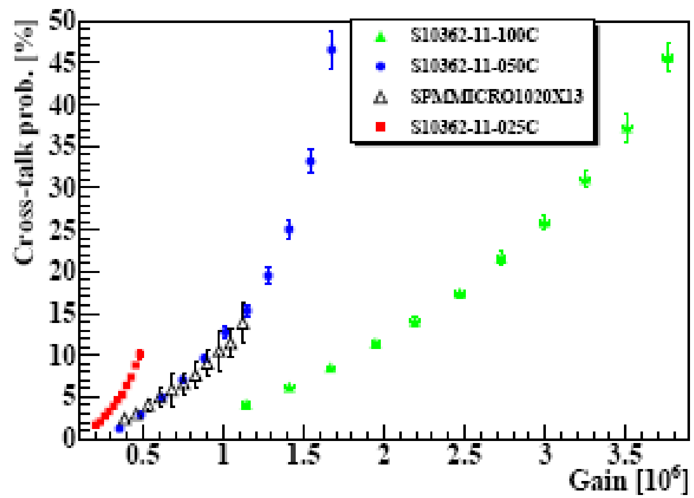


HPK, private communication

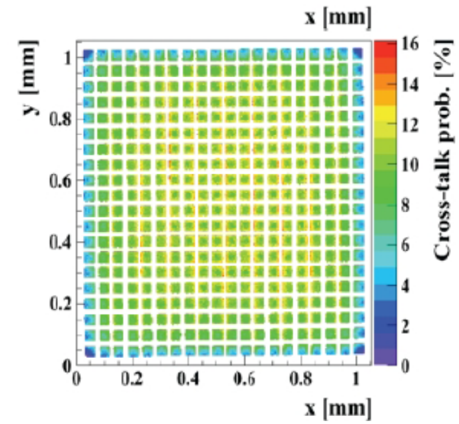
Cross-talk



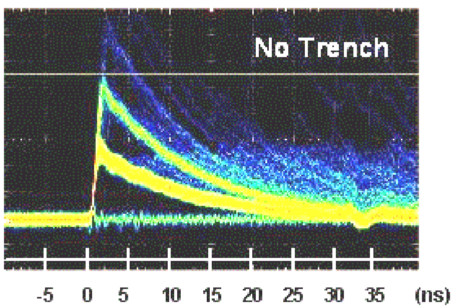
An avalanche in one pixel may produce an optical photon wich can trigger another avalanche in a neighboring pixel without delay: probability 3.10^{-5} / carrier to emit photons with E > 1.12 eV

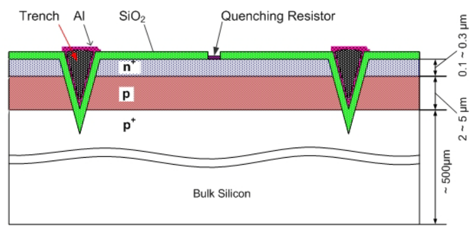


P. Eckert, arXiv:1003.6071v2

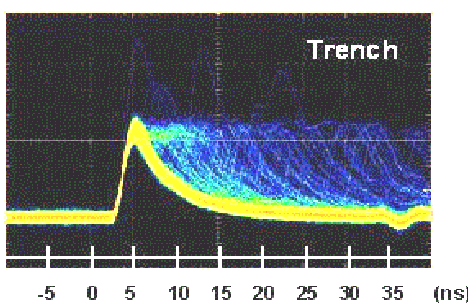


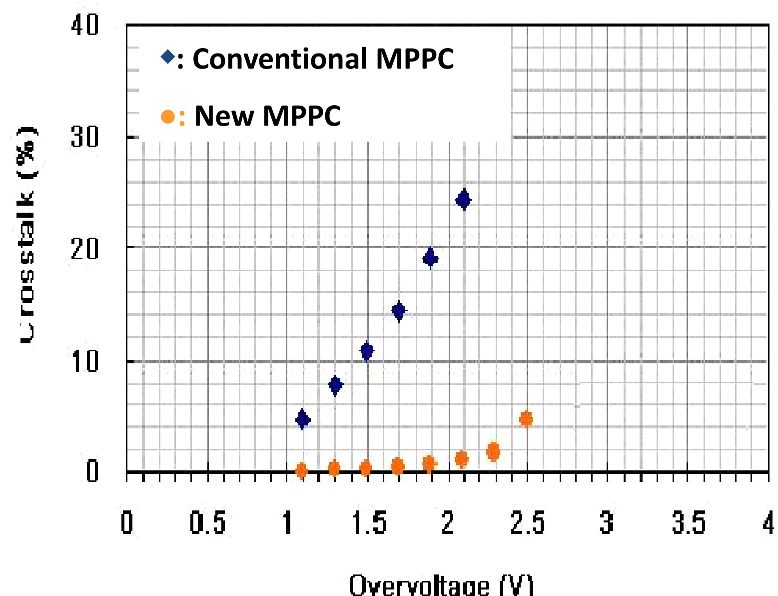
A. Tadday, SiPM Workshop DESY 2012





Trenches between pixels



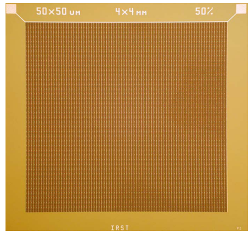


HPK, private communication

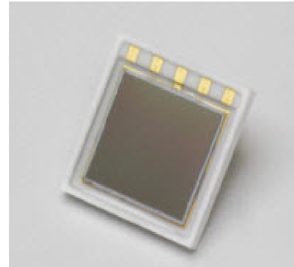
Large SiPMs: large sensitive area but high DCR …

ZECOTEK MAPD-3N

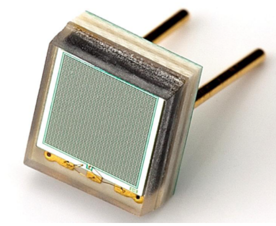
ASD-SiPM4S



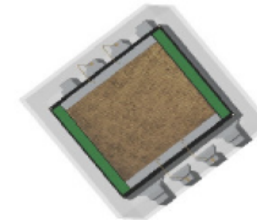
HAMAMATSU S10985



KETEK PM3350



STMicroelectronics

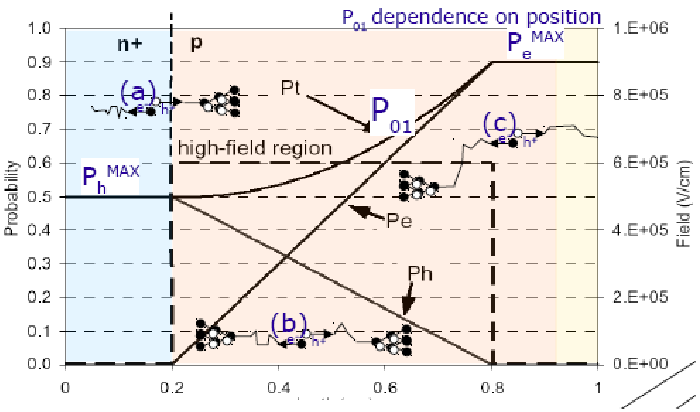


Producer	Reference	Area (mm^2)	PDE max @ 25 °C *	Dark Count Rate (Hz) @ 25°C *	Gain *
ZECOTEK	MAPD-3N	3 x 3	30% @ 480 nm	$9.10^5 – 9.10^6$	10^5
FBK - AdvanSiD	ASD-SiPM4S	4 x 4	30% @ 480 nm	$5.5\ 10^7$ - $9.5\ 10^7$	$4.8\ 10^6$
HAMAMATSU	S10985-50C	6 x 6	50% @ 440 nm (includes afterpulses & crosstalk)	$6.10^6– 10.10^6$	$7.5\ 10^5$
KETEK	PM3350	3 x 3	40% @ 420 nm	4.10^6	$2\ 10^6$
STMicrolectronics	SPM35AN	3,5 x 3,5	16% @ 420 nm	$7.5\ 10^6$	$3.2\ 10^6$

** datasheet data*

Ongoing R&D to increase the active area at KETEK, AdvanSiD, Excelitas (6 x 6 mm^2)
Other solution to get larger area : connection of several channels of a matrix

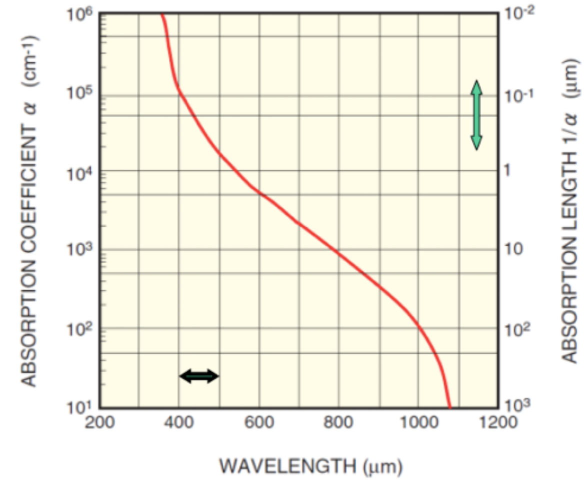
Sensitivity : Photo Detection Efficiency (PDE)



W.Oldham , IEEE TED (1972)

Qε: carrier Photo-generation

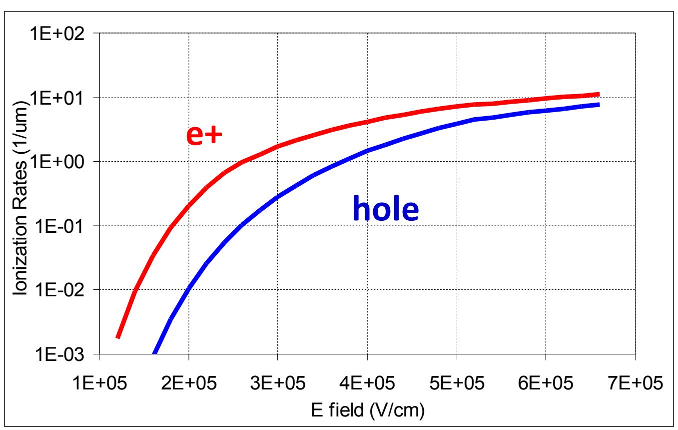
probability for a photon to generate a carrier that reaches the high field region in a pixel



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

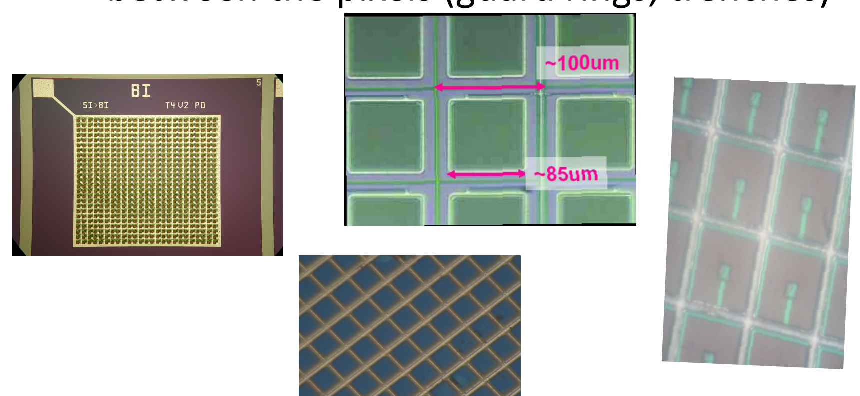
Ptrig : avalanche triggering

probability for a carrier traversing the high-field to generate the avalanche

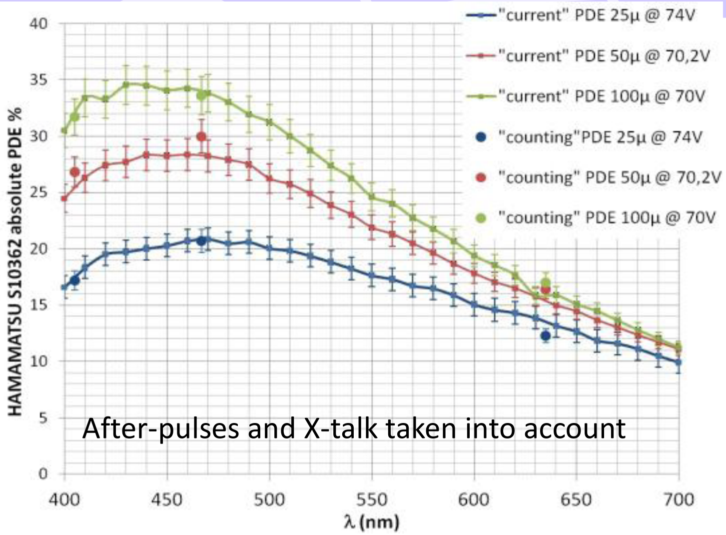


ε_{geom} : geometrical Fill Factor

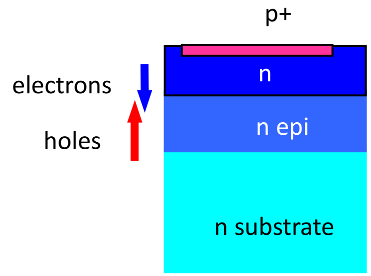
fraction of dead area due to structures between the pixels (guard rings, trenches)

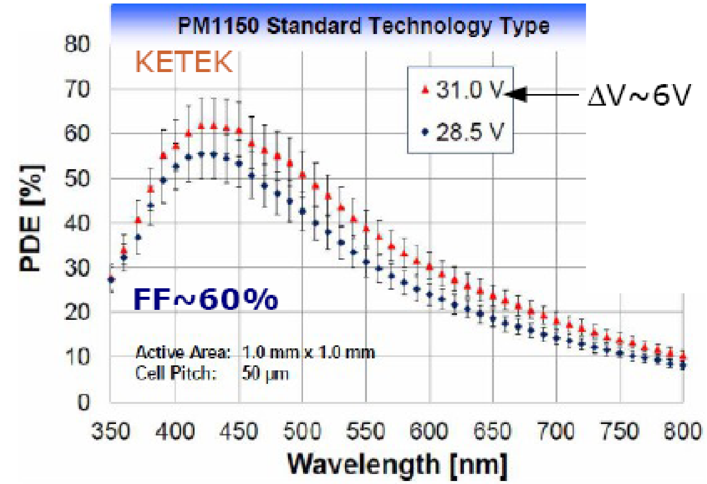


PDE of SiPMs



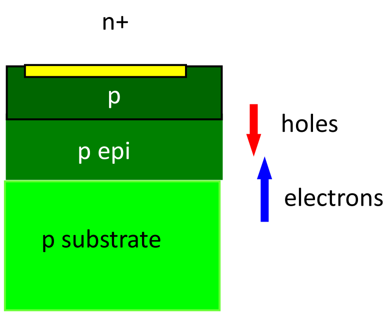
V. Chaumat, PoS(PhotoDet 2012)058

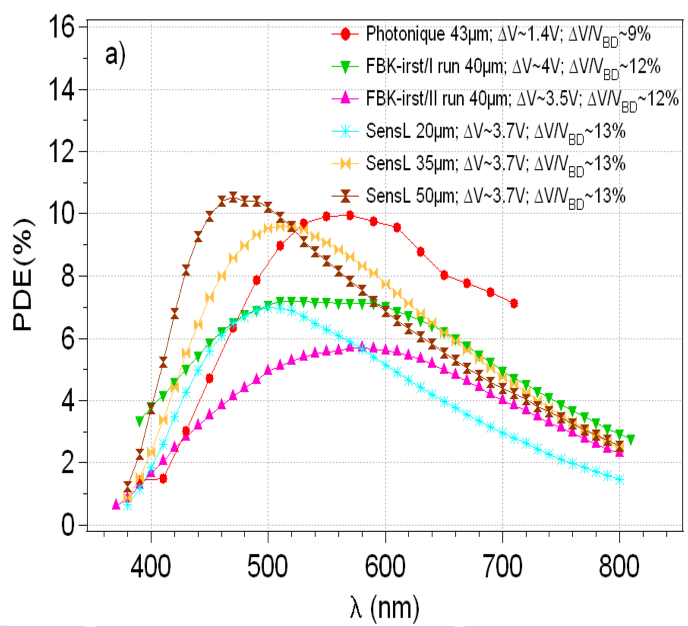




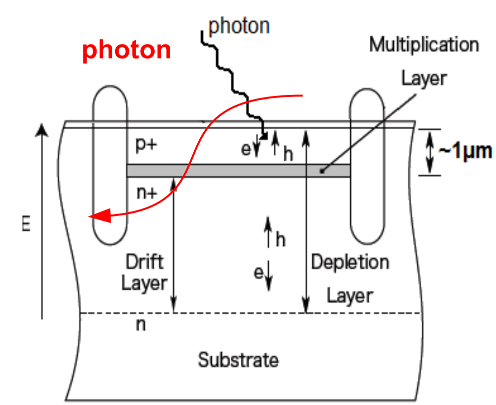
F.Wiest – AIDA 2012

PDE shape is dependent of the structure: p-on-n is more blue sensitive than n-on-p (e- trigger avalanches at short λ)





N. Dinu, NIMA A 610 (2009)

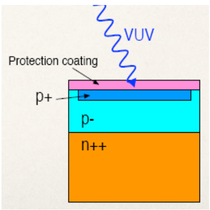


Otte, PD09

New 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

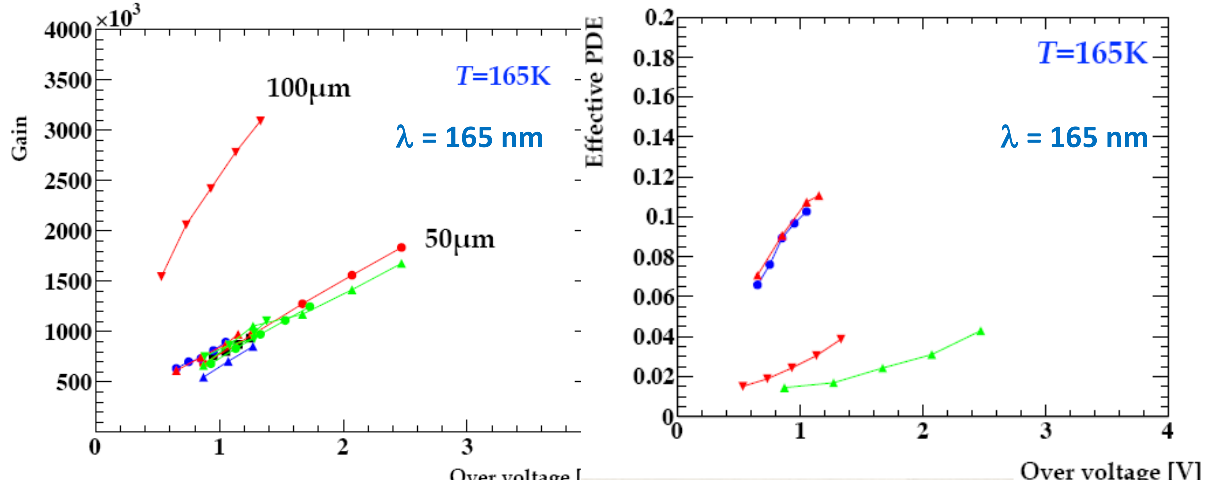
Possible solutions:

- 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: 3×3mm² (cell size = 50 µm)

- PDE (165 nm) = 10 % (best sample)
- Gain ≈ 10^6 @ 165 K
- DCR = 0 @ 165 K
- large R_q → long tail (≈ 150 ns)



W. Ootani, PhotoDet2012

New NUV SiPMs

FBK NUV-SiPM (Near-UV SiPM)

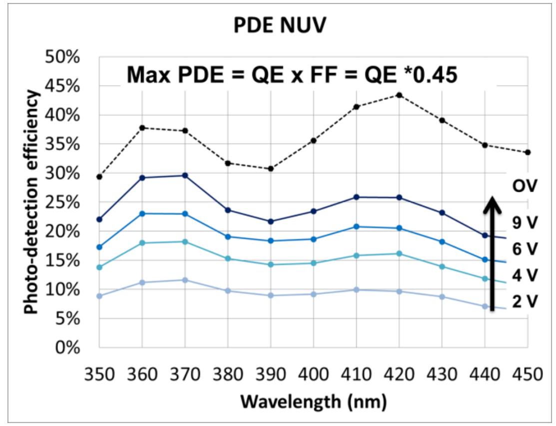
1x1mm^2 50x50 µm^2 cell

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

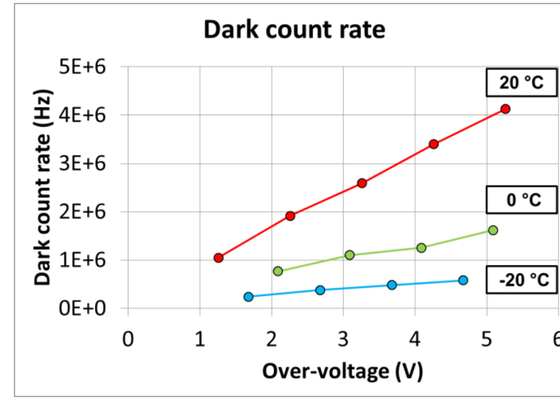
Results (FBK measurements):

✣ PDE (350 nm) = 30 % (FF = 45 %)

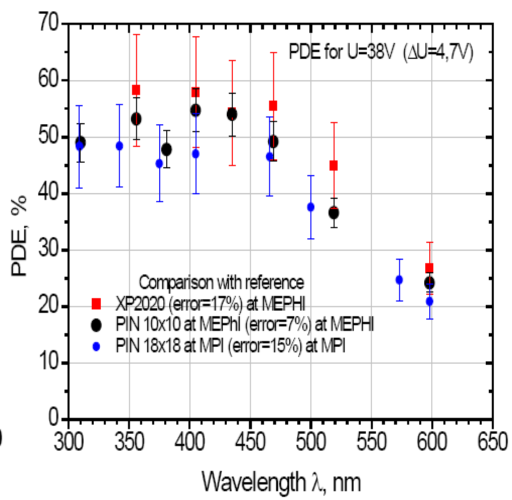
✣ DCR = 200 kHz @ 20°C (ΔV = 5V)



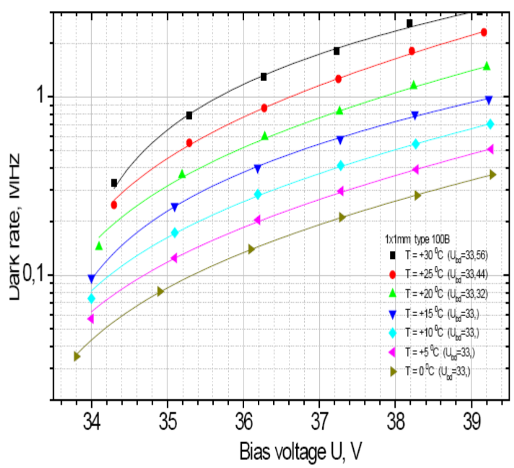
DCR



A. Ferri, NIMA 718

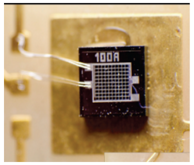


E. Popova, PhotoDet2012



E. Popova, NDIP2011

Excelitas



Collaboration between Excelitas, MEPHI and MPI : 1×1 mm² (cell size = 100 µm)

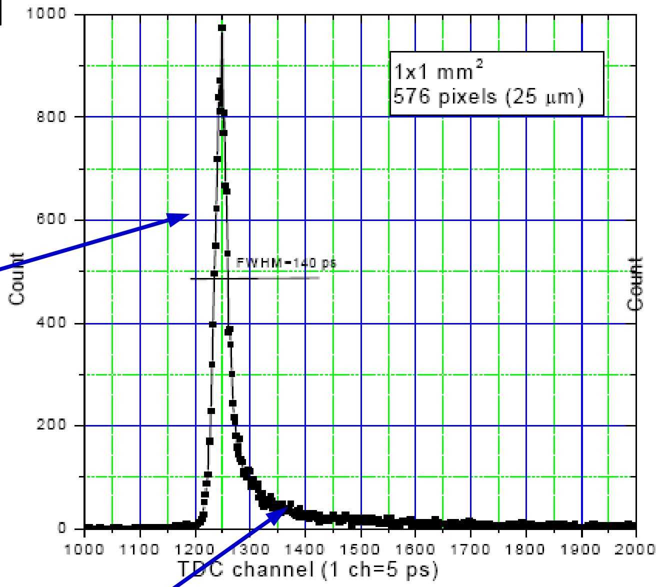
✣ PDE (350 nm) = 50 %

✣ DCR = 800 kHz @ 20 °C (ΔV = 4V)

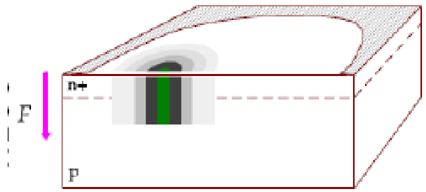
Ongoing R&D to improve the PDE in the VUV + large area (> 10 mm²)

active layer very thin
breakdown development fast → good timing properties expected
big amplitude of the signal

Time spread distribution

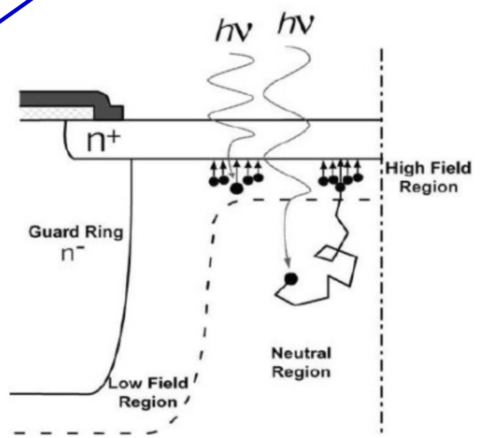


fast component of Gaussian shape with 50 ps< σ < 150ps
The fluctuation are due to the variance of the transverse diffusion speed and the variance of transverse position of photo-generation.



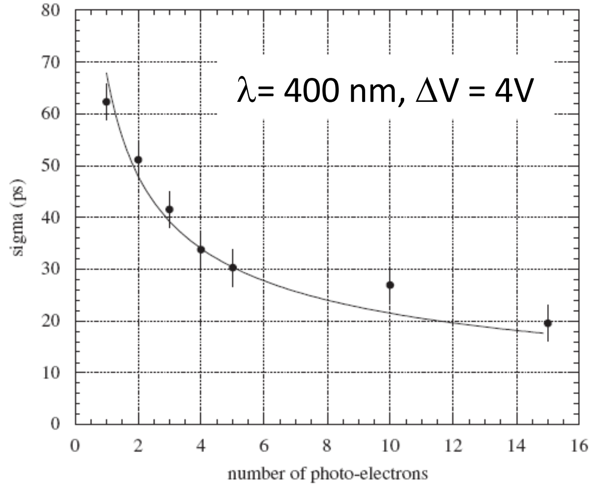
Transverse multiplication

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.

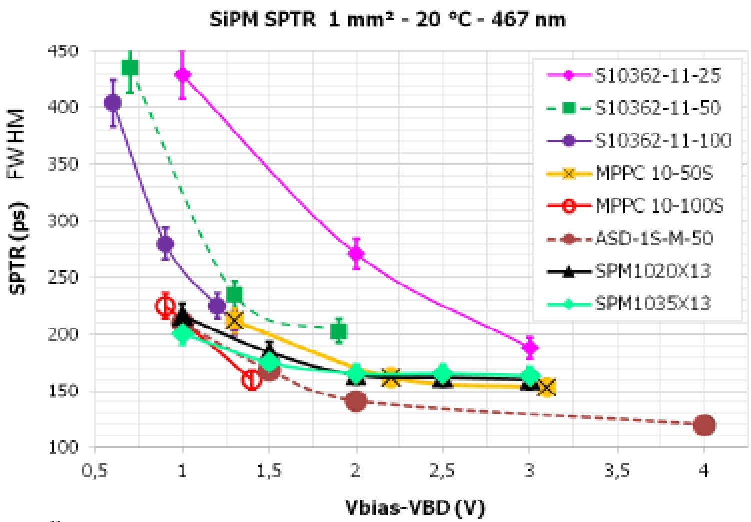


Time response of SiPMs

Timing resolution as a function of the incident number of photons

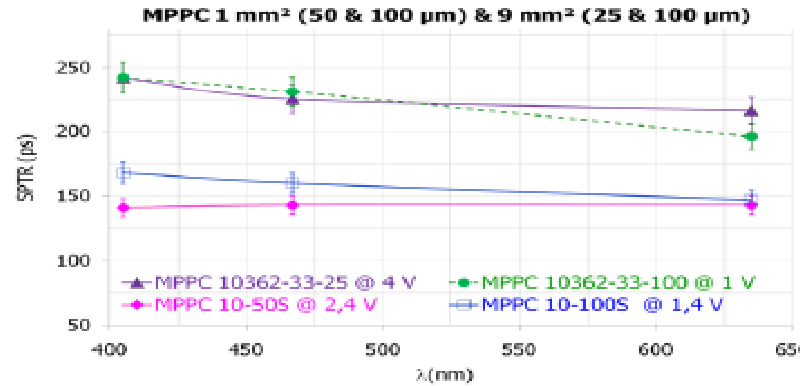


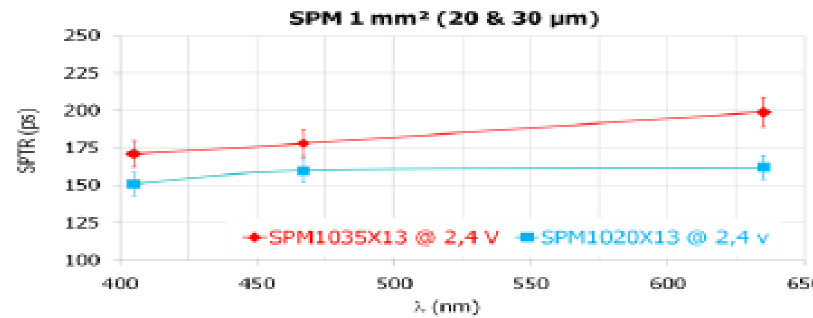
Single Photoelectron Timing resolution

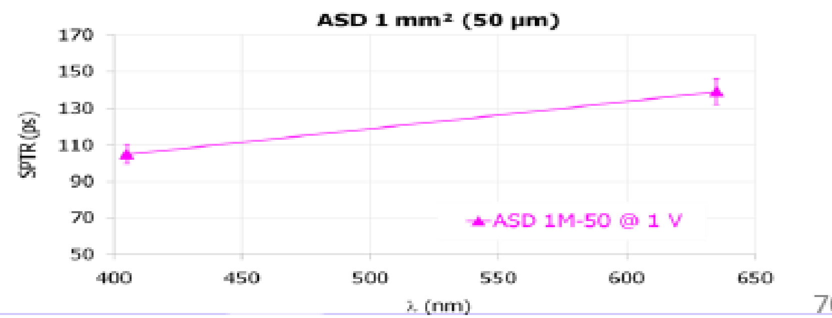


V. Puill, NIMA 695, 2012

SPTR (FWHM) as a function of λ







V. Puill, NIMA 695, 2012

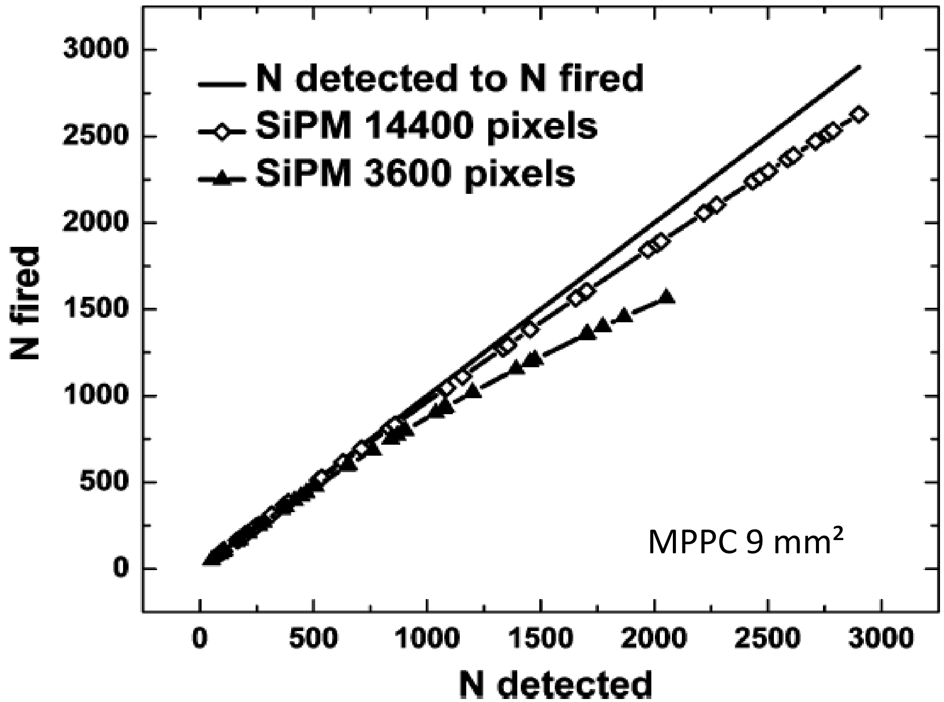
SiPM saturation

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

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

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

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



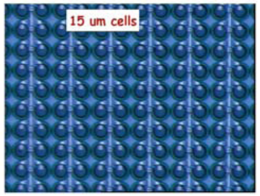
A. Nassalski, IEEE n° 57

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)

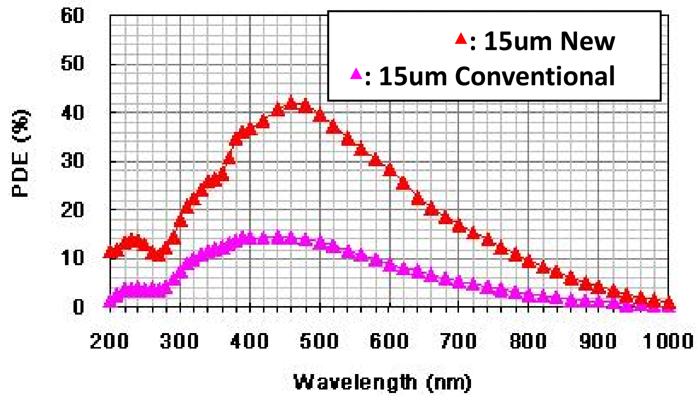
Saturation: solution = large dynamic range

large dynamic range in Calorimetry or PET ➡ high density SiPM : device with more than 1000 cells/mm²

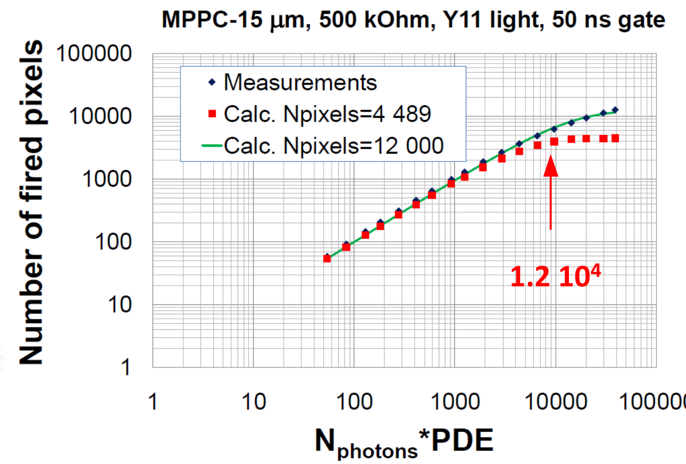
HAMAMATSU



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



HPK, private communication

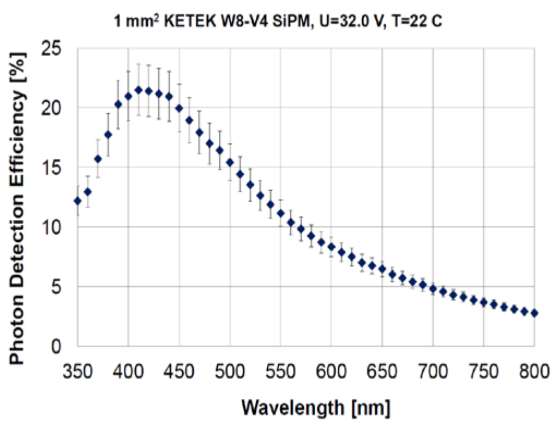


Y. Musienko, NDIP-2011

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

KETEK

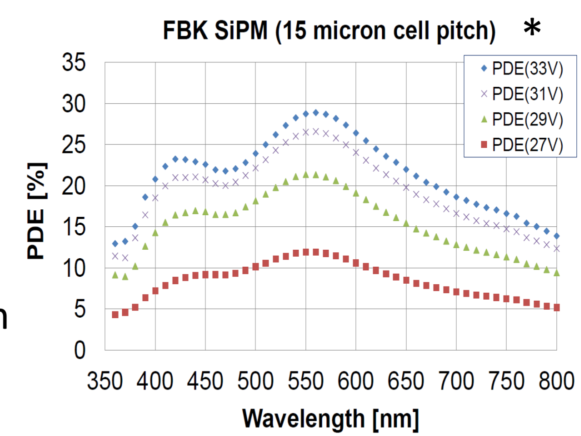
1 mm²
4489 cells
cell size : 15 µm
gain = 0.7x10^6
recovery time = 8 ns



FBK

RGB-SiPM-HD

2.2 x 2.2 mm²
4404 cells
cell size : 15 µm

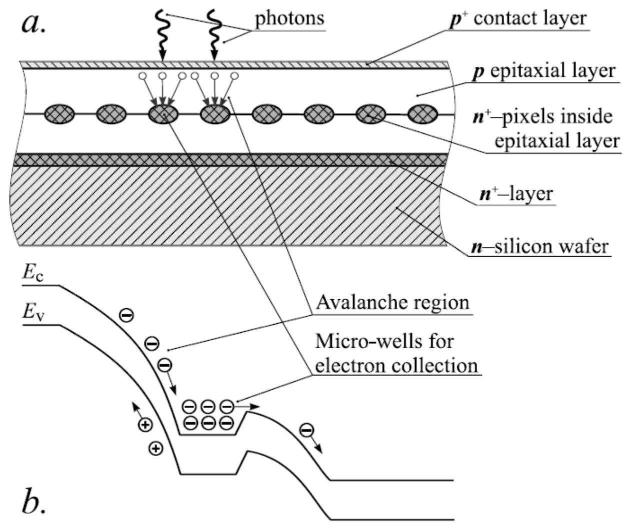


** measurements by Y.Musienko @ CERN*

Saturation: solution= very large dynamic range

ZECOTEK

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



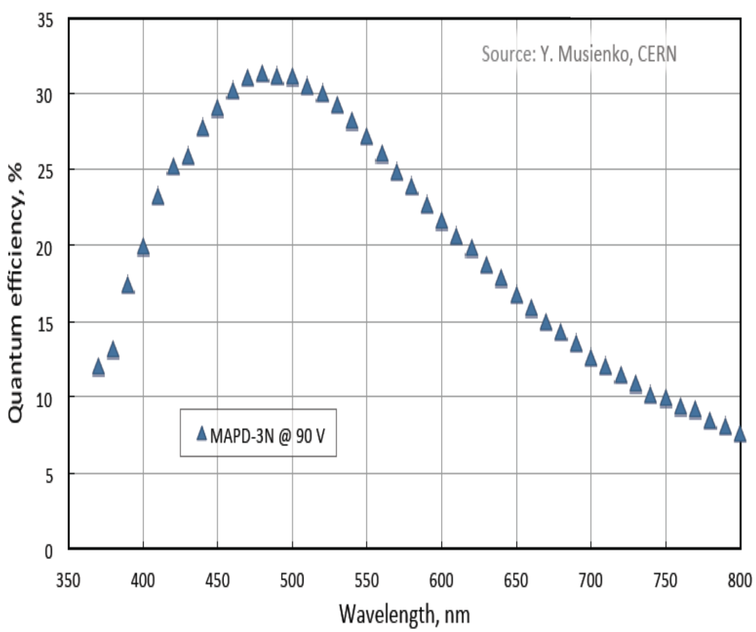
MAPD-3N

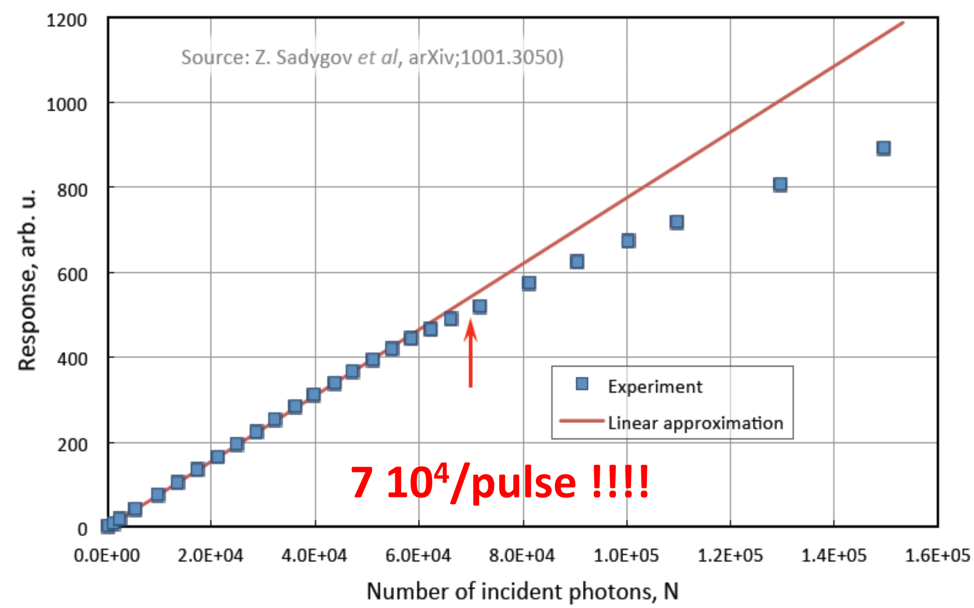
3 x 3 mm²

1350000 cells (15000/mm²)

gain = 10^5

slow cell recovery time : 300 µs





Radiation-hardness of SiPMs (1)

protons / neutrons

bulk damages caused by lattice defects

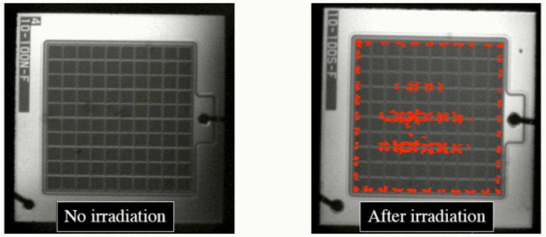
γ-rays

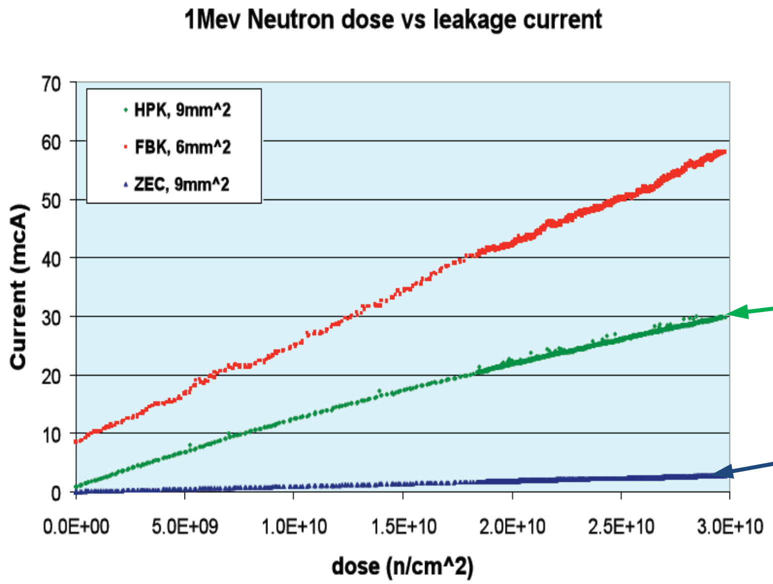
creation of trapped charges near the Si-insulator interface

Radiation hardness, an issue for photodetector in Calorimeters

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

- ❖ limitation of the low light detection capability
- ❖ destruction of the device





Y. Musienko, LHC on the March workshop 2011

HAMAMATSU have developed new MPPC more resistant to irradiation

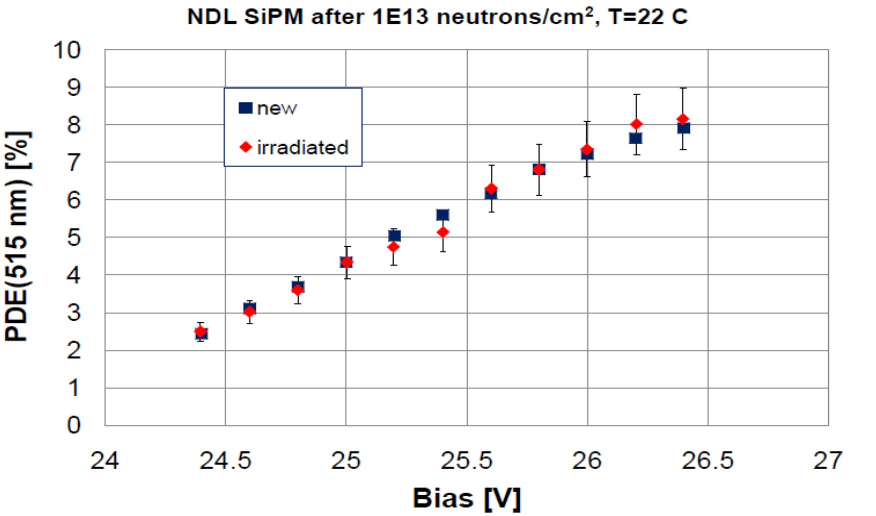
MAPD have a good behavior under irradiation but its recovery time is long (300 µs)

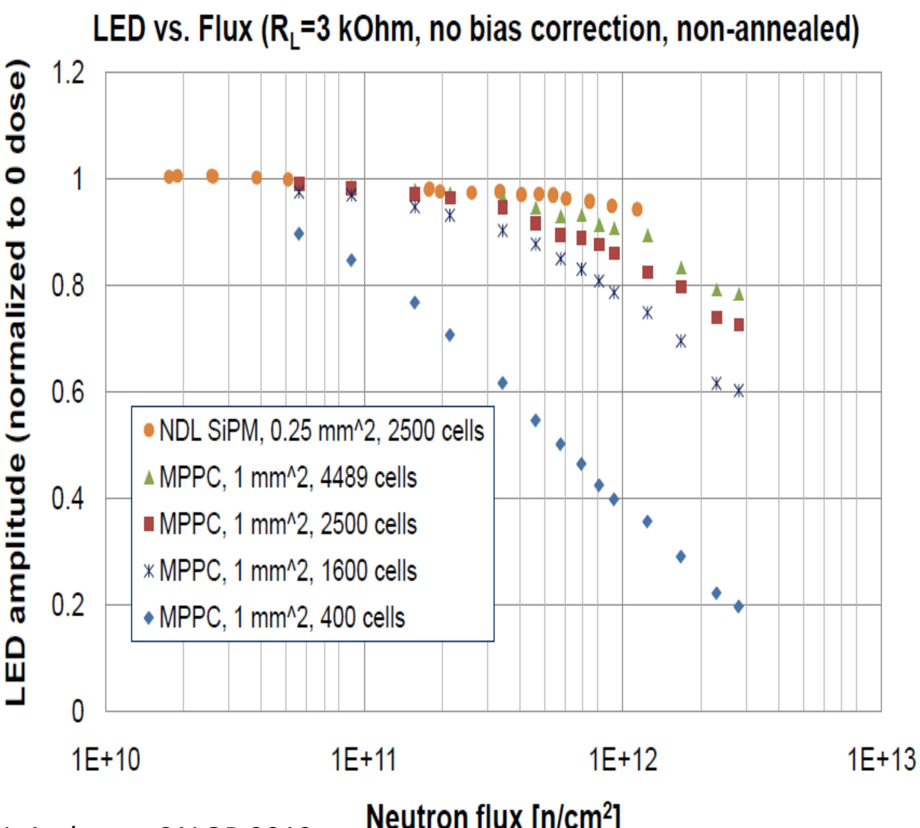
Radiation-hardness of SiPMs (2)

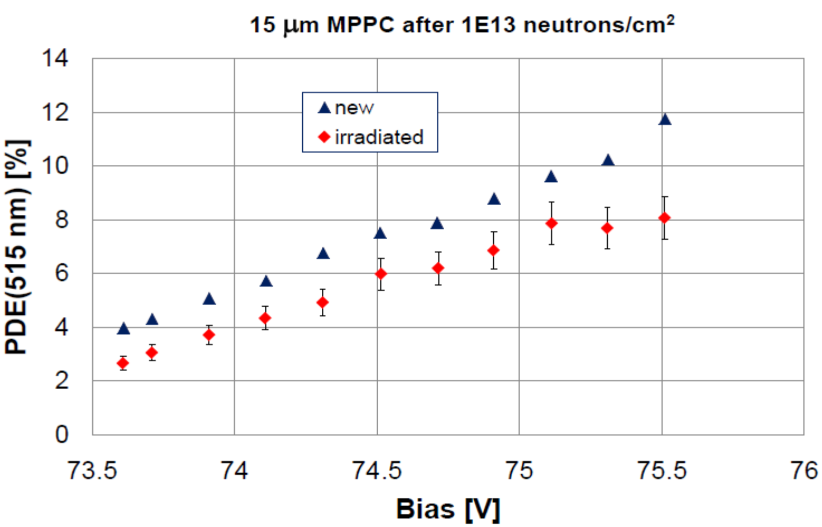
HAMAMATSU and NDL developed new devices :

- 15 µm cell size MPPC (1 mm²)
- 10 µm cell size NDL (0.25 mm²) SiPM

which **survived 10^{13} n/cm² 1 MeV equivalent neutron flux** (10^{8} n/cm² 3 years ago)







Y. Musienko, NDIP 2011

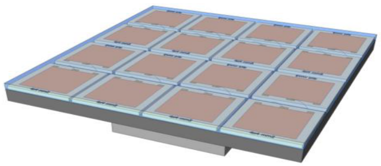
J. Anderson CALOR 2012

Matrixes: SiPMs discrete arrays

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

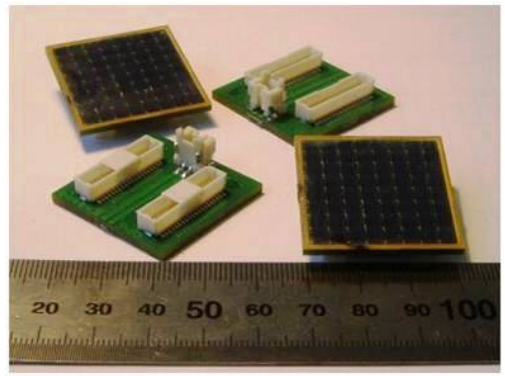
FBK

ASD-SiPM4S-P-4×4T-50



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

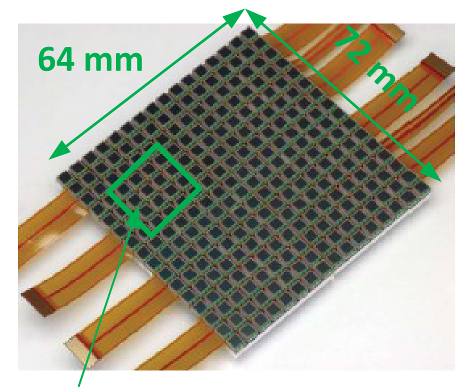
Zecotek



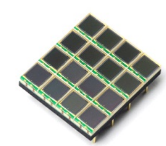
8x8 channels
1 channel = 3x3 mm²
15000 cells /channel

HAMAMATSU

S11834-3388DF

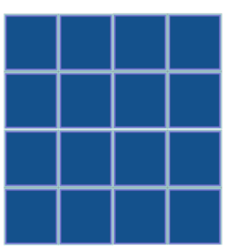


S11064-025



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

Excelitas Ketek



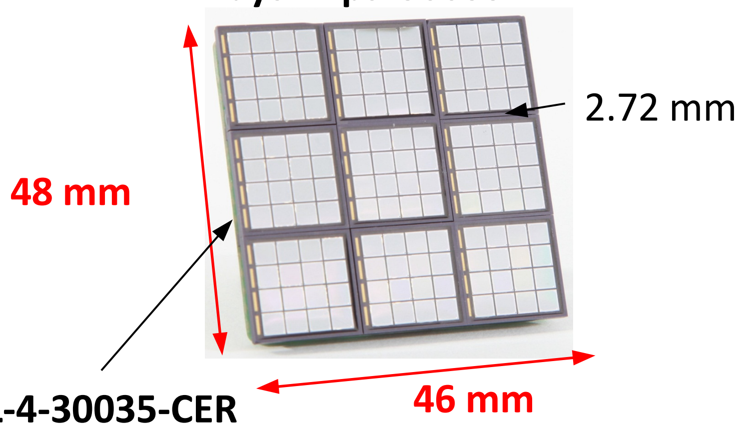
R&D in progress

Matrixes of 16 channels with 3 x 3 or 6 x 6mm²

SiPMs discrete arrays

Sensl

ArraySL-4p9-30035



SL-4-30035-CER

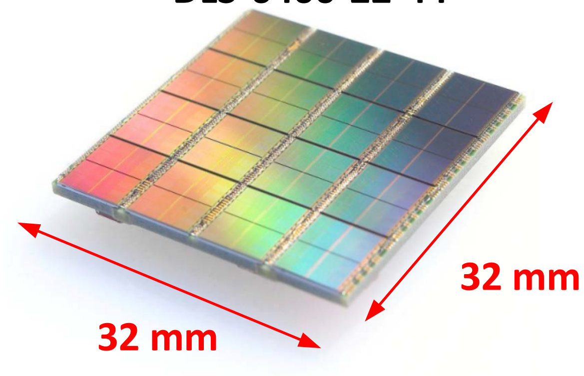
4x4 channels
1 channel= 3 x 3 mm²
4774 cells (35 x 35 µm²) /channel

ArraySM-8

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

Philips Digital Photon Counting

DLS-6400-22-44



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

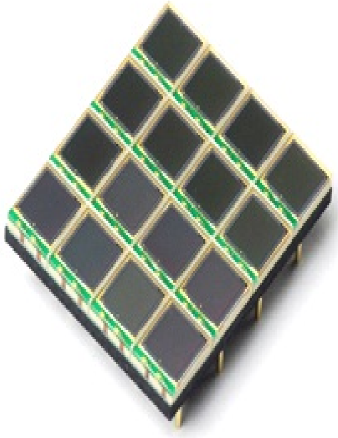
Evolution of the matrix: packaging and technology

Requirements for the SiPM matrixes:

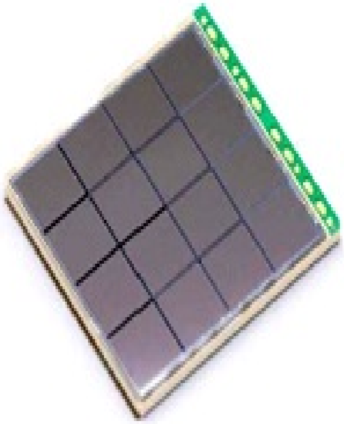
- improvement of the spatial resolution and PDE
- simplification of the assembly for the building of detectors with large surface

Important effort on the packaging + development of monolithic SiPM matrices (all the channels are on the same substrate)

Discrete Array



Monolithic Array

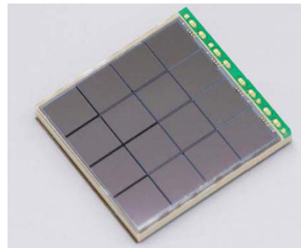


3-side buttable Tiling

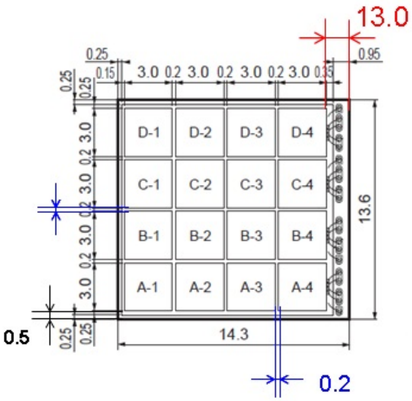
SiPMs monolithic arrays

HAMAMATSU

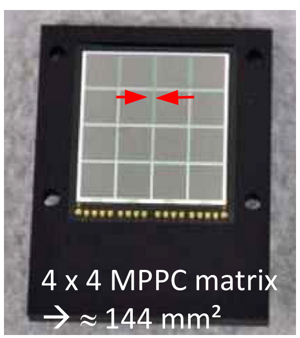
4x4 channels
1 channel = 3x3 mm²
3600 cells (50x50 µm²)/channel



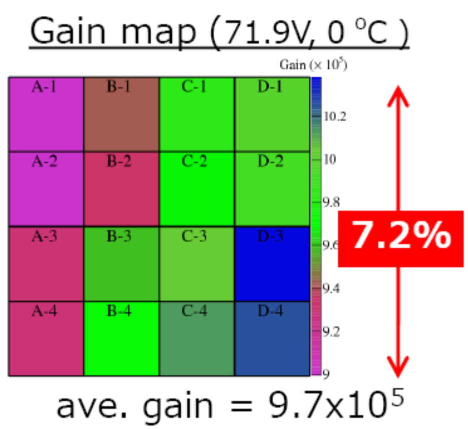
S11828-3344



3 sides tileable
1 cathode – 16 anodes

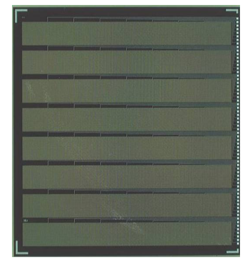


S10985 - 36x36 mm²
57600 cells



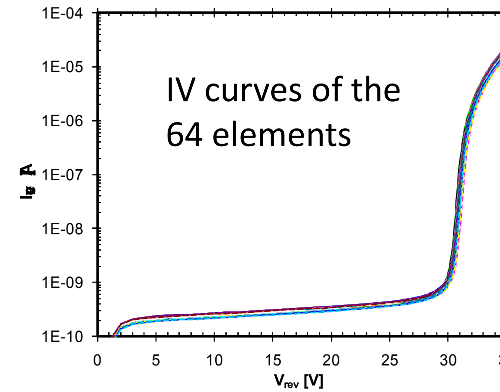
Kato et al, NIMA 638 (2011) 83–91

FBK



8 x 8 channels

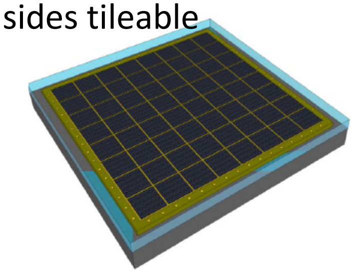
DASiPM2 project



Marcatili et al, NIMA 659 (2011) 494–498

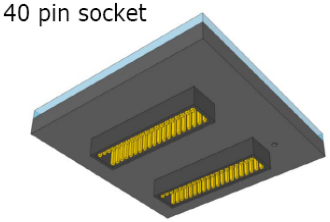
Ongoing R&D at AdvanSiD to improve the performances

4 sides tileable

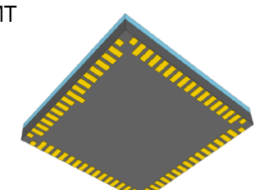


64 channels
1.5x1.5 mm² SiPMs (pixels)

40 pin socket



SMT



C. Piemonte, private communication

Discret array with TSV technology

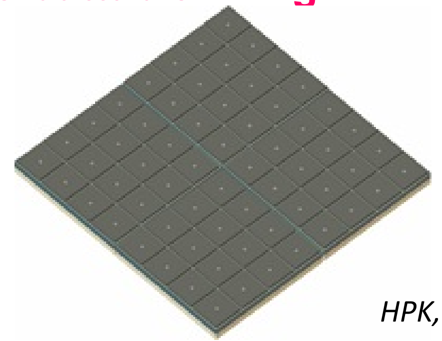
HAMAMATSU development: another way to improve the fill factor and therefore the PDE

Through Silicon Via Technology

Discrete Array

NEW June 2013

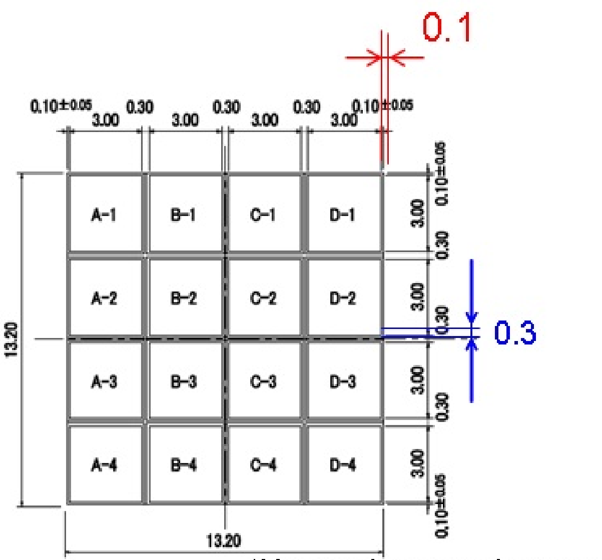
4-side buttable Tiling



HPK, private communication

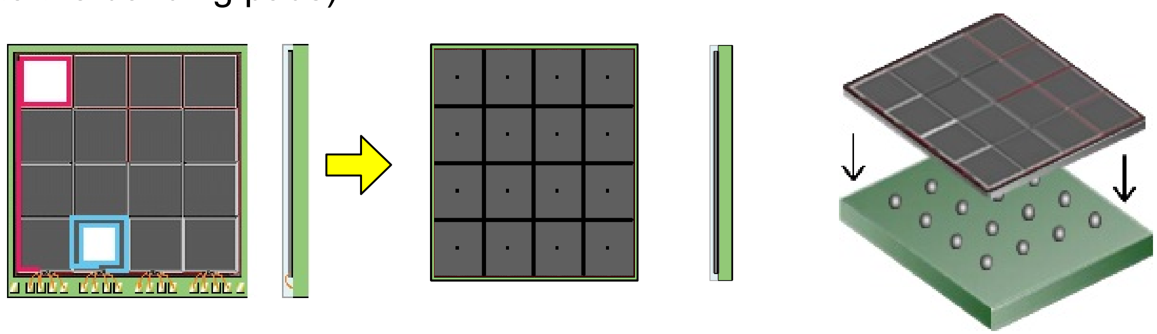
8x8 channels

1 channel = 3x3 mm²



*Non-resin protection type

with wire bonding (traces to the bonding pads) ⇒ with TSV



should have a better PDE and timing resolution

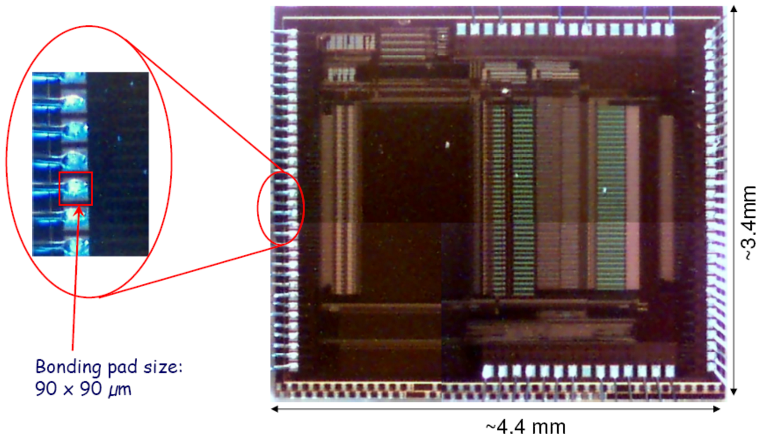
SiPM matrix readout circuits

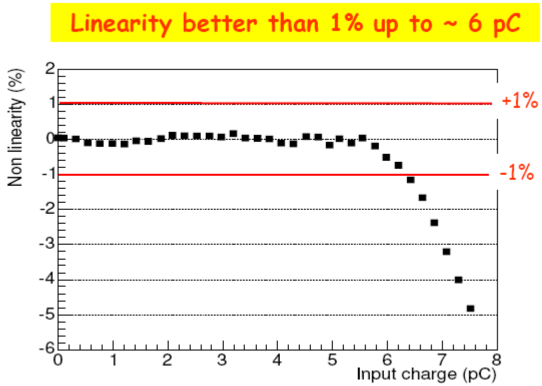
Chip Name	Measured quantity	Application	Input configuration	Technology
FLC_SiPM	Pulse charge	ILC Analog HCAL	Current input	CMOS 0,8 µm
MAROC	Pulse charge, trigger	ATLAS luminometer	Current input	SiGe 0,35 µm
SPIROC	Pulse charge, trigger, time	ILC HCAL	Current input	SiGe 0,35 µm
NINO	Trigger, pulse width	ALICE TOF	Differential input	CMOS 0,25 µm
PETA	Pulse charge, trigger,time	PET	Differential input	CMOS 0,18 µm
BASIC	Pulse height, trigger	PET	Current input	CMOS 0,35 µm
SPIDER (VATA64-HDR16)	Pulse height, trigger, time	SPIDER RICH	Current input	
RAPSODI	Pulse height, trigger	SNOOPER	Current input	CMOS 0,35 µm

W. Kucevisz, SiPM workshop CERN 2010

SiPMmatrix readout circuits: examples

Chip **VATA64-HDR16** developed for SiPM applied in Ring Imaging Cherenkov Detector of SPIDER (Space Particle IDentifiER) Experiment: 64 channels, low noise, large dynamic range



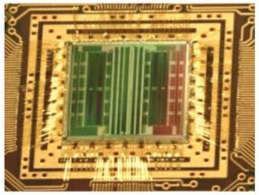


RMS noise ~ 0.5 fC (ASIC only)
~ 0.85 fC (with board)

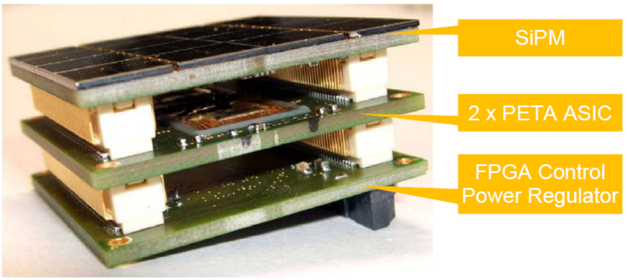
Dynamic range ~ 1000 MIP

P.S.Marrocchesi

PETA: (**Position-Energy-Time-ASIC) chip was developed within FP7 EU** Project HIPERIMAGE



- Amplification (differential voltage amp.)
- Discrimination (per channel threshold trim)
- Time Stamping (50ps bins)
- Integration (self gated, program. int. time)
- Digitization (~8 Bit resolution)
- All digital readout (LVDS handshake)
- Self triggered, asynchronous operation

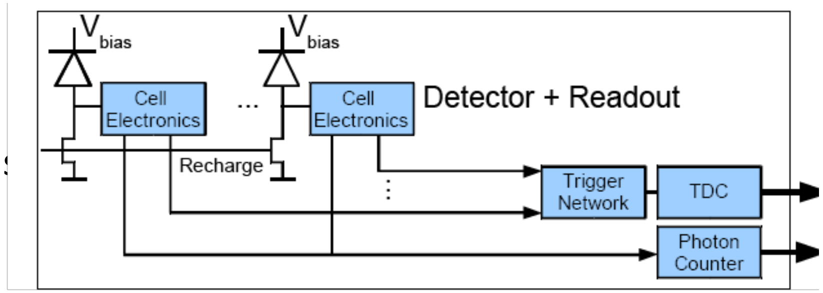


W. Shen, Heidelberg Detector Workshop 2010

New techno: Digital SiPM from Philips

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

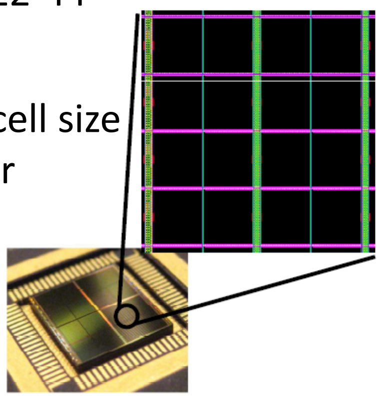
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells

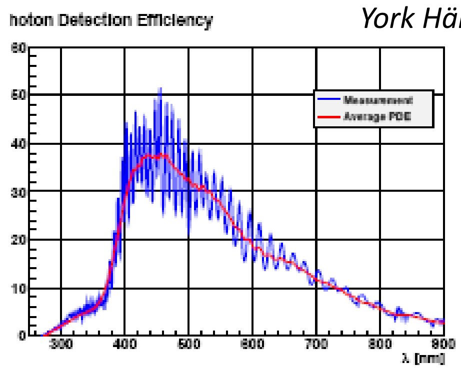


York Hämisch, TIPP 2011

DLS-3200-22-44

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





T. Frach, 2012 JINST 7 C01112

- *afterpulsing ~ 0.1% (20 °C)*
- *DCR = 100 kHz/mm² (20 °C)*
- *temperature sensitivity ~ 0.33 %/°C*
- *timing resolution (SPTR) = 60 ps (FWHM)*
- *recovery time : 10 – 40 ns*

<u>Drawbacks:</u>

➢requires a dedicated readout provided by Philips (can be an advantage when you do not want to develop your own electronics !)

➢dead space around the sensor ?

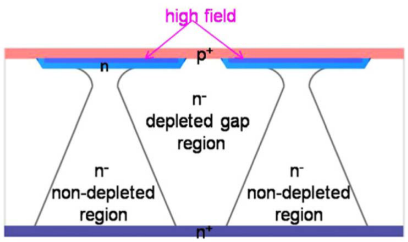
<u>Opened question:</u>

what about the radiation hardness of this device ?

New techno: SiPMs with bulk integrated resistors

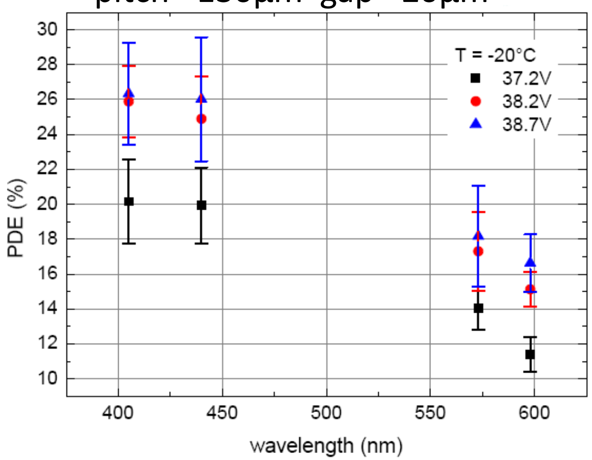
Using of Silicon bulk as a quenching resistor instead of a polysilicon structure on top of the detector

MPI



- Fill factor= 71.6%
- Cross-talk=15%
- DCR= 10 MHz/mm² (27 °C)
- PDE (440 nm) = 20 %

pitch =130µm gap =20µm



C. Jendrysik, 12th Pisa Meeting on Advanced Detectors, 2012

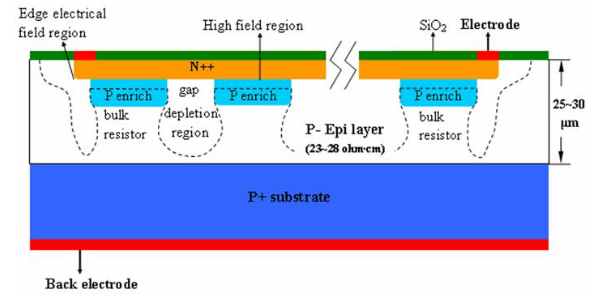
Advantages

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

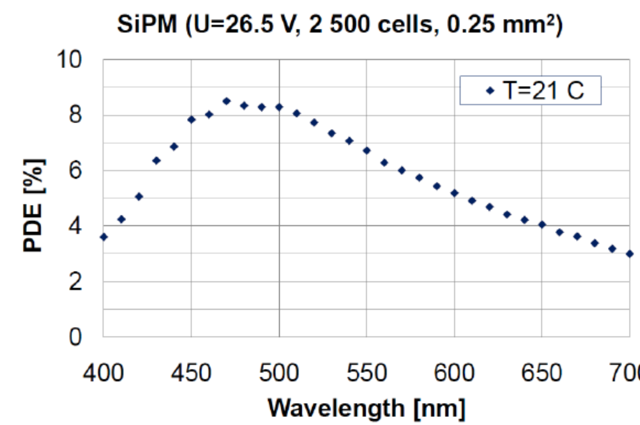
Promising results

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

NDL



- 0.5 ×0.5 mm² cell size : 10 µm
- 10000 cells/mm²
- DCR = 9 MHz/mm² (21 °C)
- Gain = 1.2 10^5 (21 °C)
- PDE (475 nm) = 8 %
- recovery time : 4.8 ns



H. Dejun, NDIP2011

Conclusion

Quick comparison between PMT, MCP-PMT and SIPM

Advantages and drawbacks of PMTs and SiPMs

		
PMT	▪ High gain (10^6) with 1000 – 2000 V ▪ Low noise ▪ High quantum efficiency (35 % in blue) ▪ Large area (> 10000 mm²) ▪ Large number of configurations ▪ Commercial products since 70 years	▪ Non linearity ▪ Response uniformity ▪ Affected by magnetic field ▪ Long-term stability ▪ Fragility ▪ Only 2 producers on the market
MCP-PMT	➢ High gain (10^7) ➢ High quantum efficiency (20 %) ➢ Very good timing properties (SPTR = 30 ps)	➢ Affected by magnetic field ➢ Fragility ➢ Cost
SiPM	• High gain (10^5-10^6) with low voltage (< 100 V) • Single photo detection • Good timing resolution (SPTR = 50 ps) • Insensitivity to magnetic field (up to 7 T) • High photon detection efficiency (35 % 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 :

- **EDIT 2011 school @ CERN**
- **Vacuum based photodetector**, IEEE NSS 2012, **Katsushi Arisaka**
- **PhotoDet 2012 workshop**, LAL Orsay: The SiPM Physics and Technology - a Review , ***Gianmaria Collazuol***
- **SiPM workshop,** 16.02.2011, CERN: State of the art in SiPM's, ***Yuri Musienko***

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:

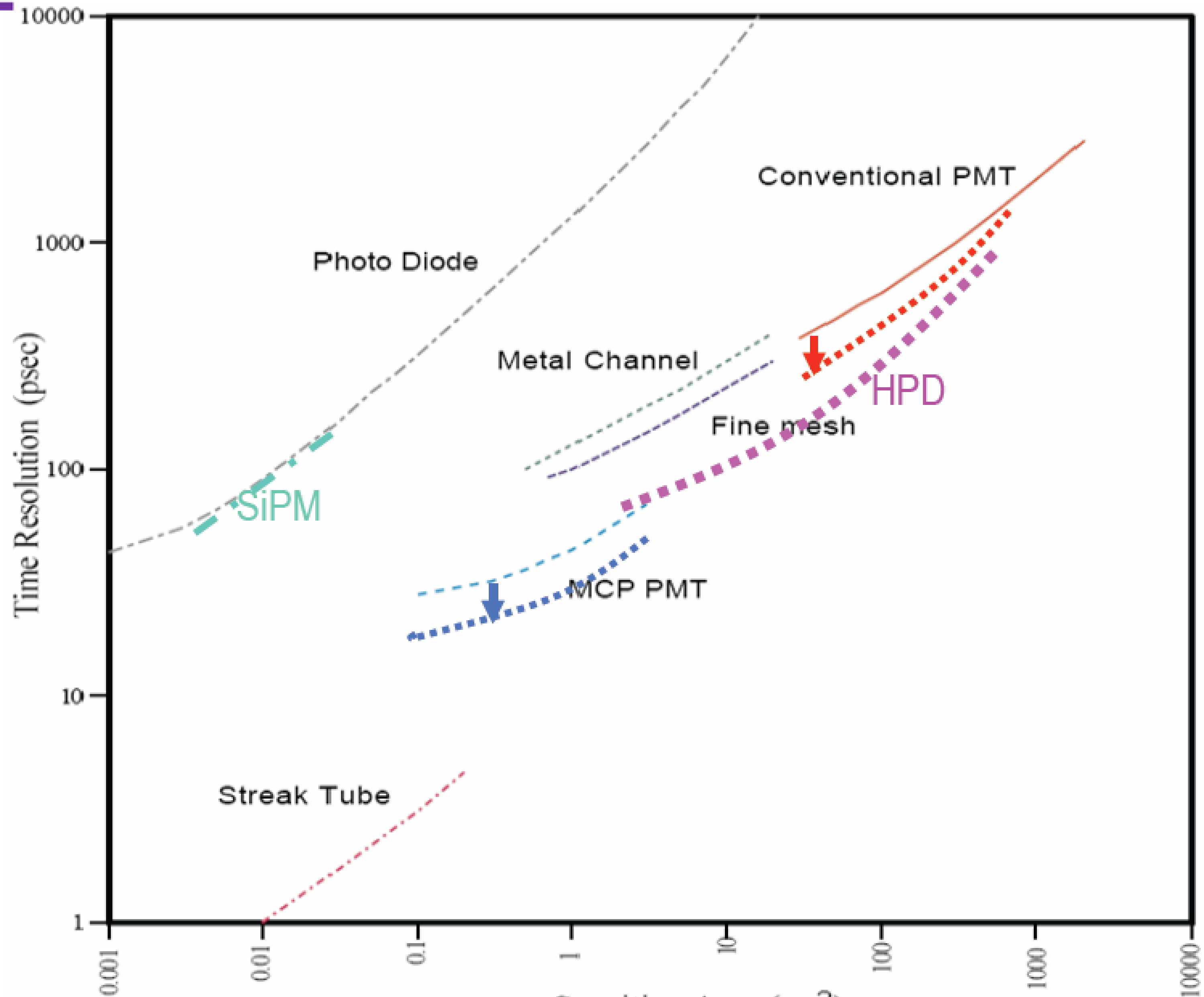
- **Hamamatsu PMT Handbook**
- **Burle PMT book**

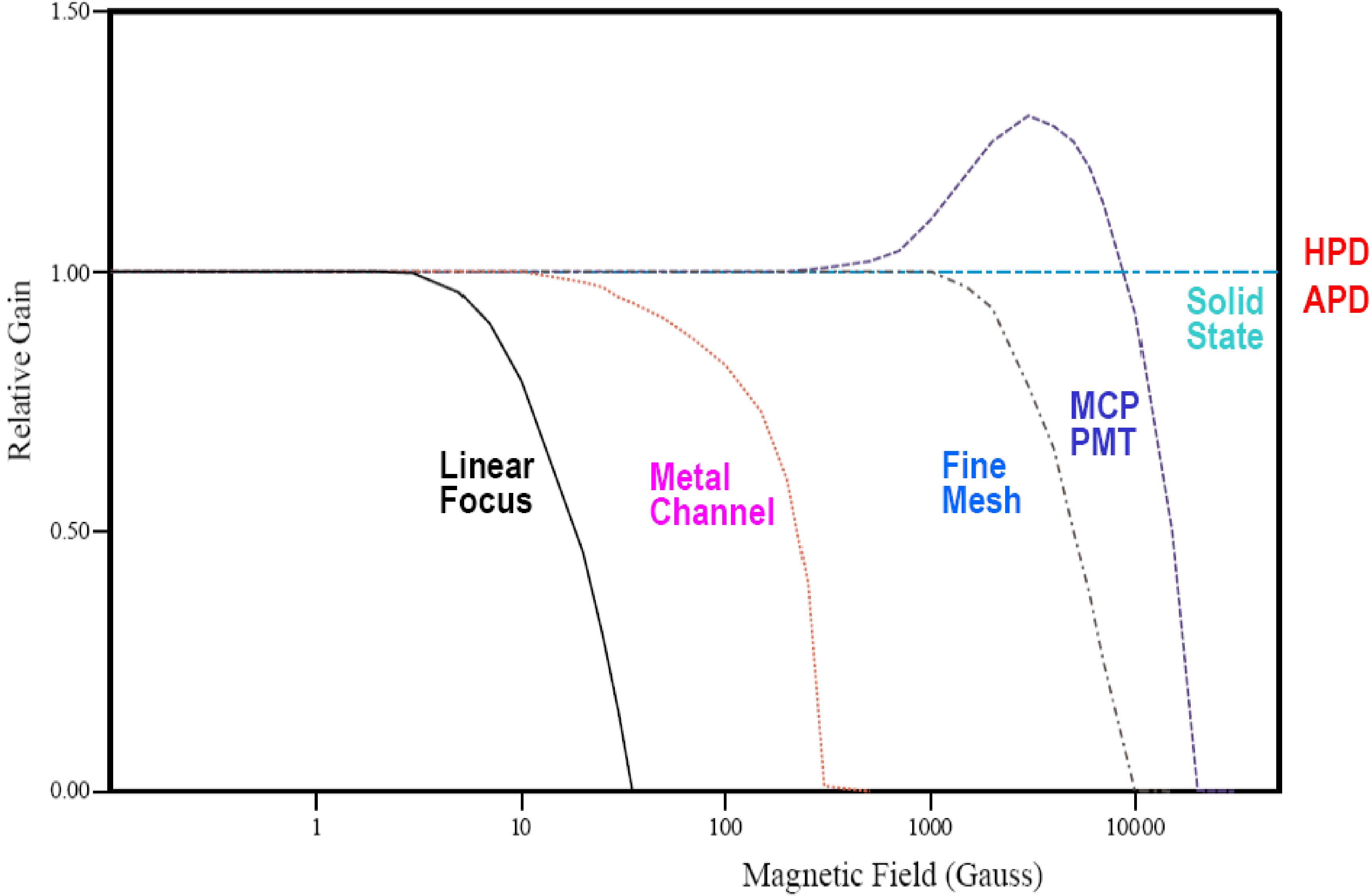
Articles and presentations:

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

The End

Backup

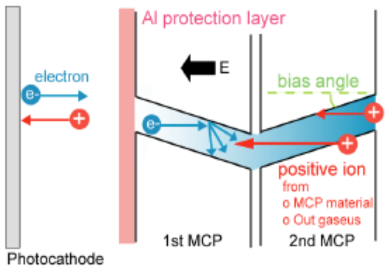

10000
1000
100
10
1
Time Resolution (psec)
Photo Diode
Conventional PMT
Metal Channel
HPD
Fine mesh
SiPM
MCP PMT
Streak Tube
0.001
0.01
0.1
1
10
100
1000
10000
Sensitive Area (cm^2)



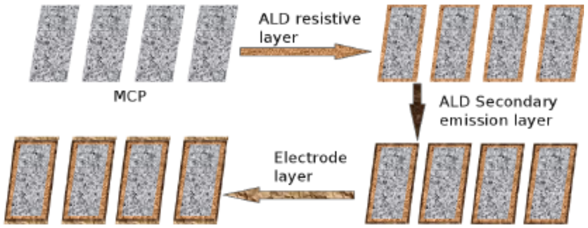
1.50
1.00
0.50
0.00
Relative Gain
1
10
100
1000
10000
Magnetic Field (Gauss)
HPD
APD
Solid State
MCP PMT
Fine Mesh
Metal Channel
Linear Focus

Approaches to Increase Lifetime

- Protection layer
  - In front of first MCP layer (older BINP and Hamamatsu)
    - disadvantage: reduction of collection efficiency
  - Between MCP layers (new Hamamatsu)
    - anode region is hermetically sealed from photo cathode region [NIM A629 (2011) 111]



- Improved vacuum + treatment of MCP surfaces [NIM A639 (2011) 148]
  - Electron scrubbing (older PHOTONIS and new BINP)
  - Atomic layer deposition (new PHOTONIS



- New photo cathode [JINST 6 C12026 (2011)]
  - $Na_2KSb(Cs) + Cs_3Sb$ (new BINP)
    - disadvantage: significantly higher dark count rate

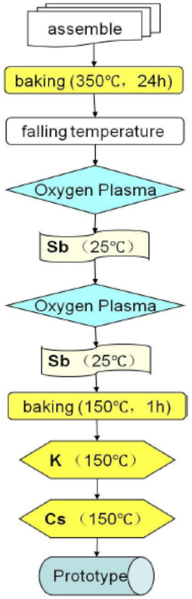
Albert Lehmann 12th Pisa Meeting on Advanced Detectors -- May 20 - 26, 2012 14

Progress on Bialkali Photocathode Production at Argonne

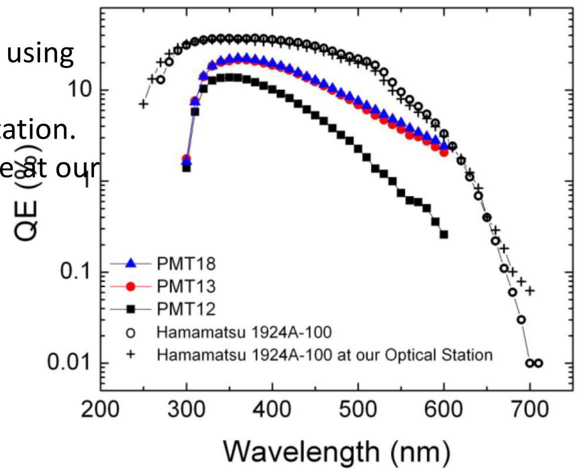
Junqi Xie, Marcel Demarteau, Ed May, Sasha Paramonov, Bob Wagner, Zikri Yusc

LAPPD Collaboration
High Energy Physics Division
Argonne National Laboratory
Tuesday, July 10th, 2012

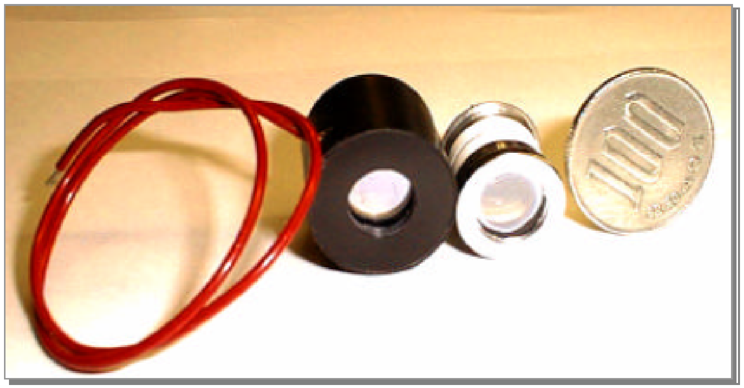
Bi-Alkali Photocathode Deposition Process

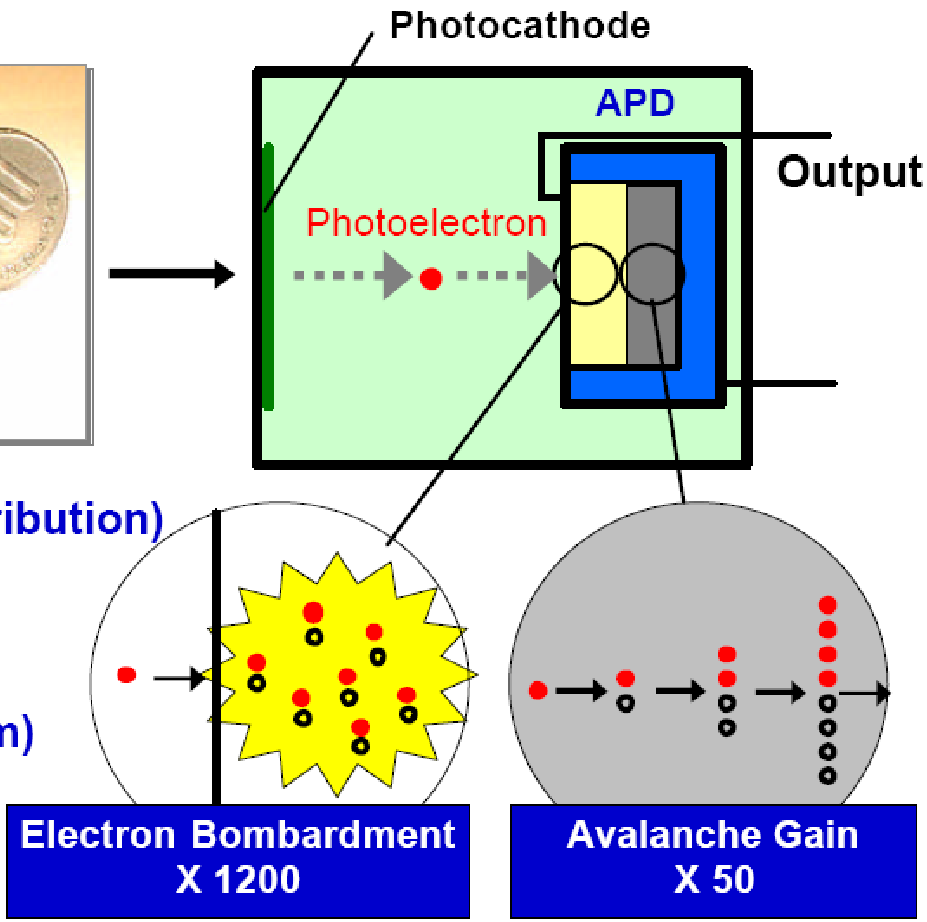


QE scans of three K-Cs-Sb bialkali photocathodes grown at Argonne using the PMT photocathode growth system acquired from Photonis. The QE values were measured using our new Optical Station system. A scan of a Hamamatsu PMT with "Super Bialkali" photocathode is also shown as part of the commissioning procedure of the Optical Station. The open circle shows the Hamamatsu's QE scan, while the cross shows the scan done at our Optical Station.



Z. Ysof, TIPP 2011



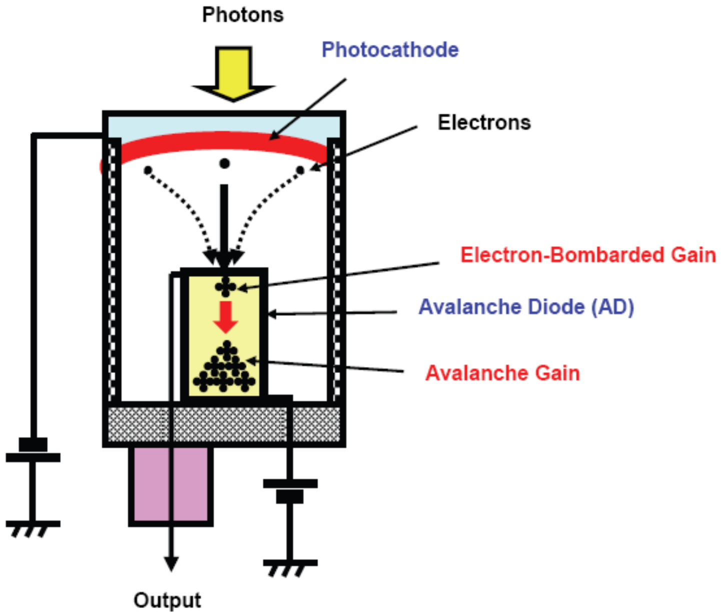


Good PHD (Pulse Height Distribution)
Good Uniformity
Immunity to Magnetic Field
Fast Time Response
Compact (16mm in dia x 16mm)

<Photocathode>
Multi-Alkali, GaAsP, GaAs

Combination of EB and avalanche gain

HPD



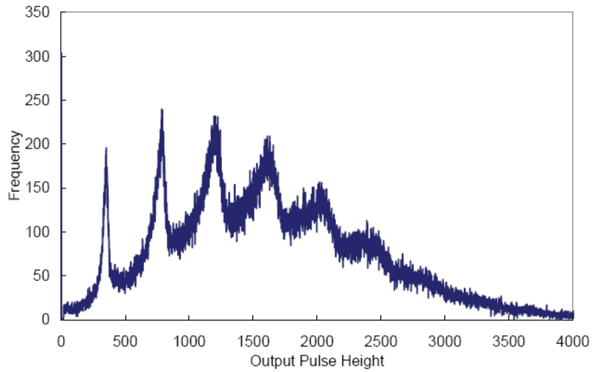
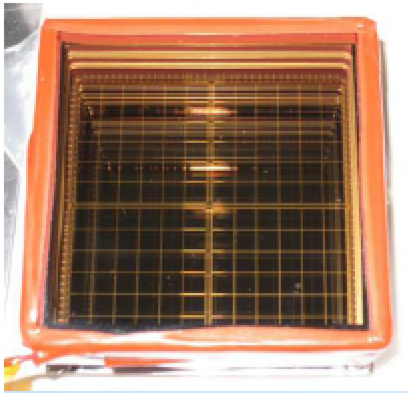
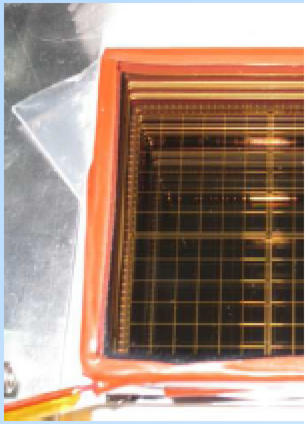


Figure 13: The pulse height spectrum for multi photons clearly shows peaks corresponding up to 6 photoelectrons.

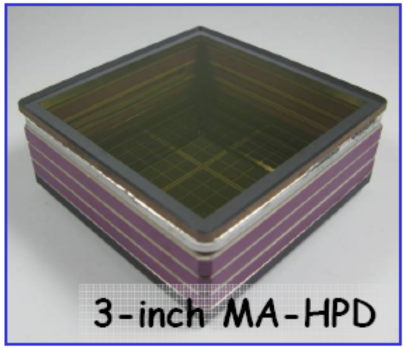


Belle II aerogel RICH HAPD

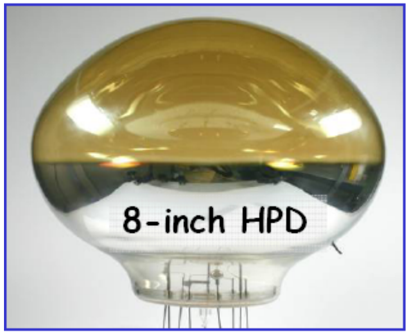
- proximity focusing configuration → operation in magnetic field
- HV ~8kV, gain ~100k (2000x50)
- 144 channels
- ~ 65% effective area
- tested up to 1000 Gy and 10^{12} n(1MeV)/cm^2
- Belle + Hamamatsu



R&D on HPD

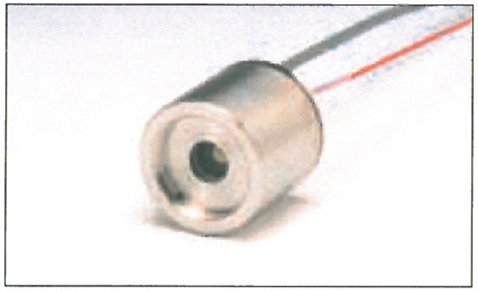


RICH/Belle upgrade



Water Tank Detector

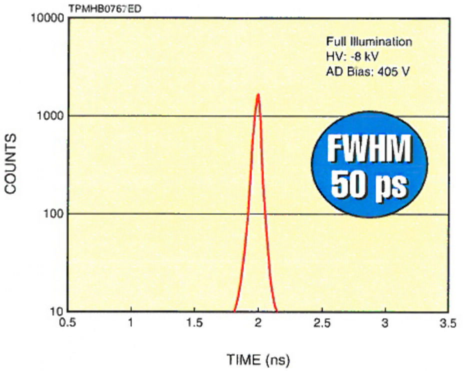
The HPD (Hybrid Photodetector) utilizes the "electron bombardment" method in which photoelectrons are accelerated in a strong electric field to directly strike an avalanche diode (AD) in a vacuum tube. This mechanism achieves excellent quality of amplification.
Using a new AD with very low capacitance,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



R10467U series

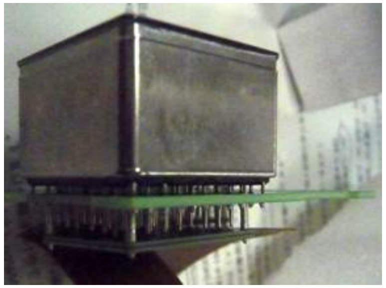
Parameter		R10467U-06	R10467U-40	R10467U-50	Unit
Spectral Response		220 to 650	300 to 720	380 to 890	nm
Photocathode	Material	Bialkali	GaAsP	GaAs	—
	Effective Area	$\phi 6$	$\phi 3$		mm
Quantum Efficiency		28 ①	45 ②	14 ③	%
Gain ④		1.2×10^5			—
Rise Time		400			ps
T.T.S. (Transit Time Spread) ⑤ (FWHM)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



Example of ASICs for MaPMTs

SPACIROC



Analog part:

1. Photoelectron counting (20-50MHz)
2. Q-to-T converter

Digital part :

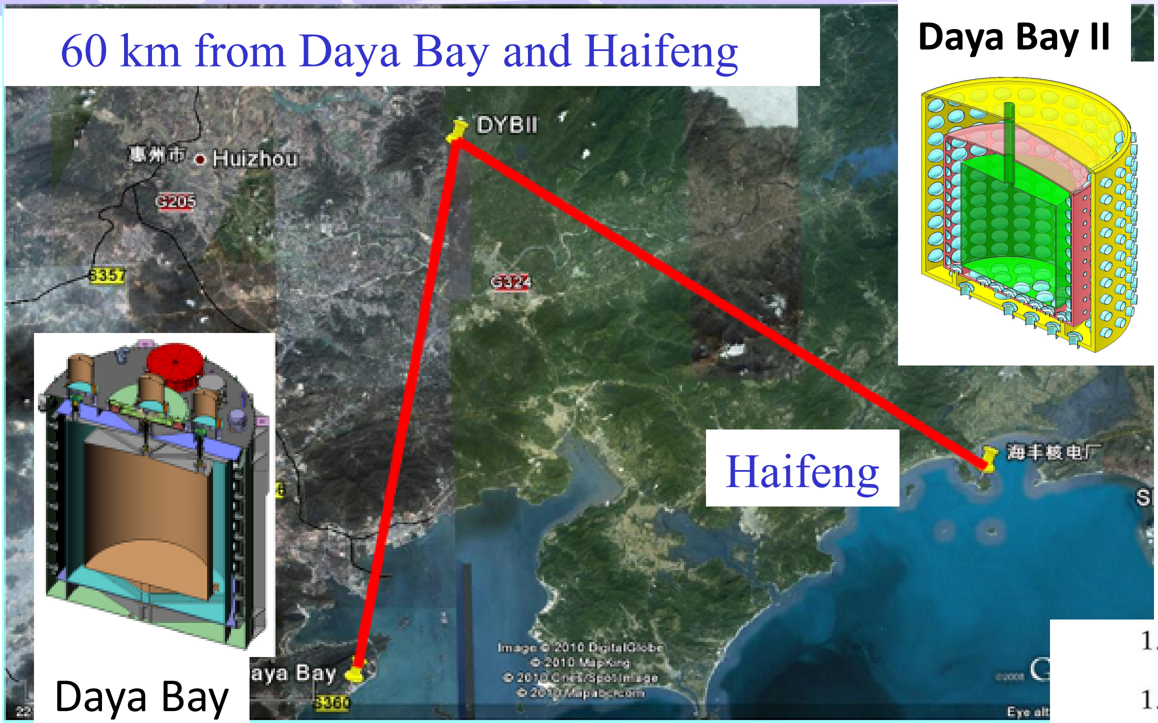
1. Digitization,
2. Memory,
3. Send data to FPGA for triggering

Crucial points

- **Power consumption < 1 mW/ch**
- data flow ~ 384 bits / 2.5 µs
- **Radiation tolerant**

P. Barrillon, LAL, EUSO BAllon

Next generation Neutrino Experiment in China

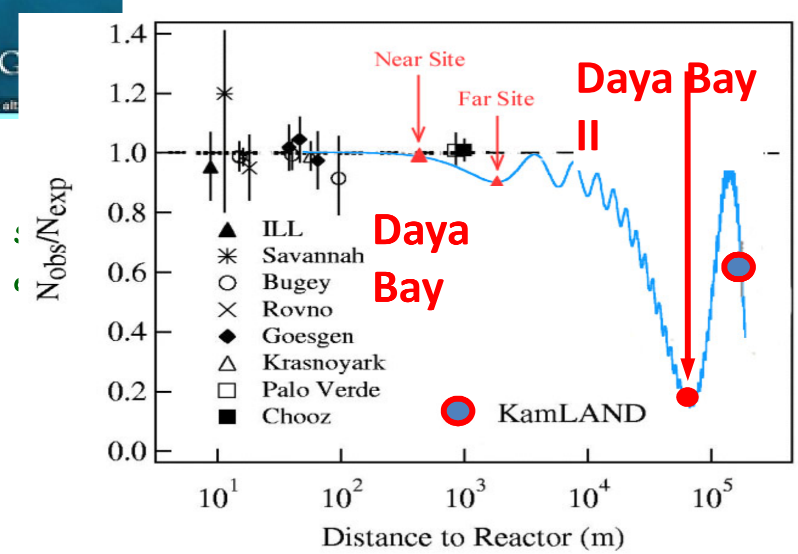


Huge Detector （ LS + PMT

Energy resolution ~ 3%/√E

- Neutrino target: 30m(D)×30m(H)
- LS, LAB based : ~20kt
- Oil buffer: ~6kt
- Water buffer: ~10kt
- PMT (20") :~20,000

Reactor experiments:



The Main Scientific goals:

⇨ Mass Hierarchy

⇨ Mixing matrix elements

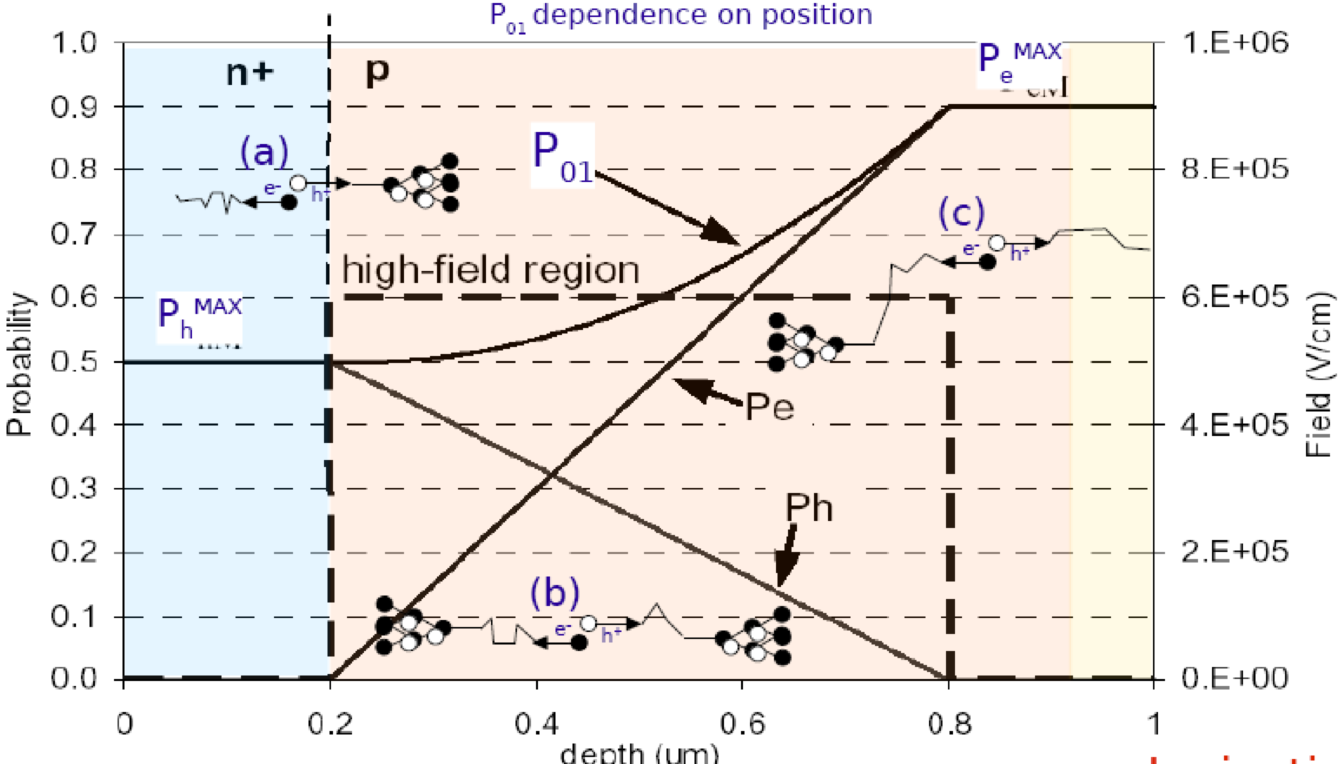
⇨ Supernovae

⇨ geo-neutrinos

L. Zhan, et. al., Phys.Rev.D 78:111103,2008
L. Zhan, et. al., Phys.Rev.D 79:073007,2009

2

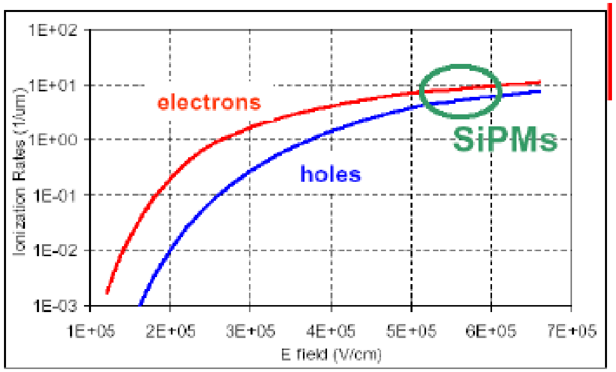
Avalanche trigger probability (P_{01})



C.Piemonte
NIM A 568
(2006) 224

Example with constant high-field:
(a) only holes may trigger the avalanche
(b) both electrons and holes may trigger
(but in afraction of the high-field region)
(c) only electrons may trigger

Ionization rate in Silicon



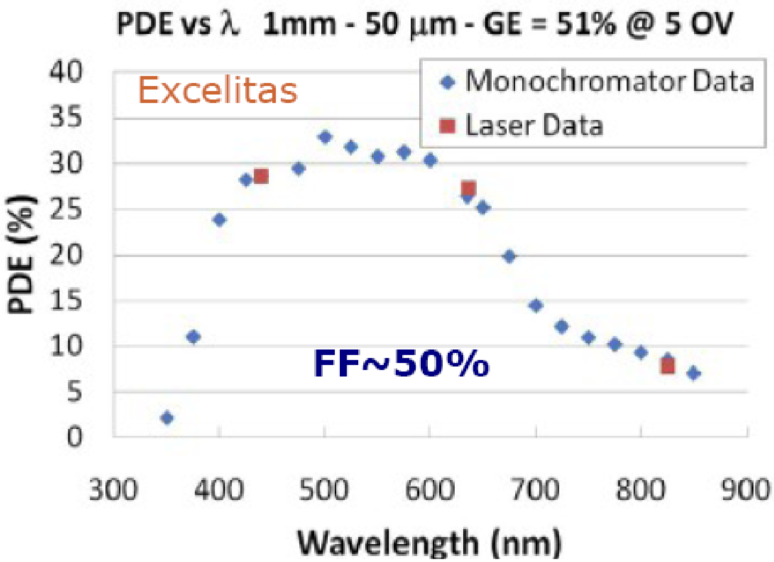
P_{01} optimization

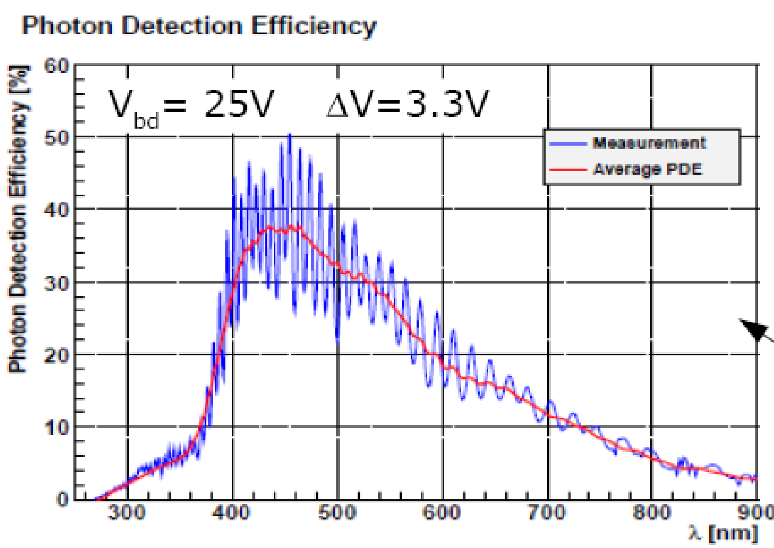
- high over-voltage
- photo-generation in the p-side of the junction

G.Collazuol - LIGHT11 3/11/2011

Improving PDE

Barlow – LIGHT 2011

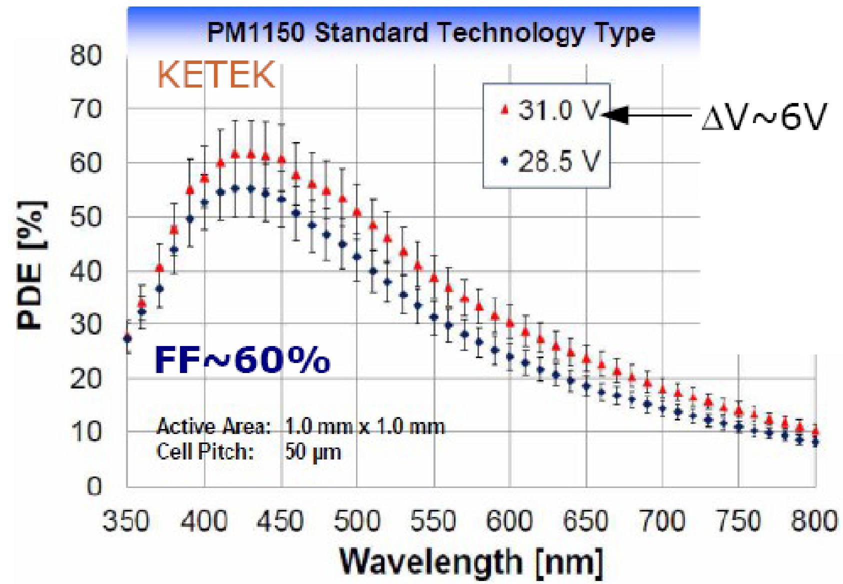




T.Frach 2012 JINST 7 C01112

→ PDE peak constantly improving for many devices
→ every manufacturer shape PDE for matching target applications
→ UV SiPM eg from MePhi/Excelitas (see *E.Popova at NDIP 2011*)
→ DUV SiPMs in development too

F.Wiest – AIDA 2012 at DESY



dSiPM (latest sensor 2011)
→ up to now no optical stack optimization
→ no anti-reflecting coating
→ potential improvement up to 60% peak PDE (*Y.Haemish at AIDA 2012*)

G.Collazuol - PhotoDet 2012

53

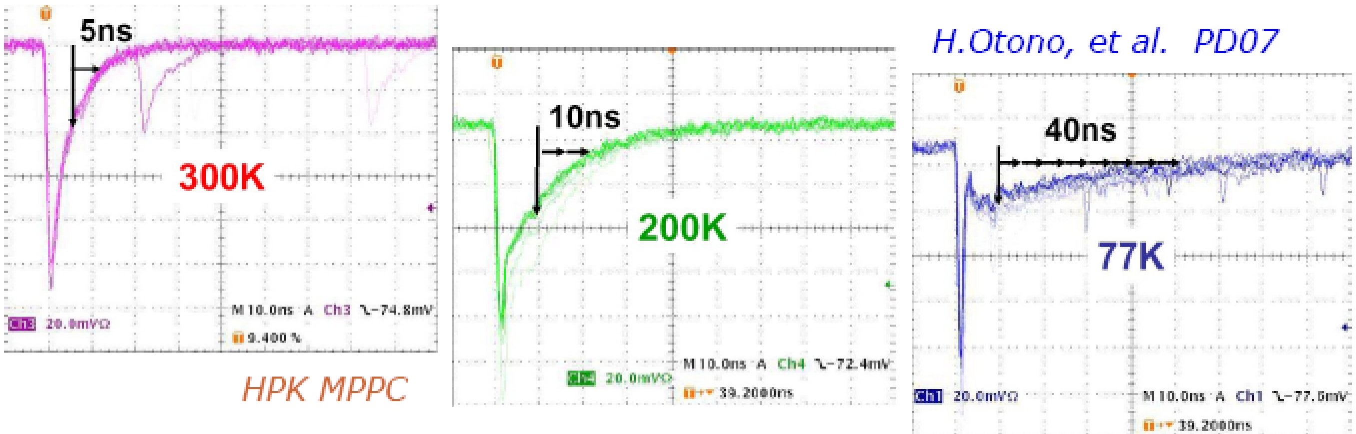
Pulse shape: dependence on Temperature

The two current components behave differently with Temperature

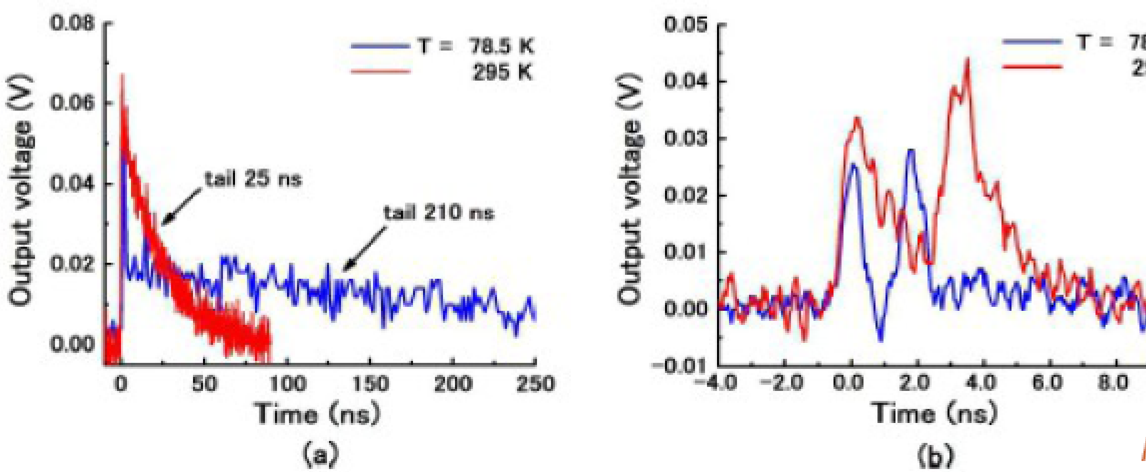
→ fast component is independent of T because C_{tot} couples to external R_{load}

→ slow component is dependent on T because $C_{d,q}$ couple to $R_q(T)$

H.Otono, et al. PD07



HPK MPPC



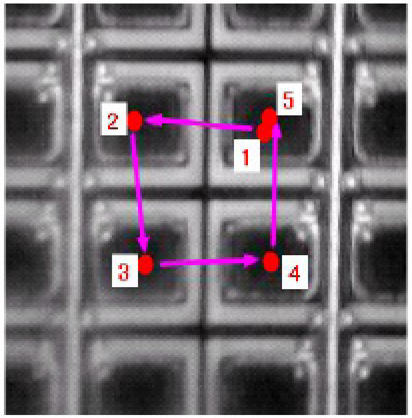
high pass filter / shaping
→ recover fast signals

HPK MPPC

Fig. 2. (a) Output signals from the MPPC when no high-pass filter is used, and (b) output signals from the high-pass filter when two pulses were generated successively.

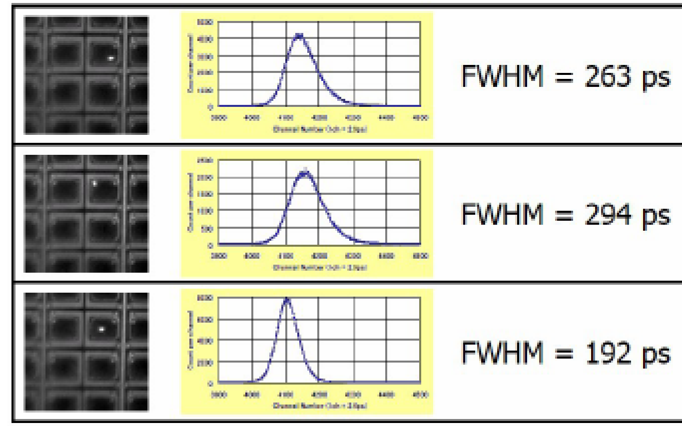
Akiba et al Optics Express 17 (2009) 16885

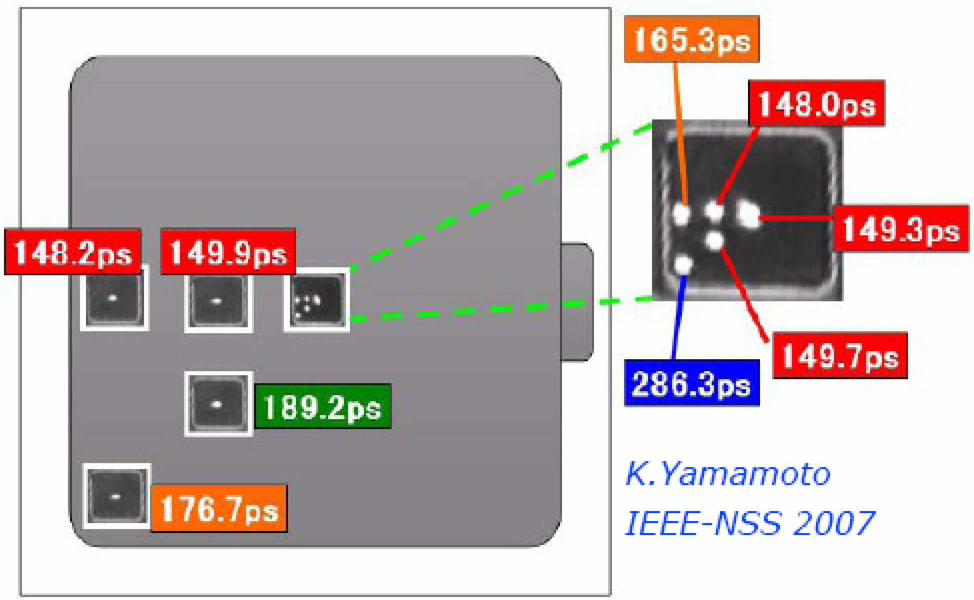
SPTR: position dependence → cell size



	FWHM (ps)	FWTM (ps)
1	199	393
2	197	389
3	209	409
4	201	393
5	195	383

K.Yamamoto PD07





K.Yamamoto IEEE-NSS 2007

Data include the system jitter (common offset, not subtracted)

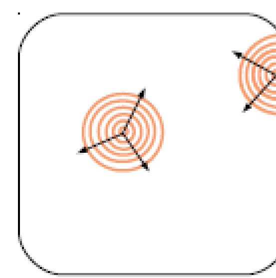
Larger jitter if photo-conversion at the border of the cell

Due to:

1) slower avalanche front propagation

2) lower E field at edges

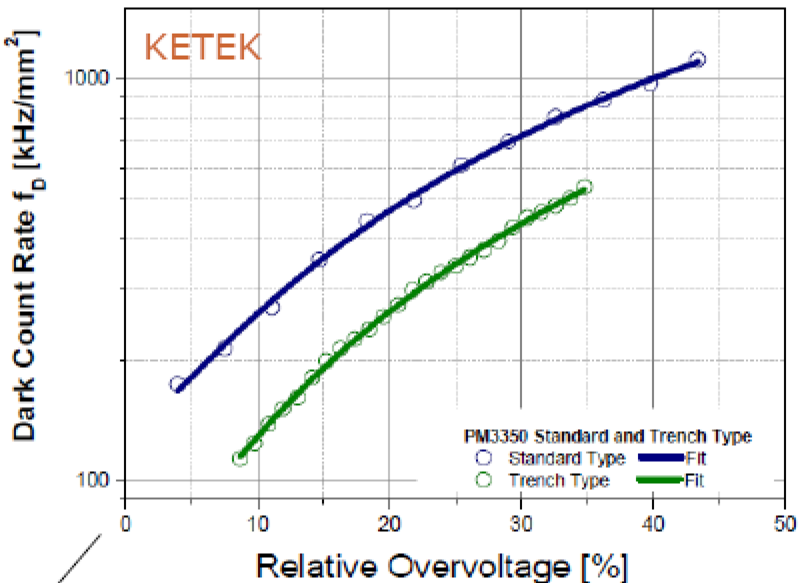
→ cfr PDE vs position



G.Collazuol - PhotoDet 2012

Dark Count Rate

KETEK PM 3350 (p^+-on-n, shallow junction)
3x3mm² active area pixel size 50x50 μm²



V_{bd} ~ 25V *F.Wiest – AIDA 2012 at DESY*

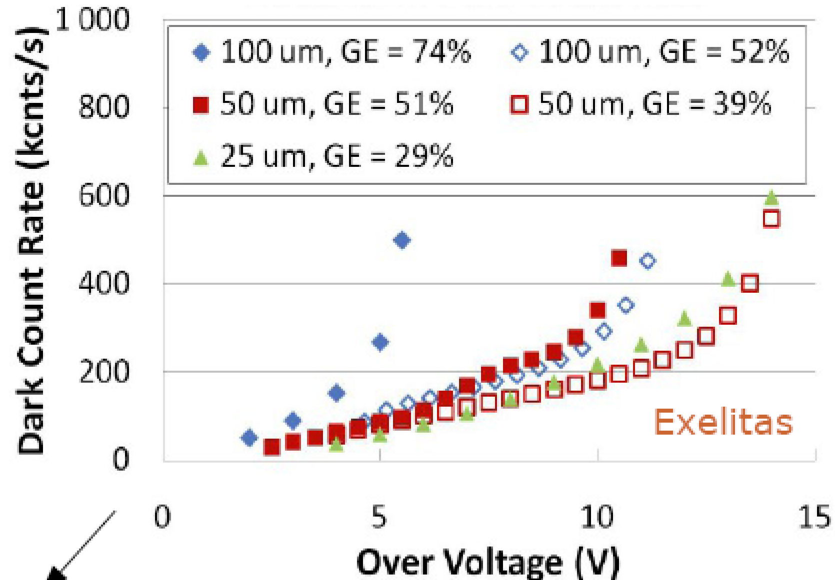
Latest Hamamatsu devices reached ~80kHz/mm²

HPK claiming for additional improvements coming (*HPK at LIGHT 2011*)

Critical issues:

- quality of epitaxial layer
- gettering techniques
- Efield engineering (low T)

Exelitas 1st generation SiPM 2011
(p^+-on-n) 1x1mm²



V_{bd} ~ 140V *P.Berard – NDIP 2011*

G.Collazuol - PhotoDet 2012

Radiation damage: effects on SiPM

1) Increase of dark count rate due to introduction of generation centers

Increase (ΔR_{DC}) of the dark rate:

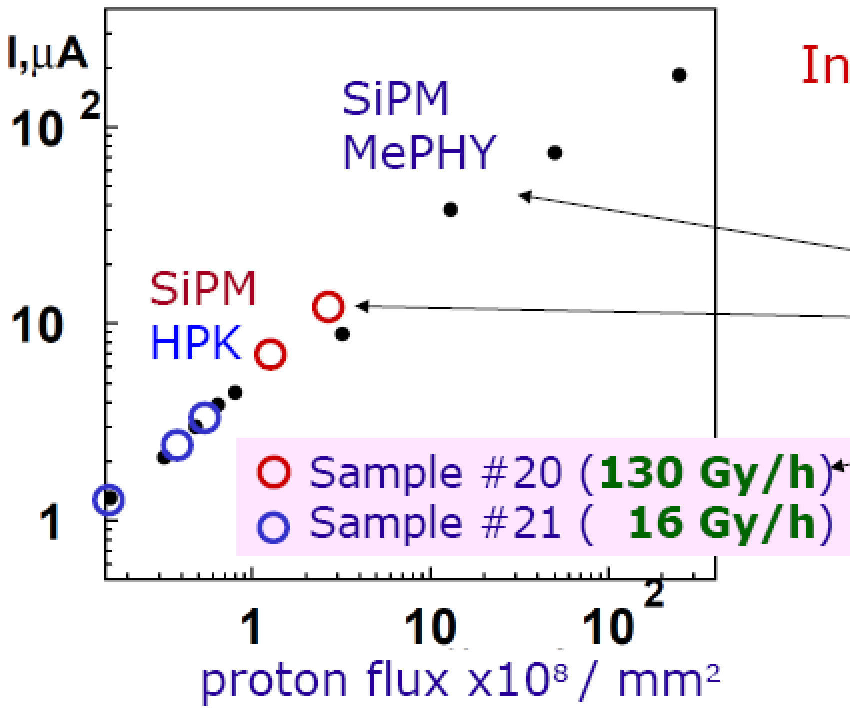
$\Delta R_{DC} \sim P_{01}\ \alpha\ \Phi_{eq}\ Vol_{eff} / q_e$

where $\alpha \sim 3 \times 10^{-17}$ A/cm is a typical value of the radiation damage parameter for low E hadrons and $Vol_{eff} \sim Area_{SiPM} \times \varepsilon_{geom} \times W_{epi}$

NOTE:
The effect is the same as in normal junctions:
- independent of the substrate type
- dependent on particle type and energy (NIEL)
- proportional to fluence

2) Increase of after-pulse rate due to introduction of trapping centers

→ loss of single cell resolution → no photon counting capability



Indications from measurements:

1) no dependence on the device
similar effects found for SiPM from MePHY (Danilov) and HPK (Matsumura) (normaliz. to active volume)

2) no dependence on dose-rate
HPK (Matsumura)

3) n similar damage than p

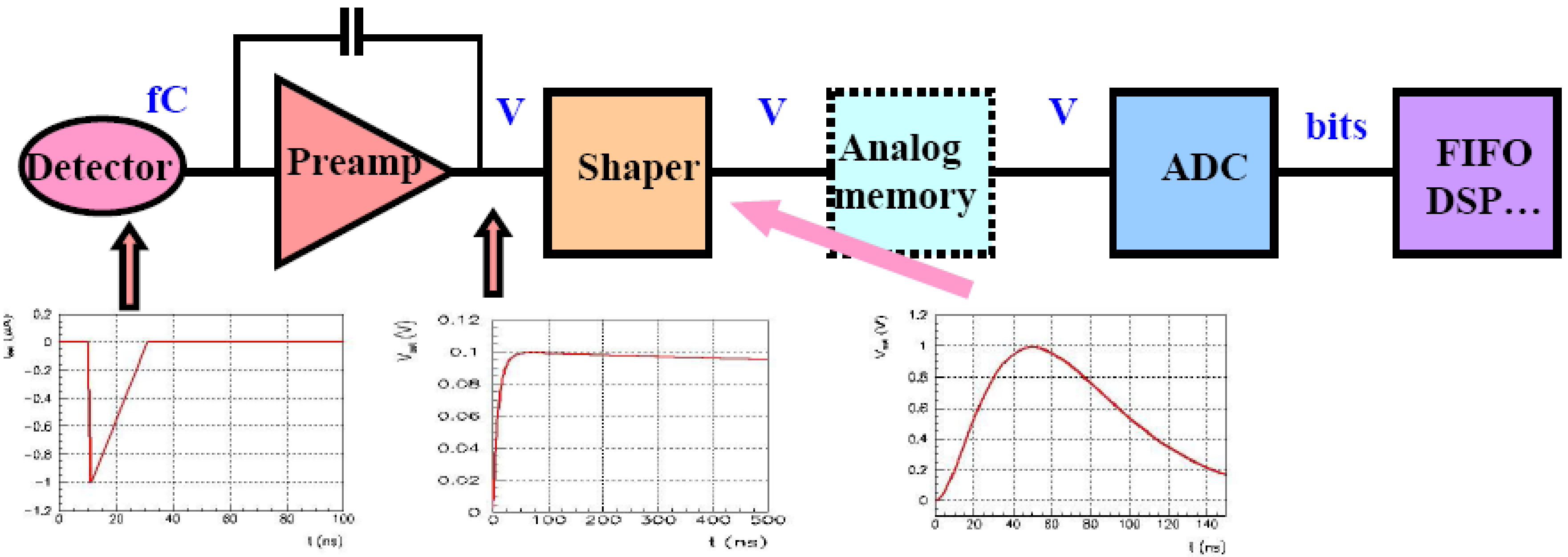
4) p x10^1-10^2 more damage than γ

G.Collazuol - PhotoDet 2012

Overview of readout electronics

C. De La Taille
IN2P3 Microelectronic
Lecture

- Most front-ends follow a similar architecture



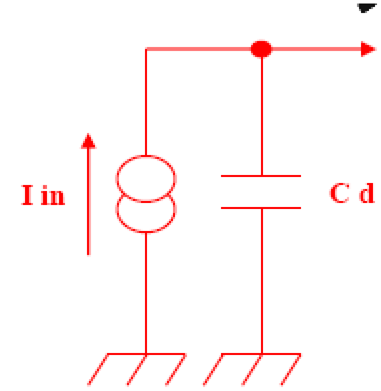
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels
- Trends : high speed, low power

Detector modelization

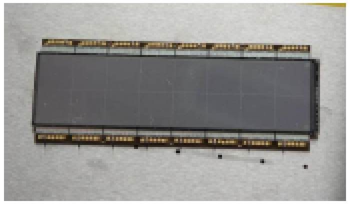
- Detector = capacitance Cd
  - Pixels : 0.1-10 pF
  - PMs : 3-30pF
  - Ionization chambers 10-1000 pF
  - Sometimes effect of transmission line

- Signal : current source
  - Pixels : ~100e-/µm
  - PMs : 1 photoelectron -> 10^5-10^7 e-
  - Modelized as an impulse (Dirac) : $i(t)=Q_0\delta(t)$

- Missing :
  - High Voltage bias
  - Connections, grounding
  - Neighbours
  - Calibration…



Detector modeilization



CMS pixel module

ATLAS LAr calorimeter

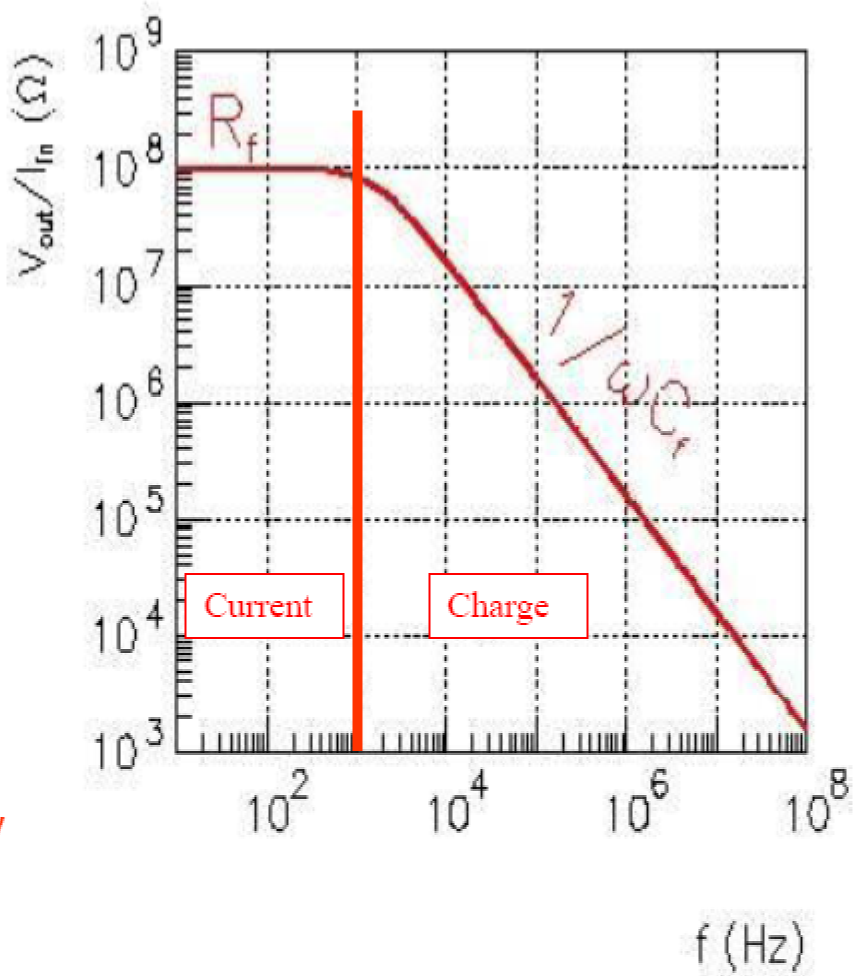
Charge vs Current preamps

- Charge preamps
  - Best noise performance
  - Best with short signals
  - Best with small capacitance

- Current preamps
  - Best for long signals
  - Best for high counting rate
  - Significant parallel noise

- Charge preamps are not slow, they are long

- Current preamps are not faster, they are shorter (but easily unstable)



SiPMs for Calorimeters : CALICE AHCAL

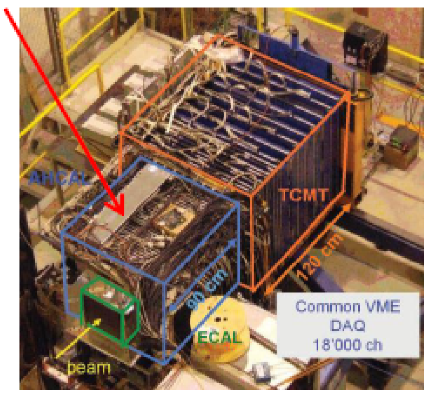
High granularity hadronic calorimeter optimised for the Particle Flow measurement of multi-jets final state at the ILC

Photodetector requirements:

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

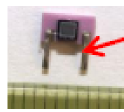
studied SiPMs : MePHI/PULSAR, CPTA

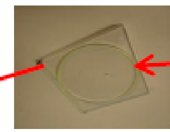
HCAL prototype (from 2007 to 2011)



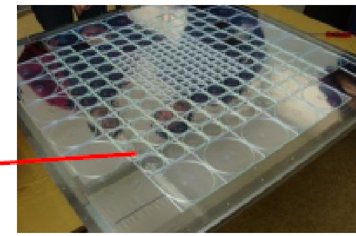
38 layers - ~ 7600 SiPMs from MePHI/PULSAR

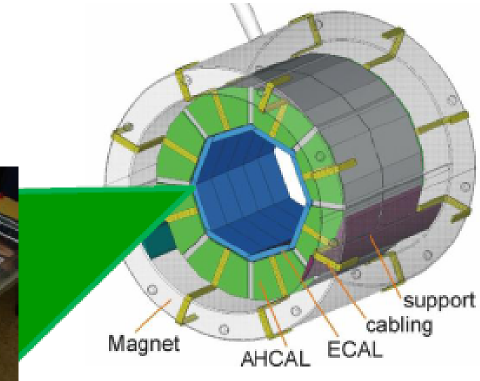
temperature dependance (variation of PDE x Gain : 3.7%/°C %)→ correction of response variations





scintillator tiles

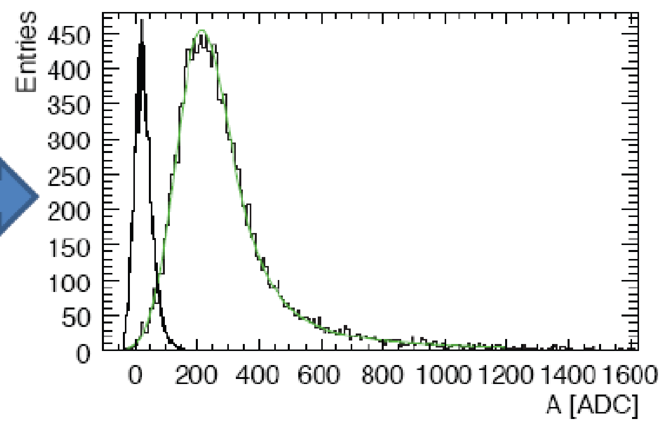




Michal Tesař, PhotoDet2012

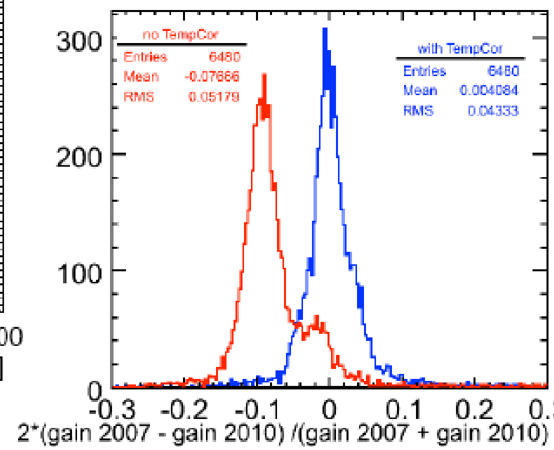
MePHI/PULSAR SiPM

HCAL test beams at SPS H8



MIP distribution of muons

CALICE Collaboration, 2010 JINST 5 P05004



S. Lu, LCWS11

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

Annealing

Proposal to Test Improved Radiation Tolerant Silicon Photomultipliers

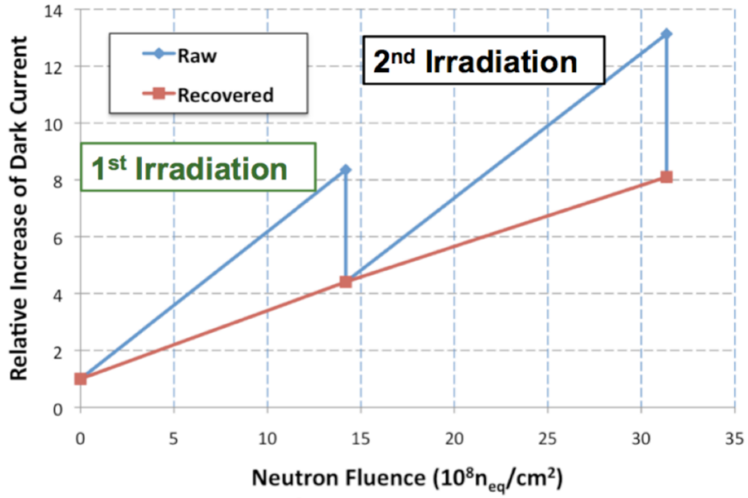
F. Barbosa, J. McKisson, J. McKisson, Y. Qiang, E. Smith, D. Weisenberger, C. Zorn
Jefferson Laboratory

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

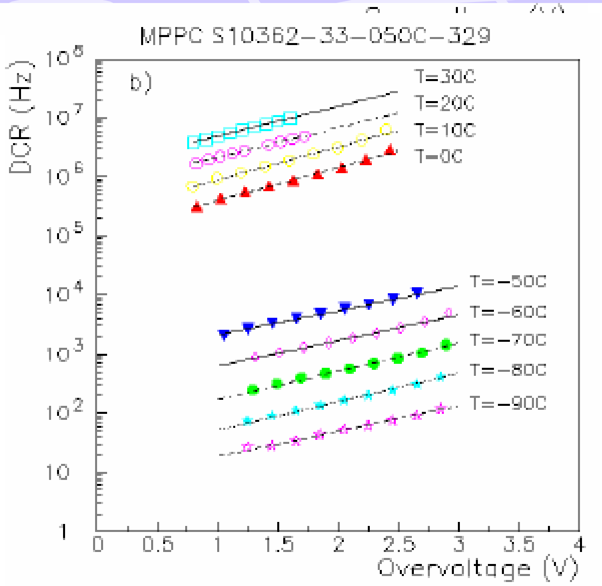


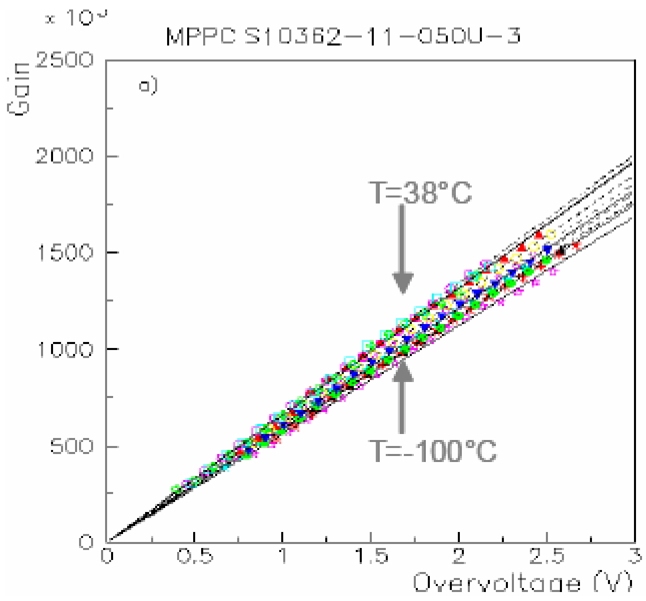
Neutron Fluence with 10^8 g/s on LH_2 Target with 1/3 efficiency
-> $3x10^8$ $n_{eq}/cm^2/year$

At 25°C, annealing requires at least 5 days

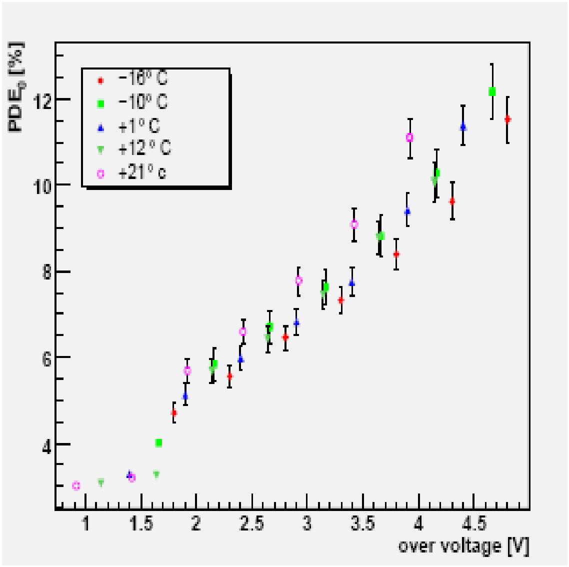
Heating to above 40°C can reduce the annealing time to less than 24 hours

Variations of SiPMs with temperature





Dinu, IEEE NSS 2010

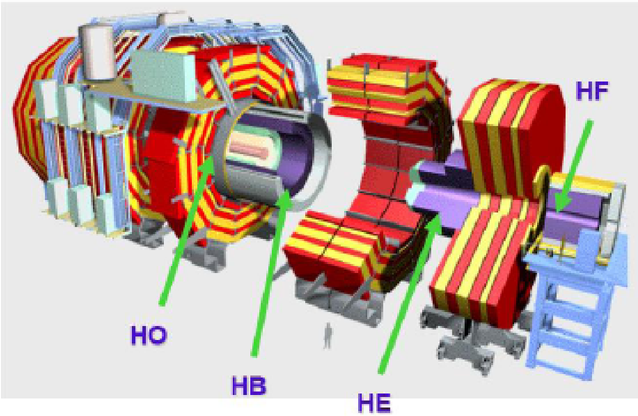


M. Ramilli

no temperature dependence of the PDE

SiPMs for Calorimeters : Upgrade of the CMS HCAL

HB & HE upgrade

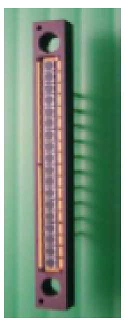


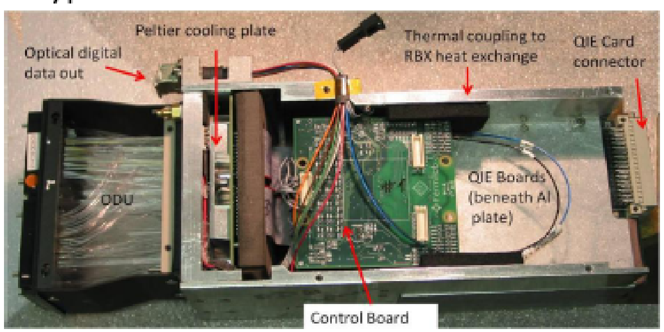
<u>Photodetector requirements (to replace the HPD)</u>:

- very large dynamic range: a few p.e → 2500 p.e
- high occupancy in front layers in SLHC → fast recovery time (5 – 100 ns)
- radiation hard up to 3.10^{12} 1 MeV neutrons/cm² for 3000 fb^{-1} (Gain*PDE change ≤ 20%)

<u>Studied SiPM</u> :
HAMAMATSU, ZECOTEK, FBK, CPTA , ST-Micro, Sensl, NDL, KETEK

Prototype HB RM used at 2011 Testbeam



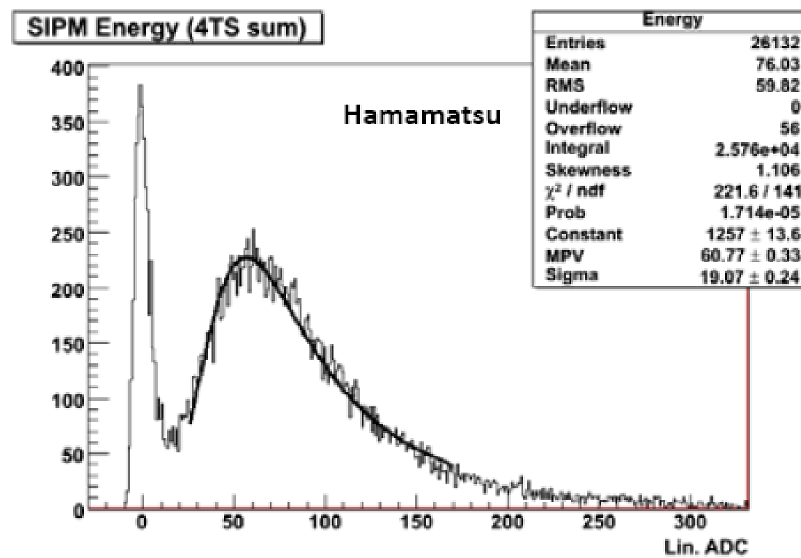


Y. Musienko, NDIP 2011

Temperature dependence → control @ 0.2 °C

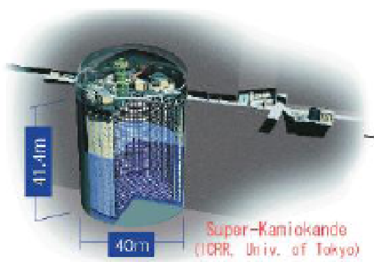
Significant progress on the SiPM development over the last 2 years (HAMAMATSU , Zecotek, NDL) → the MPPCs from HAMAMATSU are close to satisfy most of the requirements.

Muon response in a single tower of CMS HO



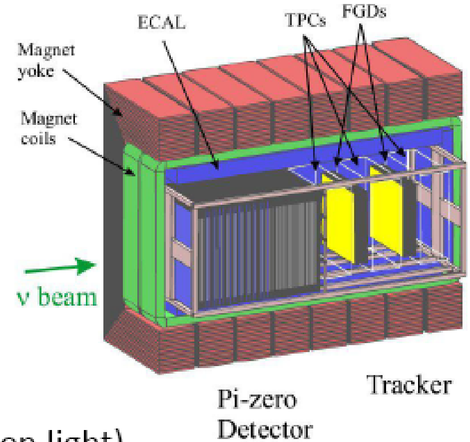
J. Freeman, FERMILAB-CONF-09-601-E

SiPMs for neutrino oscillation experiment: T2K



Far detector : Super Kamiokande

<u>ND280</u> : near detector complex - neutrino beam flux and spectrum measurements



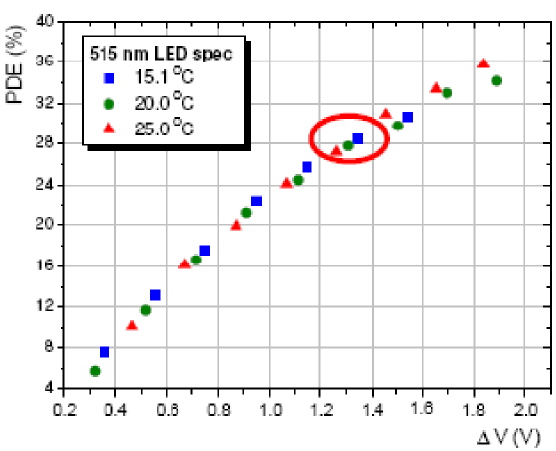
HAMAMATSU MPPC customized device

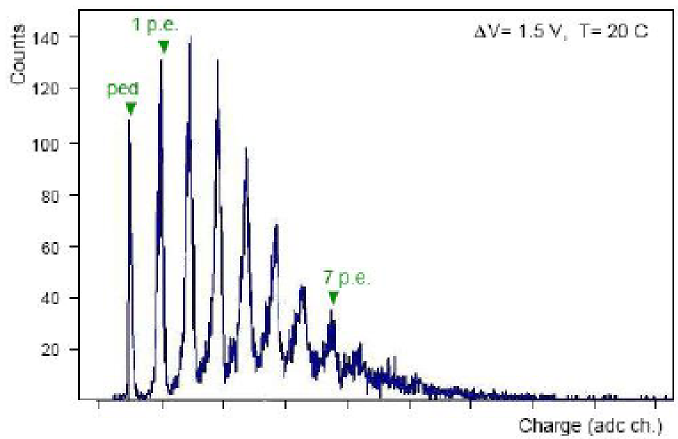
1.3 x 1.3 mm²

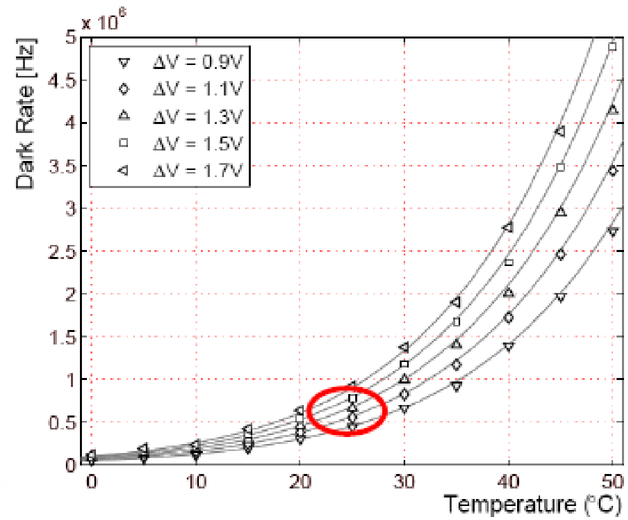
667 cells (50 x 50 μm²)

<u>Photodetector requirements</u>:

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





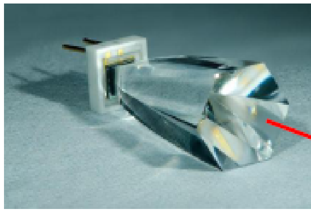


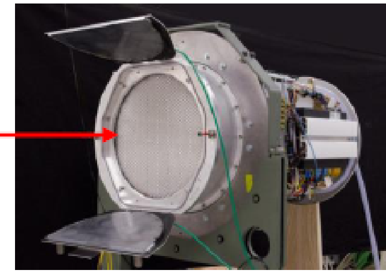
A. Vacheret, arXiv:1101.1996

<u>55996 MPPC tested</u> : 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

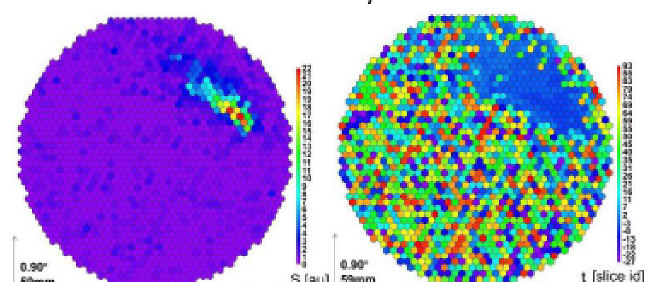
Th. Krähenbühl, Photodet 2012

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



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

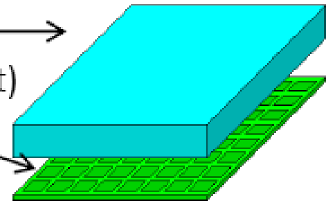
P. Vogler, TWEPP 2012

SiPMs for medical applications : PET

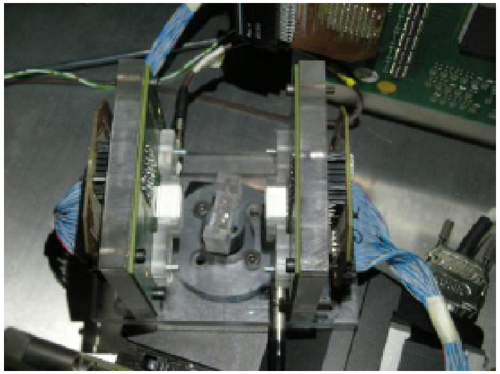
Small animal PET

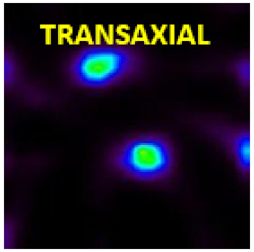
miniature, high-resolution camera for a small-animal PET imaging system that is based on a combination of SiPM with a continuous scintillation crystal.

- LYSO continuous crystal (12 x 12 x 5 mm^3)
- monolithic matrices from FBK (DASIPM project)



- ➢ $\Delta E/E$ ~ 15% FWHM (at 511 keV)
- ➢ $\Delta x = \Delta y$ ~ 0.7 mm FWHM

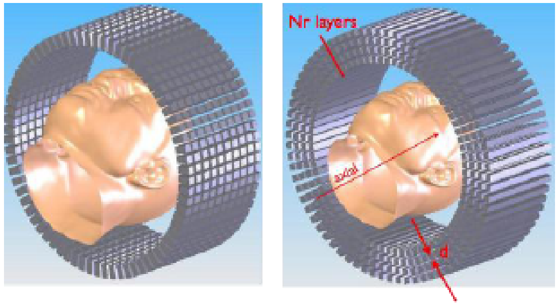




G. Llosa, PSMR 2012

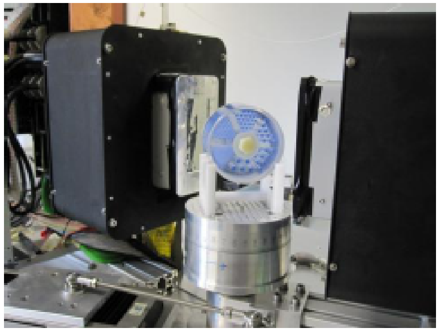
AX-PET

from radial… … to axial



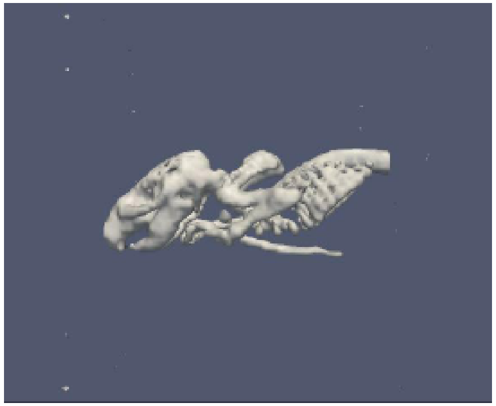
C. Joram, NIM A 654 (2011) 546-559

- long LYSO crystals (3×3×100 mm^3)
- orthogonal WLS strips
- readout by SiPMs from Hamamatsu
- 3D reconstruction of photons



Some results

- ➢ $\Delta E/E$ ~ 12% FWHM (at 511 keV)
- ➢ $\Delta x = \Delta y$ ~ 2 mm FWHM
- ➢ Δz (axial) = 1.8 mm FWHM



Latest development:
Use of Digital SiPM (Philips) for AX-PET with TOF → CRT < 200 ps FWHM.