Recent Progress and Perspectives in Solid State Photomultipliers

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Outline

- Introduction and brief history of SiPM/SSPM invention
- SiPM principles of operation and properties
- SiPM parameters
- Recent progress in SiPMs
- SiPM radiation damage
- Exotic SSPM structures
- Applications of SiPMs in HEP
- Summary and SiPM/SSPM perspectives

Introduction

Significant progress in understanding of physics of SiPM operation was achieved during last 3-5 years.

As a result → a breakthrough in SiPM understanding/development. SiPMs with **reduced correlated noise (X-talk, afterpulsing)**, improved PDE, reduced dark noise were developed and produced.

Here I will review current (June 2017) status of SiPM/SSPM development.

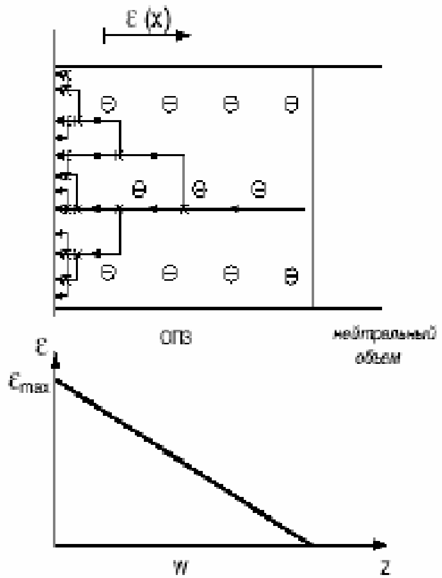
A special attention is paid to new developments in the field of radiation-hard SiPMs. Possible perspectives of SiPM/SSPM development will be also discussed.

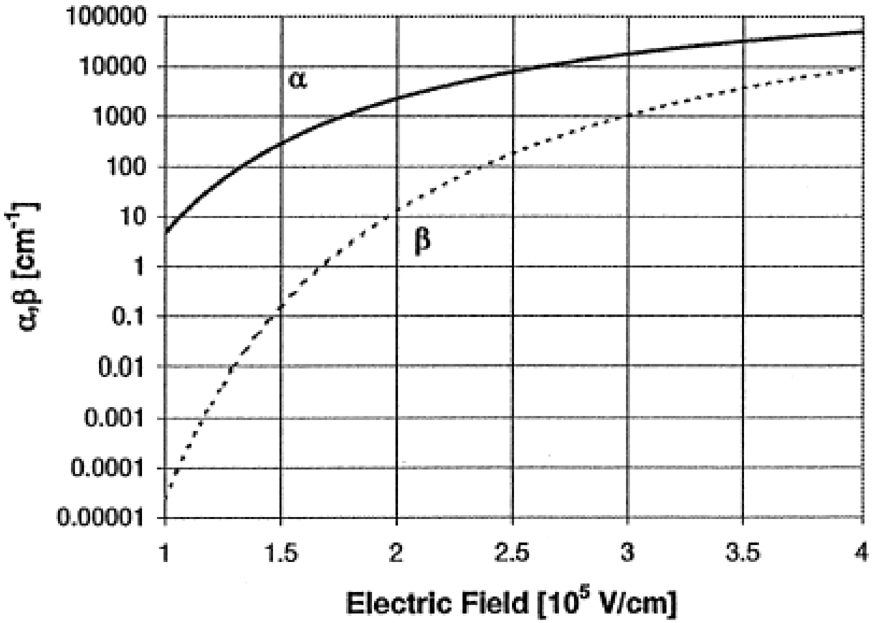
I would like to thank all the people whose slides (shown at PhotoDet-2012, NDIP-2014, PhotoDet-2015, VCI-2016, Elba-2015, 2nd SiPM Advanced workshop-Geneva-2014, CPAD-2016 and RICH-2016, IEEE-NS/MIC-2016, INSTR-2017 conferences etc.) are used in this presentation.

Avalanche multiplication in Si

Applying high electric field in uniform p-n junction may cause an avalanche multiplication of electrons and holes created by absorbed light

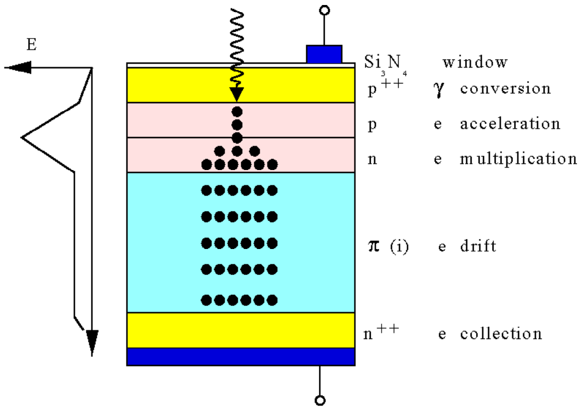
Dependence of ionization coefficients of electrons and holes in Si on the electric field at room temperature

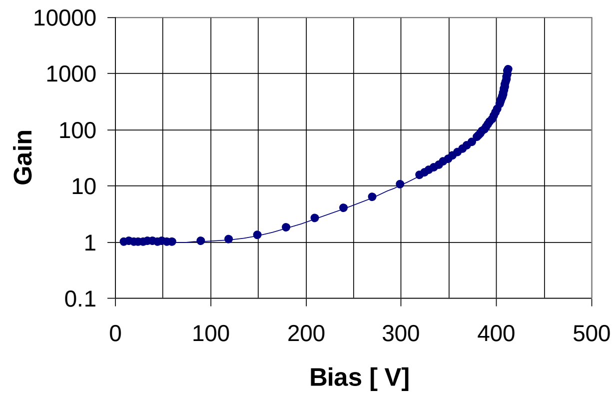


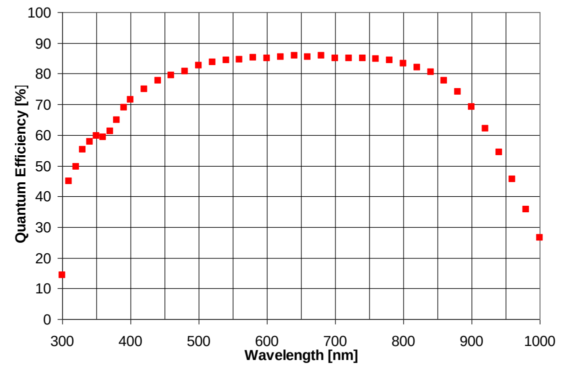


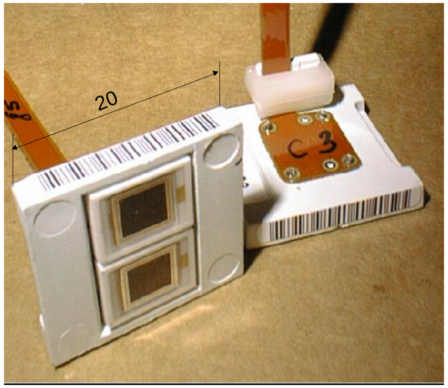
Silicon is a good material for APD construction: high sensitivity in visible and UV range, significant difference between ionization coefficients for electrons and holes – smaller positive feedback and smaller multiplication noise

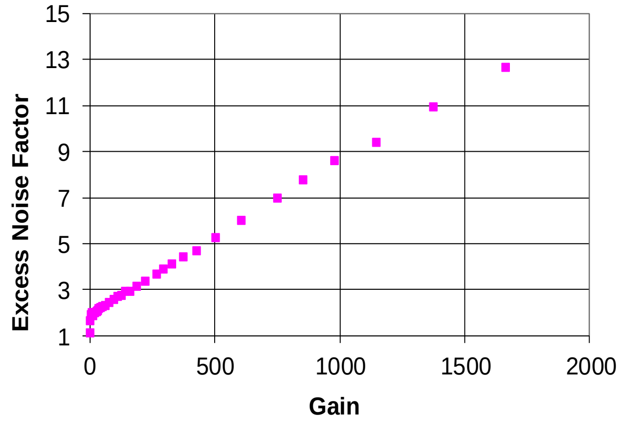
Silicon avalanche photodiodes operated below breakdown (CMS APDs)

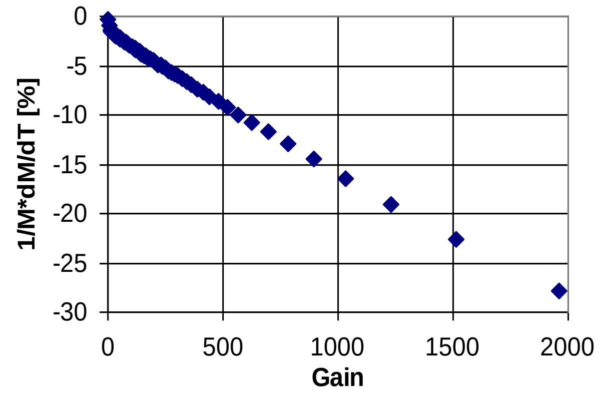












Advantages: high QE, gain up to 1000, area up to 2 cm^2

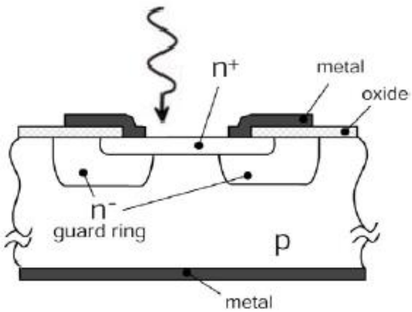
Disadvantages: ENF(multiplication noise) and temperature coefficient increases with increasing gain

APDs operated in Geiger mode

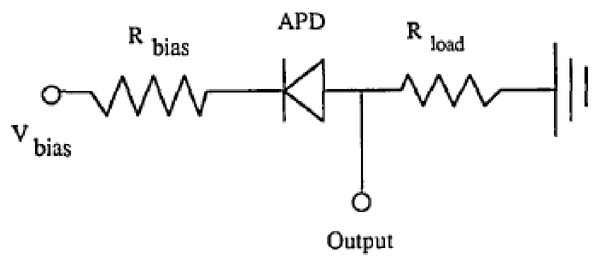
High gain → operate APDs over breakdown → Geiger mode APDs

Single pixel Geiger mode APDs developed a long time ago

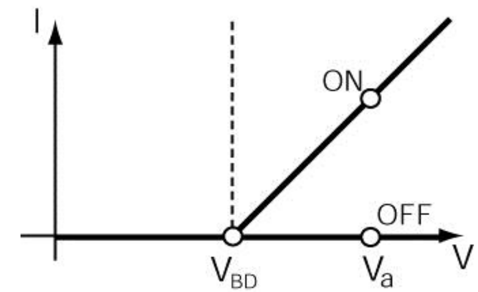
(see for example: *R.Haitz et al, J.Appl.Phys. (1963-1965)*)



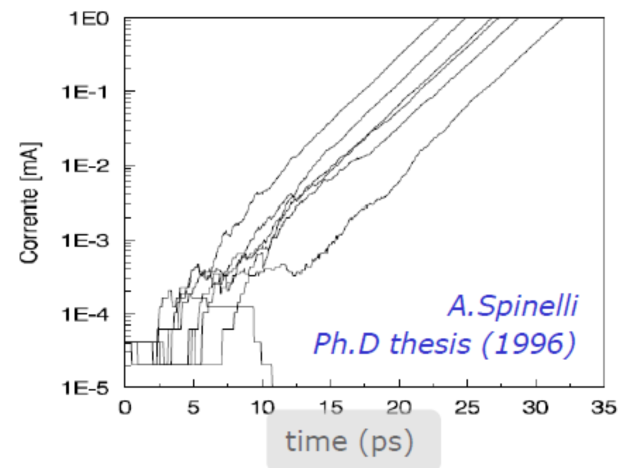
Planar APD structure



Passive quenching circuit



In G-M operation mode an APD bias voltage is set to few volts over breakdown voltage. In high electric field free carrier undergoes avalanche multiplication → produces very rapid current increase (few tens of ps). Rise of the current → drop of the voltage due to resistor in APD biasing circuit → current is reduced to a such level ("latch current") that statistical fluctuations may quench the avalanche. "Latch" current is ~20 μA. This sets a limit on the quenching resistor value (>100 kOhm for a few volts overvoltage). Finally voltage on APD is recovered to an initial value with time constant equal C_{APD}*R → APD is ready for another free carrier …

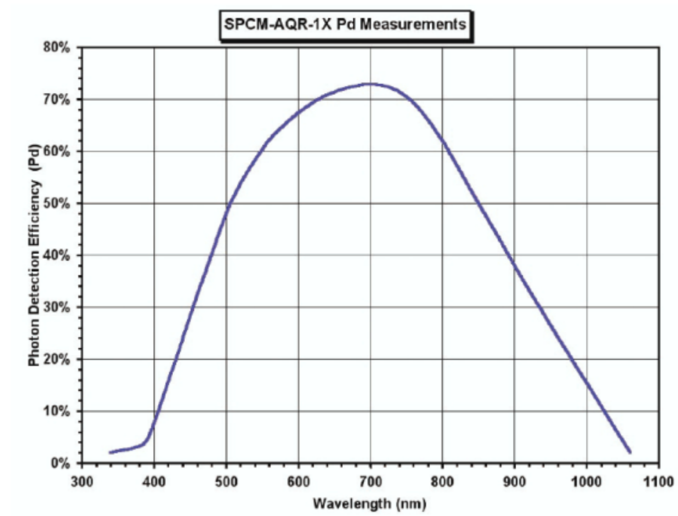


Single cell Geiger mode APDs

Photon counting module (Perkin Elmer/Excelitas)

Features

- Peak Photon Detection Efficiency @ 650 nm:
- 70% Typical
- Active Area: SPCM-AQR-1X: 175 µm
- Timing Resolution of 350 ps FWHM
- User Friendly
- Gated Input
- Single +5v Supply



- Very high PDE (up to 70 %) of APDs operated in Geiger mode

<u>but:</u>

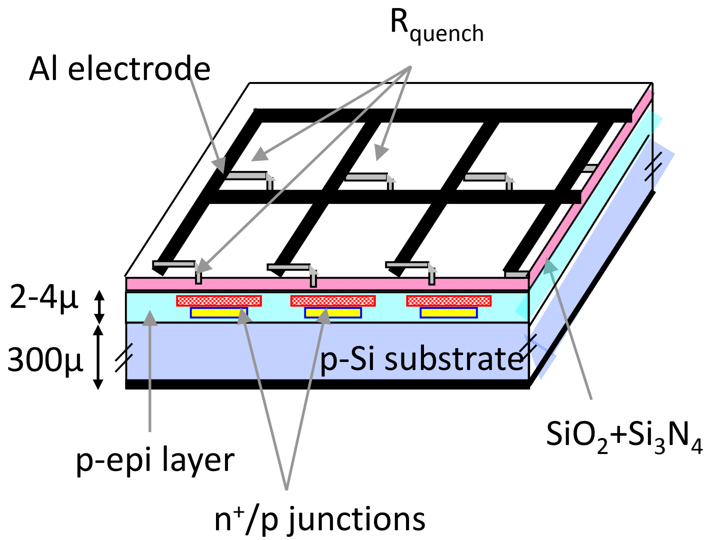
- Single pixel devices are not capable of operating in multi-photon mode
- Sensitive area is limited by dark count and dead time (few mm^2 Geiger mode APD can operate only at low temperature, needs “active quenching”)

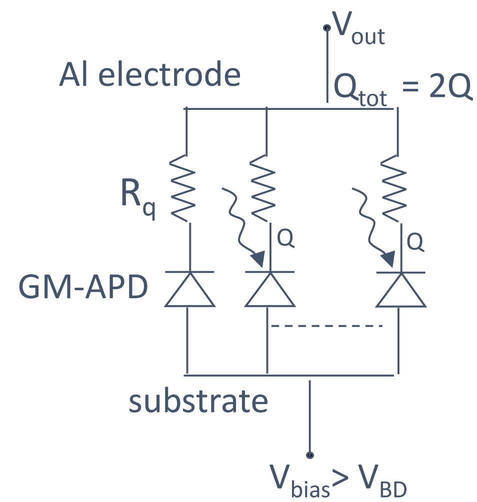
Solution: Multi-cell Geiger mode APD (SiPM)

Dark count rate – 500 Hz (25 Hz -selected)

Silicon photomultipliers (SiPMs)

Simplified SiPM structure and principles of operation (briefly)





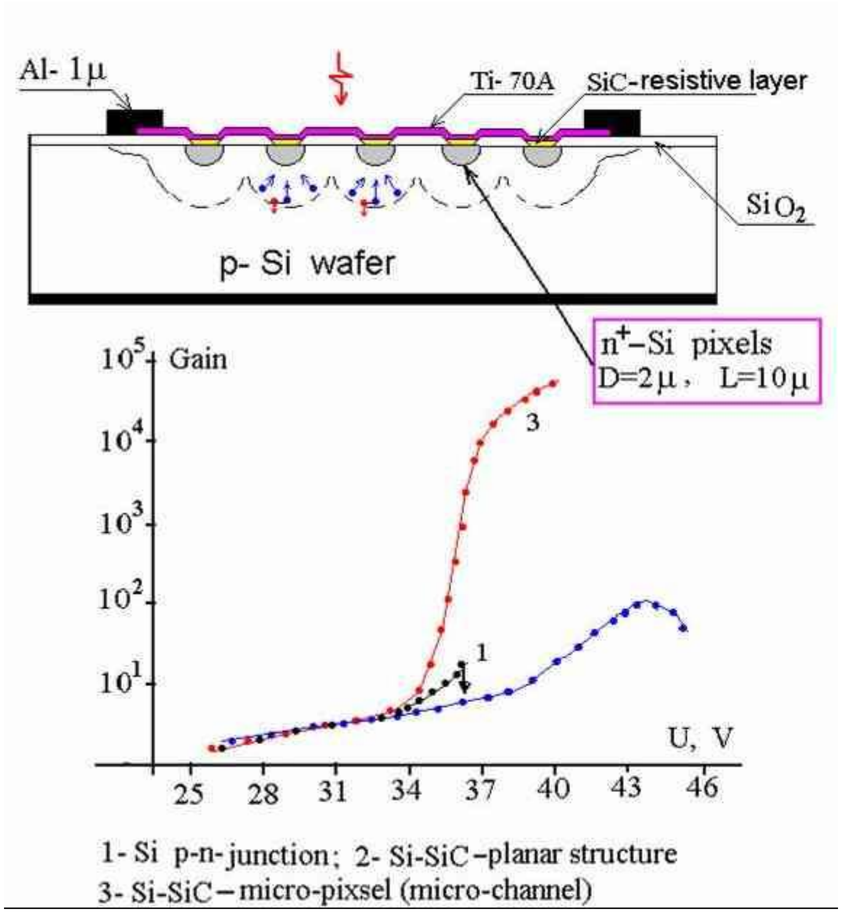
(EDIT-2011, CERN)

- *SiPM is an array of small cells (SPADs) connected in parallel on a common substrate and operated in Geiger mode*
- *Each cell has its own quenching resistor (from 100kΩ to several MΩ)*
- *Common bias is applied to all cells (~10-20% over breakdown voltage)*
- *Cells fire independently*
- *The output signal is a sum of signals produced by individual cells*

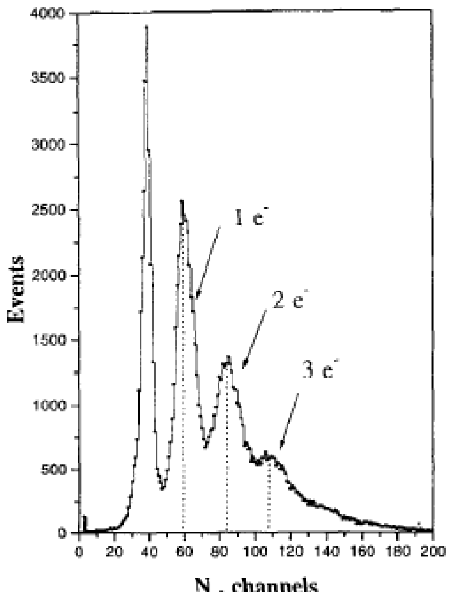
For small light pulses ($N_\gamma << N_{pixels}$) SiPM works as an analog photon detector

The very first SSPM design (MRS APD, 1989)

The very first metall-resitor-smiconductor APD (MRS APD) were proposed in 1989 by A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov (Russian patent #1702831, from 10/11/1989). APDs up to 5x5 mm2 were produced by MELZ factory (Moscow).



Few % photon detection efficiency for red light was measured with 0.5x0.5 mm^2 APD. Good pixel-to-pixel uniformity. Small geometrical efficiency. Very low QE for green and blue light.



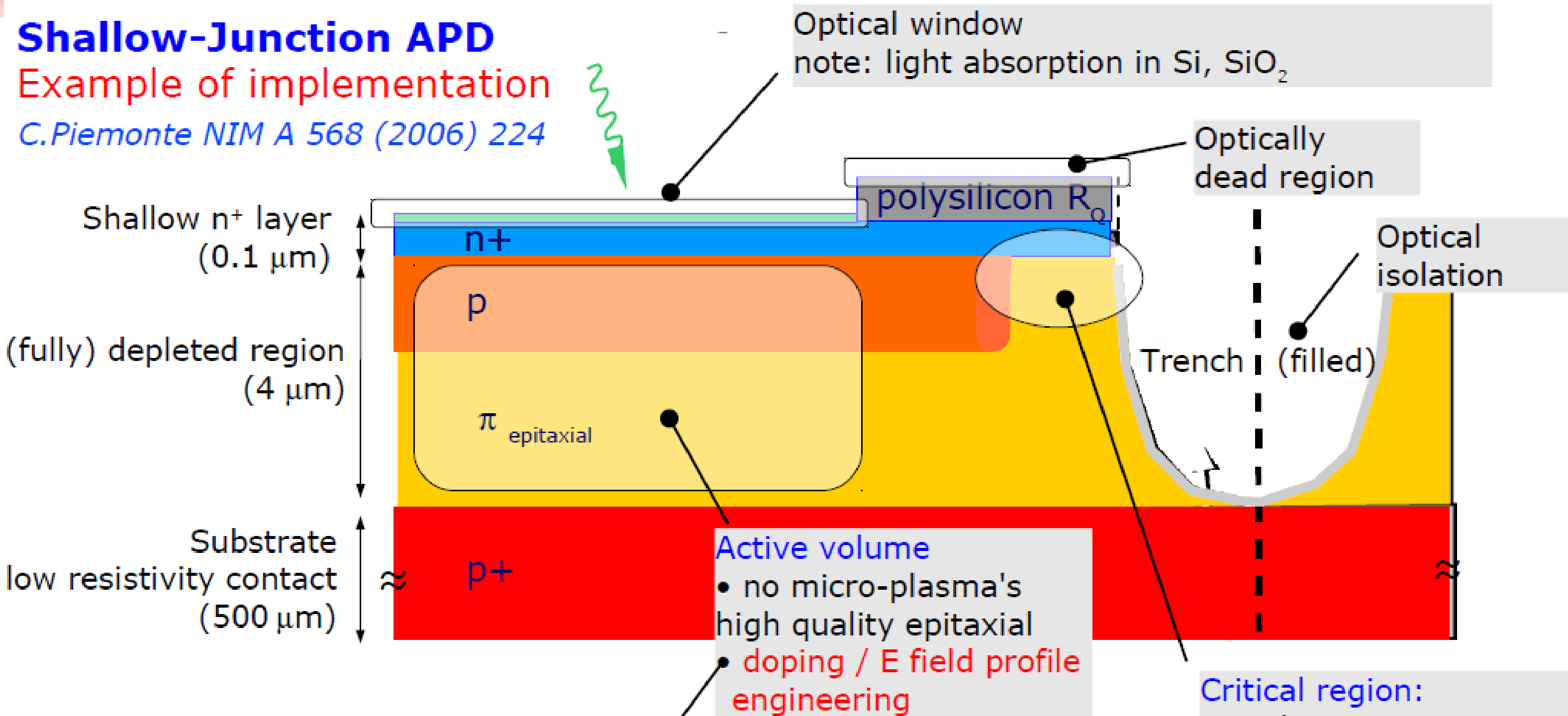
LED pulse spectrum
(A. Akindinov et al., NIM387 (1997) 231)

Key elements of typical SiPM cell

Shallow-Junction APD

Example of implementation

C.Piemonte NIM A 568 (2006) 224



Critical region:
- Leakage current
- Surface charges
- Guard Ring for
  - preventing early edge-breakdown
  - isolating cells
  - tuning E field shape

→impact on Fill Factor

- n⁺ on p abrupt junction structure
- Anti-reflective coating (ARC)
- Very thin (100nm) n⁺ layer: "low" doping
  → minimize Auger and SHR recombination
- Thin high-field region: "high" doping p layer
  → limited by tunneling breakdown
  → fixes V_{BD} junction well below V_{BD} at edge

Optimization for blue light (420nm)

- R_Q by poly-silicon
- Trenches for optical insulation (cross-talk)
- Fill factor: 20% - 80%

(slide taken from presentation of G. Collazuol at PhotoDst-2012)

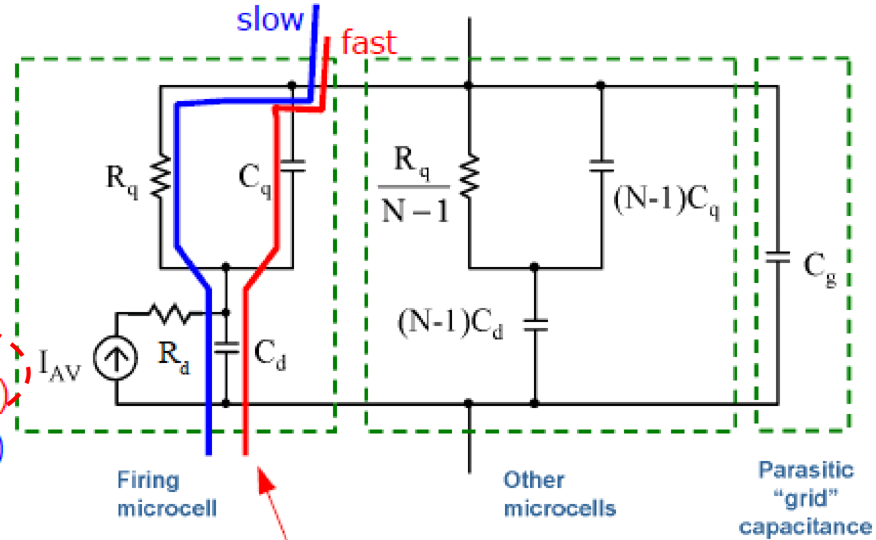
SiPM equivalent circuit (small signal model) and pulse shape

Single cell model → $(R_d||C_d)+(R_q||C_q)$
SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

Signal = slow pulse $(\tau_{d\,(rise)}, \tau_{slow\,(fall)})$ +
+ fast pulse $(\tau_{d\,(rise)}, \tau_{fast\,(fall)})$

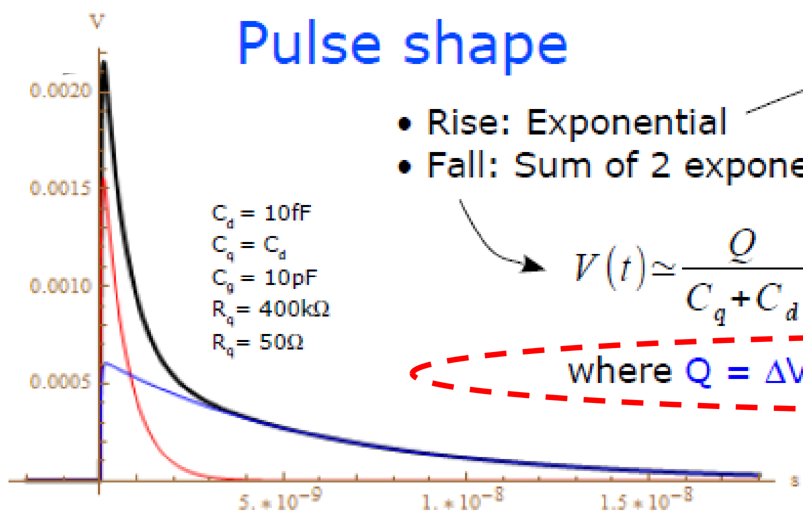
- $\tau_{d\,(rise)} \sim R_d(C_q+C_d)$
- $\tau_{fast\,(fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{slow\,(fall)} = R_q(C_q+C_d)$ (slow; cell recovery)

F.Corsi, et al. NIM A572 (2007) 416
S.Seifert et al. IEEE TNS 56 (2009) 3726



Cq → fast current supply path in the beginning of avalanche

Pulse shape



- Rise: Exponential → Sp.Charge Rd x Cd,q filtered by parasitic inductance, stray C, … (Low Pass)
- Fall: Sum of 2 exponentials

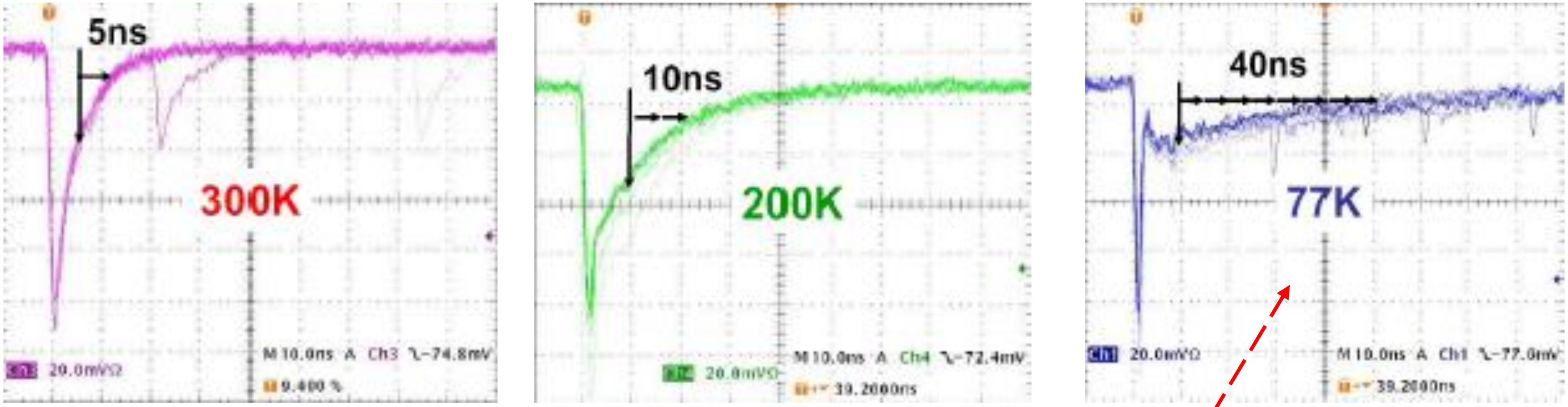
$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right) \quad \text{for } R_{load} << Rq$$

where $Q = \Delta V\ (C_q+C_d)$ is the total charge released by the cell

→ 'prompt' charge on C_{tot} is $Q_{fast} = Q\ C_q/(C_q+C_d)$

(slide taken from presentation of G. Collazuol at PhotoDst-2012)

Pulse shape vs. T



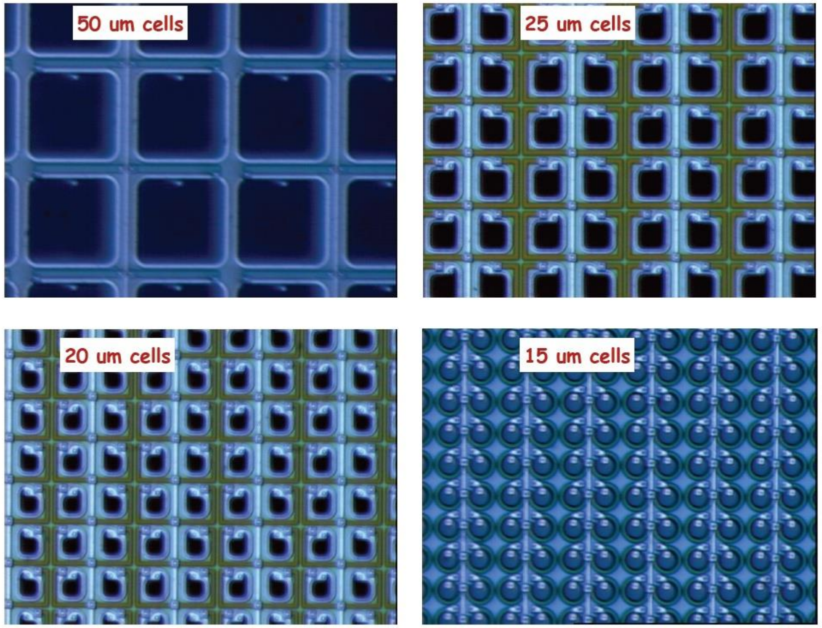
(H. Otono et. al, PD-07)

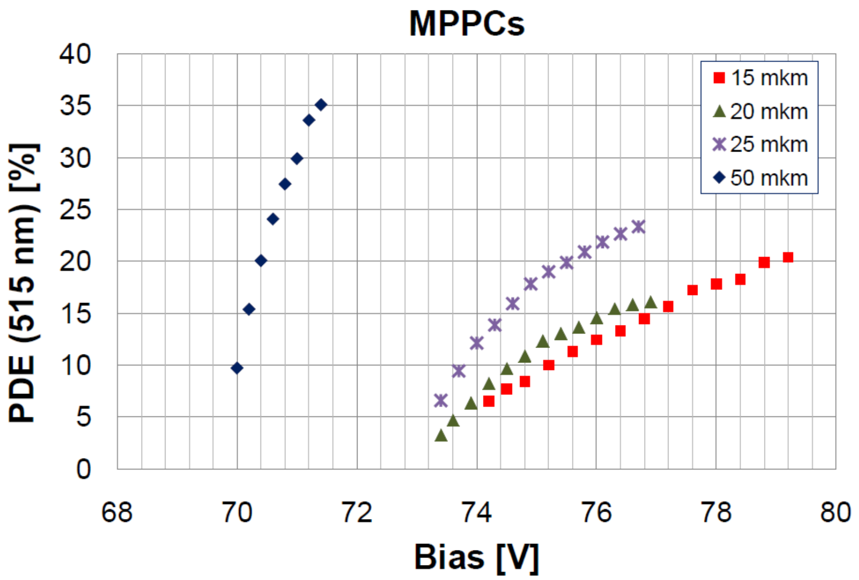
Fast and slow components behave differently with temperature:

- Fast - doesn't depend
- Slow – time constant increases with T due to R_q increase

For HPK SiPM with polysilicon quenching resistor the slow time constant increases ~8 times when temperature drops from 300 K to 77 K

Photon detection efficiency & Geometric factor



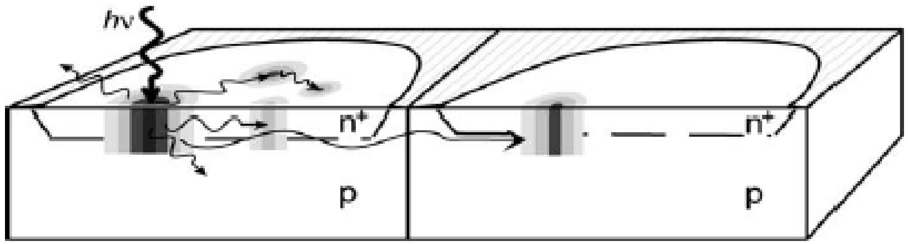


(Yu.Musienko, CTA SiPM Workshop, Geneva, 2014)

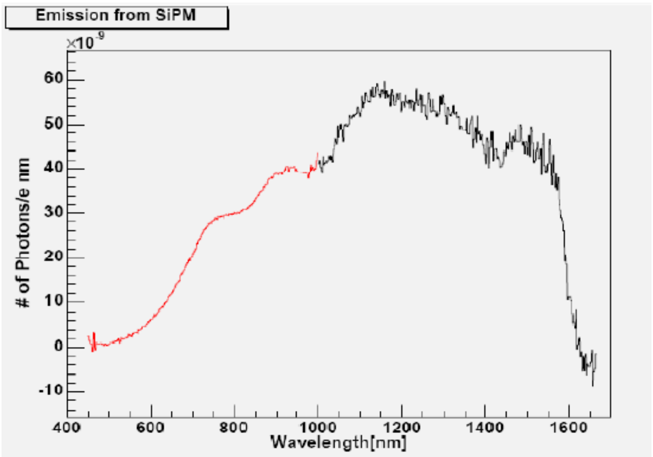
$PDE(\lambda, U,T) = QE(\lambda)*G_f*P_b(\lambda,V,T)$

Cells should be electrically independent → "dead" space between SiPM cells reduces its PDE. It is especially important for the small cell pitch SiPMs

Optical cross-talk between cells (direct cross-talk)



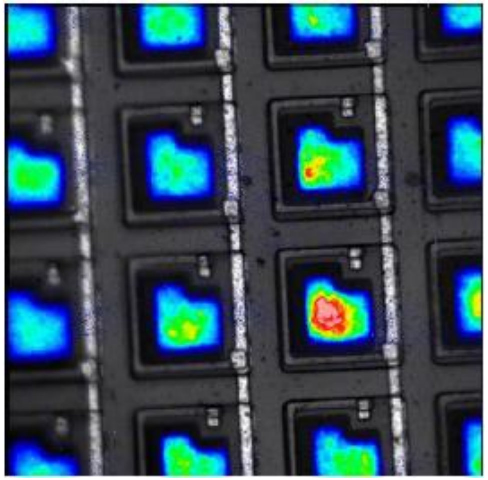
A. Lacaita et al, IEEE TED (1993)



(R. Mirzoyan, NDIP08, Aix-les-Bains)

Cellls are not optically independent!
Light is produced inside firing cell due to hot-carrier luminescence process:
10^5 carriers produces ~3 photons with an wavelength less than 1 μm.
Optical cross-talk causes adjacent pixels to be fired → increases gain fluctuations → increases noise and excess noise factor !

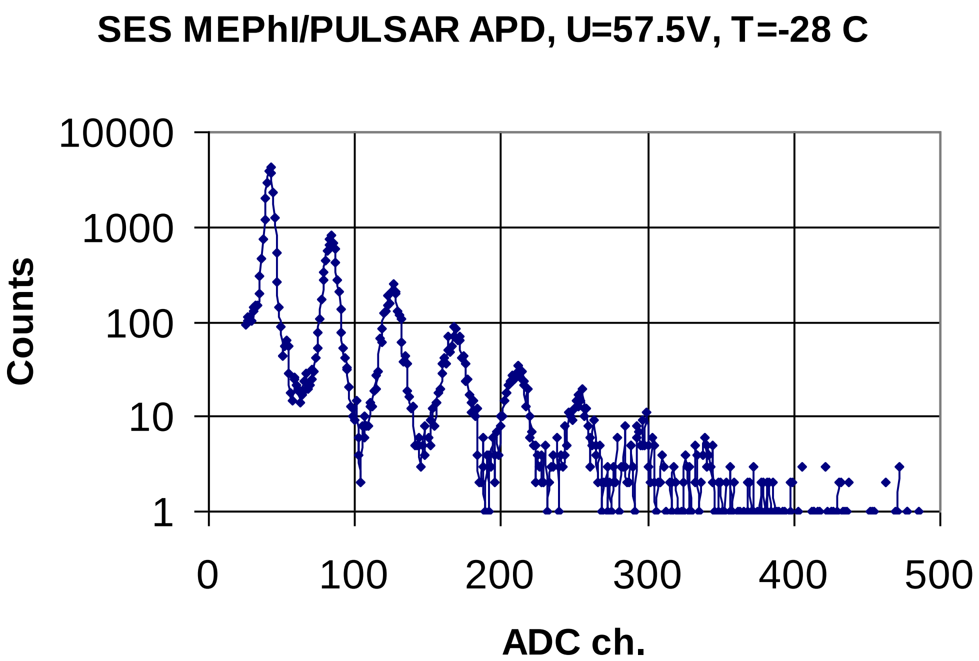
Avalanche luminescence



N.Otte, SNIC-2006

Optical crosstalk and Single electron spectra

When $V-V_b$>>1 V typical single pixel signal resolution is better than 10% (FWHM)). However an optical cross-talk results in more than one pixel fired by single photoelectron. This results in deterioration of SiPMs SES and …



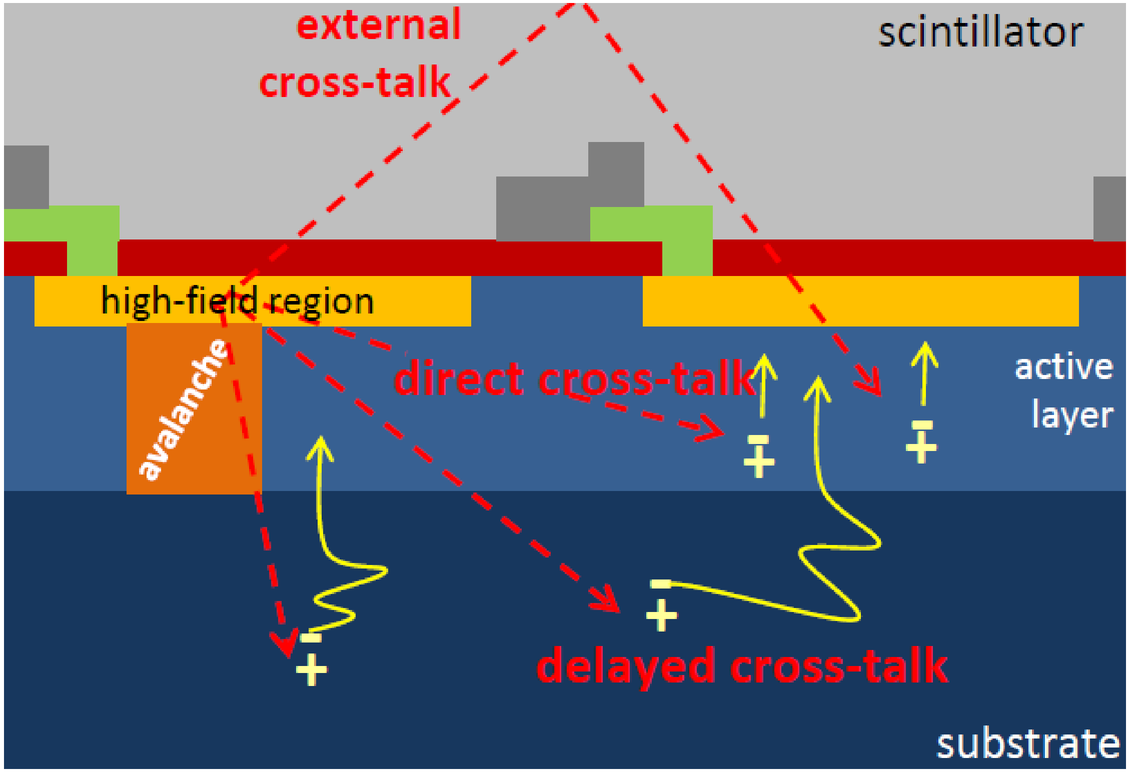
Amplitude spectra of SiPM measured with very low light intensity (<<1 photon/pulse) and electronics threshold ~0.5 pe.

(Y. Musienko, NDIP-05, Beaune)

SiPMs: Optical cross-talk - II

Other effects of cell luminescence:

- External cross-talk (light can be reflected from optical interface to another SiPM cell)
- Delayed pulses from light absorbed in non-depleted region (look like after-pulses)

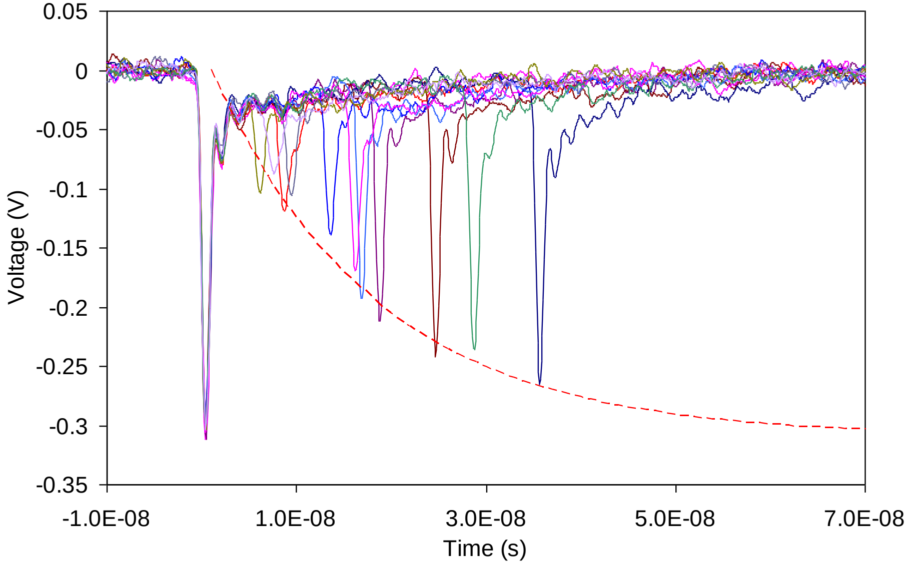


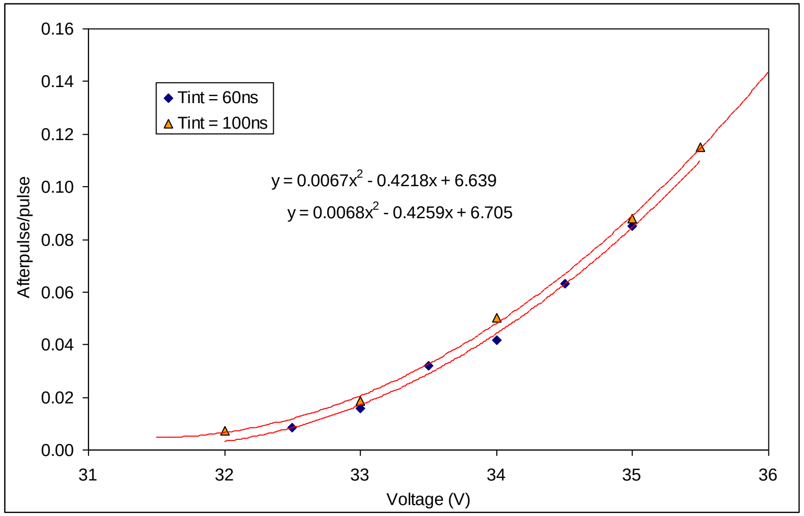
Fabio ACERBI - PhotoDet 2015

After-pulses

Carriers trapped during the avalanche discharging and then released trigger a new avalanche during a period of several 100 ns after the breakdown → after-pulses

(C. Piemonte: June 13th, 2007, Perugia)



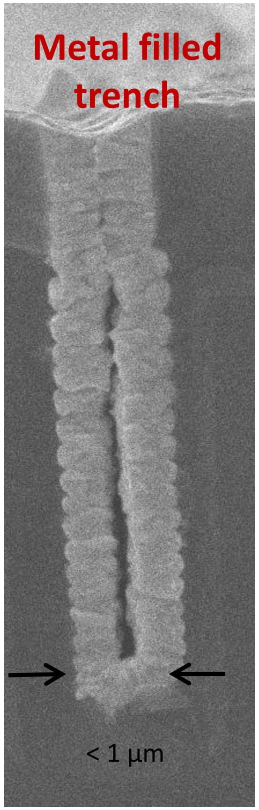


Events with after-pulse measured on a single cell.

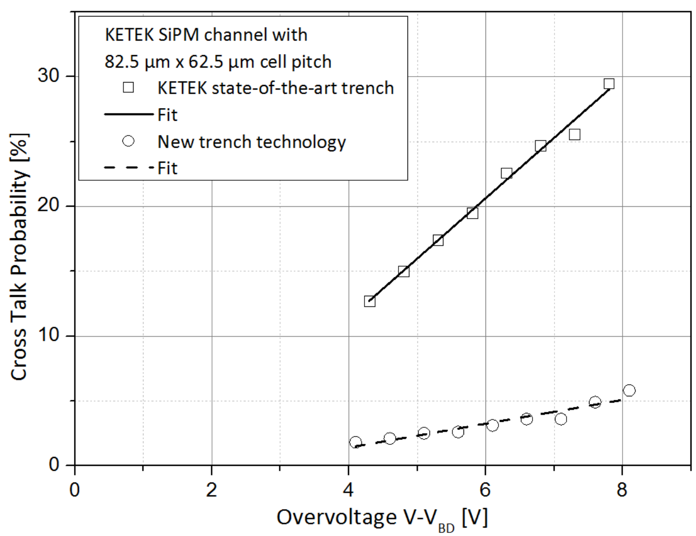
After-pulse probability *vs* bias

Solution: "cleaner" technology, smaller gain, blocking layer to stop delayed pulses from Si bulk → after-pulsing reduced to < 2%

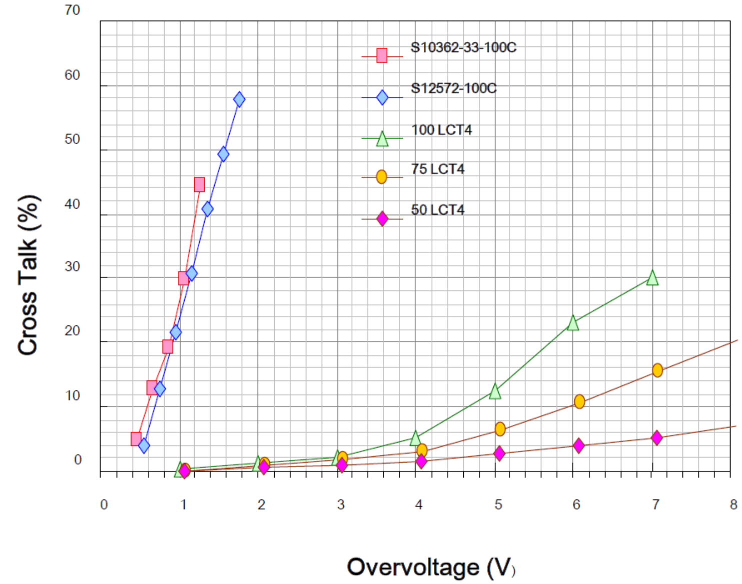
X-talk reduction



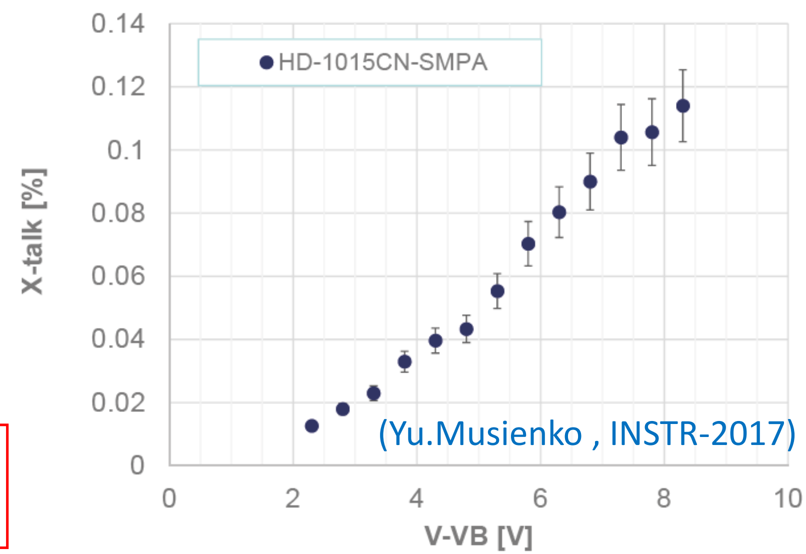
The way to reduce X-talk: trench filled with non-transparent material (tungsten)



(KETEK – Photodet-2015 (Troitsk))



(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)



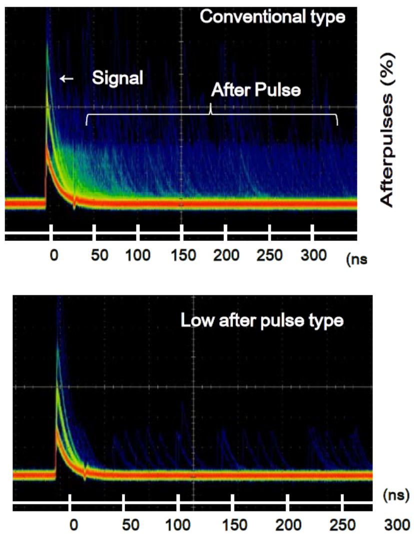
(Yu.Musienko , INSTR-2017)

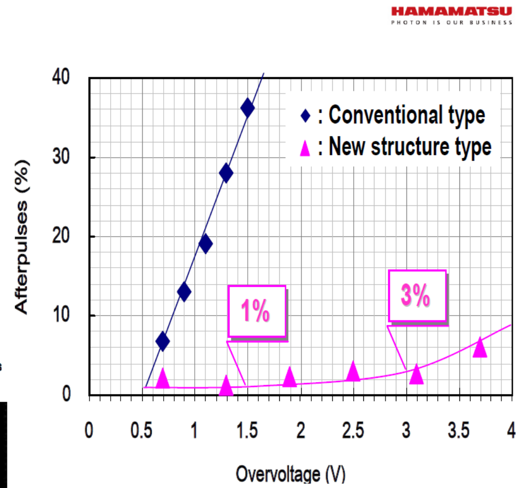
Extremely low X-talk value of 0.05% was measured for the Hamamatsu HD-1015CN SiPM

Afterpulsing and delayed X-talk reduction

Low After Pulses

Example of After pulse suppression





After pulse probability has been suppressed by optimization of structure and material.
All new MPPC series have very lower after pulses compared with conventional type.

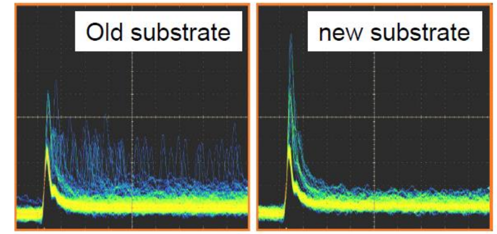
(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

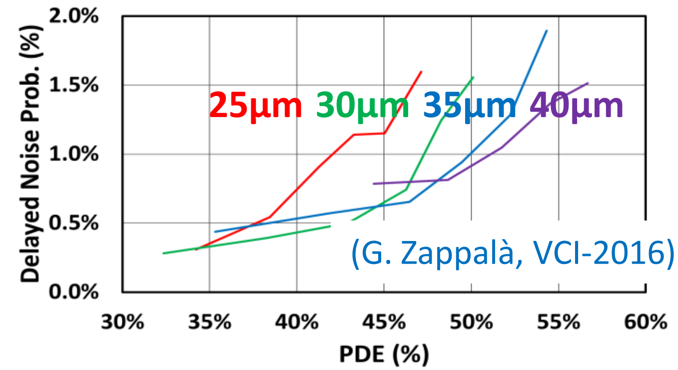
- Improved substrate

Minority carrier lifetime reduced ~ 2 order of magnitude

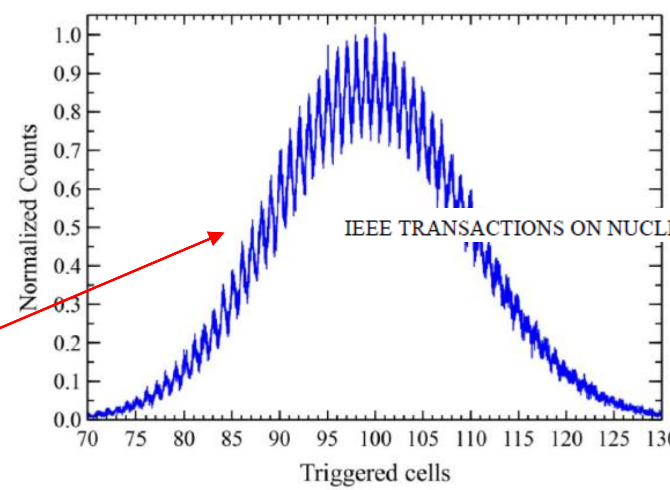
→ lower delayed correlated noise

F. Acerbi et. al., IEEE T. Nucl. Sci., vol. 62, n. 3, 2015





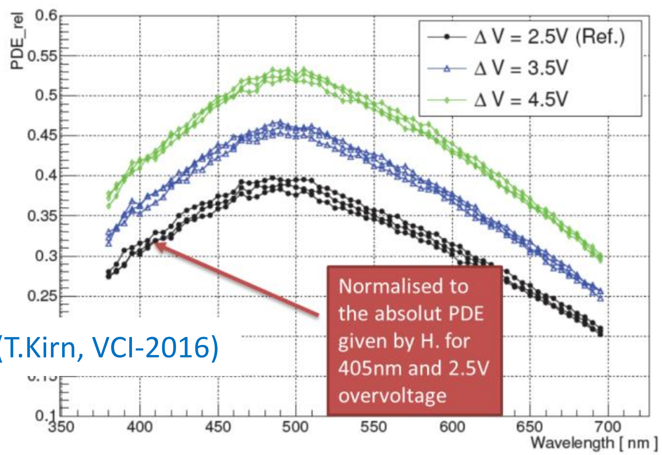
(G. Zappalà, VCI-2016)



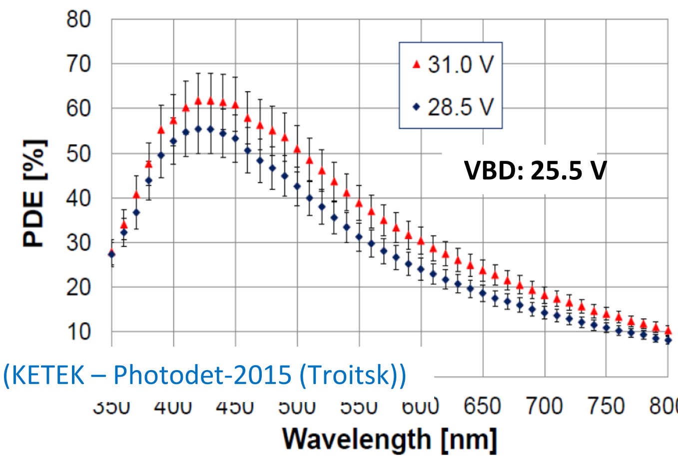
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 3, JUNE 2015

After-pulsing and delayed X-talk were reduced from 30% to <1.5% at high overvoltage (FBK NUV SiPM)

SiPMs: PDE increase

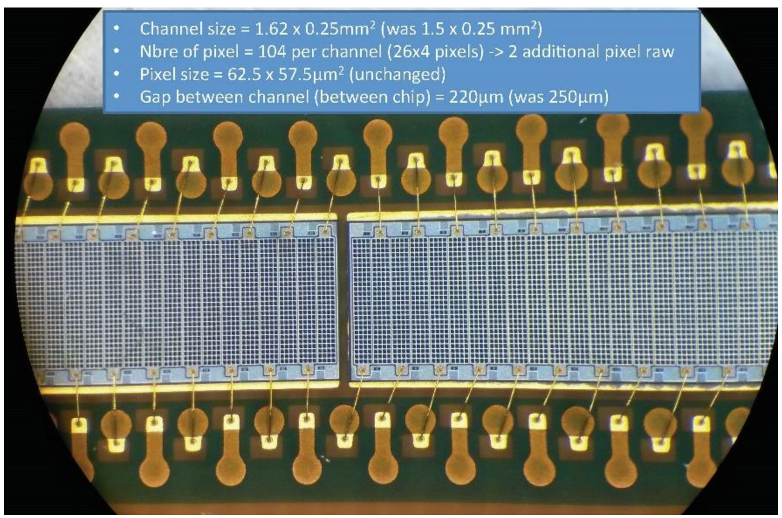


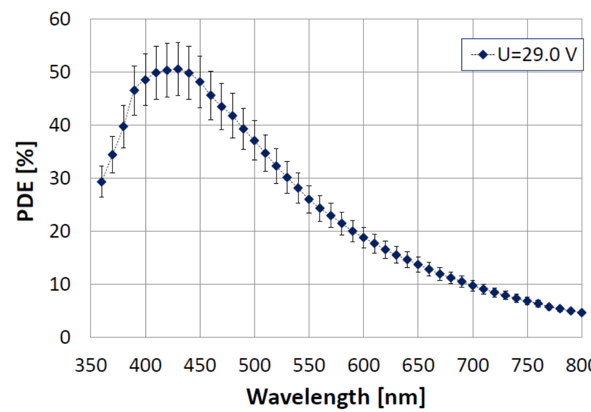
(T.Kirn, VCI-2016)



(KETEK – Photodet-2015 (Troitsk))

SiPM array for LHCb Scintillating Fibre Tracker



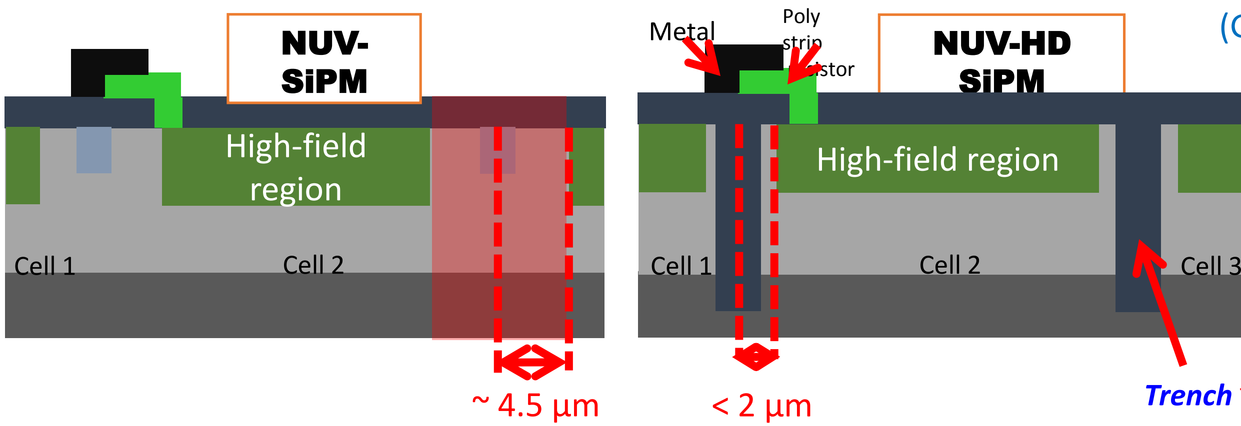


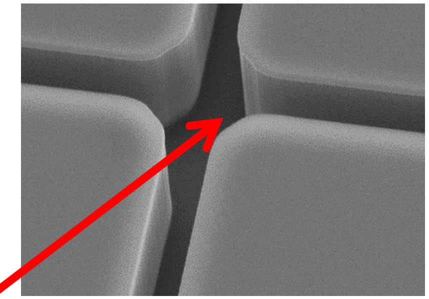
(SensL MicroFJ-SMA-3035-E46, CERN APD Lab)

Small X-talk and after-pulsing allow SiPM operation at high over-voltages. As a result maximum PDE increased from 20 ÷ 30% to 50 ÷ 60 % (SiPMs with 43÷50 µm cell pitch).

PDE increase: SiPMs with very thin trenches

(G. Zappalà(FBK), VCI-2016)



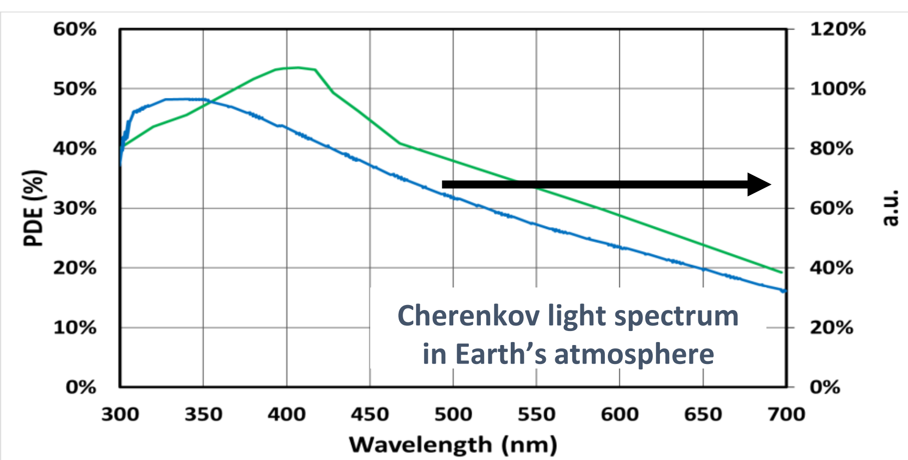


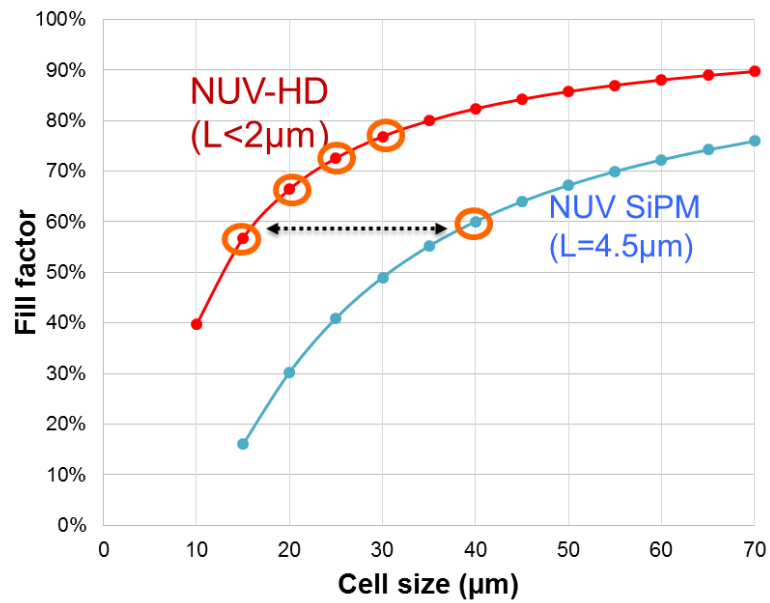
NUV High-Density (HD) technology:

Lower dead border region → Higher Fill Factor

Trenches between cells → Lower Cross-Talk

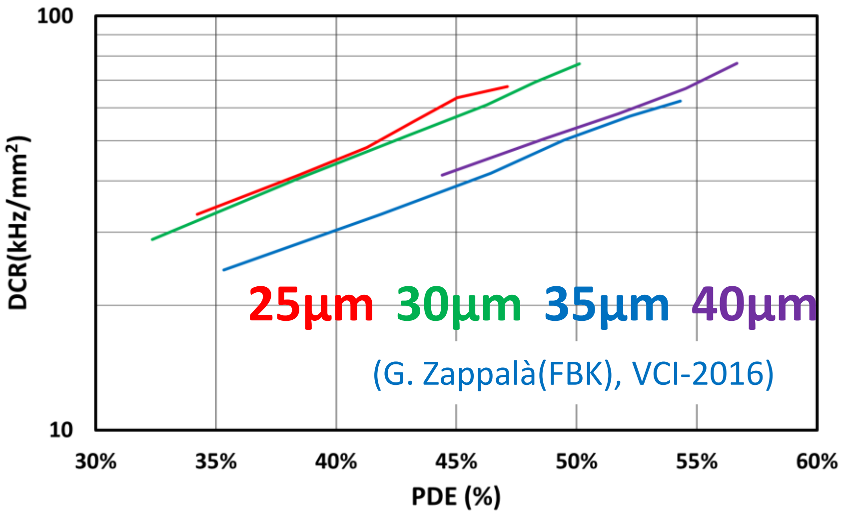
NUV-HD 30µm Cell Pitch PDE, 10V OV

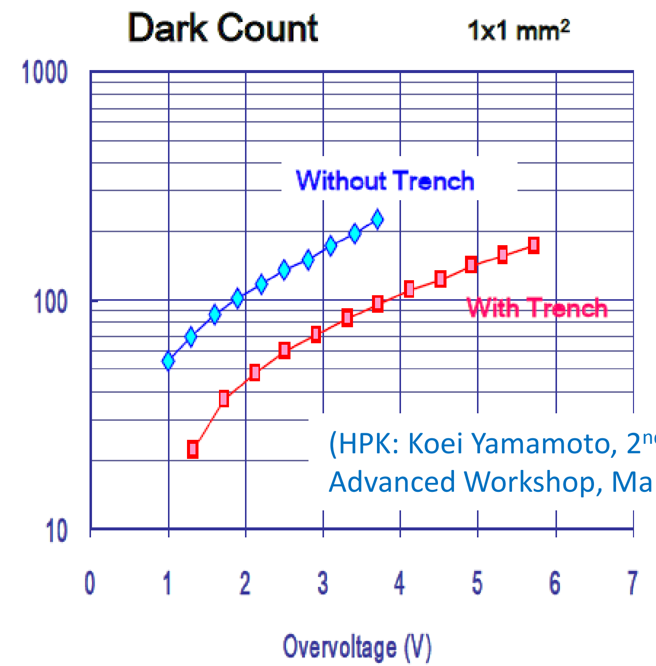




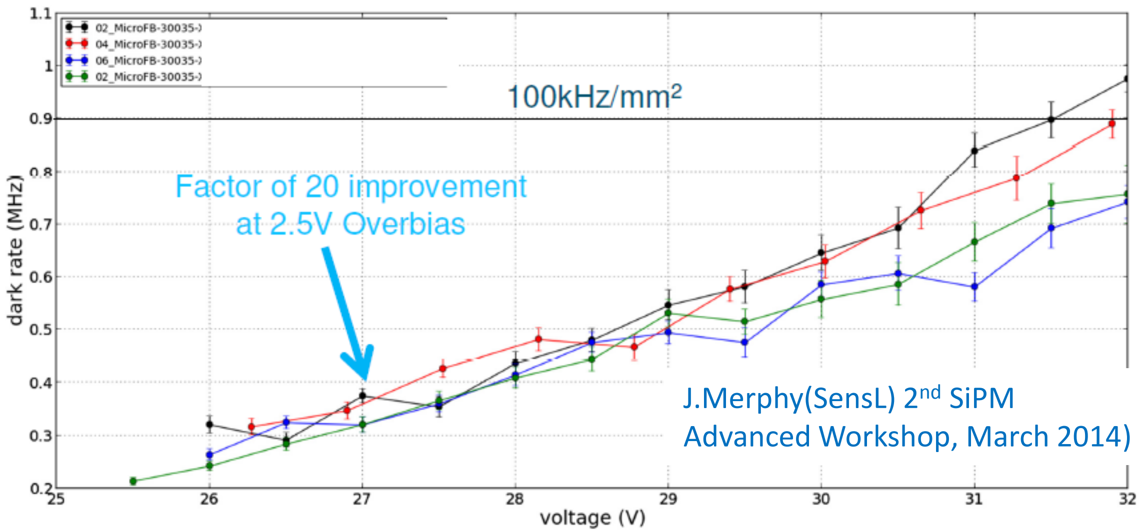
30 µm cell pitch SiPMs: GF=77% → PDE>50 % !!

Dark noise reduction





(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

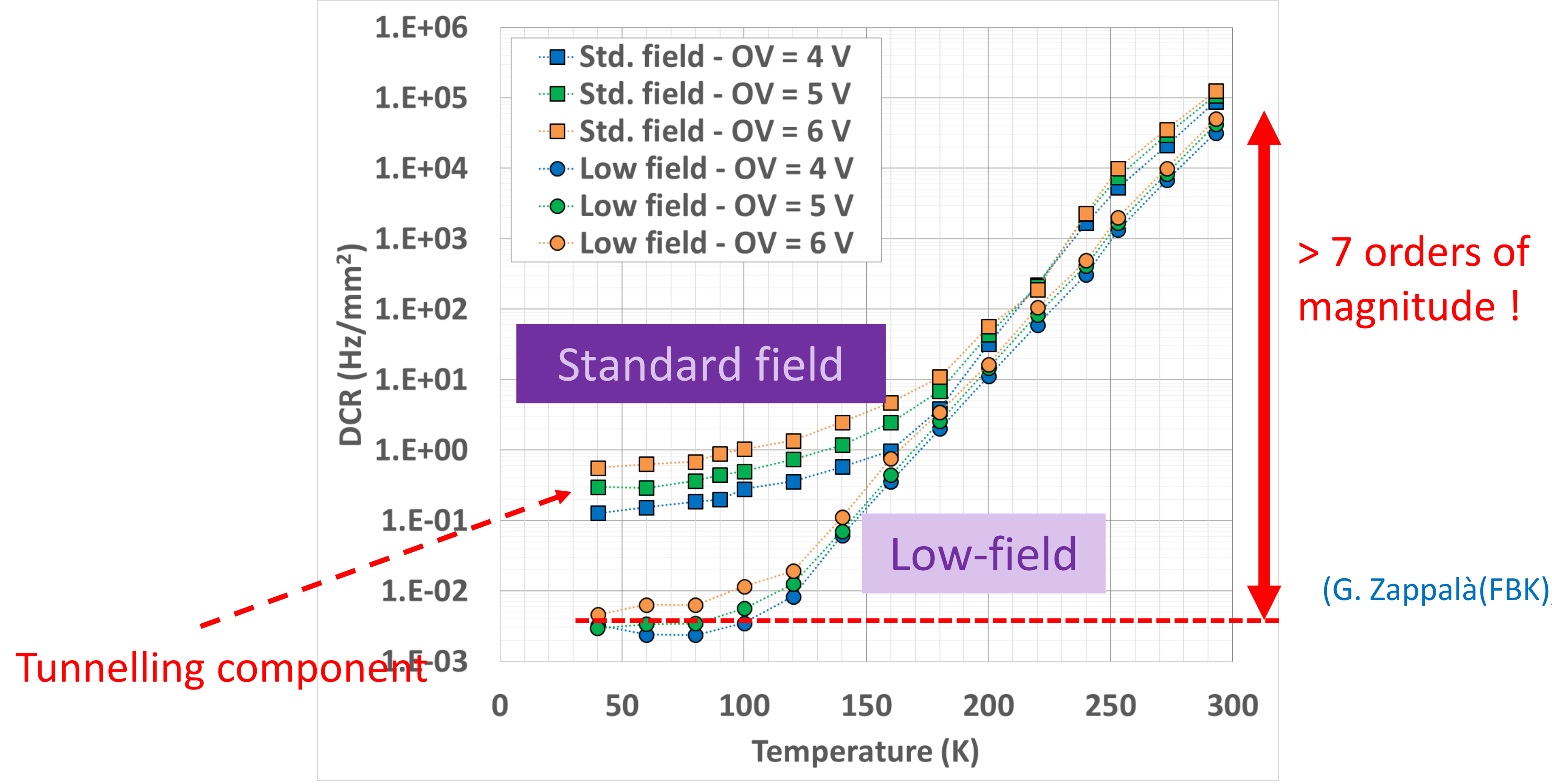


J.Merphy(SensL) 2nd SiPM Advanced Workshop, March 2014)

Gettering? Dark Count ~30 kHz/mm² was measured at dVB=2÷3 V at room temperature with SiPMs from several producers. Now it becomes a standard!!

Dark noise at low temperature

Dark noise can be significantly reduced by lowering SiPM temperature. However, tunnelling is a limiting factor for SiPM dark noise reduction at low T.
A low-electric field NUV-HD version has been developed by FBK to reduce the tunnelling component of the DCR.



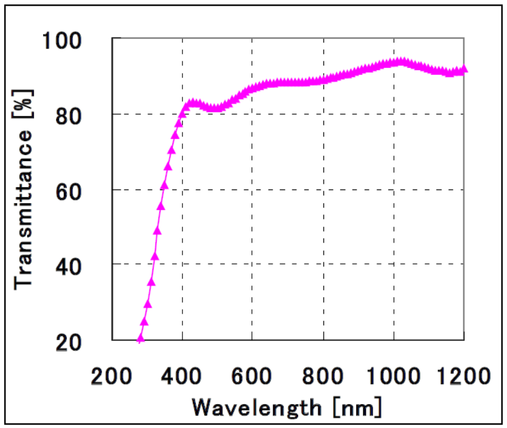
(G. Zappalà(FBK), VCI-2016)

A 10x10 cm^2 SiPM array would have a total DCR < 100 Hz!

Further GF increase: Metal Film Quenching Resistor

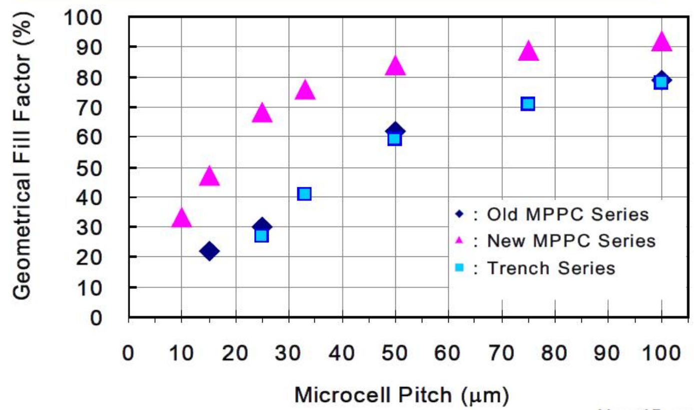
Polysilicon quenching resistors occupy some of the cell's sensitive area. They are non-transparent for UV/blue/green light. The loss of sensitivity can be significant (especially for small cells). Solution proposed by Hamamatsu → transparent MFQ resistors

Metal Film Transmittance

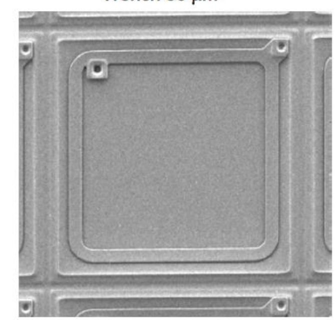


(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

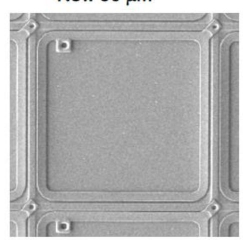
Microcell Pitch, Geometrical Fill Factor



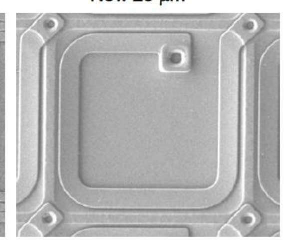
Trench 50 µm



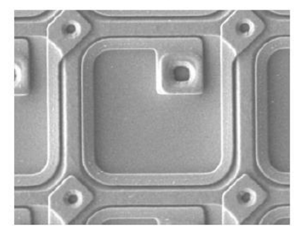
New 50 µm



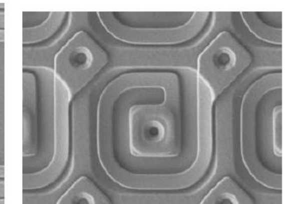
New 25 µm



New 15 µm



New 10 µm



Good Uniformity of resistance
(full 6-inch wafer)

Width	Poly-Si	Metal
2 µm	19%	9%
1 µm	37%	11%

Low Temperature coefficient of resistance

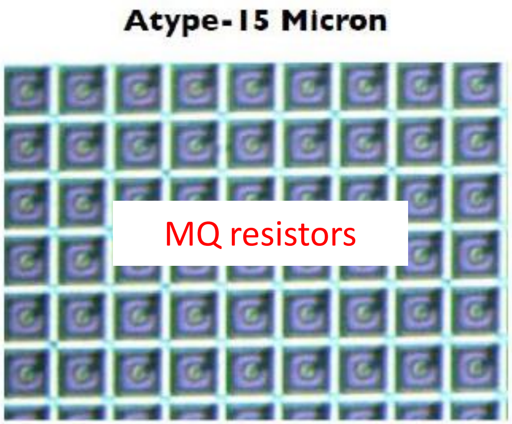
Poly-Si	Metal
-2.37 kΩ	-0.43 kΩ

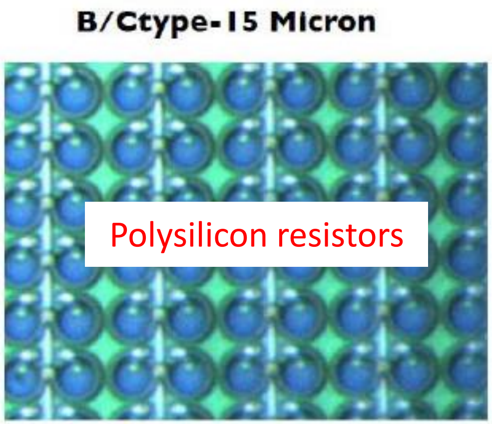
(/deg C)

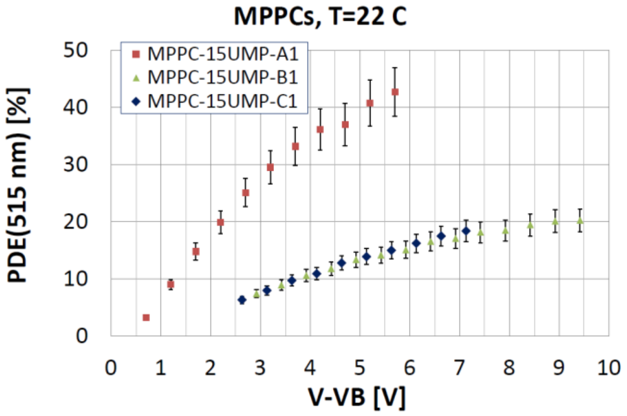
Another advantages of MFQ resistors are better uniformity and relatively small temperature coefficient → smaller cell recovery time change with temperature

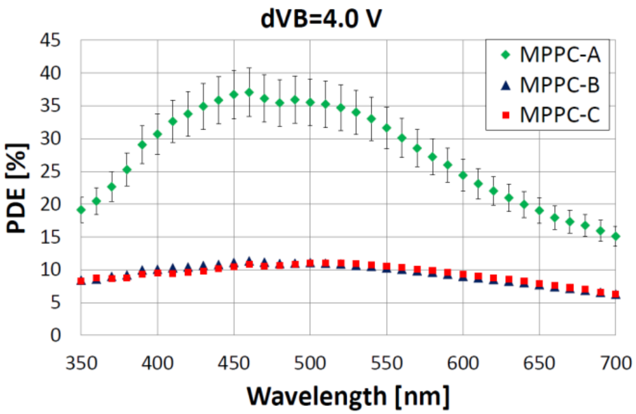
SiPMs with Metal Quenching Resistor: PDE increase

MPPCs developed by HPK for the CMS HCAL Upgrade project









PDE(515 nm)>30% for 15 μm cell pitch MQR MPPCs. It was improved by a factor of >3 in comparison to the 15 μm cell pitch MPPCs with polysilicon quenching resistors.

Linearity and dynamic range (small signal model)

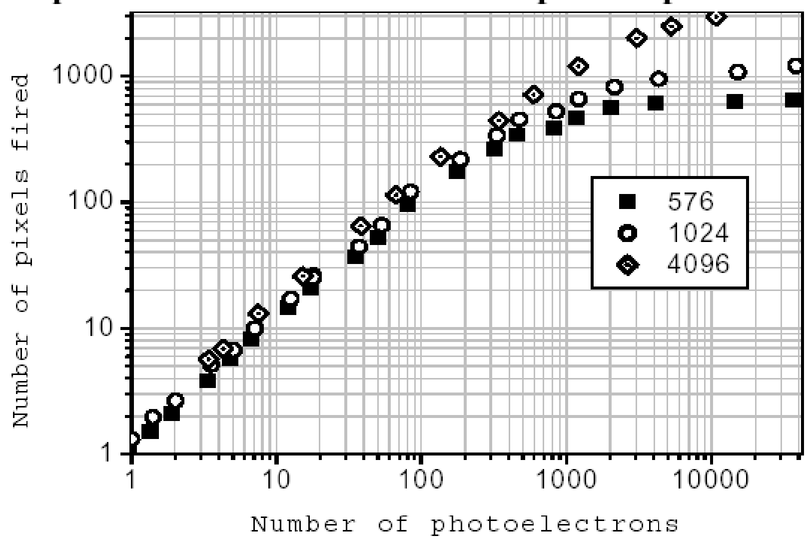
Linearity of SiPM is determined by its total number of pixels

In the case of uniform illumination:

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

This equation is correct for light pulses which are shorter than pixel recovery time , and for an “ideal” SiPM (no cross-talk and no after-pulsing). For slow light pulses SiPM dynamic range increases by a factor of:
τ(emission)/τ(cell recovery)

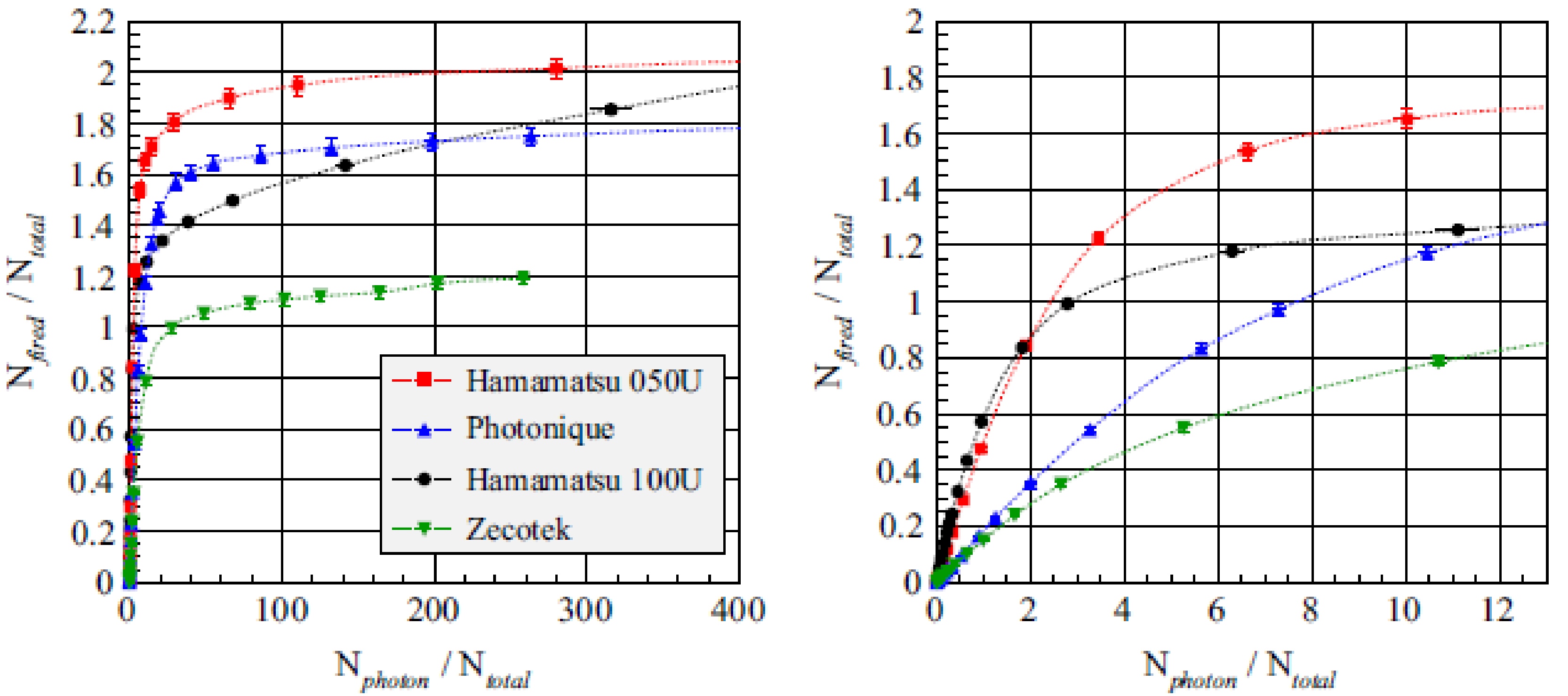
Response functions for the SiPMs with different total pixel numbers measured for 40 ps laser pulses



(B. Dolgoshein, TRD05, Bari)

Over saturation behaviour of SiPMs at high photon exposure

L. Gruber et al. / Nuclear Instruments and Methods in Physics Research A 737 (2014) 11–18

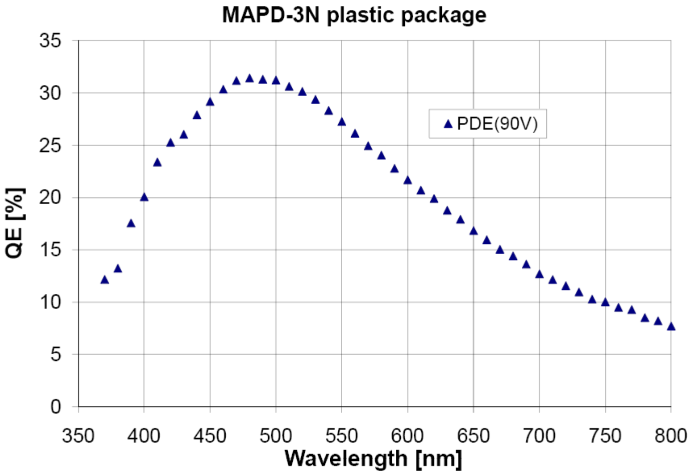


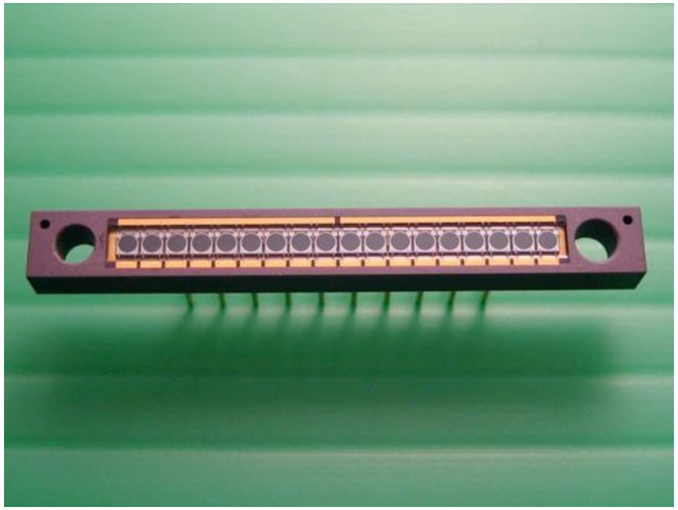
Over saturation behaviour of SiPMs at high photon exposure was observed by L. Gruber et al. Several types of silicon photomultipliers were exposed to short pulsed laser light (~30ps FWHM) with its intensity varying from single photon to well above the number of microcells of the device. A significant deviation of the output of SiPMs from the expected behaviour was observed at very high photon exposure.

The future of SiPMs: UHD SiPMs

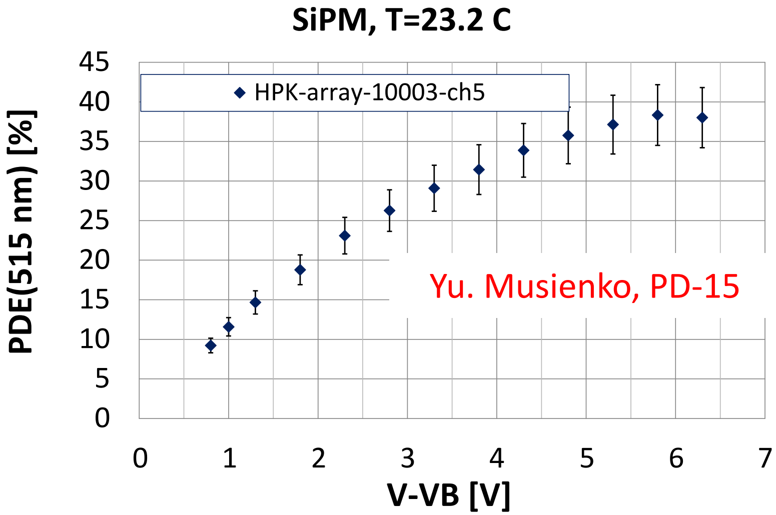
During last 3 years very high geometric factors (up to 80%) were achieved with small cell pitch SiPMs or (Ultra High Density SiPMs). Small cells have many advantages: low gain → smaller X-talk, after-pulsing, recovery time; larger dynamic range, possibility to operate SiPMs at high over-voltages, better resistance to radiation: smaller dark currents of irradiated SiPMs, smaller power dissipation, reduced blocking effects. Small cells potentially should provide better timing resolution (smaller avalanche development time)

Previous development: linear array of MAPDs (18x1 mm^2 , 15 000 cells/mm^2) produced by Zecotek for the CMS HCAL Upgrade project.

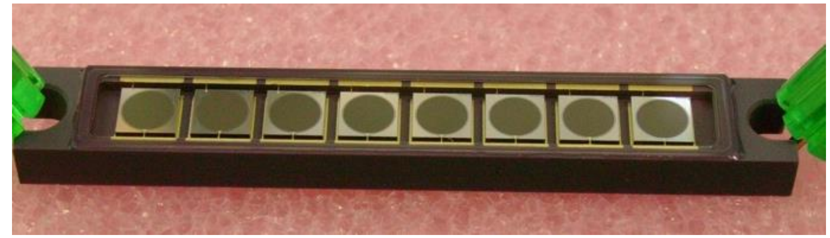




Large dynamic range SiPMs for the CMS HE HCAL Upgrade

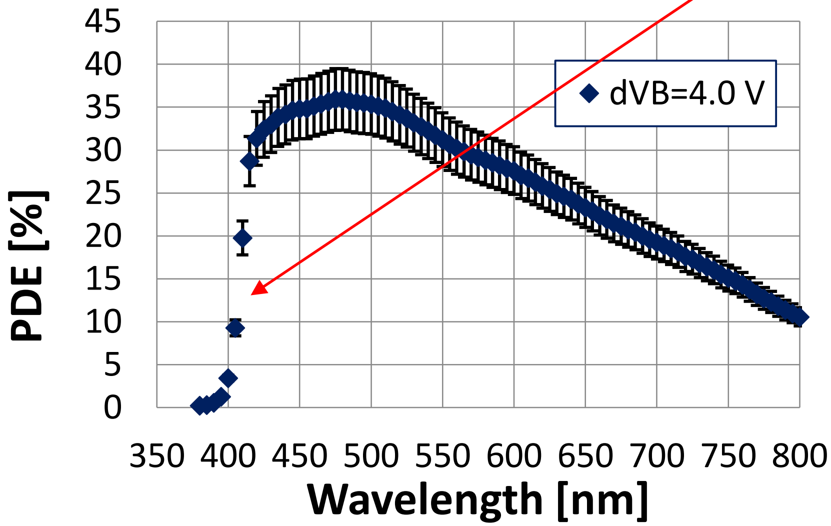


8-ch. SiPM array for the CMS HE HCAL Upgrade project: Ø2.8 mm SiPMs, 15 μm cell pitch

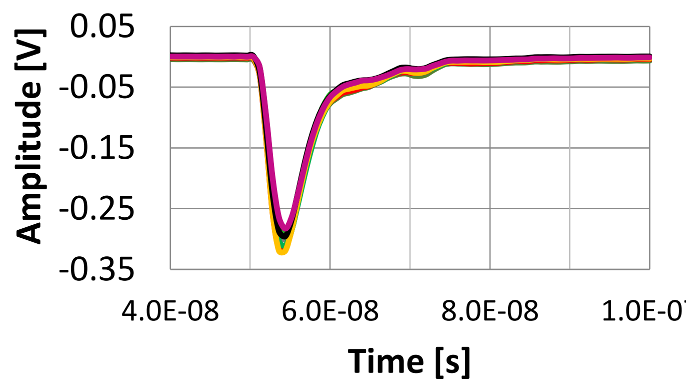


Glass widow with special filter was designed by HPK to cut off UV light which can be produced by muons and hadrons in plastic fibers

1400 SiPM arrays have been delivered to CERN during this year

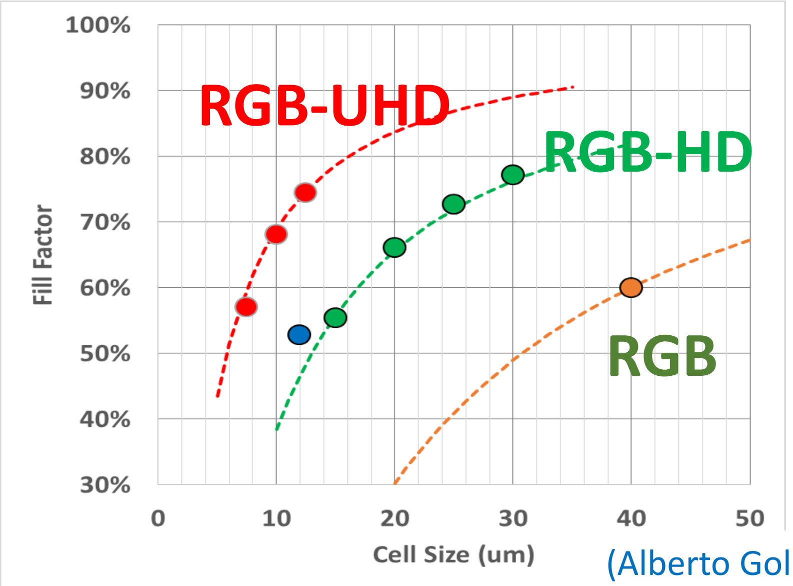


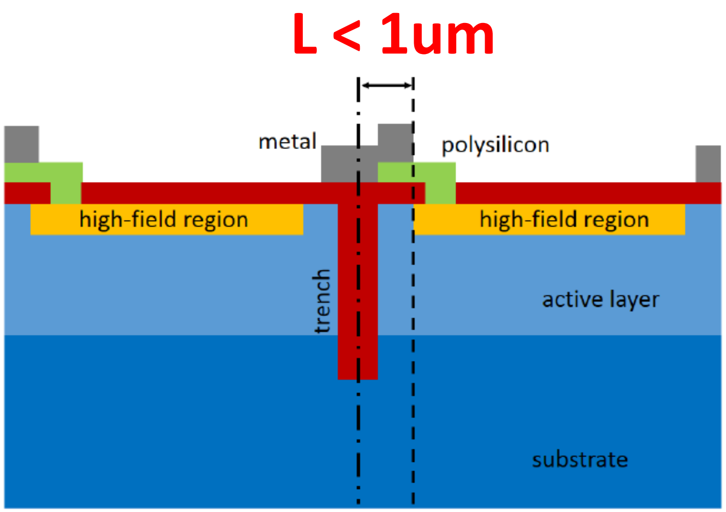
SiPM laser response



Recovery time 7-8 ns

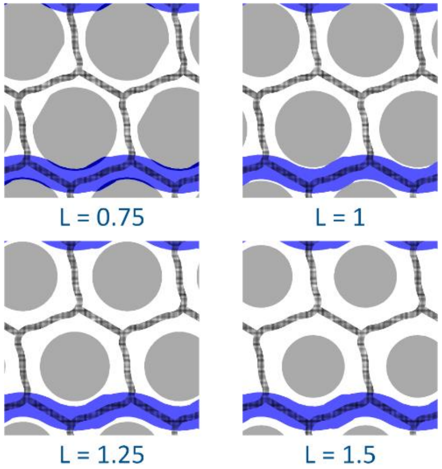
FBK UHD2 SiPMs



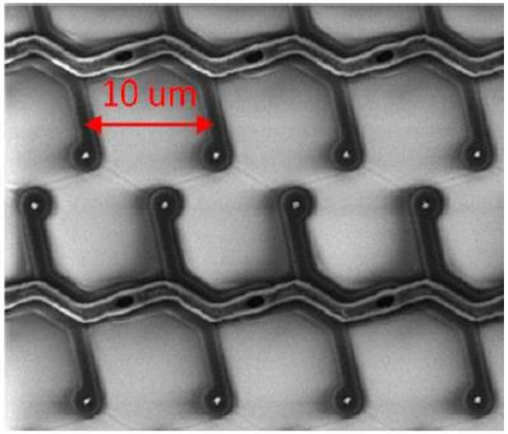


(Alberto Gola – PhotoDet 2015, Troitsk)

Cell sensitive area vs. trench width



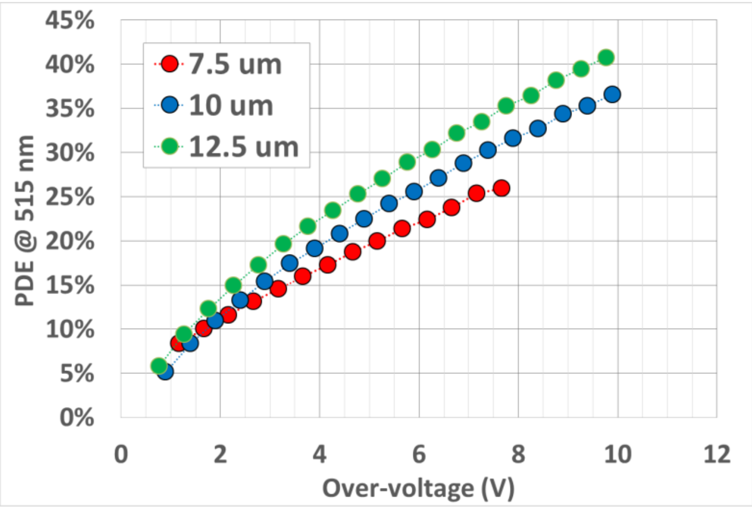
Finished 10 μm cell pitch SiPM

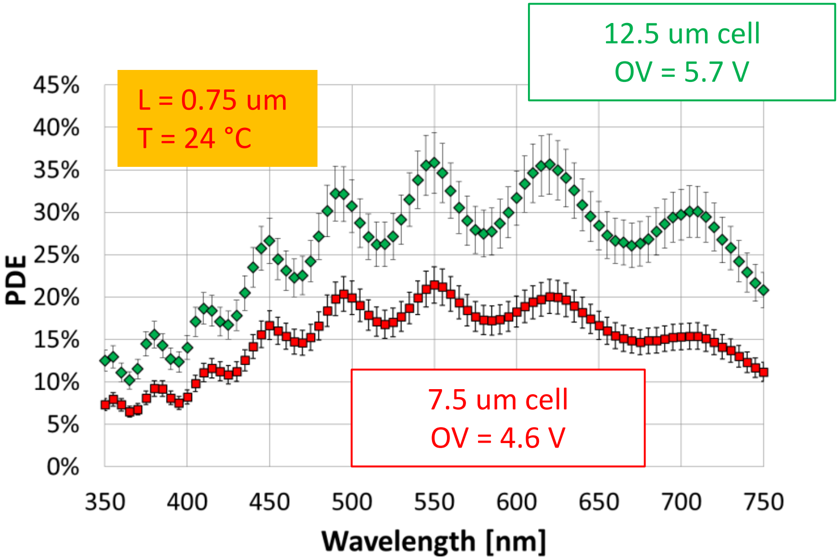


Fill Factor vs. trench width

L (um)	Fill Factor
0.75	57.1%
1	48.8%
1.25	40.3%
1.5	32.6%

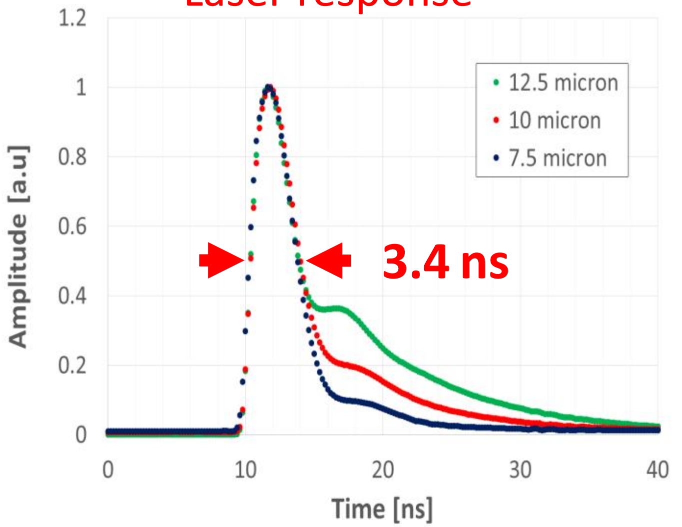
UHD2 SiPM parameters



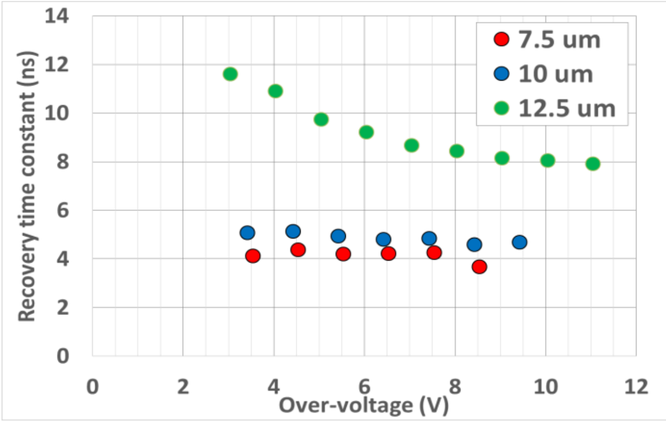


(Alberto Gola – PhotoDet-2015 , Troitsk)

Laser response

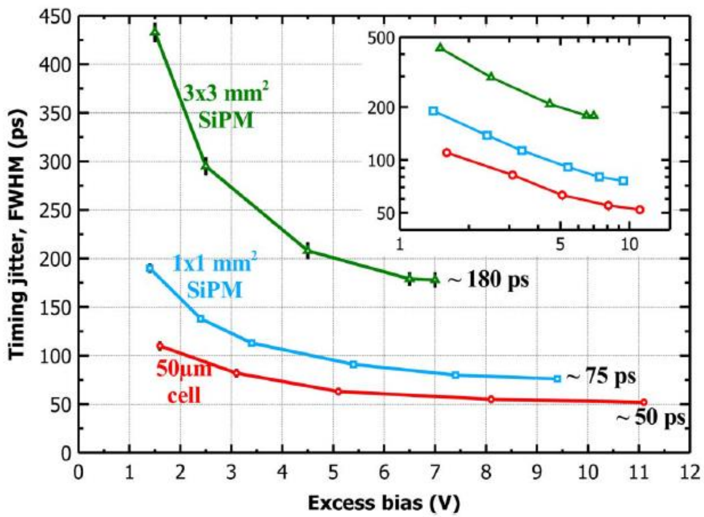


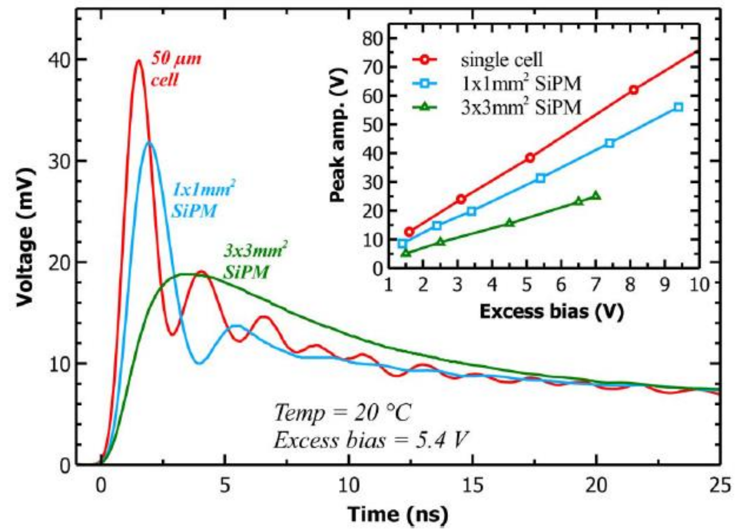
Recovery time

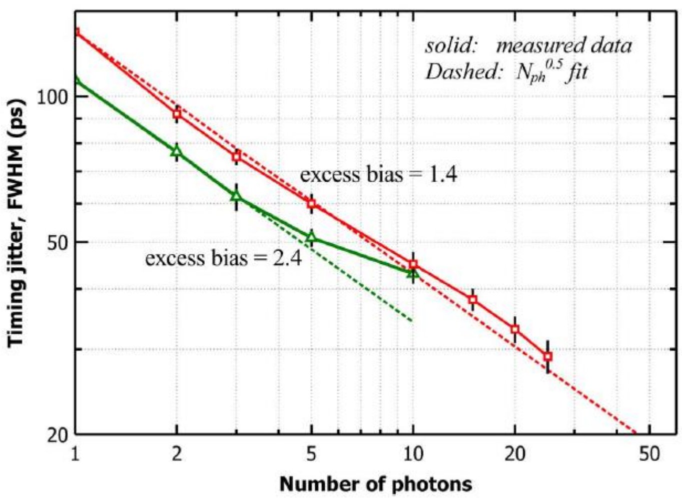


SiPM timing

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 61, NO. 5, OCTOBER 2014

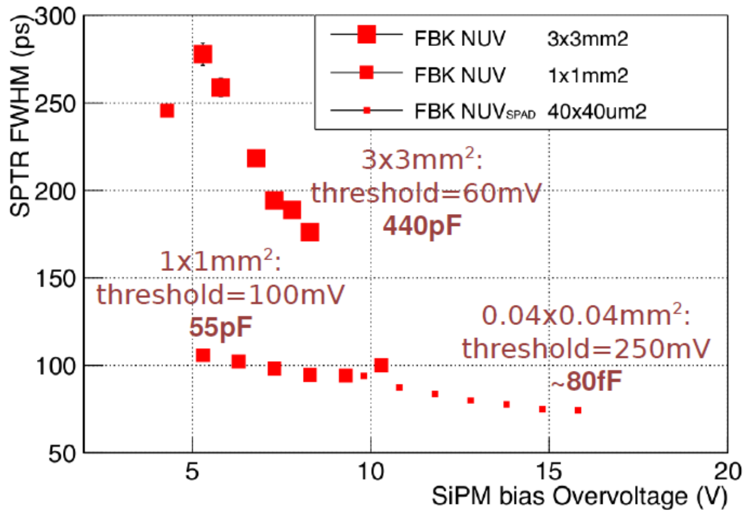






SiPM cell size small, avalanche development time ~ tens of picoseconds. This promises very good time resolution. Single-photon time resolution for 3 SiPM area, measured at different biases for 425 nm light. Larger area SiPMs have slower signal rise-time. Factors limiting SPTR are signal rise-time, signal electron resolution and correlated noise (X-talk and delayed pulses). The latest is especially important for multi-photon events. The result which is shown here is among the best measured so far.

SiPM time resolution - II

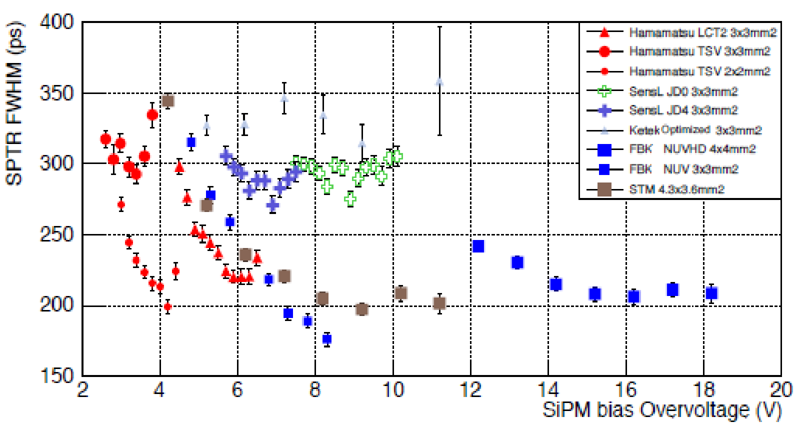


FBK NUV 3x3mm²:
SPTR=175ps FWHM

FBK NUV 1x1mm²:
SPTR=94ps FWHM

FBK NUV single SPAD 40µm:
SPTR=75ps FWHM

Laser pulse width: 42ps FWHM

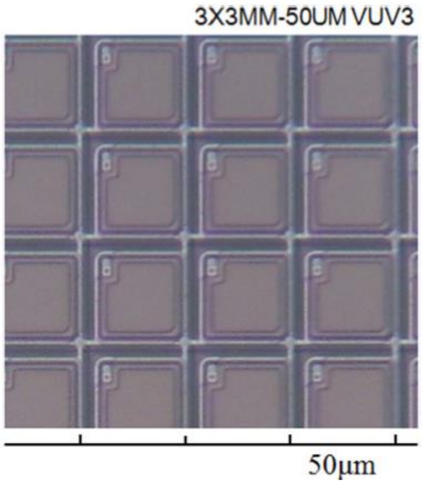


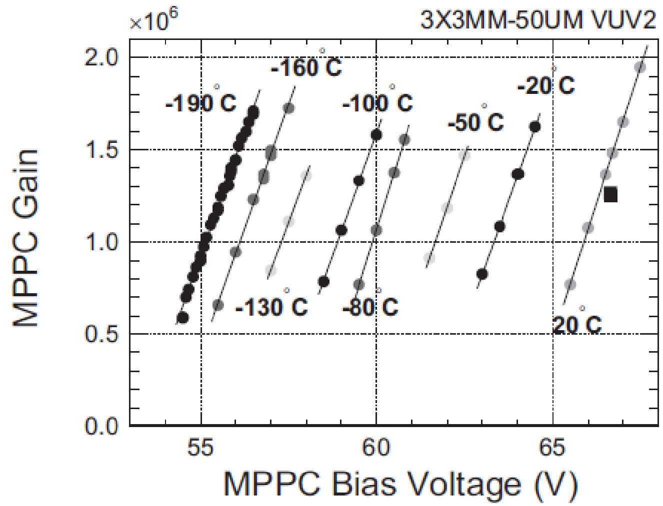
...apudi et.al, October 2016. JINST 11 P10016

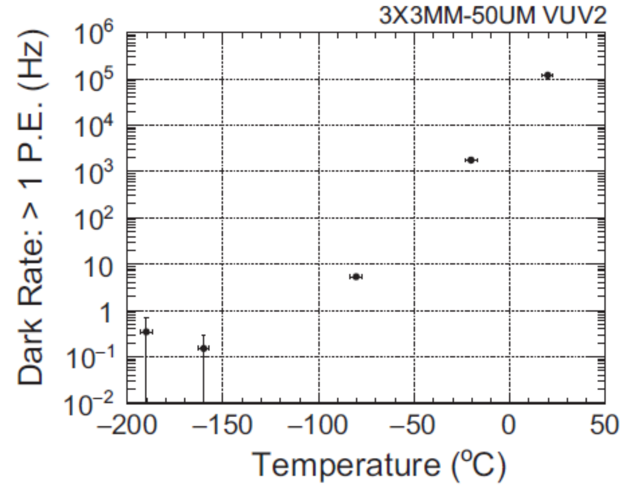
SiPM	Device area (mm²)	Cell size (µm)	Capacitance pF	SPTR FWHM	Overvoltage (V)	CT %	DCR MHz
STM	4.3×3.6	50	1250	200 ± 8	9.2	28	40
FBK NUVHD	4×4	25	610	205 ± 7	16.2	57	5.5
FBK NUV	3×3	40	440	175 ± 7	8.3	40	1.2
FBK NUV	1×1	40	55	94 ± 5	9.3	-	0.2
FBK NUV	SingleCell	40	-	75 ± 4	15.8	-	
Ham TSV	3×3	50	315	290 ± 7	2.6	34	0.6
Ham TSV	2×2	50	154	215 ± 5	3.4	30	0.8
Ham LCT2	3×3	50	340	220 ± 7	6.1	38	1.0
SensL JD0	3×3	35	790	290 ± 7	8.7	32	0.9
SensL JD4	3×3	20	690	270 ± 7	6.9	16	0.8
Ketek Optimized	3×3	50	820	330 ± 7	5.2	20	2.5

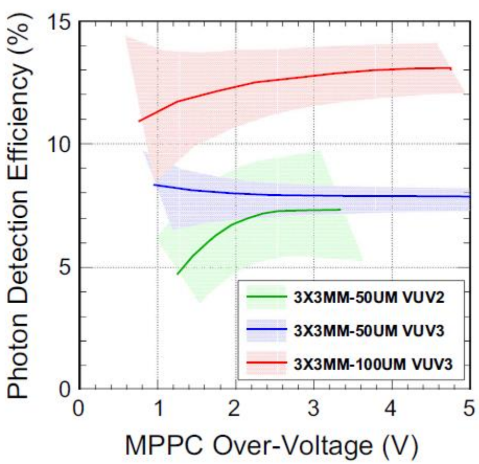
Vacuum ultra violet (VUV) SiPMs

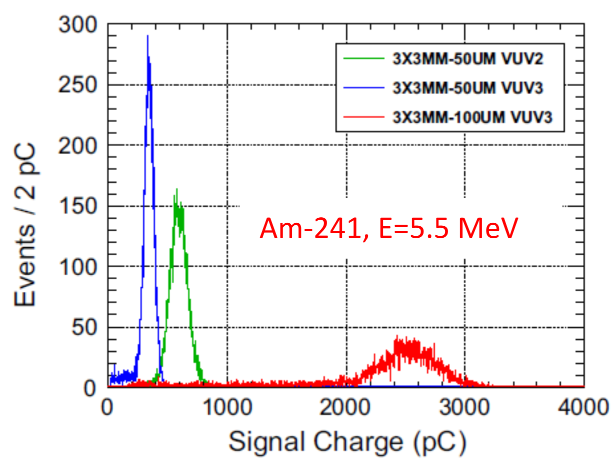
Another important development: SiPMs sensitive to VUV light (<150 nm) were recently developed by HPK for detection LAr (T=-186 °C) scintillation light (λ = 128 nm).







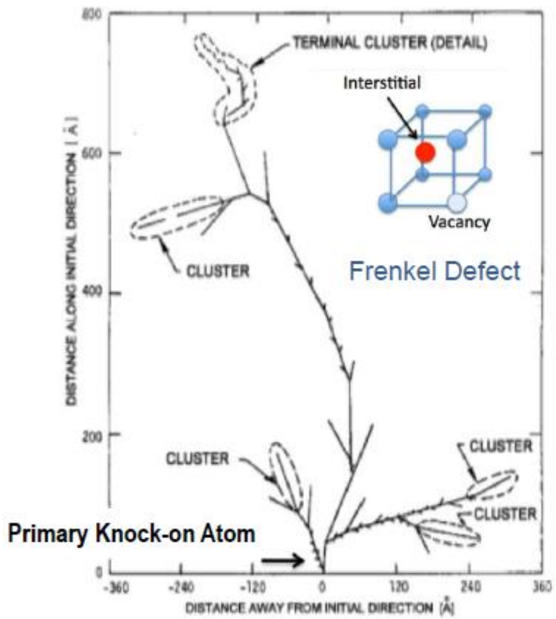




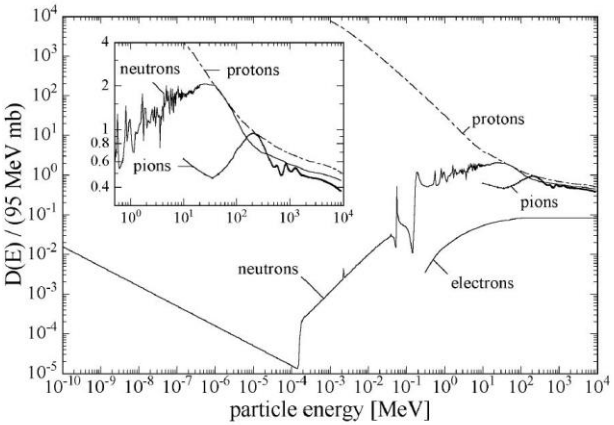
The PDE(128 nm) was measured ~8% for 50 μm pitch SiPMs and ~13% for 100 μm pitch SiPM at dVB=3 V

(NIM A833 (2016) 239–244)

Radiation induced damage in Silicon



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings



Two types of radiation damage are produced by radiation in Si detectors:

Bulk damage:

- Incoming particle transfers a certain amount of energy to atom
- If the energy transferred to the atom is large than the binding energy of a silicon atom (~190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy → single point or cluster defects
- Number of defects is proportional to the Non Ionizing Energy Loss (NIEL)

Surface damage:

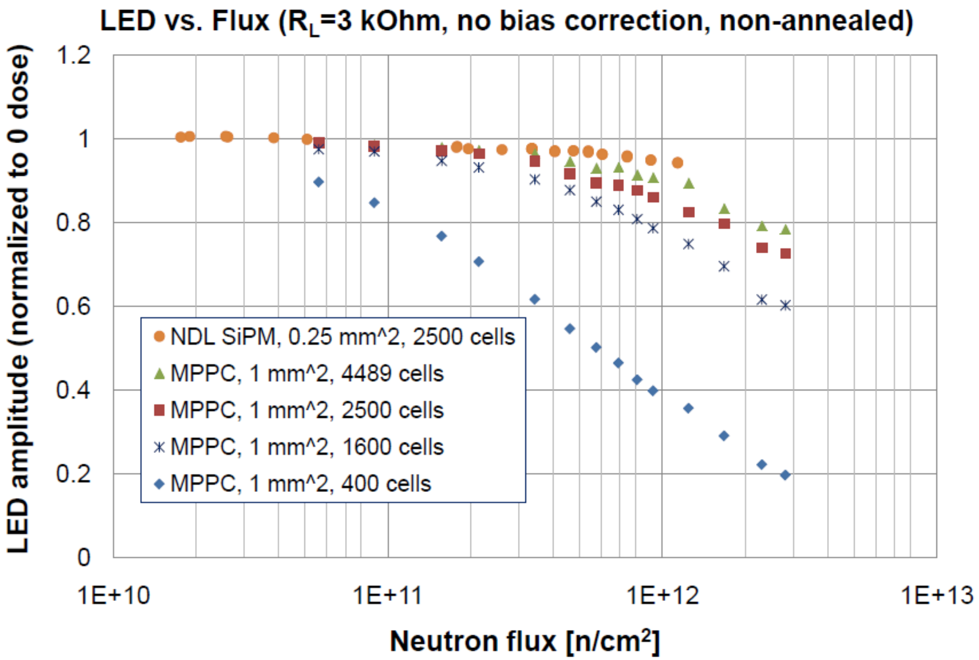
- Low energy X-rays can produce surface damage affecting the SiO_2/Si_3N_4 layer
- Ionizing particles can produce charging up effects affecting the internal fields inside the device

SiPM: radiation hardness

In SiPMs radiation may cause:

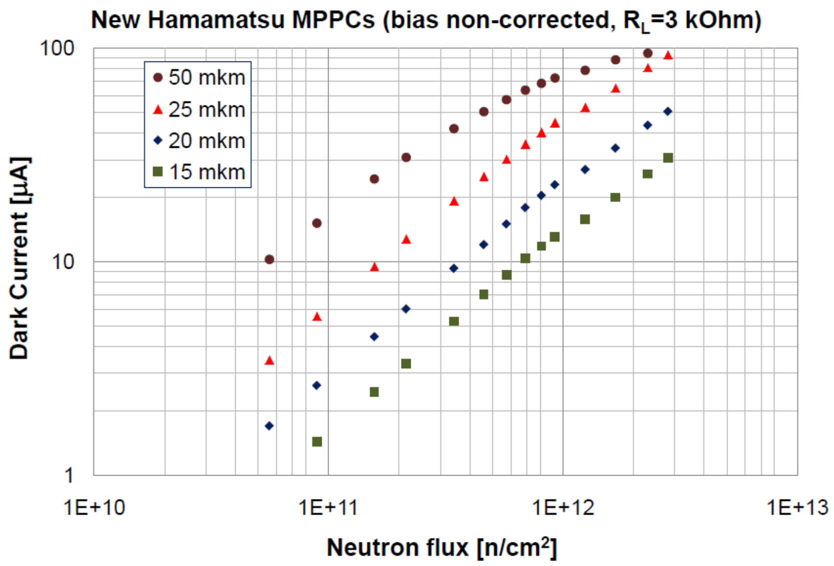
- Fatal SiPMs damage (SiPMs can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPM cell "blocking" effects due to high induced dark carriers generation-recombination rate)
- Breakdown voltage, PDE, Gain change due to donor/acceptor concentration change

Relative response to LED pulse vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



SiPMs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm^2 (gain change is< 25%).

Dark current vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

$$I_d \sim \alpha * \Phi * V * M * k,$$

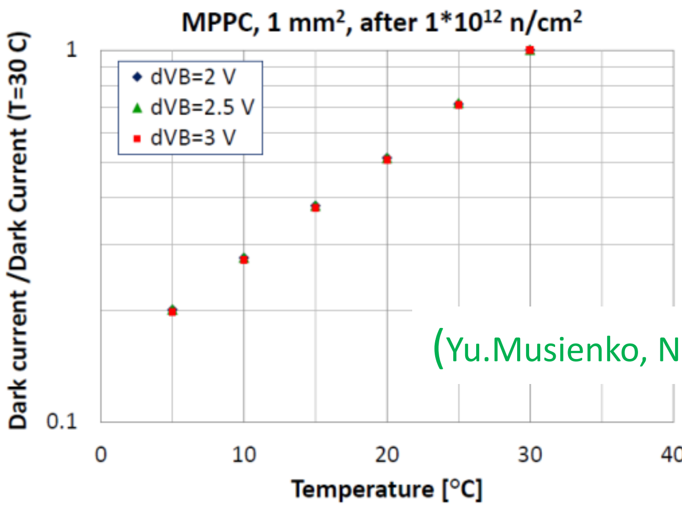
α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – silicon active volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~$4*10^{-17}$ A*cm after 80 min annealing at T=60 °C (measured at T=20 °C)
Damage produced by 40 neutrons (1 MeV) in 1 µm thick Si → 1 dark count/sec at 20 °C

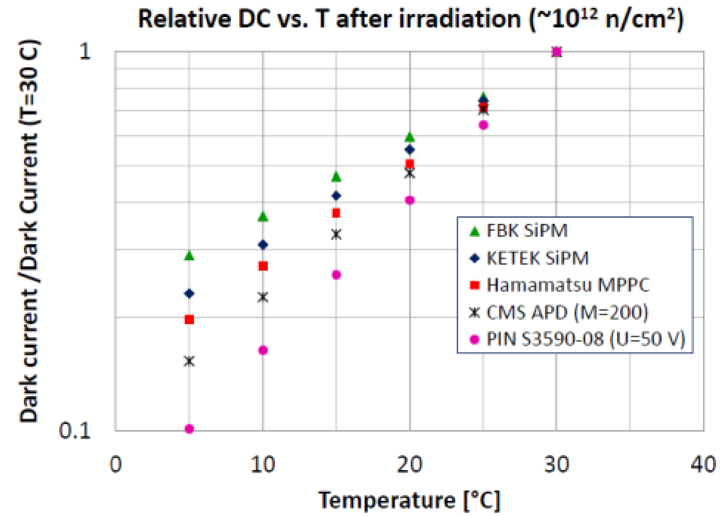
Thickness of the epi-layer for most of SiPMs is in the range of 1-2 µm, however d_{eff} ~ 4 ÷ 50 µm for different SiPMs. High electric field effects (such as phonon assisted tunneling and field enhanced generation (Pool-Frenkel effect) play significant role in the origin of SiPM's dark noise.

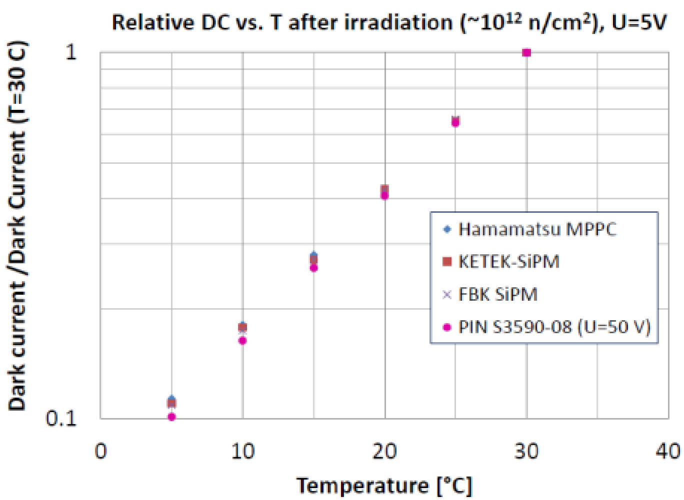
$V \sim S * G_f * d_{eff}$,
S - area
G_f - geometric factor
d_{eff} - effective thickness

Dependence of the SiPM dark current on the temperature (after irradiation)



(Yu.Musienko, NDIP-2014)

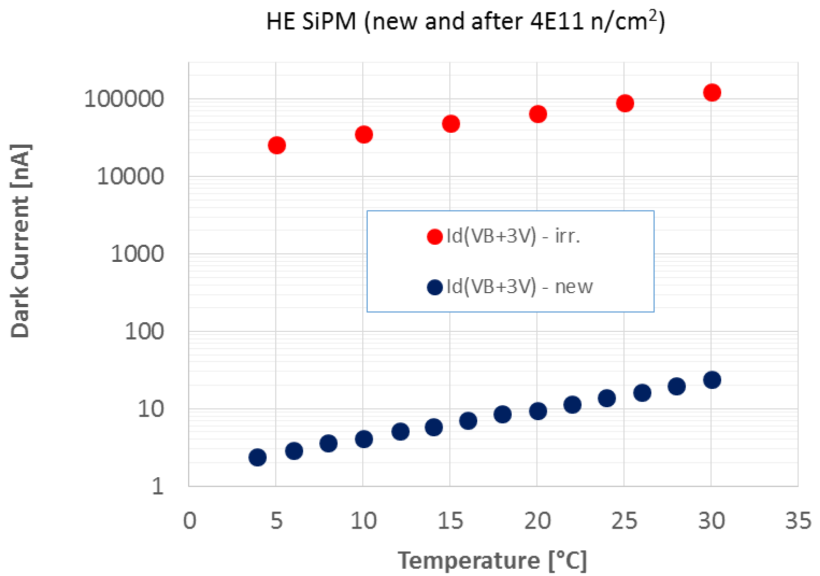




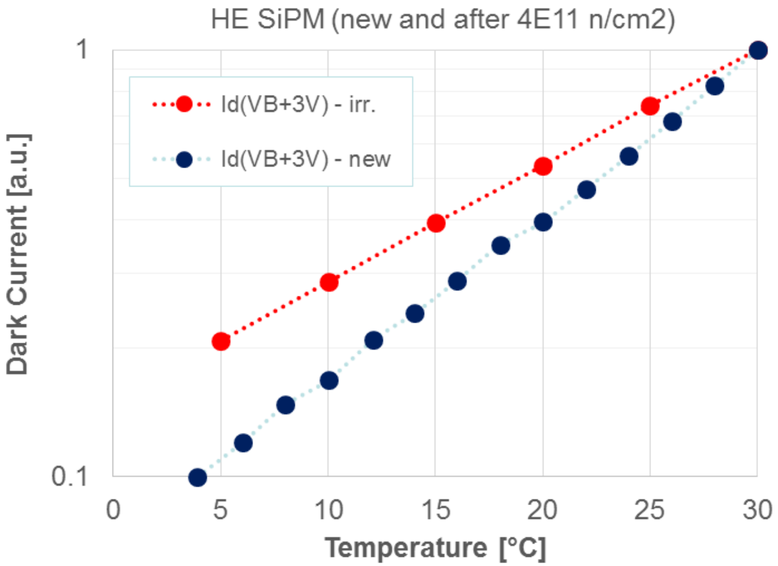
SiPM dark currents at low voltage (5V) behave similar with temperature to that of the PIN diode. However we observed significant difference of this dependence for differenet SiPM types when they operate over breakdown! General trend is that SiPMs with high VB value have faster dark current reduction with the temperature.

Dependence of the SiPM dark current on the temperature (before/after irradiation)

Dark current at V-VB=3 V vs. temperature (SiPM was irradiated with 4E11 n/cm^2)



Normalized dark current at V-VB=3 V vs. temperature (for new and irradiated SiPM)

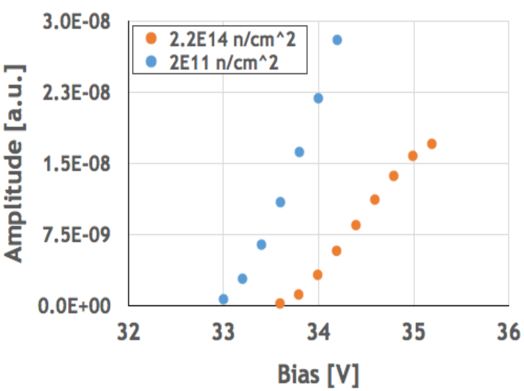


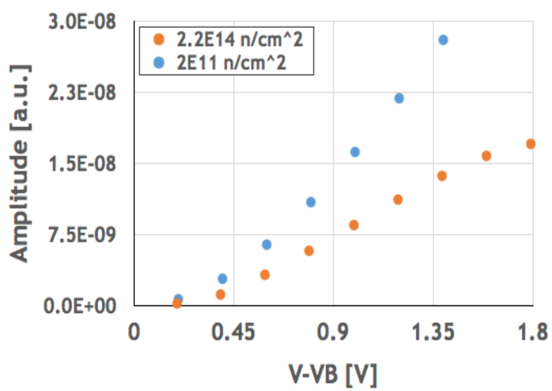
Interesting observation: dependence of the SiPM dark current on the temperature before and after irradiation is quite different:

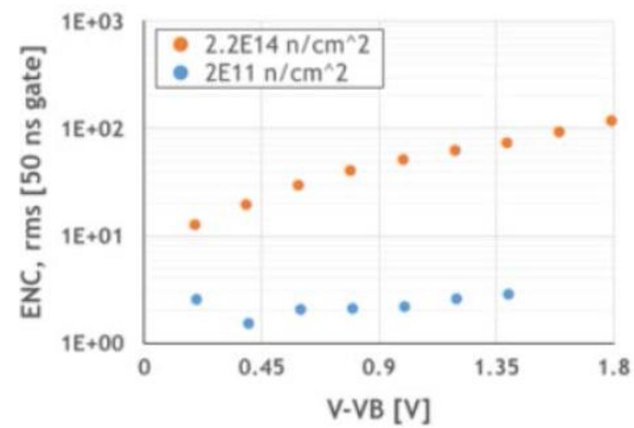
- For irradiated HE MPPC, Id reduction: ~1.88 times/10 °C
- For non-irradiated HE MPPC, Id reduction: ~2.4 times/10 °C (like it should be for silicon diodes!)

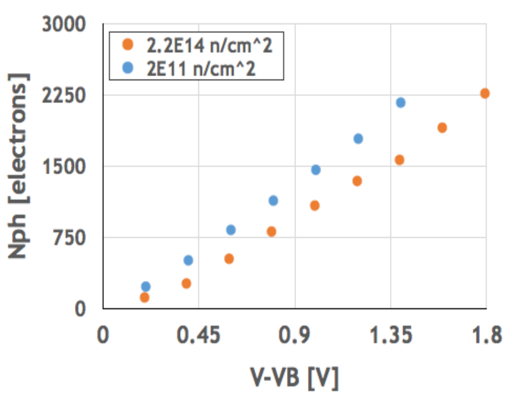
SiPM irradiated up to $2.2 \cdot 10^{14}$ n /cm^2

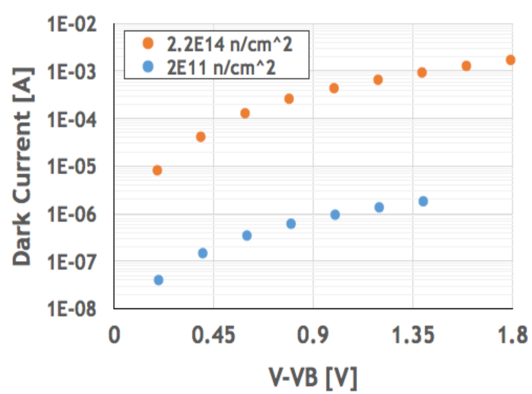
Can SiPM survive very high neutron fluences expected at high luminosity LHC? Yes they can! FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to $2.2 \cdot 10^{14}$ n /cm^2 (1 MeV equivalent).











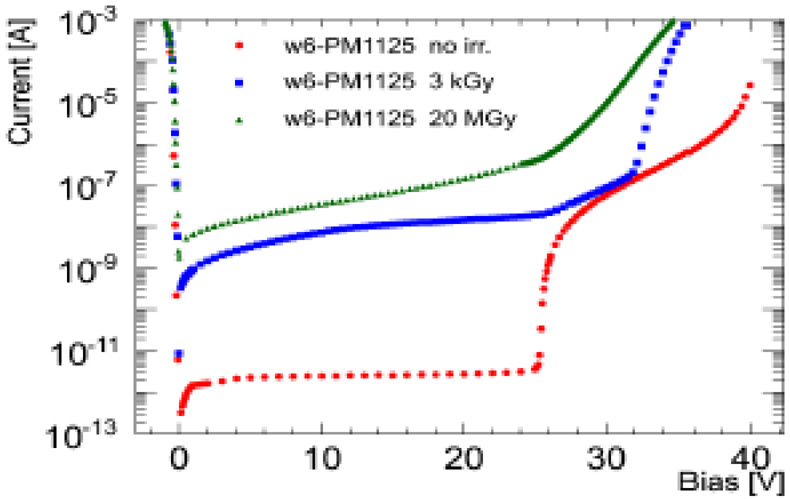
We found:

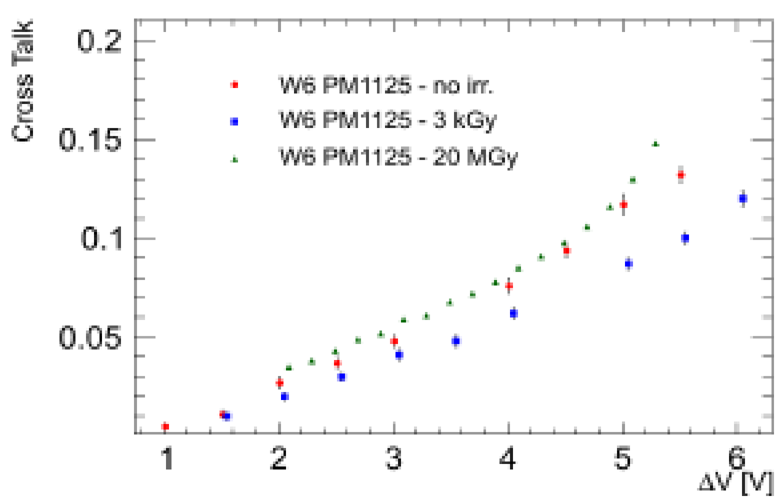
- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

The main result is that SiPM survived this dose of irradiation and can be used as photon detector!

(A.Heering et al., NIM A824 (2016) 111)

X-ray damage





KETEK PM1125 (1.2 x 1.2 mm, 25 μm pixels)

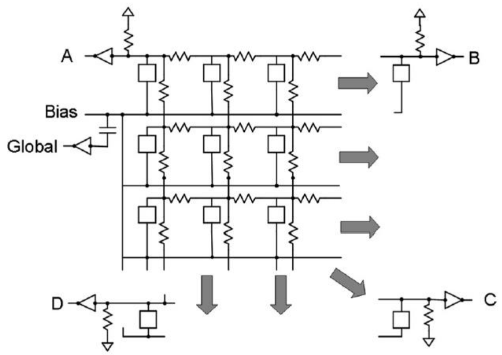
Left: KETEK PM1125 I-V curves before irradiation (in red), compared with 3 kGy irradiation (blue) and 20MGy irradiation (green); measurements have been performed at 20 ◦C. Right: inter-pixel cross-talk measurements for the sensors before irradiation (in red), compared with 3 kGy irradiation (blue) and 20 MGy irradiation (green); no relevant changes in cross talk probability are measured.

- No significant change in breakdown voltage
- Increased dark current below as well as above breakdown voltage
- Slight decrease in gain

(E.Garutti et.al., 2014 JINST 9 C03021)

Position-Sensitive SiPMs: PS-SiPM RMD

RMD had designed a 5x5 mm^2 position-sensitive solid-state photomultiplier (PS-SSPM) using a CMOS process that provides imaging capability on the micro-pixel level. The PS-SSPM has 11,664 micro-pixels total, with each having a micro-pixel pitch of 44.3 micron.



A basic schematics showing the design layout and pattern for PS-SSPM resistive network. Each square represents a micro-pixel. The network resistors are 246.5 Ohm each.

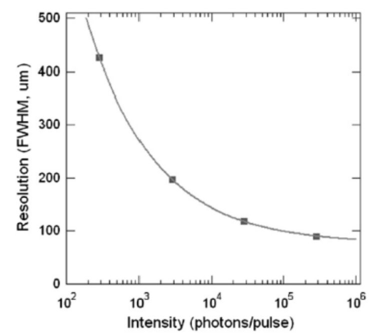
PS-SSPM parameters

Number of micro-pixels	11,664 (108 × 108)
Micro-pixel area	30 × 30 μm²
Micro-pixel pitch	44.3 × 44.3 μm²
Geometrical fill factor	46%
Quench resistors	143.8 kΩ
Network resistors	246.5 Ω
Detection efficiency @ 400 nm	~10%
Dark current (μA/mm²)	10
Dark count rate (kHz/pixel)	~117
Operating bias	~32 V
Operating gain	~10^6
Excess noise factor	~1
Capacitance (fF/pixel)	150

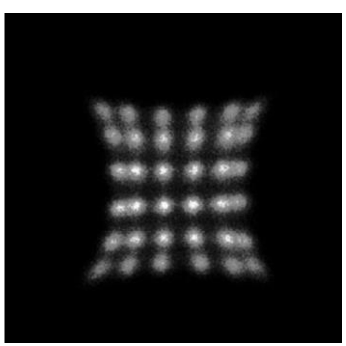
Anger logic:

$$X = \frac{(A+B)-(C+D)}{\Sigma}$$

$$Y = \frac{(A+D)-(B+C)}{\Sigma}$$



A plot of the X–Y spatial resolution (FWHM) as a function of the incident beam spot light intensity. Spot size was ~30 micron.

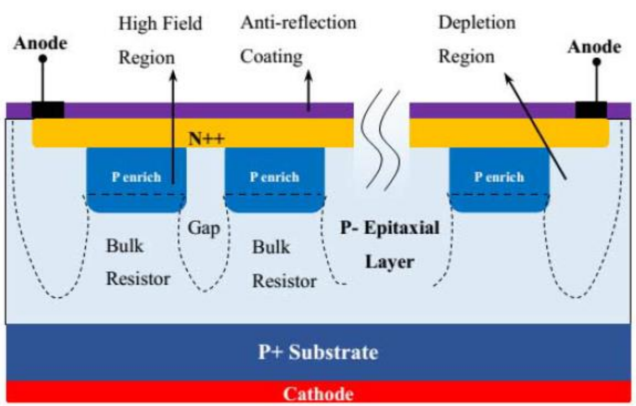


An image of a 66 LYSO array having 0.5 mm pixels uniformly irradiated with ^{22}Na.

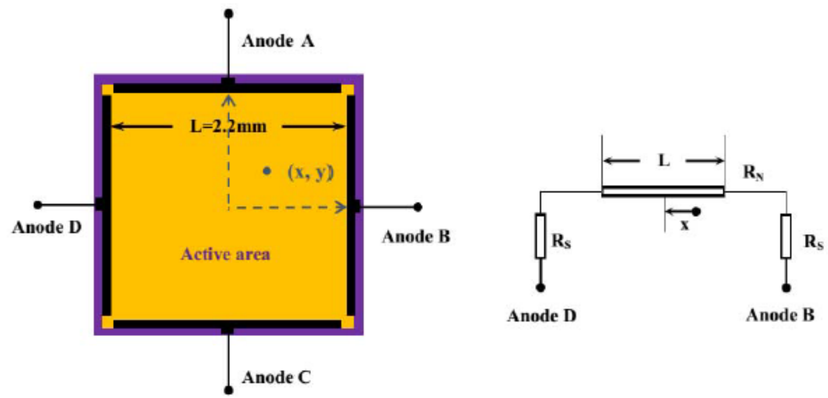
M. McClish et al. / Nuclear Instruments and Methods in Physics Research A 652 (2011) 264–267

PS SiPM - NDL

The device takes advantages of the sheet N+ layer as the intrinsic continuous cap resistor for charge division, the same way adopted in PIN or APD PSD



Schematic cross-section of the PS-SiPM with bulk quenching resistor

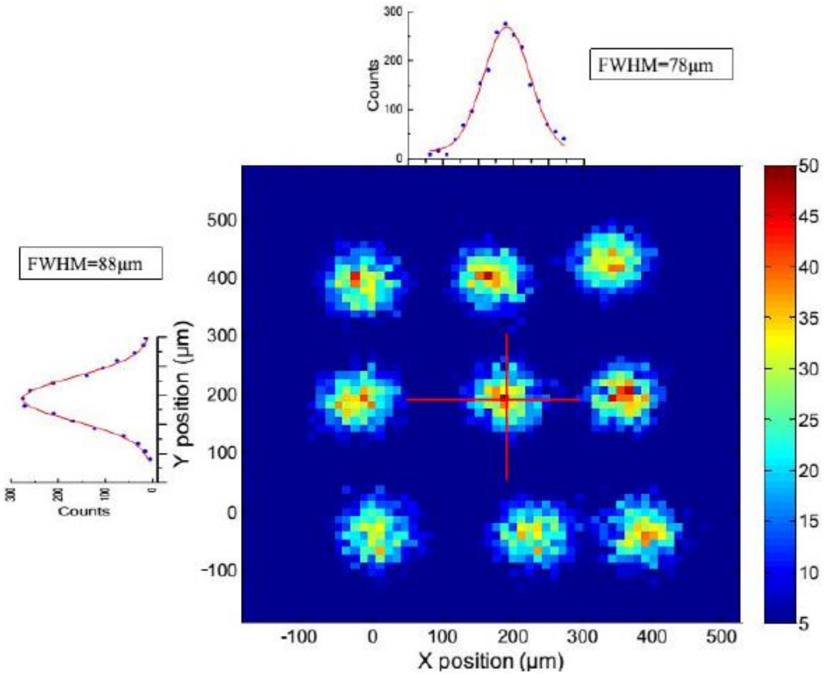


Top view of tetra-lateral type electrodes of the PS-SiPM with 4 anodes

$$x = \frac{P_B - P_D}{P_B + P_D} \cdot \frac{2R_S + R_N}{2R_N} \times L$$

$$y = \frac{P_A - P_C}{P_A + P_C} \cdot \frac{2R_S + R_N}{2R_N} \times L$$

PS-SiPM – NDL (II)

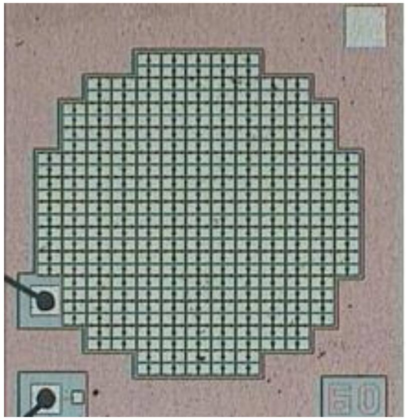


The device, with an active area of 2.2 mm × 2.2 mm, demonstrated spatial resolution of 78–97 μm, gain of 1.4 × 10^5 and 46-ps time jitter of transmission delay for 210–230 photons.

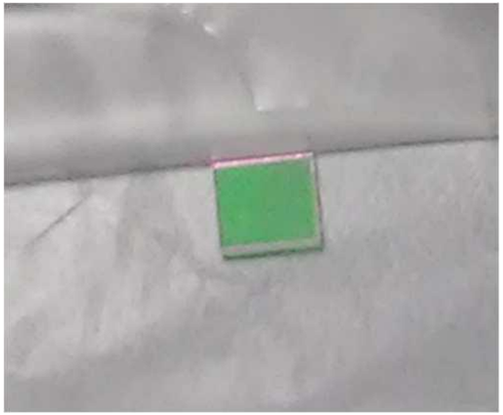
Reconstruction of nine positions of light spots from optical fiber tested in the central part of the device

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 61, NO. 9, SEPTEMBER 2014

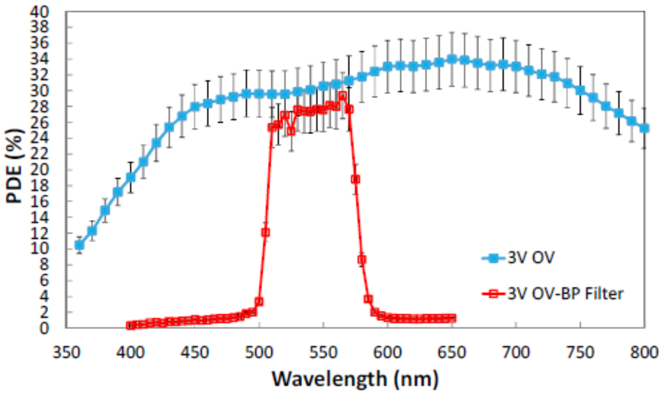
SiPMs with Bandpass Dichroic Filters



Optical microscope picture of the STMicro SiPM (548 cells, 67.4% geometrical factor)

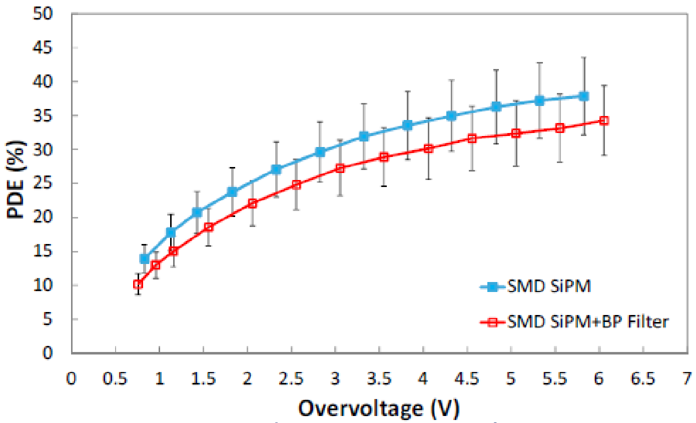


Green bandpath filter with 5x5 mm area and 1.1 mm thickness



PDE spectral shape measured at 24 °C and dVB=3 V on n-on-p SiPM with and without BP filter

Such a photo-sensor can be very used in applications where protection of the detector from unwanted light background (ambient light for example) is required.



PDE measured at 515 nm vs bias on n-on-p SiPM with and without BP filter

(M.Mazillo et al., to be published in Sensors)

SiC SSPM

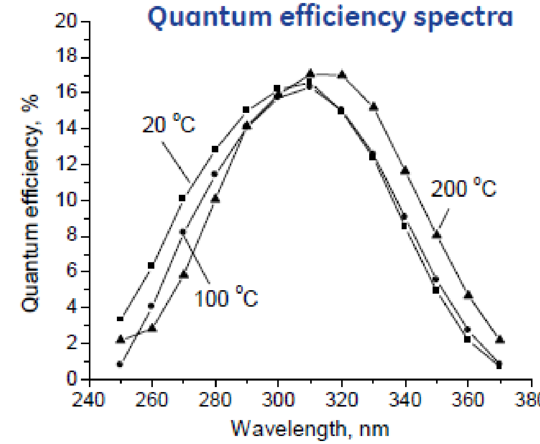
Why SiC?

Dark count rate in Si-PM increases rapidly with temperature, resulting in a maximum operating temperature below 50°C

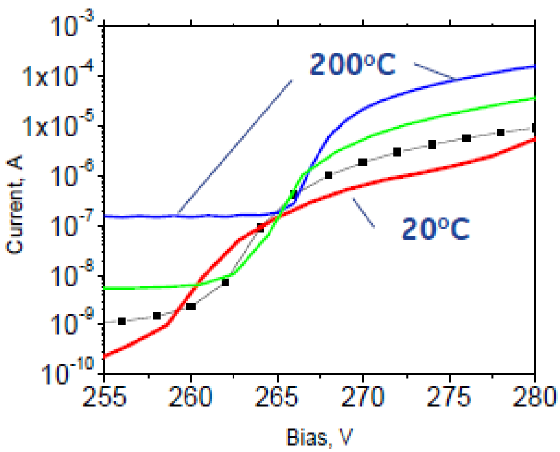
SiC has larger bandgap (3.26 eV)
- Lower leakage current
- Higher operating Temperature
- Higher sensitivity in UV spectra

Packaged SiC SSPM

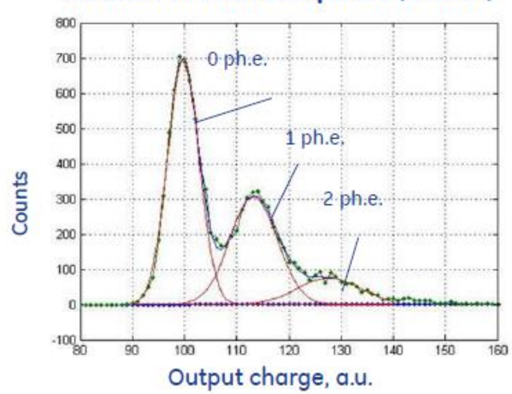
Active area: 4x4 mm²
Pixel size: 60 um
16 sub arrays
Area of sub-array: 1x1 mm²



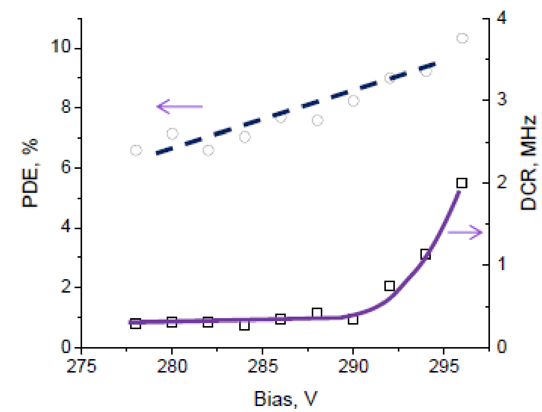
Dark current vs. temperature



Single Photoelectron spectrum recorded for SiC-PM with 256 pixels (1 mm²)



Photodetection efficiency and dark count rate as functions of voltage bias

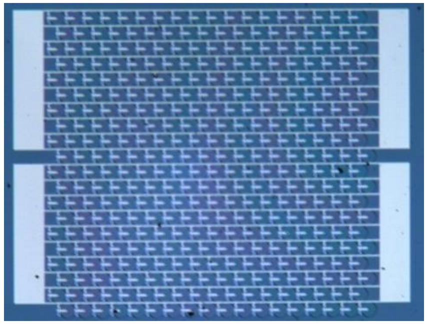


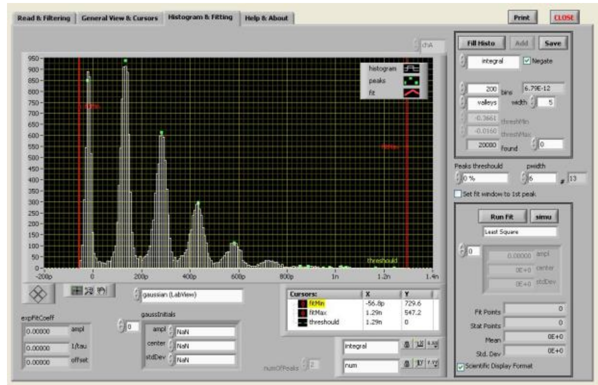
Potentially can be more radiation hard than silicon

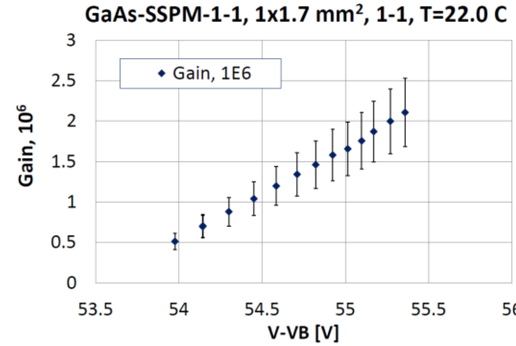
(S.Dolinsky, GE, NDIP-2014)

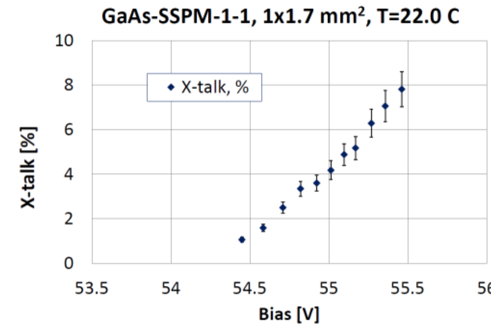
GaAs SSPM

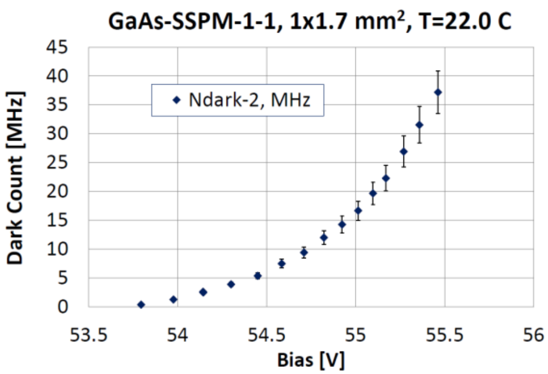
LightSpin Photomultiplier Chip™

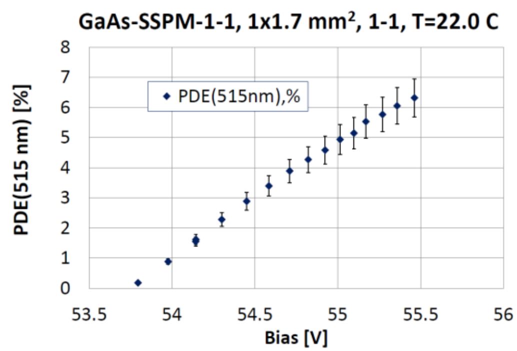


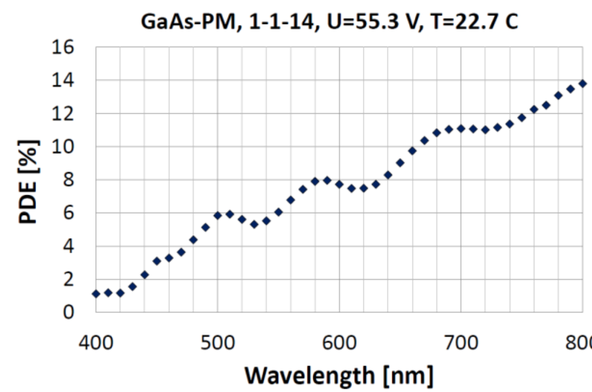








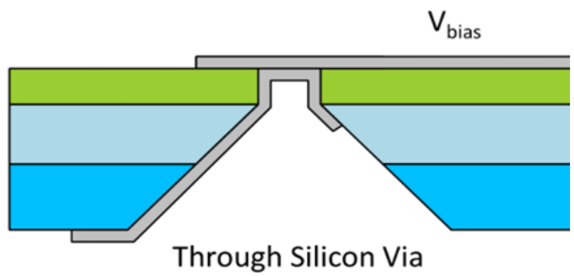


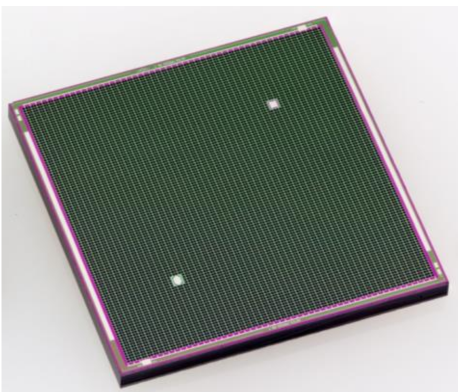


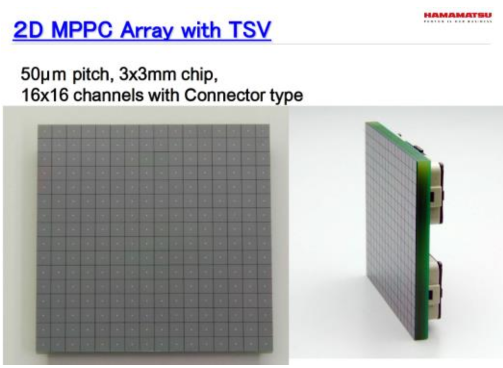
Wide bandgap (1.42 eV): potentially can be more radiation hard than silicon. Timing with GaAs SSPM can be also better (high mobility of electrons and holes, fast avalanche development – direct semiconductor)

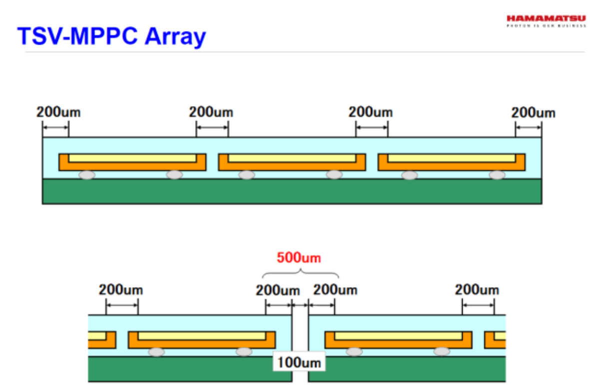
TSV technology (no bonding wire)

TSV Technology:
Further improved geometrical efficiency for arrays ,









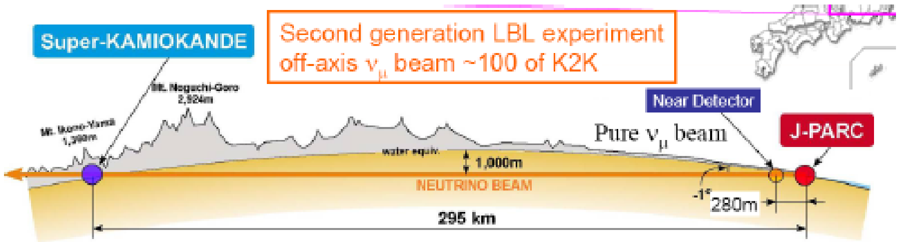
(KETEK – Photodet-2015 (Troitsk))

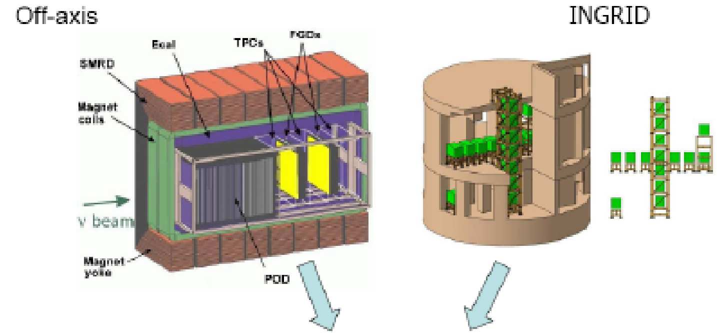
(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

Applications in HEP and astroparticle experiments (some!)

SiPMs for T2K experiment (near detector)

First large scale (~60 000) use of SiPMs in HEP experiments: scintillator detector with WLS fiber read out for T2K near detector.

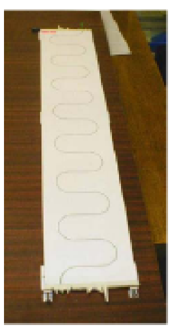




Scintillator detectors with WLS fibers
- Individual fiber readout
  FGD, POD, Ecal, SMRD, INGRID: ~ **60000 readout channels**
- Limited space for photosensors
- Magnetic field

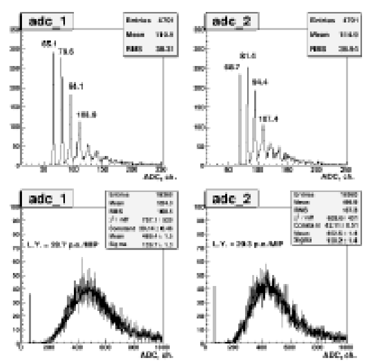
SMRD detectors

Extruded plastics ~7x170x870 mm^3
Y11 fibers embedded in S-grooves



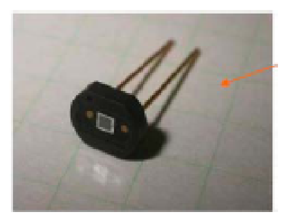
MIP detection efficiency	**> 99.9%**
σ_t (MIP)	**~ 0.7 ns**
Spatial resolution	**~ 7 cm**

Light yield



l.y. (sum of 2 ends) = 58 p.e./MIP

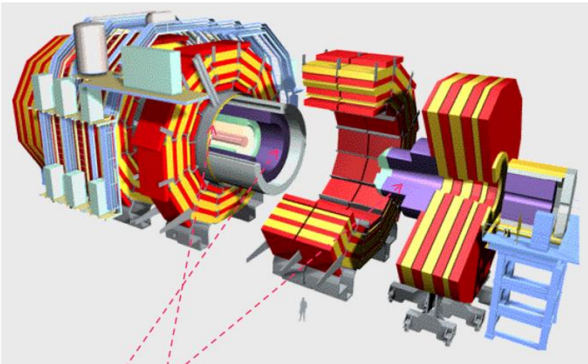
Hamamatsu MPPC: active area 1.3×1.3 mm^2

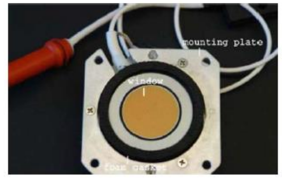


Number of pixels	667
Pixel size	50×50 μm
Gain	~0.7×10^6
PDE at 525 nm	25-30%
Dark rate, th = 0.5 p.e.,22C	≤1000 kHz
Pulse width	<100 ns
Cross-talk	10-15%
After pulses	10-15%

(Yu. Kudenko, G-APD workshop, GSI, Feb. 2009)

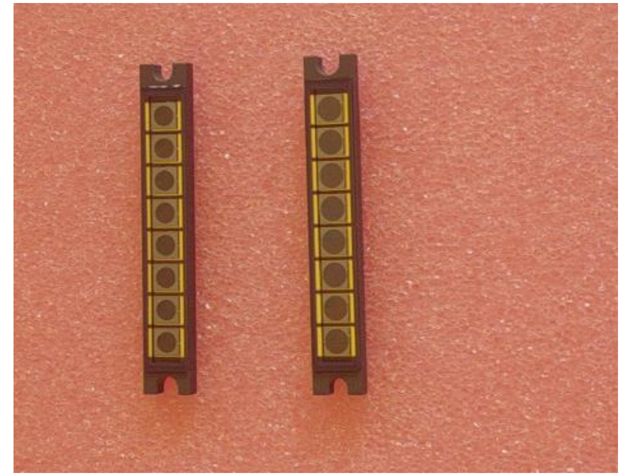
CMS HCAL Upgrade





HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber readout, brass (steel for HO) absorber. HPD was selected as the CMS HCAL photodetector.
The CMS HCAL photodetector upgrade was proposed after several years of successful operation of the HPDs at the LHC.

3



Motivation for the HB/HE photo-detector upgrade

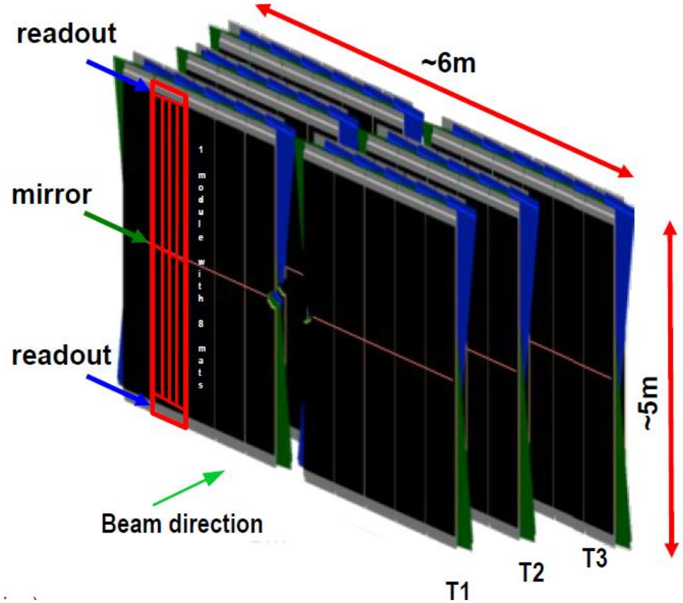
1. SiPMs have better quantum efficiency, higher gain, and better immunity to magnetic fields than HPDs. Since SiPMs operate at relatively low voltages, they do not produce large pulses from high voltage breakdown that mimic energetic showers like HPDs do. These features of the SiPMs together with their low cost and compact size compared to HPDs enable several major changes to the HCAL.
2. Implementation of depth segmentation which has advantages in coping with higher luminosities and compensating for radiation damage to the scintillators. This is made possible by the use of SiPMs.
3. Use of timing to clean up backgrounds, made possible by the extra gain and better signal-to-noise of the SiPMs.

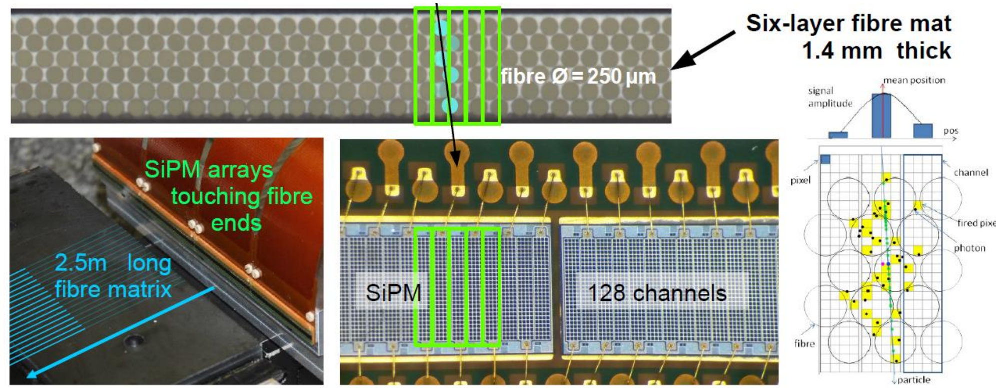
- Area: ~Ø3 mm
- PDE(515 nm): > 15%
- Operating voltage: <90 V
- Gain: <700 000
- ENF: <1.3
- Optical X-talk between cells: <20%
- Temperature coefficient: <5%/°C
- Dynamic range: > 20 000 “effective” cells/SiPM
- Cell recovery time: <10 ns
- Dark current (T=24 °C, after $2*10^{12}$ n/cm^2): <1000 µA
- Fractional Gain*PDE (after $2*10^{12}$ n/cm^2): >65%
- Neutron sensitivity: low

~20 000 large area SiPMs will be used for the Phase I CMS HCAL upgrade

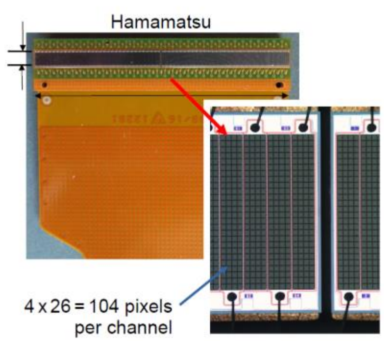
(Yu.Musienko, PD-15, Troitsk)

Sci Fi tracker of LHCB experiment

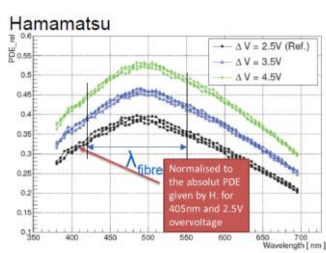




- Staggered layers of 250 µm thin, double-clad scintillating fibres, to form a 6-layered hexagonal packed mat
- Read out by the SiPM arrays covering one fibre mat end face
- Signal is shared between the adjacent SiPM array channels allowing for a resolution better than pitch / √12
- Mirror opposite to readout end increases the light yield by ≥ 65% for the hits close to the mirror



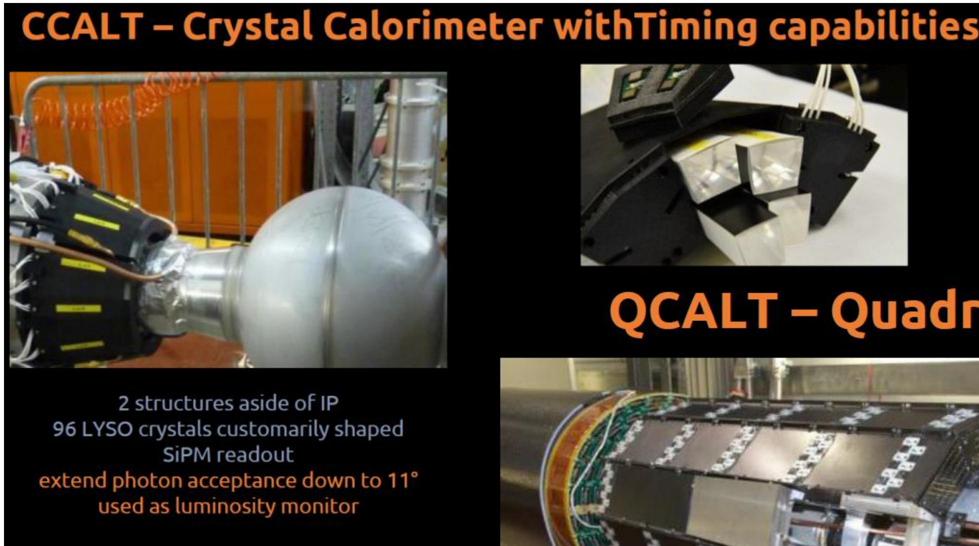
- 128 (2x64) channel SiPM arrays
- 250 µm channel pitch (= fibre diameter)
- high photon detection efficiency ~45%
- low crosstalk probability < 10%
- neutron fluence $1 \cdot 10^{12}$ n_{eq}/cm^2 (1 MeV)
  → cooling needed to reduce noise
- small distance between fibres and silicon

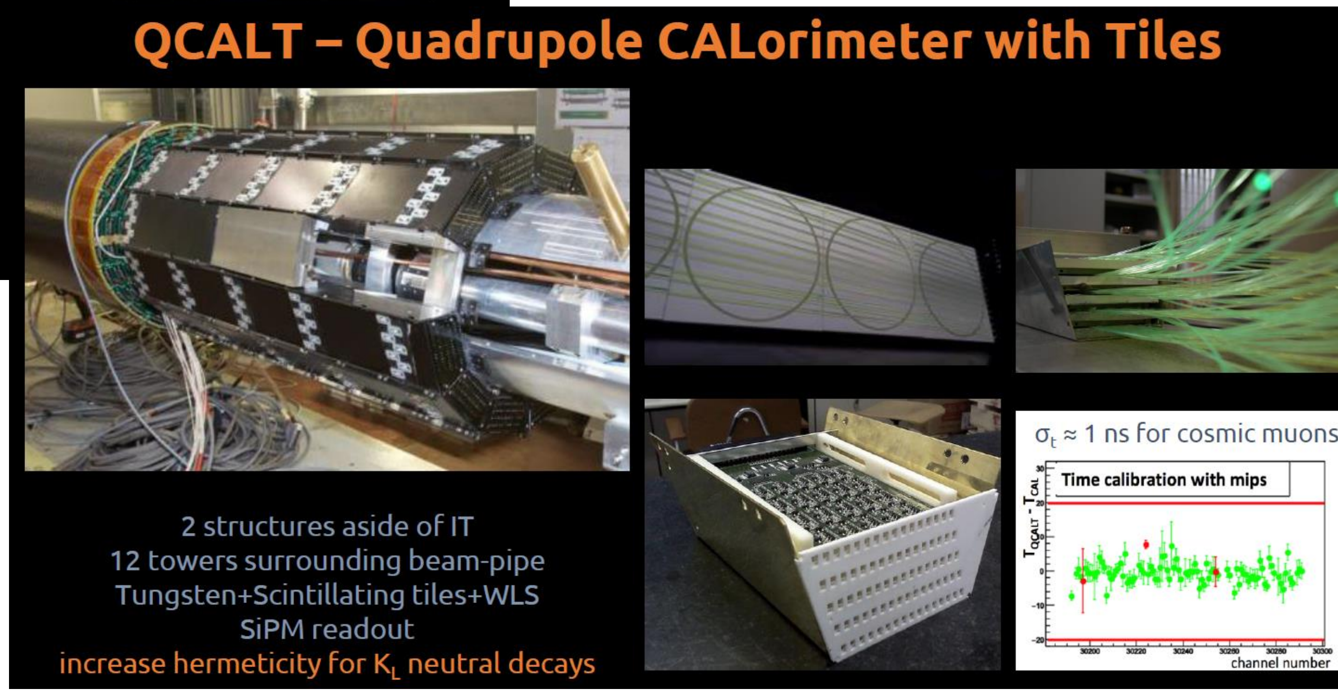


6 layers of 2.5 m long, 250 µm dia. scintillating fibres will be read out by 128 channel SiPM arrays

(A. Malinin, INSTR-17, Novosibirsk)

KLOE-2 experiment (Frascati)



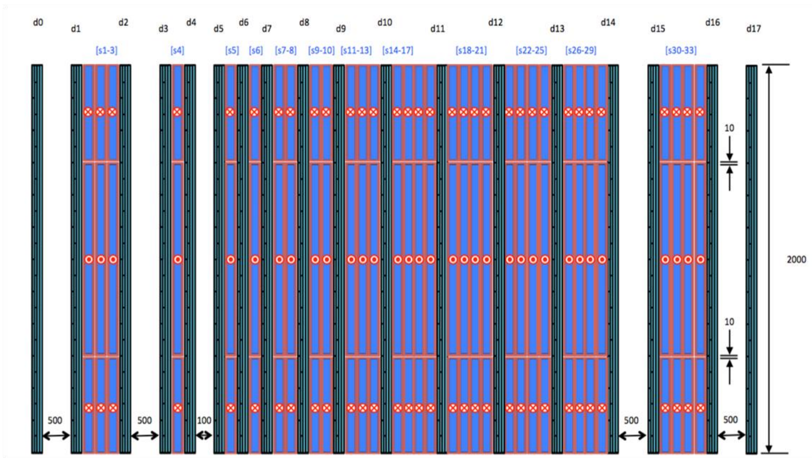


SiPMs will be used to read out LYSO crystals and W/Sci tiles with WLS fibers

(Danilo Domenici, INSTR-17, Novosibirsk)

Baby-MIND experiment

Neutrino magnetized detector Baby-MIND - NP05 project in framework of CERN Neutrino Platform



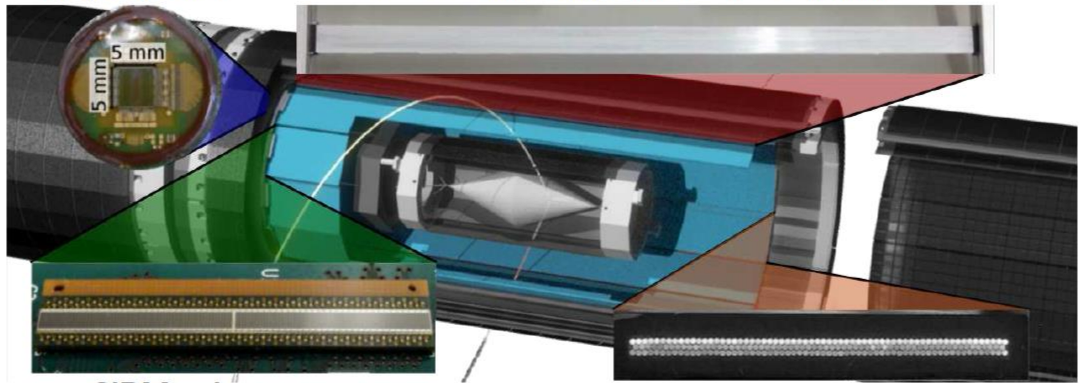
Baby-MIND has 18 active modules
Active elements – scintillator detectors with WLS/SiPM readout
Each module: 95 horizontal bars and 16 vertical bars
Horizontal bar: 2900(L)x30(W)x7(t) mm^3
Vertical bar: 1950(L)x210(W)x7(t) mm^3
In total ~1800 horiz and 250 vert sci bars and 3-cm thick 33 magnetized iron plates

A spectrometer to measure muon momentum and charge identification.

(Yu. Kudenko, INSTR-17, Novosibirsk)

Scintillator plane

Mu3e experiment (SciFi detector)



Components

- cylindrical r ∼ 6 cm; l = 28-30 cm
- 12 ribbons of 3-4 layers of 250 μm fibres
- SiPM column arrays
- mixed mode ASIC: MuTRiG

Requirements

- as thin as possible; $\leq 0.5\,\%\ X/X_0$ (1 mm)
- as efficient as possible; ∼ 100 %
- time resolution better than 500 ps
- up to 250 kHz/fibre;

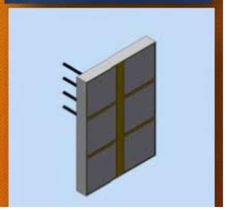
Kuraray SCSF-81M
($\boldsymbol{\tau} \approx \mathbf{2.4\,ns}$, $y_{\mathrm{SCSF-81}} < y_{\mathrm{BCF-12}}$)
optional TiO_2 in glue
Hamamastu S12571-050P ($1 \times 1\,\mathrm{mm}^2$)
and SiPM columm array (same as LHCb)

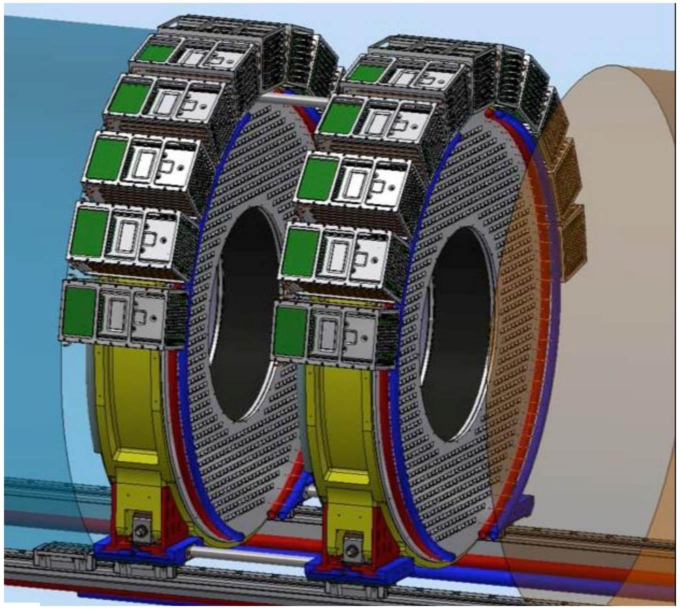
(Simon Corrodi, INSTR-17, Novosibirsk)

Mu2e experiment (calorimeter)

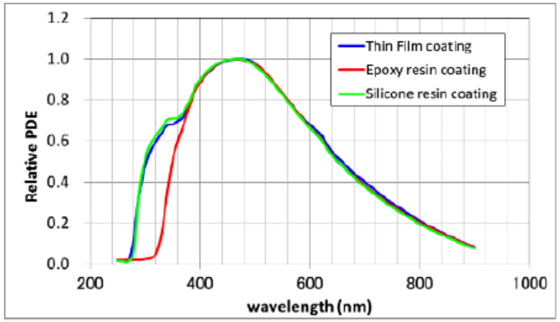
- The calorimeter has two identical annuli, spaced apart by 700 mm (½ λ of the helical trajectory of the conversion electron)
- *r_{inner} = 374 mm*
  r_{outer} = 660 mm
  depth = 10 X_0 (200 mm)
- Each annulus contains 674 square CsI crystals with dimensions 34 x 34 x 200 mm³
- Each crystal is read out by two large area (14x20 mm²) six element UV-extended SiPMs

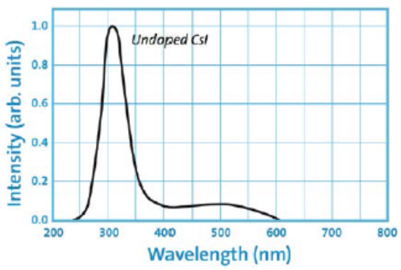
  The analog front end electronics is directly mounted on the SiPM





The Mu2e calorimeter contains 1348 CsJ crystals read out by 2696 14x20 mm² UV extended SiPMs





- The calorimeter radiation dose is driven by the beam flash (the interaction of the proton beam on target).
- The dose from muon capture is 10x smaller
- Dose is mainly to the inner radius (up to 400 mm)
- Highest dose/year ~ 10 krad
- Highest n flux/year on crys. ~ 2x10^{11} n/cm²
- Highest dose/year on SIPM ~ 6x10^{10} n_1Mev eq/cm²

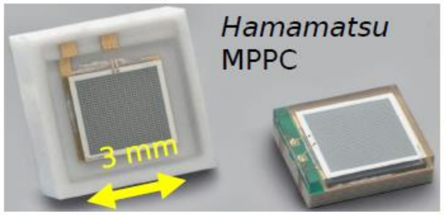
(David Hitlin, INSTR-17, Novosibirsk)

MEGII experiment (PSI)

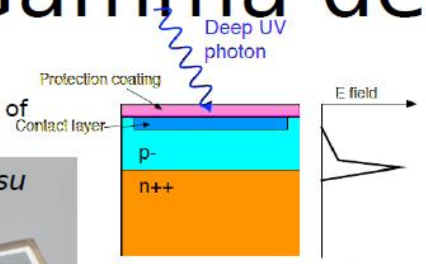
Gamma detector

Upgrade:

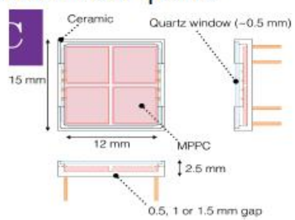
- Replace PMTs on inner face of detector by MPPCs (SiPMs)



- Extend inner face along z-direction and modify PMT layout at lateral faces

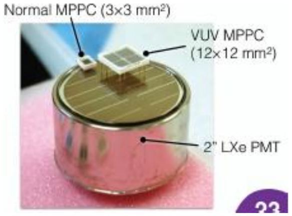


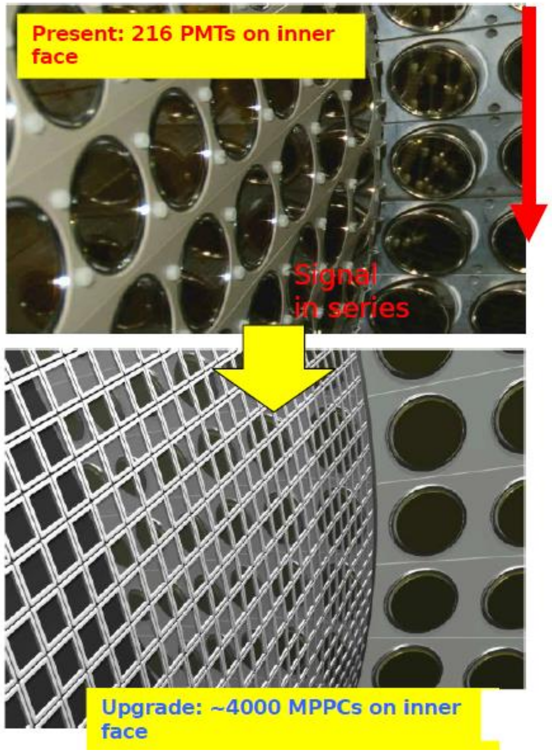
- Remove protective layer
- Fit anti-reflective coating to LXe refraction index
- Protect with quartz



MPPC development:

- ✓ VUV sensitive (PDE > 15%)
- ✓ Large area sensor(12×12 mm^2)
- ✓ Fast response (short pulse using novel SiPM connection method)





$$\mu \to e\gamma$$

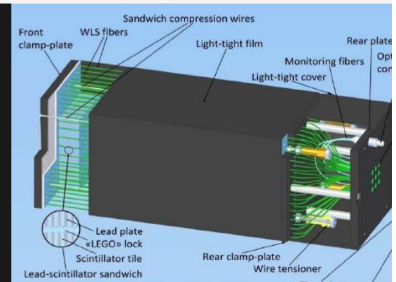
SiPMs will replace PMTs in MEGII gamma detector

(Paolo W. Cattaneo, INSTR-17, Novosibirsk)

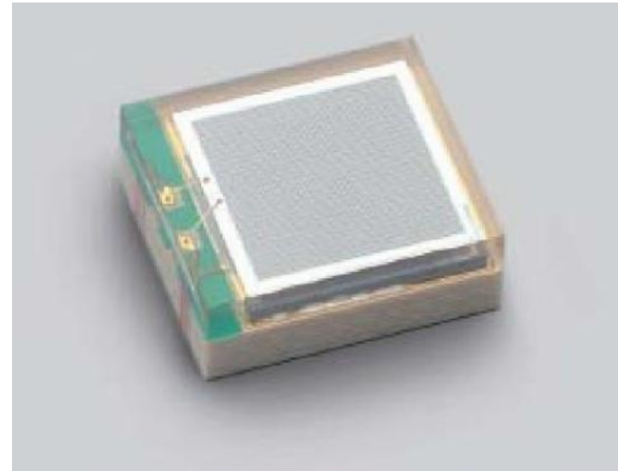
NICA MPD ECAL (Dubna)

"Shashlyk" type device meets all the above requirements

ScPb calorimeter;
(1÷2)% + (3÷5)%/√E;



Parameters	
Transverse size, mm²	40x40
Module size, mm²	120x120
Number of layers	220
Lead absorber thickness, mm	0.3
Polystyrene scintillator thickness, mm	1.5
Moli'ère radius, mm	26
Radiation length, X_0	11.8



(HAMAMATSU S12572-015P)

+ **smd devices - compactnes**
+ **Higher photon detection efficiency**
+ **Much Lower dead time Rate > 10k/s**
+ **Lower temperature dependence**
- **40000 pixels -> nonliniarity**

ZECOTEC

+ **High pixel densities of up to 40000 mm-**
- **Counting rate < 100 /s**

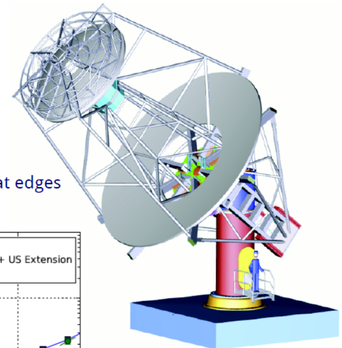
Large dynamic range SiPMs will be used to read out Shashlyk type calorimeter

(I. Tyapkin INSTR-17, Novosibirsk)

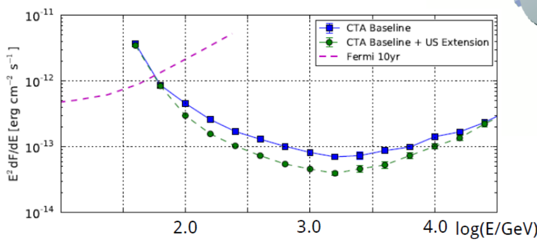
SiPM camera for CTA

The Midsize Schwarzschild-Couder Telescope

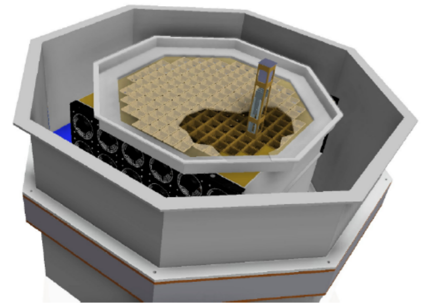
- Extending CTA Baseline array with ~25 telescopes
- Factor two gain in sensitivity

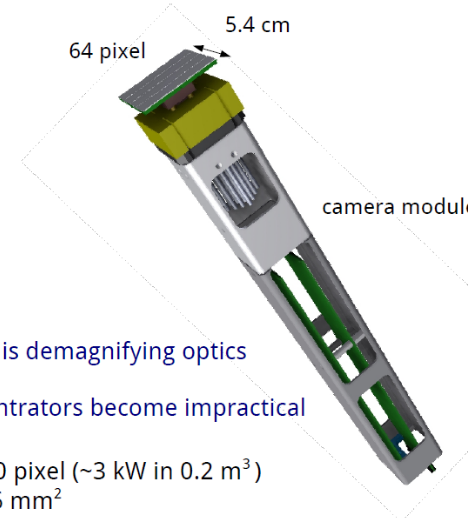


Main reason for SCT development is large field of view with little loss in optical performance at edges



SCT Camera

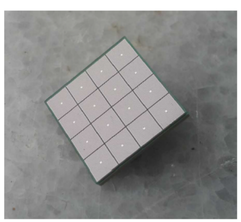




Practical advantage of SC optics is demagnifying optics
--> very compact camera
Disadvantage is that light concentrators become impractical

- 8° FoV
- Camera with ~12 000 pixel (~3 kW in 0.2 m^3)
- Pixel size 0.064°; 6x6 mm^2
- Silicon photomultipliers

Photon Detector for the Prototype

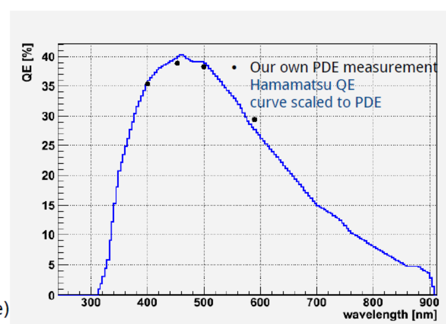


Hamamatsu (S12642-0404PA-50):

- 3x3 mm^2 SiPMs in 4x4 matrix
- TSV technology (reduced dead space)
- 50 µm cells

At 3 V above breakdown

- Peak PDE @ 450 nm is ~38%
- Optical cross talk 48%
- Dark Rate 200 kHz/mm^2 (5 times below NSB)



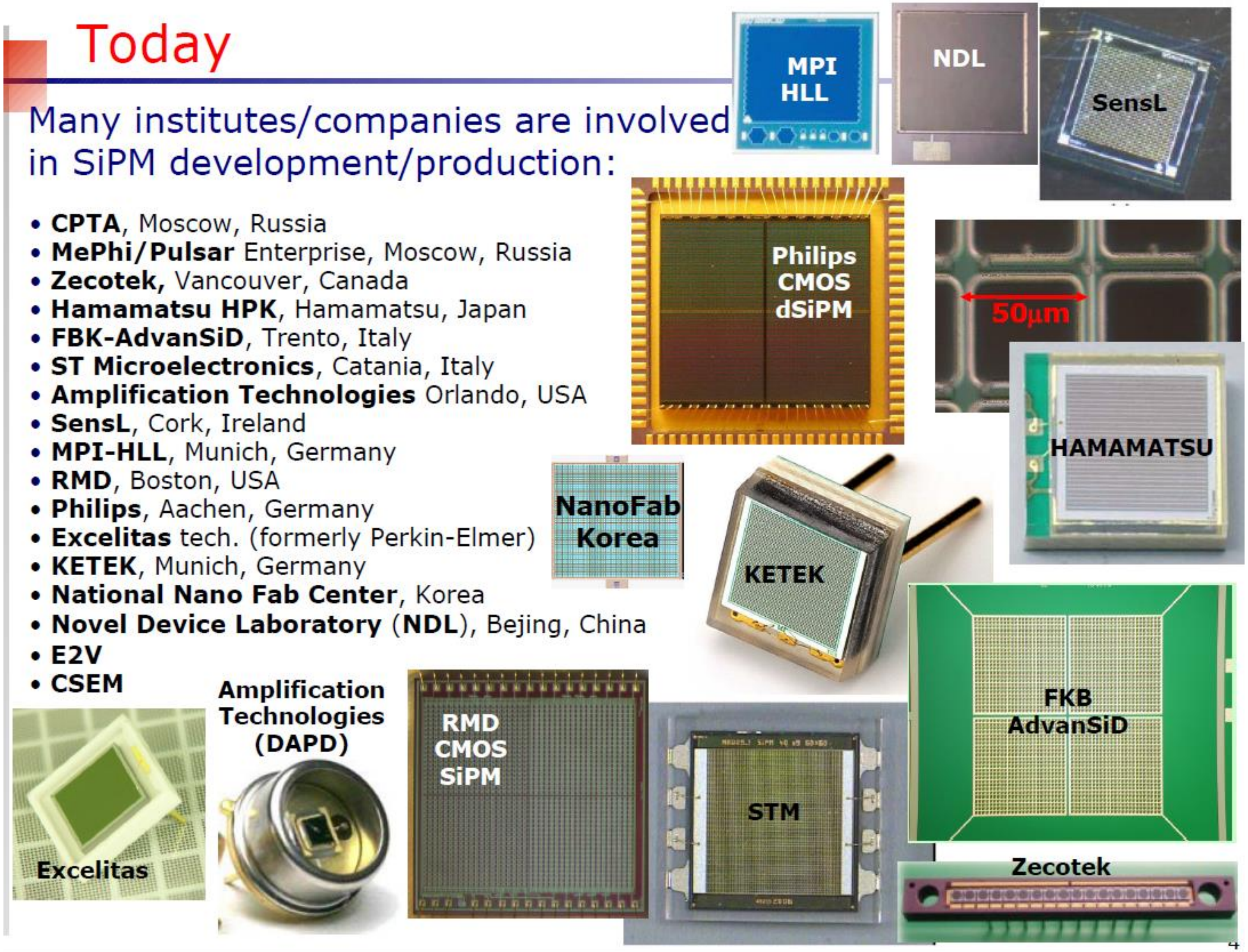
Choice for prototype but we continue to evaluate devices before we have to make a choice for the final array

Devices are rapidly improving

Use of SiPMs in MSCT camera will allow a factor of 2 gain in sensitivity and operation at full moon

(N. Otte, NDIP-14, Tours)

SiPM producers/developers



Today

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**

(G. Collazuol, PhotoDet 2012)

Summary

Significant progress in development of SiPMs/SSPMs over last 3 years by several developers:

- High PDE: ~50-60% for blue-green light
- SiPMs with good sensitivity (PDE>10%) for VUV light have been developed
- Dark count at room temperature was reduced: ~30 kHz/mm^2
- Low optical cross-talk: <1-5% for high OV
- Fast timing: SPTR~75 ps (FWHM)
- Large dynamic range: >10 000 pixels/mm^2 (with high PDE>30%)
- Very fast cell recovery time: ~4 ns
- Large area: 6x6 mm^2 and more
- TSV technology was introduced to build very compact SiPM arrays
- Position-sensitive SiPMs with good position resolution: <100 μm
- SiPMs demonstrated their rad. tolerance up to 2.2*10^{14} n/cm^2
- SiC, GaAs, InGaP SSPMs were successfully developed
- SiPM is the main topic of all photodetector/instrumentation conferences!
- Explosion of SiPM/SSPM applications!
- . . .

SiPM/SSPM perspectives (3-5 years)

My point of view:

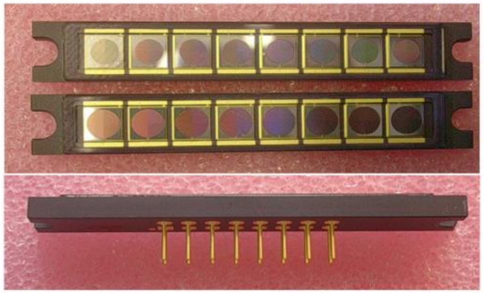
- Further work to reduce correlated noise (this is one of the limiting factors for many applications)
- Small cell pitch (5 μm), large dynamic range SIPMs
- DUV SiPMs with good sensitivity (PDE>30%) for VUV light
- Dark count at room temperature can be reduced: <10 kHz/mm^2
- Development of SiPMs for fast timing: SPTR<50 ps (FWHM)
- Fast cell recovery time: 2-3 ns
- Large area: 10x10 mm^2 and more
- PS SiPMs with position resolution: <50 μm for single photons
- SiPMs with rad. tolerance up to 5*10^{14} n/cm^2
- Further development of SiC, GaAs, InGaP SSPMs.
- Price will go down (for large quantities) <10 CHF/cm^2...

Thank you for your attention!

Back-up

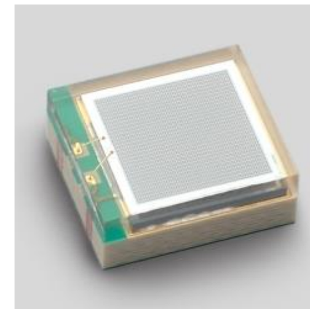
Studies of SiPMs irradiated with 2E13 n/cm²

HE MPPC arrays (Ø2.8(3.3) mm SiPMs) and 3x3 mm² MPPCs (SMD package)



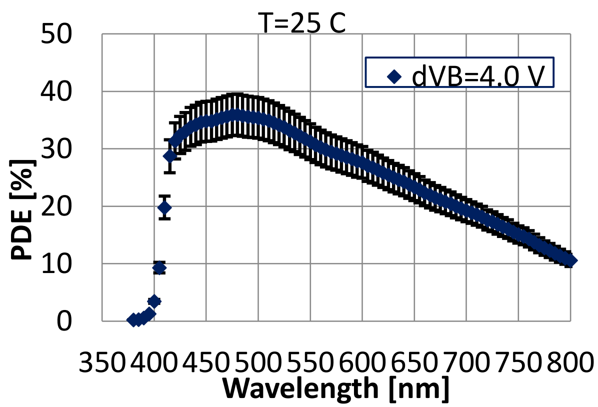
S10943-4732 and S10943-4733 MPPCs (developed by Hamamatsu and CMS SiPM group for the CMS HE HCAL):

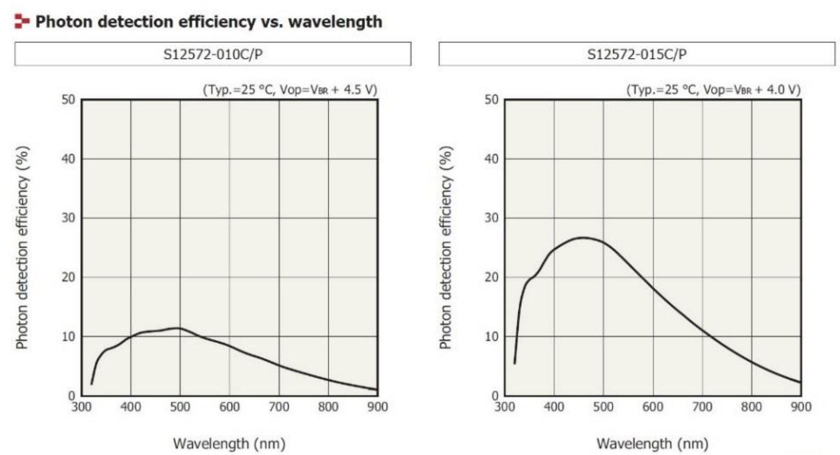
- Area: 6.15(8.55) mm²
- Cell pitch: 15 μm
- V_{op}: ~69 V
- Gain (V_{op}): ~300*10³
- PDE(515nm): 30%



S10943-4732
S10943-4733

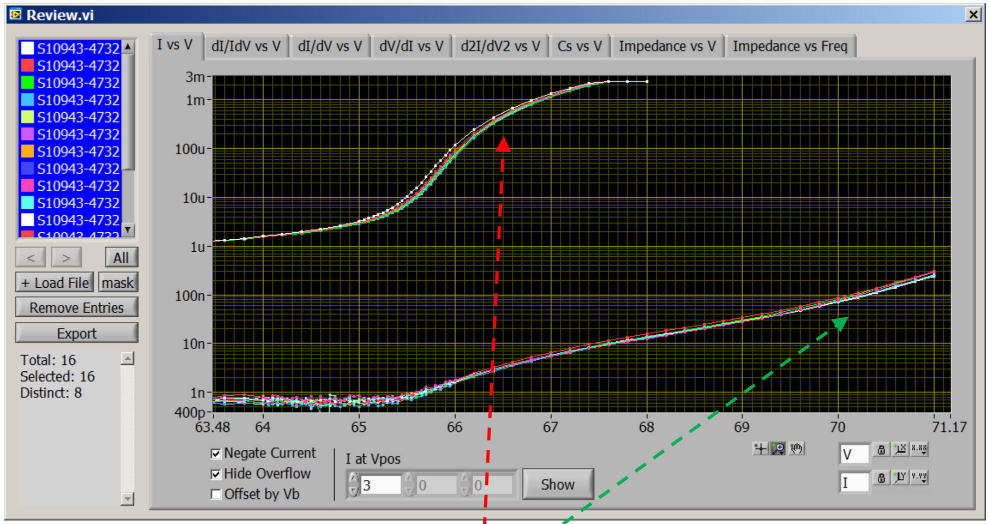
S12572-010P
S12572-015P





Irradiation performed at Ljubljana reactor

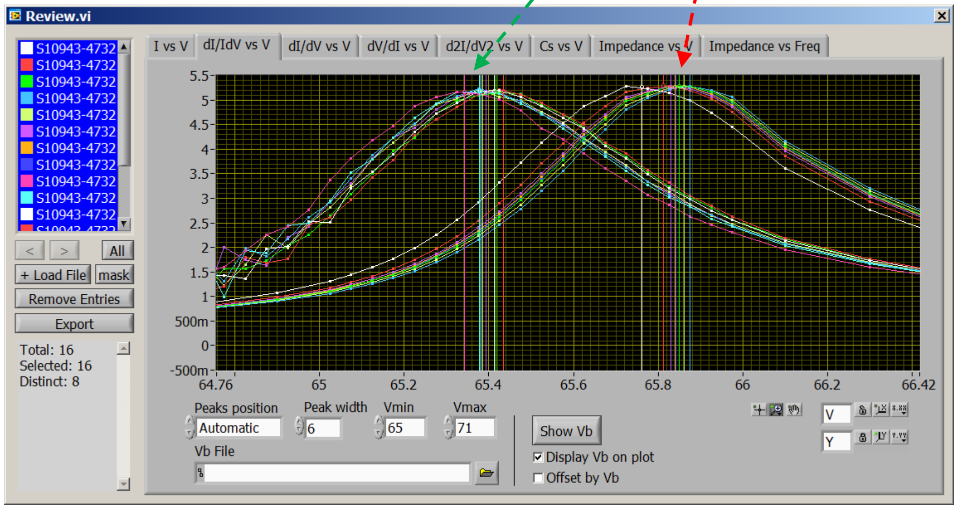
VB determination before after 2E13 n/cm^2



SiPMs VB measured using 1/I*dI/dV max. technique.

VB before/after irr.

Dark current vs. bias before/after irr.

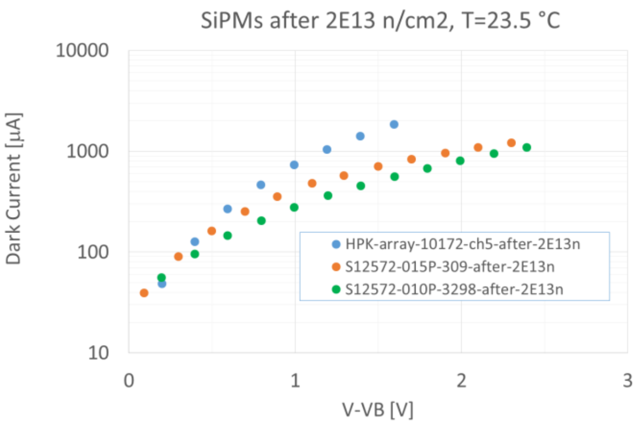


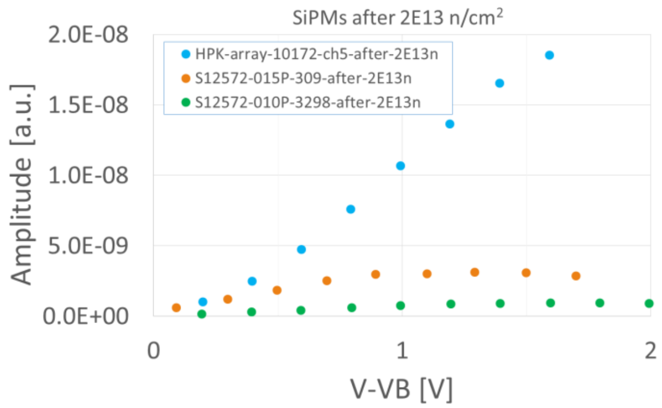
VB is increased by 0.43 V

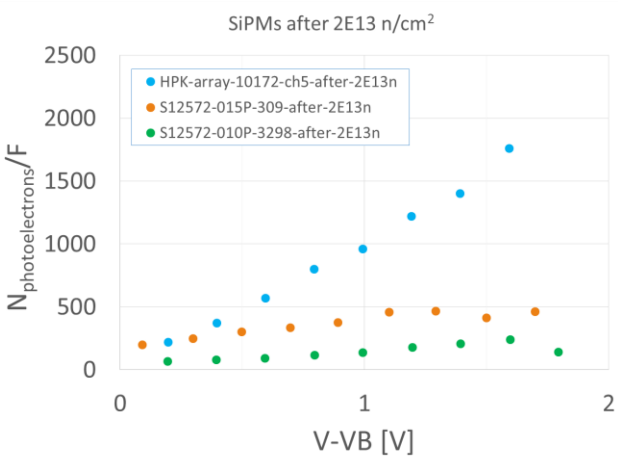
(A. Heering et.al, IEEE-NSS/MIC 2016, N27-19)

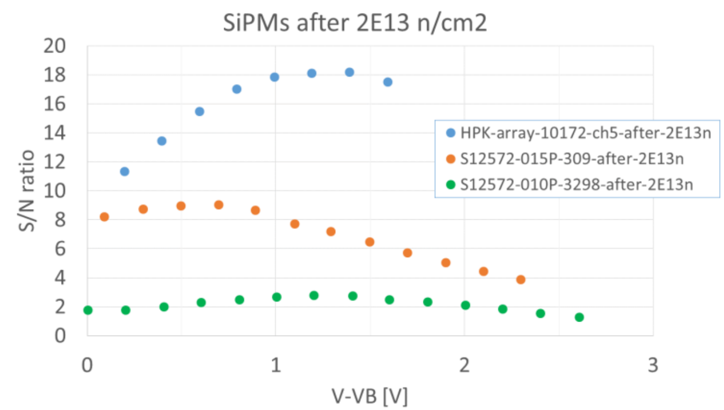
HPK SiPM after 2E13 n/cm²

LED (515 nm, 15 ns) pulse amplitude ~ 12 000 photons/pulse high enough to see signals from all SiPMs





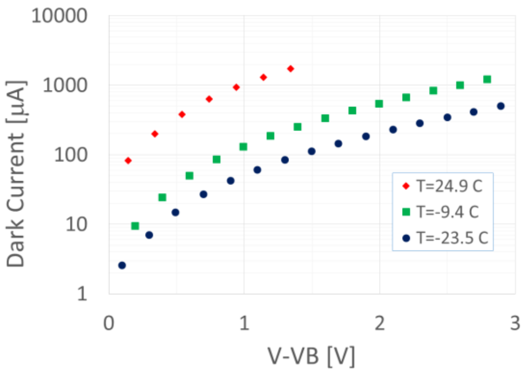


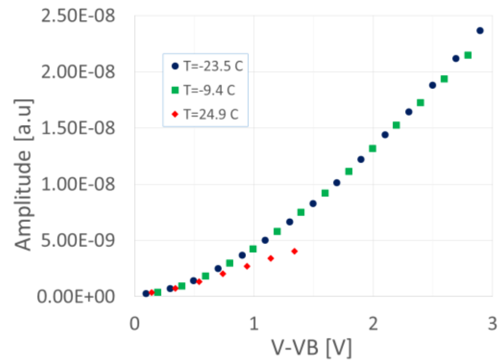


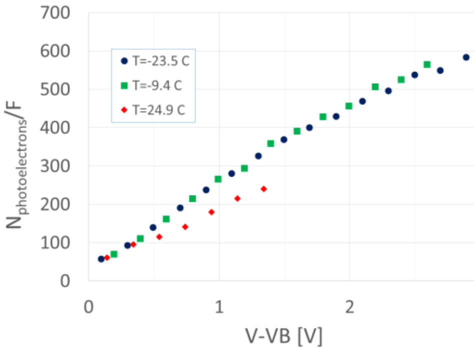
Self-heating effects? SMD package!

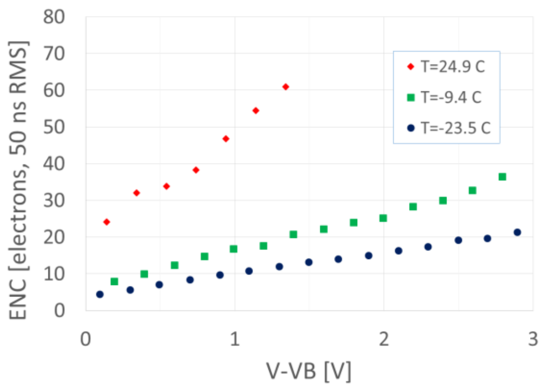
HPK S10943-4732 2.8 mm SiPM after 2E13 n/cm² at reduced temperature

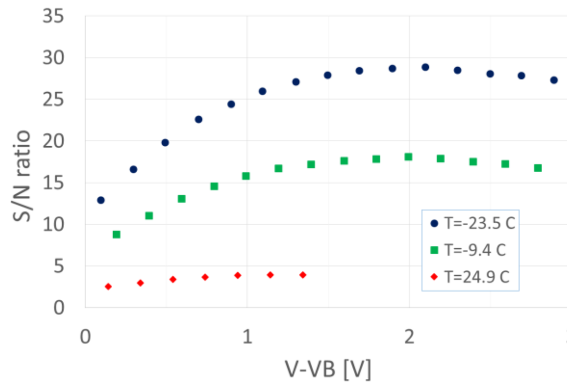
Average LED pulse amplitude ~2400 photons/pulse











- At T=-9.4 °C SiPM LED pulse response recovers to that of non-irradiated SiPM
- From 24.9 °C to -23.5 °C: ~21 times Id reduction (~1.88 times/10 °C)
- Maximum S/N improves >7 times due to dVB increase

(IEEE-NSS/MIC 2016, N27-19)

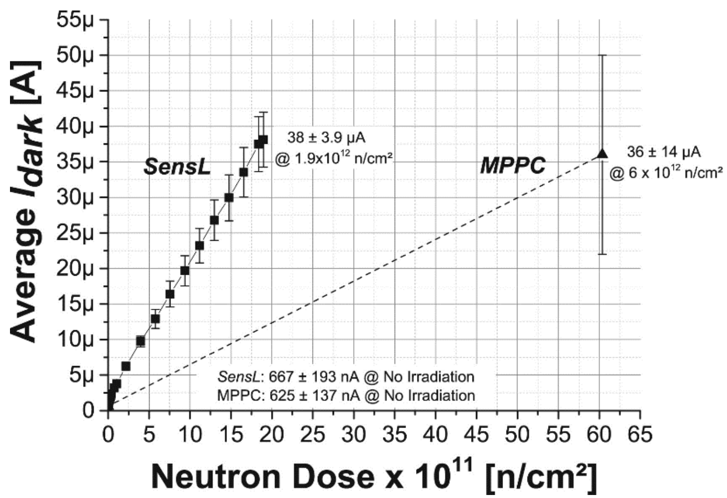
Irradiation with cold neutrons

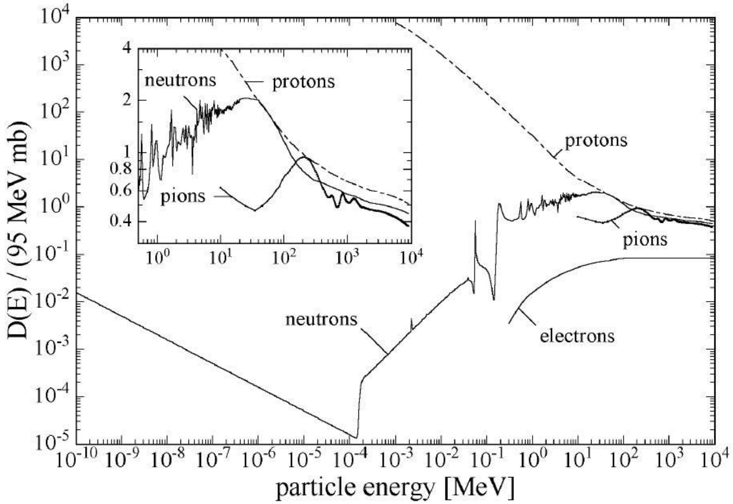
Thermal neutron study (T=23 °C) at FMR II reactor at Julich (E_n = 3.27 meV, up to 6E12 n/cm^2)

Thermal neutron capture can cause nuclear transmutations

$^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta^-$

Produces isolated defects with ~ 2-5 defects per absorbed neutron





Neutron dose dependent average dark currents measured respectively on 10 SiPM detectors from the SensL 12x12 SiPM Series-C detector board, and on 12 MPPC detectors from the Hamamatsu 8x8 MPPC array S12642–0808PB-50 detector board.

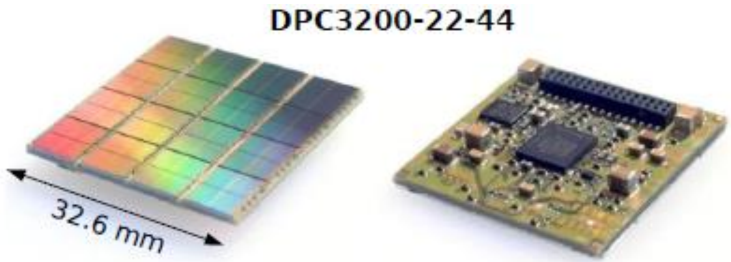
SensL: 12x12 detector array ArrayC-30035-144P-PCB, 3x3 mm^2, 35 μm cell pitch, VB+2.5 V

Hamamatsu: 8x8 MPPC array 12642–0808PB-50, 3x3 mm^2 , 50 μm cell pitch, VB+2.4 V

(D.Durini et. all, NIM A835 (2016) 99-109)

Radiation hardness study of the Philips Digital Photon Counter with proton beam

Irradiation by protons with P=800MeV/c (T=295MeV).
Beam size: $\sigma_x \approx \sigma_y \approx 1$ cm.

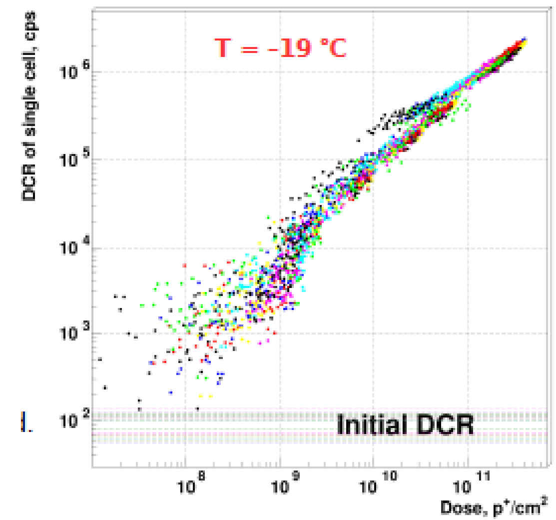


Array of 4x4 die.
Die = 128x100 cells (Geiger-mode APDs) +
+ TDC (LSB=20ps) + 4 photon counters.

Active cell quenching.
Full digital data output.
Noisy cells can be disabled

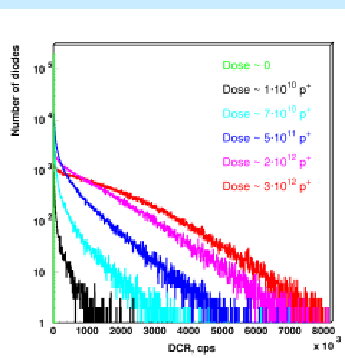
Signal from each pixel is is digitized and the information is processed on chip:

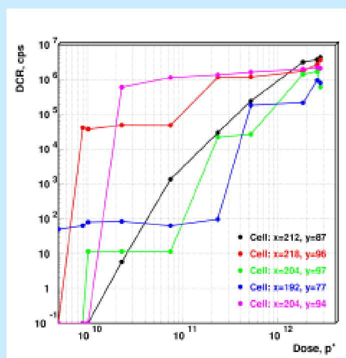
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution



Dark counting rate vs. total dose

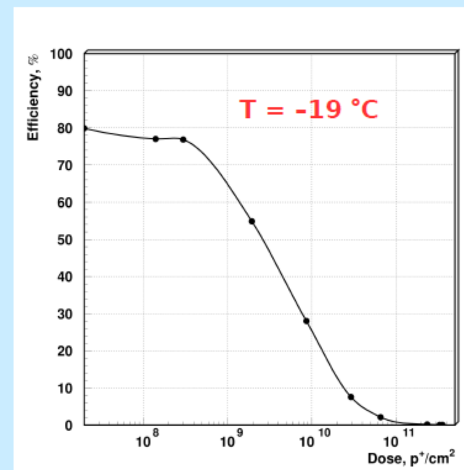
DCR spectra after different total doses accumu-lation





DCR of single cells from one subpixel as a function of total dose

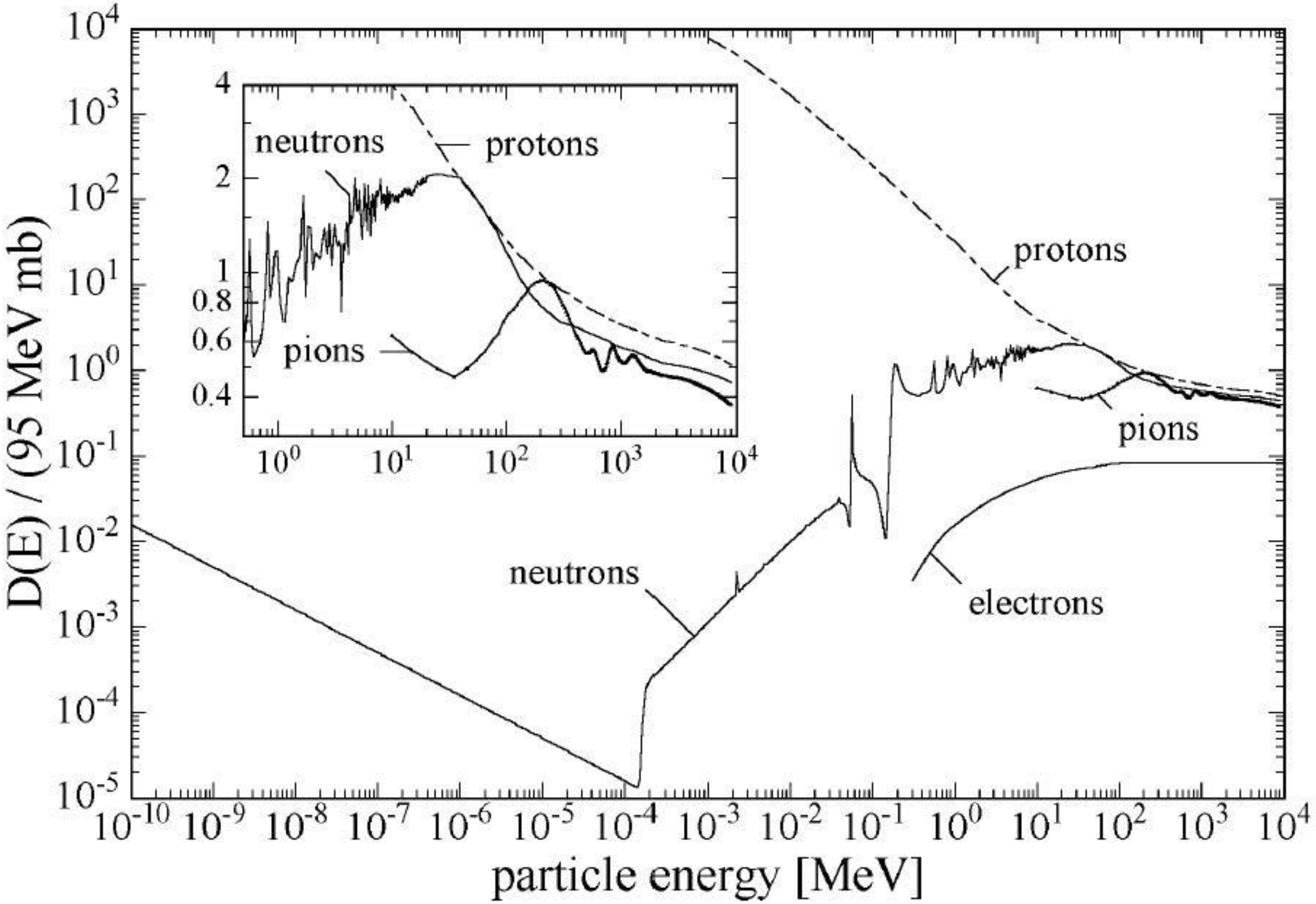
With the dose accumulation the number of noisy cells increases rather than DCR of each cell. ⇒ Cell damage caused by single interaction of p⁺ with Si lattice.



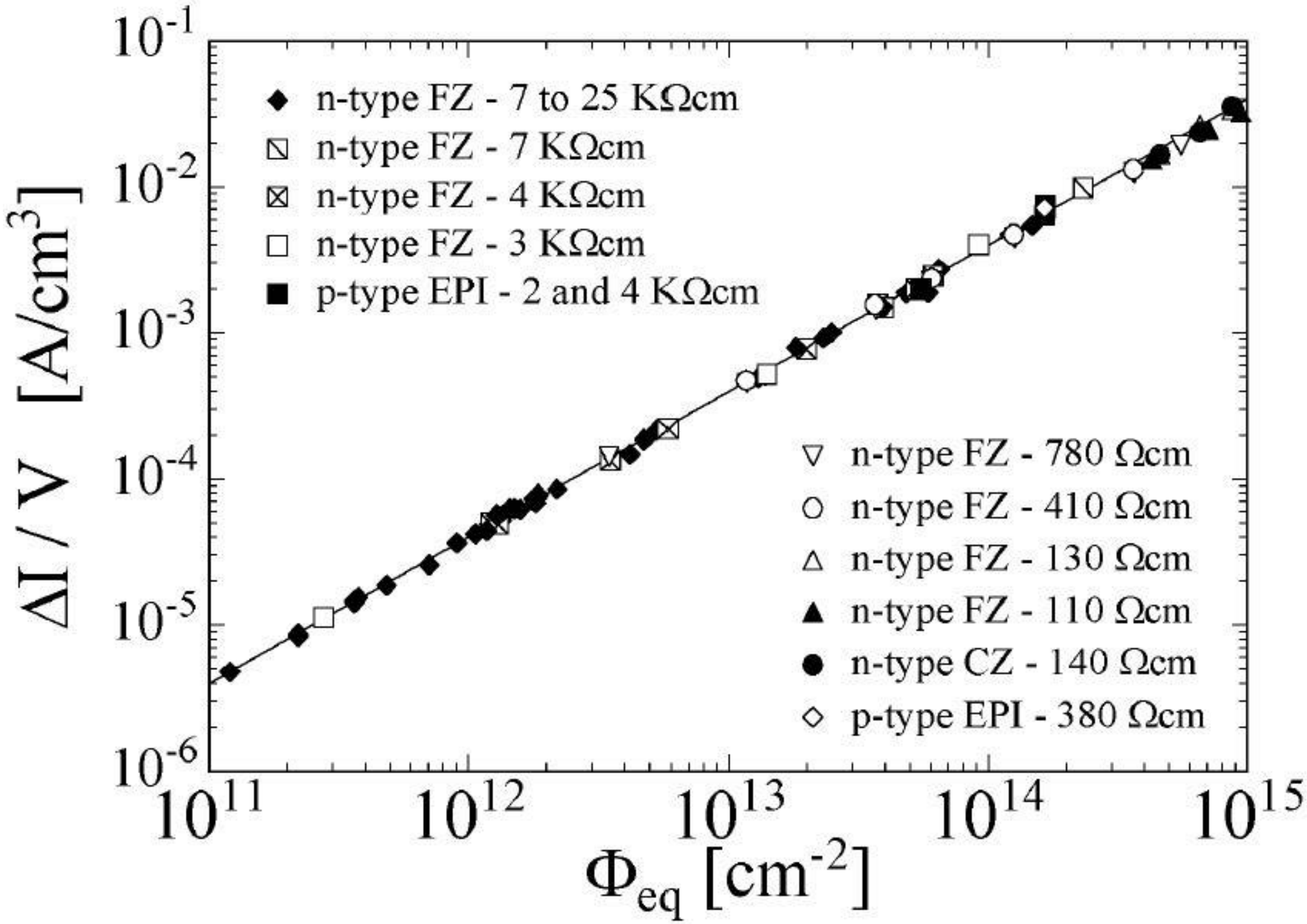
Optimal efficiency of *single photons* detection as a function of proton fluence.

(M.Barnyakov et al., Elba-2015)

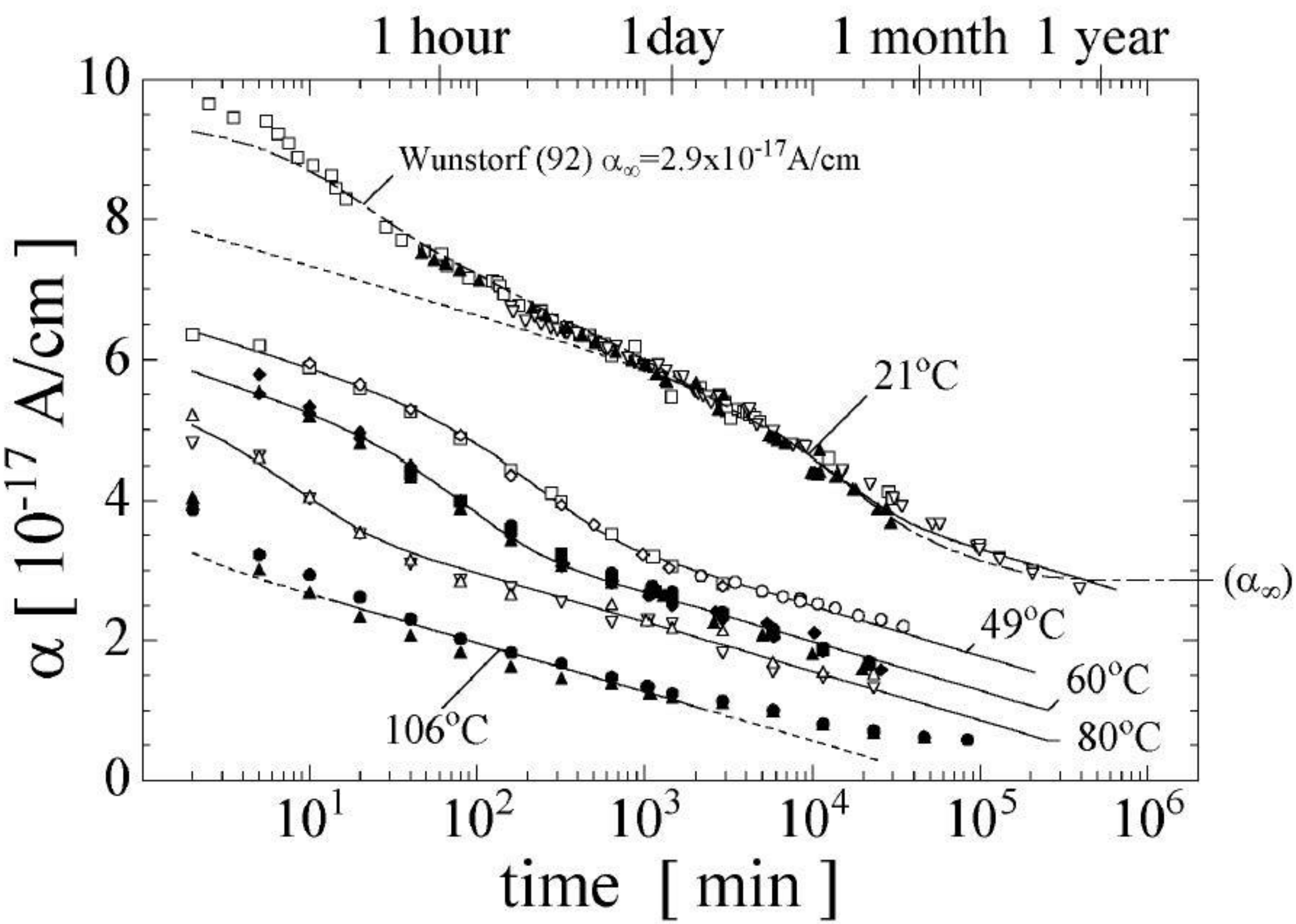
Displacement damage function (NIEL) for protons, neutrons, pions and electrons vs. their energy



Fluence dependence of leakage current for silicon detectors



Current related damage rate α as function of cumulated annealing time



(M.Moll, PhD thesis)