Innovative technology for SiPM-like detectors

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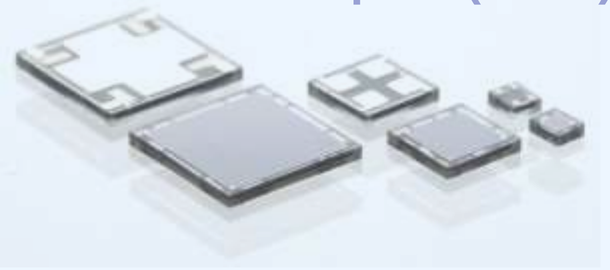
Vacuum photomultiplier (PMT)

Silicon Photomultiplier (SiPM)



- Compactness
- Low weight
- Low power consumption (~50μW)
- Low voltage supply (20-100V)
- Fast signal (~1 ns front)
- Simple FE electronics
- Room temperature operation
  - Sensitivity to single photons
  - Possibility to measure light intensity
  - Excellent amplitude resolution
  - Negligible nuclear counting effect
  - Immunity to magnetic fields up to 7 T

Outline:

1. Silicon Photomultiplier (SiPM)
2. SiPM main parameters
3. Advanced SiPMs (Innovative technology)
4. Digital and Multidigital SiPMs
5. Packaging and Matrixes
6. SiPM applications
7. Summary

Silicon Photomultiplier (SiPM)

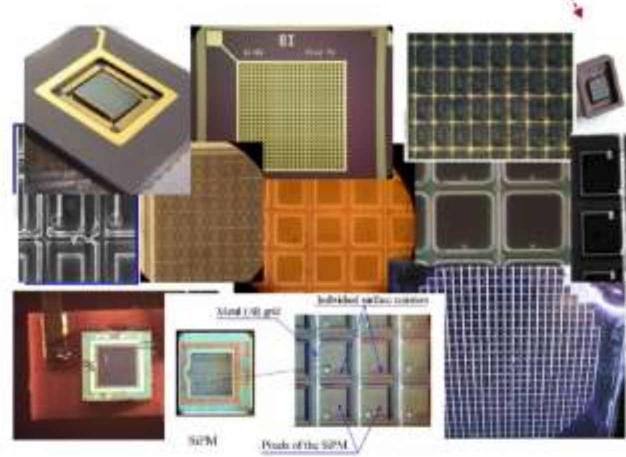
Around 1990 the initial prototypes of SiPM (**MRS** Metal- Resistor Semiconductor APD's) were invented in Russia (*V.Golovin,Z.Sadygov,N.Yusipov(Russian patent#1702831, from10/11/1989)*

They had :
Too difficult and unreproducible technology
Too low light detection efficiency (of about 1%)
Unclear operational principle

But nevertheless they look very promising detectors for Experimental Physics!

What is available

MEPhI/Pulsar (Moscow) - Dolgoshein
CPTA (Moscow) - Golovin
Zecotek(Singapore) - Sadygov
Amplification Technologies (Orlando, USA)
Hamamatsu Photonics (Hamamatsu, Japan)
SensL(Cork, Ireland)
AdvanSiD (former FBK-irst Trento, Italy)
STMicroelectronics (Italy)
KETEK (Munich)
RMD (Boston, USA)
ExcelitasTechnologies (former PerkinElmer)
MPI Semiconductor Laboratory (Munich)
Novel Device Laboratory (Beijing, China)
Philips (Netherlands)
....



Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, MPPC, SPM, DAPD, PPD, SiMPI , dSiPM…

14-15 March 2011 erika.garutti@desy.de 4/43

Homage of Boris Dolgoshein (1930-2010)

Professor MEPHI

Head of the particle-physics department of MEPHI

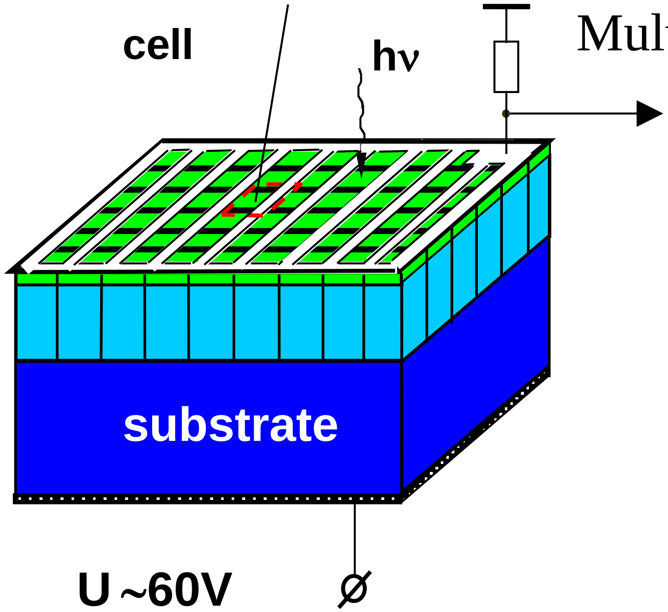
Inventor of streamer chamber (1962)

Developer and pioneer of Transition Radiation Detector (TRD)

prof. Dolgoshein started to develop novel photodetectors which he called Silicon Photomultipliers (SiPM) since 1993

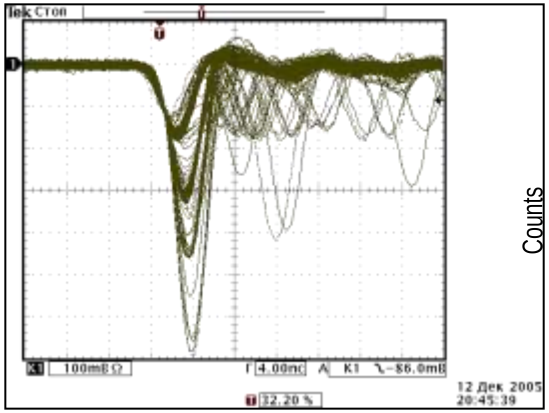
Now we have at MEPHI the new organized and well equipped in framework of the Russian Megagrant Program the Silicon Photomultipliers laboratory with ~ 50 employees

Silicon Photomultiplier (SiPM)

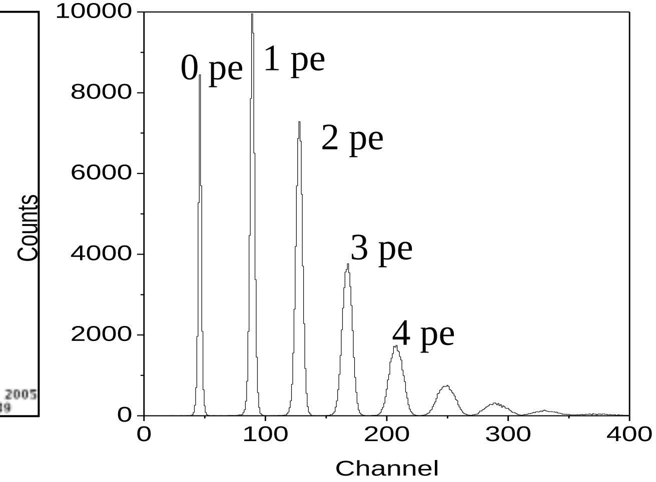


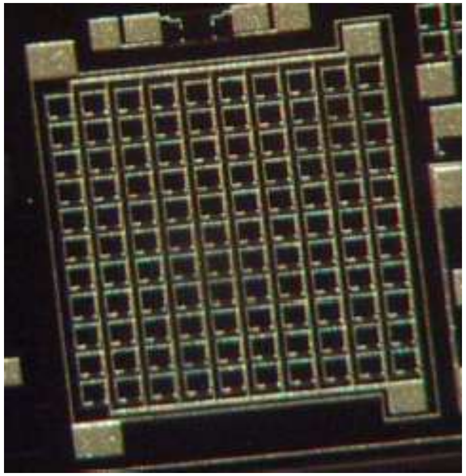
Multicell device with common readout

Scope signal



Amplitude spectrum

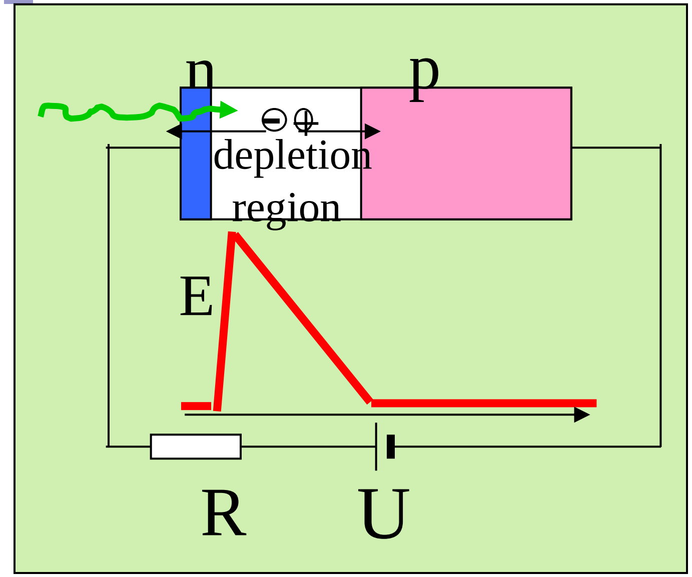




- **Each cell – p-n-junction in selfquenching Geiger mode**
- **cell numbers: ~ 100÷10000/mm^2**
- **All cells are equal**
- **Cells are independent from each other**
- **Signal – is a sum of all fired cells**

Cell signal - 0 or 1
But SiPM is analogue device

Silicon Photomultiplier (SiPM)



p-n-junction based detectors

Impact Ionization

Avalanche multiplication

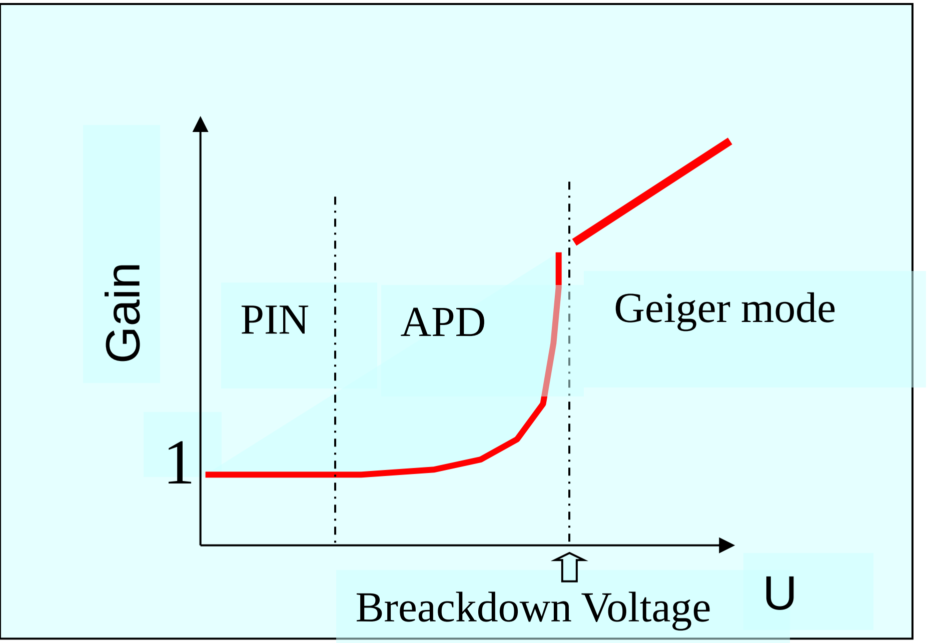
Geiger discharge

Geiger mode features

Output signal doesn't depend from input

Output signal value Q is determined by charge accumulated on a cell capacitance

$$Q = C_{cell} \cdot (V - V_{breackdown})$$



M= Q/e -microcell gain

$M = 10^5 - 10^7$

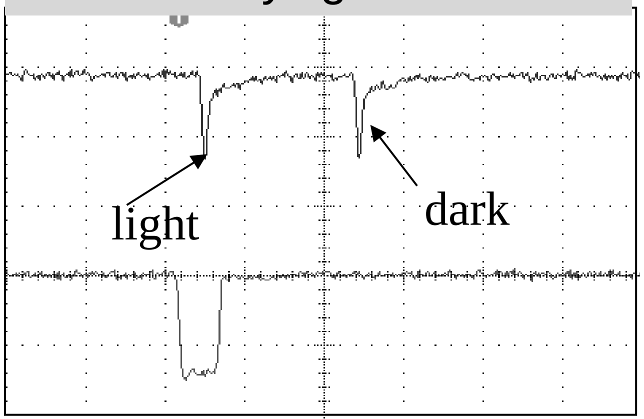
Discharge duration – of about 1 ns

(selfquenching due to resistor)

Silicon Photomultiplier (SiPM)

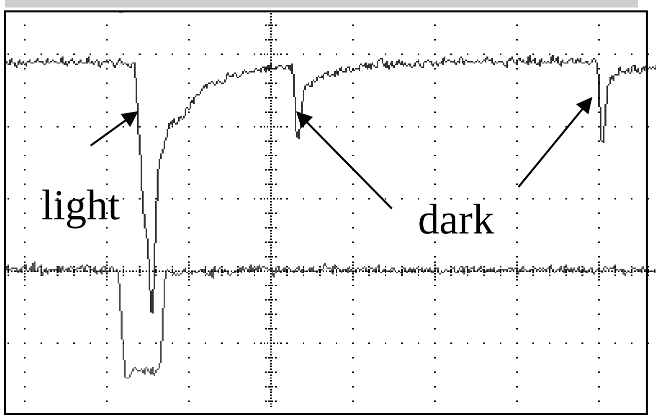
Response function for SiPMs with different microcells numbers

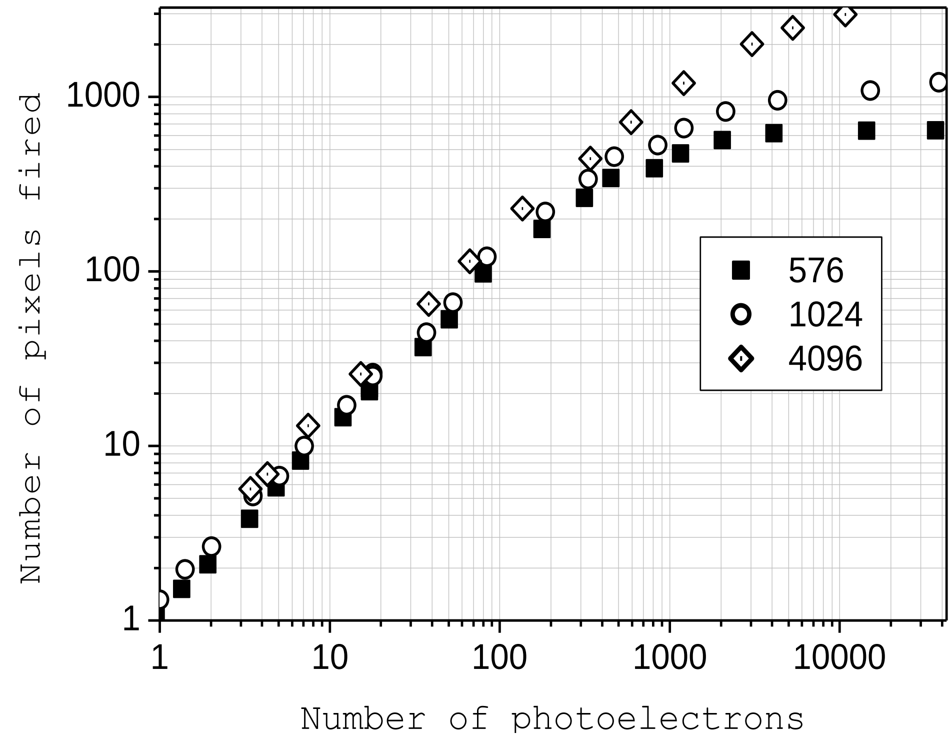
low intensity light



"light" and "dark" signals are identical

more intensive light





$$N_{firedcells} = N_{total} \cdot \left[1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}} \right]$$

- Response function depends on total number of microcells inside SiPM
- Saturation correction is possible

SiPM main parameters

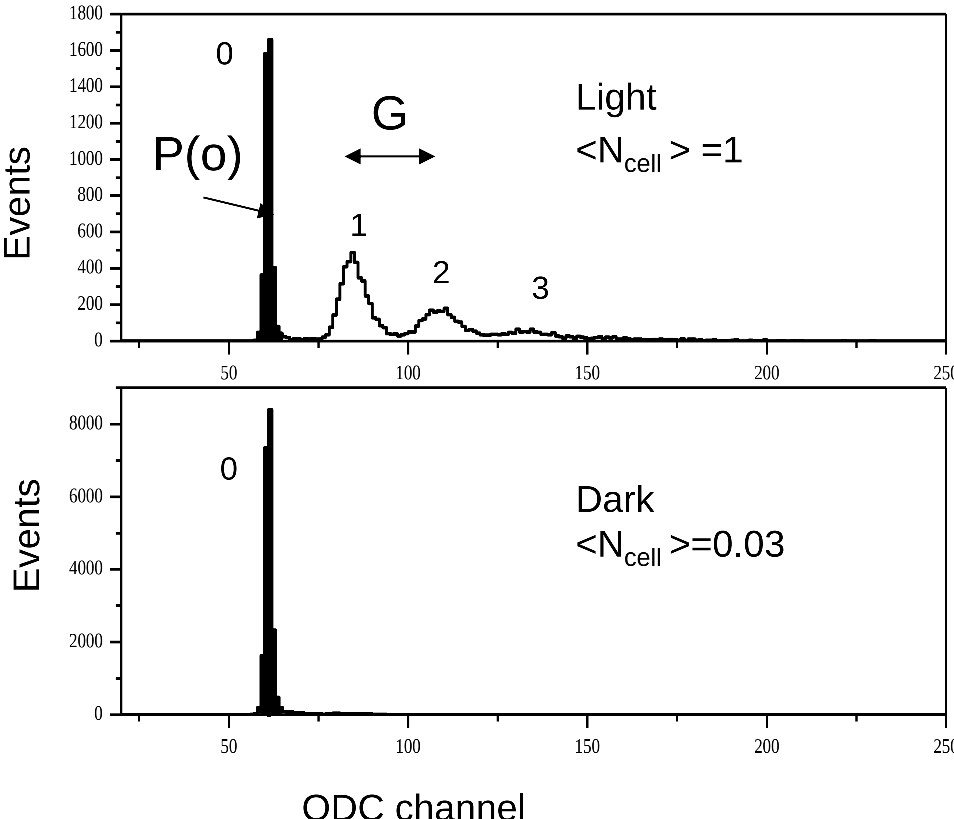
•Photon Detection Efficiency **PDE**

Important – no signal, no crosstalk!!!

$$PDE = \frac{<N_{\text{fired\_cell}}>}{<N_{photons}>} \qquad P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!} \qquad <N_{cell}> = -\ln P(0, <N_{cell}>)$$

•Crosstalk **xt** (afterpulsing **ap**)

•Gain **G**



Dark rate **f= <ndark>/T,**

where T – integration time

•Intrinsic jitter $\boldsymbol{\sigma_t}$

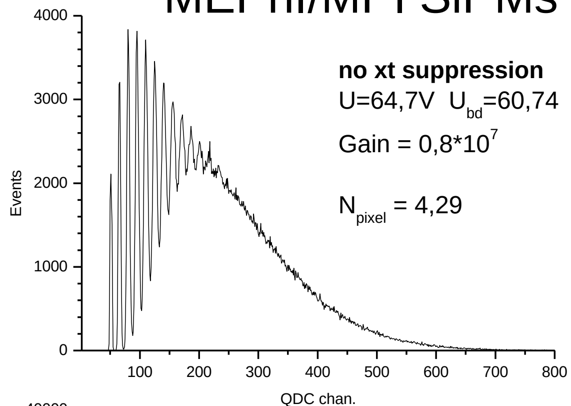
SiPM's single pixel spectrum is very useful thing for precise measurements! There are allow us to determine all main SiPM parameters.

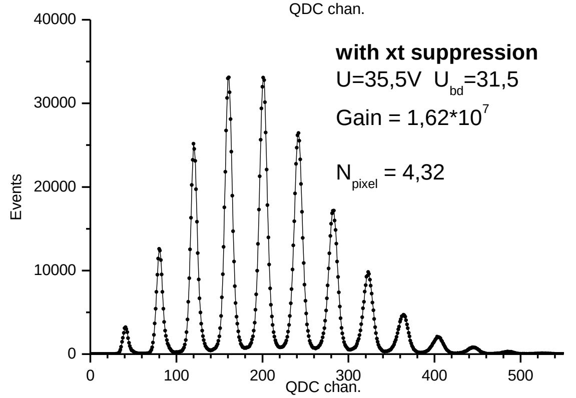
Quite important – **PDE**, **gain** and **xt** are measured independently

Crosstalk (XT)

Xt and light signal

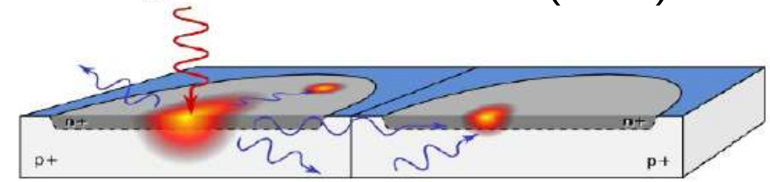
MEPhI/MPI SiPMs





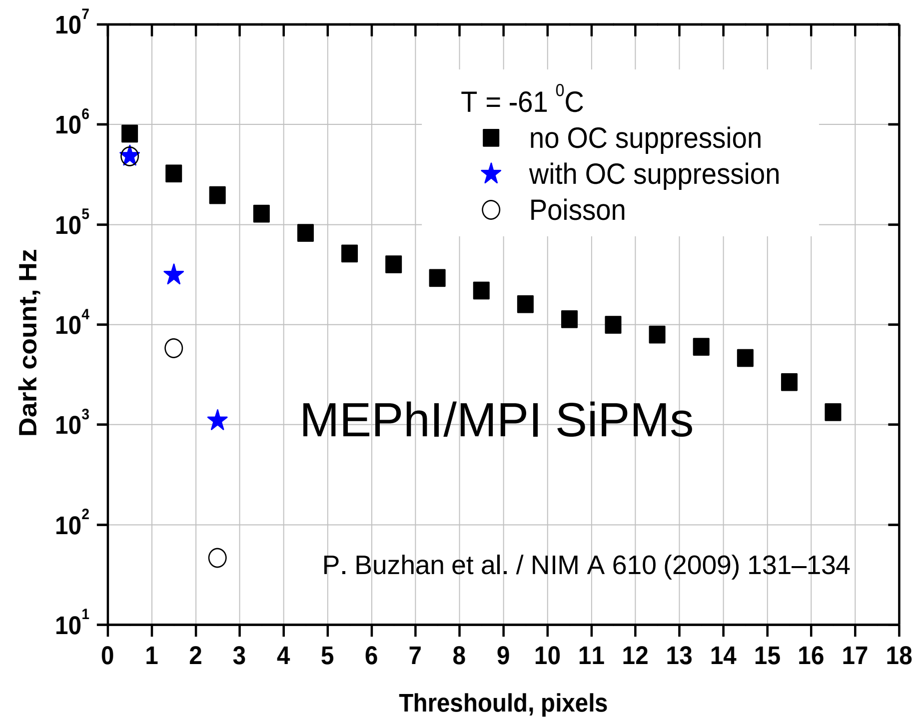
(IMAGING2010 Stockholm, Sweden June 8 – 11, 2010
B.Dolgoshein "Silicon Photomultiplier")

A.Lacaita et al. IEEE TED(1993)



Geiger discharge emits secondary photons

Xt and dark rate



Main protection from crosstalk – optical trenches between the SiPM cells

PDE vs. XT

What is better –

- High PDE and high XT?
- Low XT and low PDE?

Of course **High PDE and low XT!**

But You can find quantitative answer in Sergey Vinogradov's SiPM statistical analysis:

S. Vinogradov, Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 695 (2012) 247–251. doi:10.1016/j.nima.2011.11.086.

S. Vinogradov et al., Probability distribution and noise factor of solid state photomultiplier signals with cross-talk and afterpulsing, 2009 IEEE Nucl. Sci. Symp. Conf. Rec. (2009) 1496–1500. doi:10.1109/NSSMIC.2009.5402300.

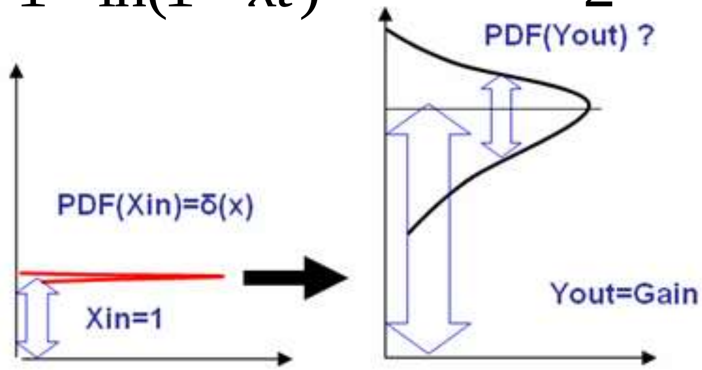
S. Vinogradov et al., Efficiency of Solid State Photomultipliers in Photon Number Resolution, IEEE Trans. Nucl. Sci. 58 (2011) 9–16. doi:10.1109/TNS.2010.2096474.

- **Crosstalk**

$$ENF_{xt} = \frac{1}{1-\ln(1-xt)} \approx 1 + xt + \frac{3}{2}xt^2 + \ldots$$

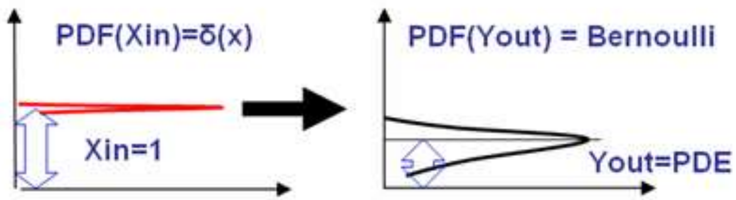
- **Multiplication**

$$ENF_{gain} = 1 + \frac{\sigma^2_{gain}}{\overline{Gain}^2}$$



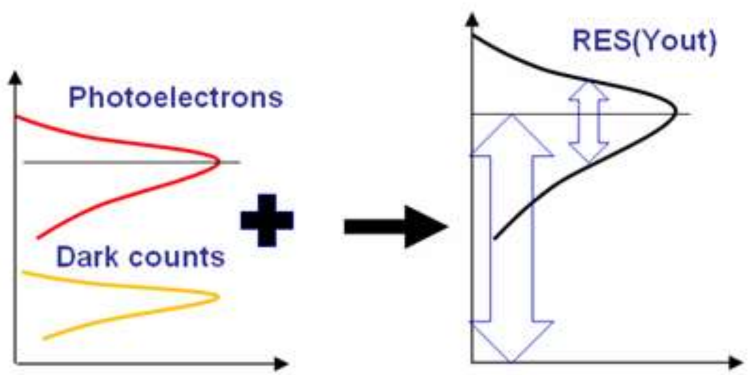
- **Photon detection**

$$ENF_{pde} = 1 + \frac{PDE \cdot (1-PDE)}{PDE^2} = \frac{1}{PDE}$$



- **Dark counts**

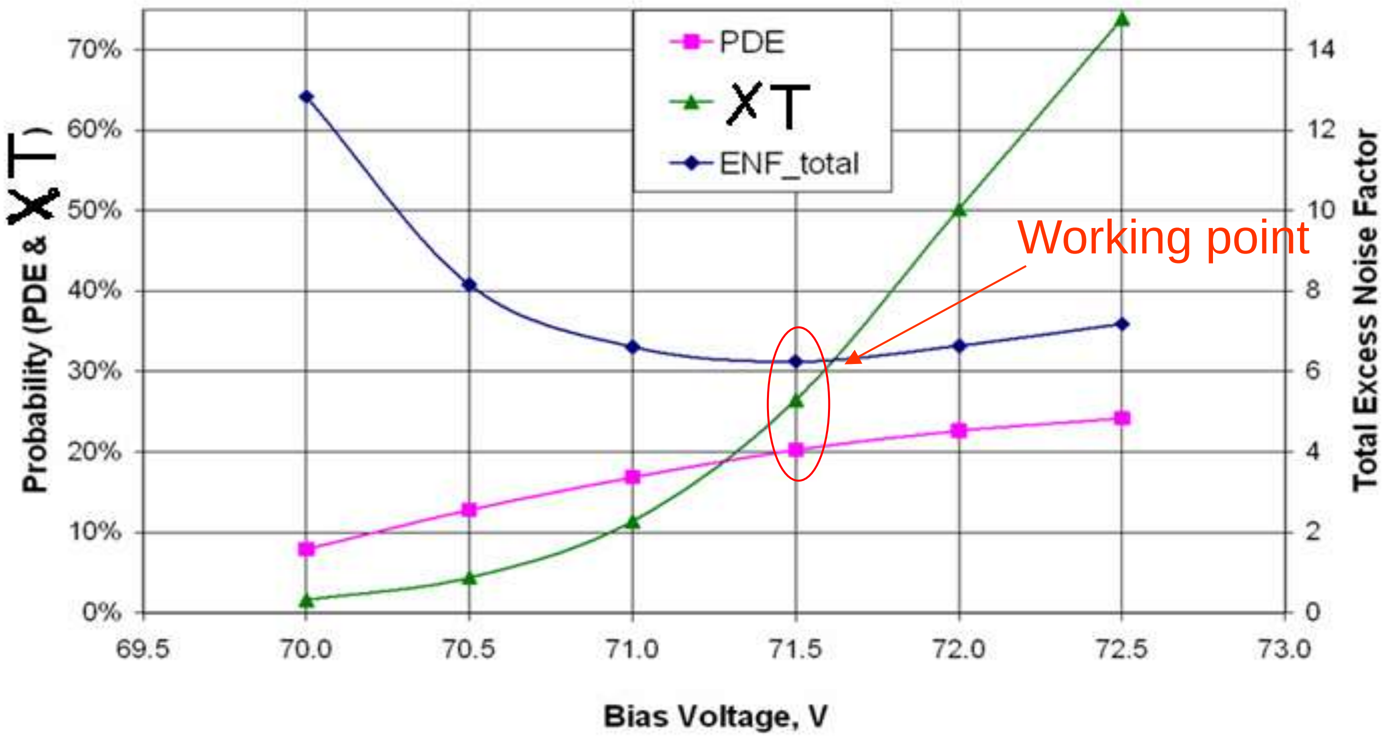
$$ENF_{dcr} = 1 + \frac{DCR \cdot t}{N_{pe}}$$



Workshop on the Latest Developments of Photon Detectors – LIGHT-2014 Ringberg, Germany, 08 October 2014 9

SiPM main parameters

PDE & XT overvoltage trade-off



Total ENF based on PDE and P_dup relation (6) in detection of 60 ps 700 photon pulses in 100 ns gate by 1 mm MPPC 1600 pixels (vendor spec. bias 71.2V). S. Vinogradov et al., IEEE NSS/MIC 2009.

Sergey Vinogradov *Workshop on the Latest Developments of Photon Detectors – LIGHT-2014* Ringberg, Germany 08 October 2014 12

- **Total ENF for a sequence of specific processes is**

$$RES(Y_{out}) = RES(X_{in}) \cdot \sqrt{ENF_{total}} = RES(X_{in}) \cdot \sqrt{ENF_{process\,1} \cdot ENF_{process\,2} \cdots}$$

SiPM main parameters

Requests from HEP experiments

2/20

- Higher Photo-detection Efficiency (or Probability)
  - Currently standard 15-20% (green), 30% (blue)
  - Limiting factor = fill factor (fraction of active to total area)
- Larger dynamic range
  - Currently standard ~1000-1500 pixels / mm^2 (25 μm)
  - Drawback for larger dynamic range = reduction of fill factor
- Single photon counting = lower dark rate (DR) and cross-talk (XT)
  - Currently standard DR ~0.5-1 MHz/mm^2 (dependent on U_{ex})
  - Currently standard XT ~10-15% (dependent on U_{ex})
- Large surface photo-detectors (or photo-detector array)
  - Strong interest also for medical applications

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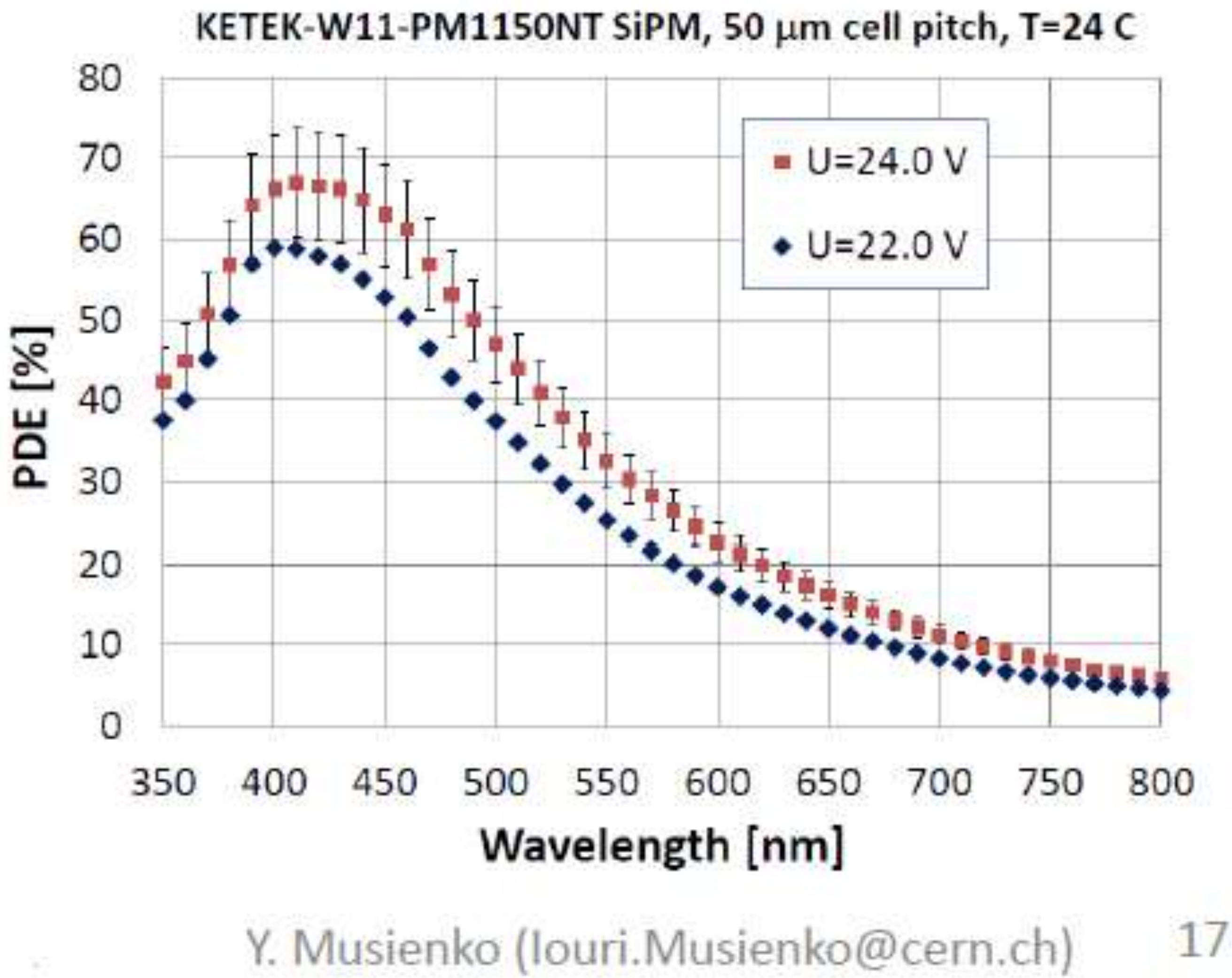
Terascale Alliance - Detector workshop, 15/03/12

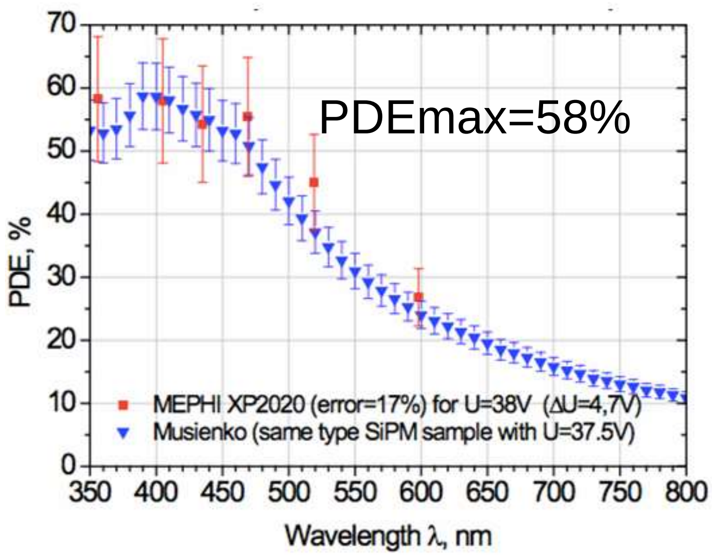
Photon Detection Efficiency (PDE)

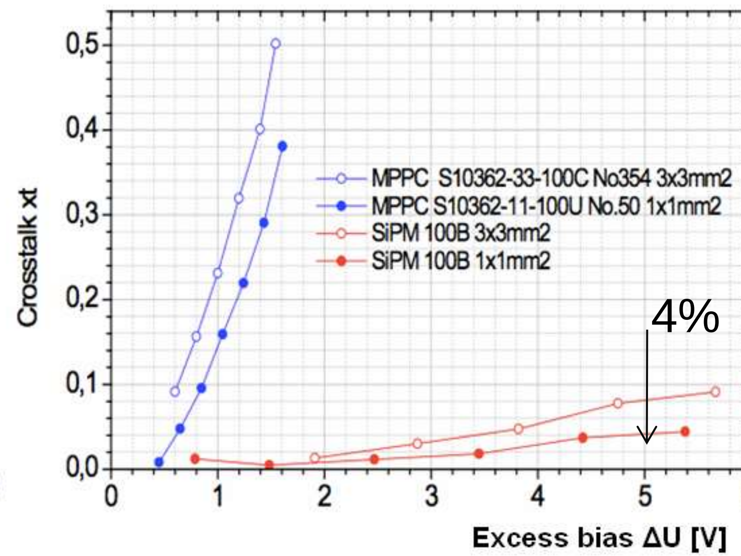


2nd advanced SiPM CTA workshop (March 2014)

PDE is higher then 60%!

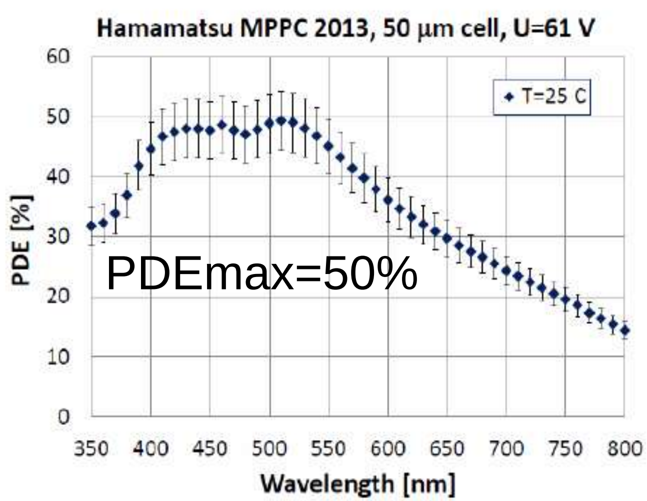
MEPHI/MPI
NDIP2011

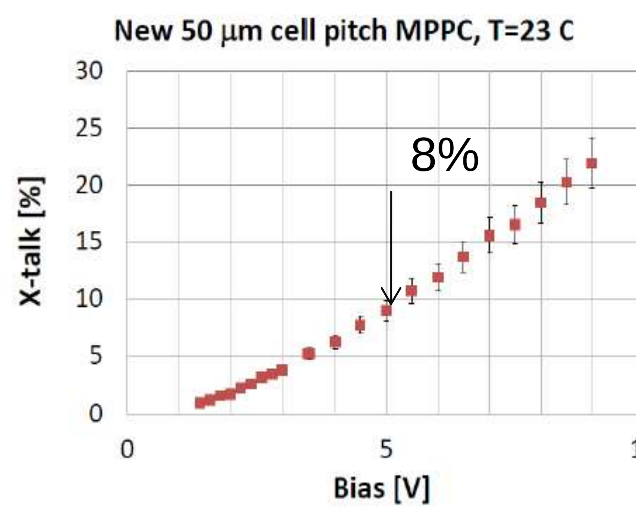




Elena Popova, MEPhI (NDIP 2011)

Hamamatsu
2014

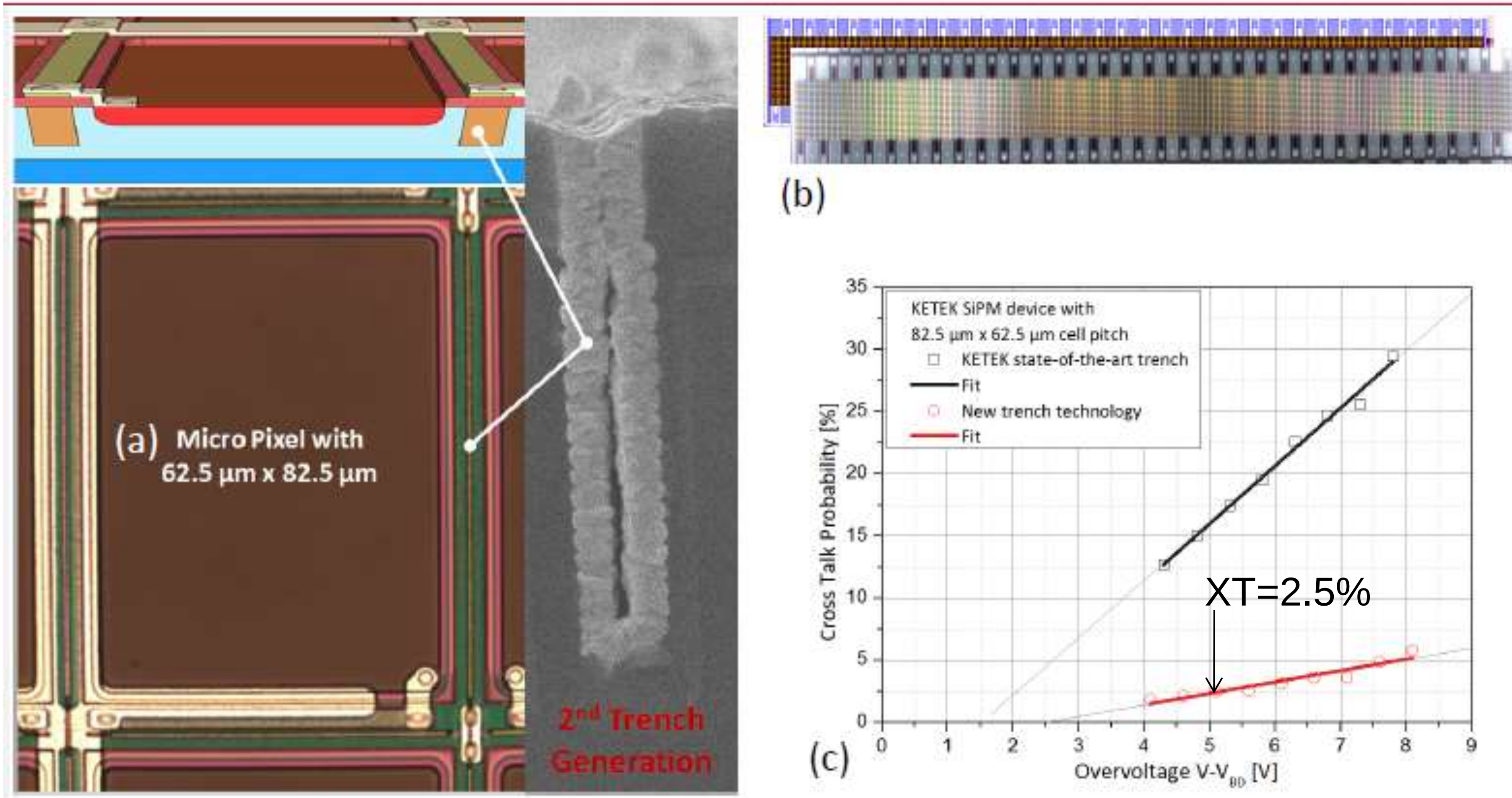




2nd advanced SiPM CTA workshop 2014

Y. Musienko (Iouri.Musienko@cern.ch)

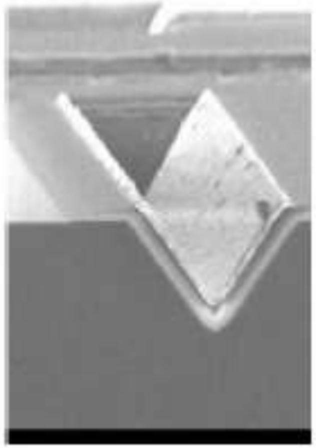
Second generation of optical trenches developed by KETEK

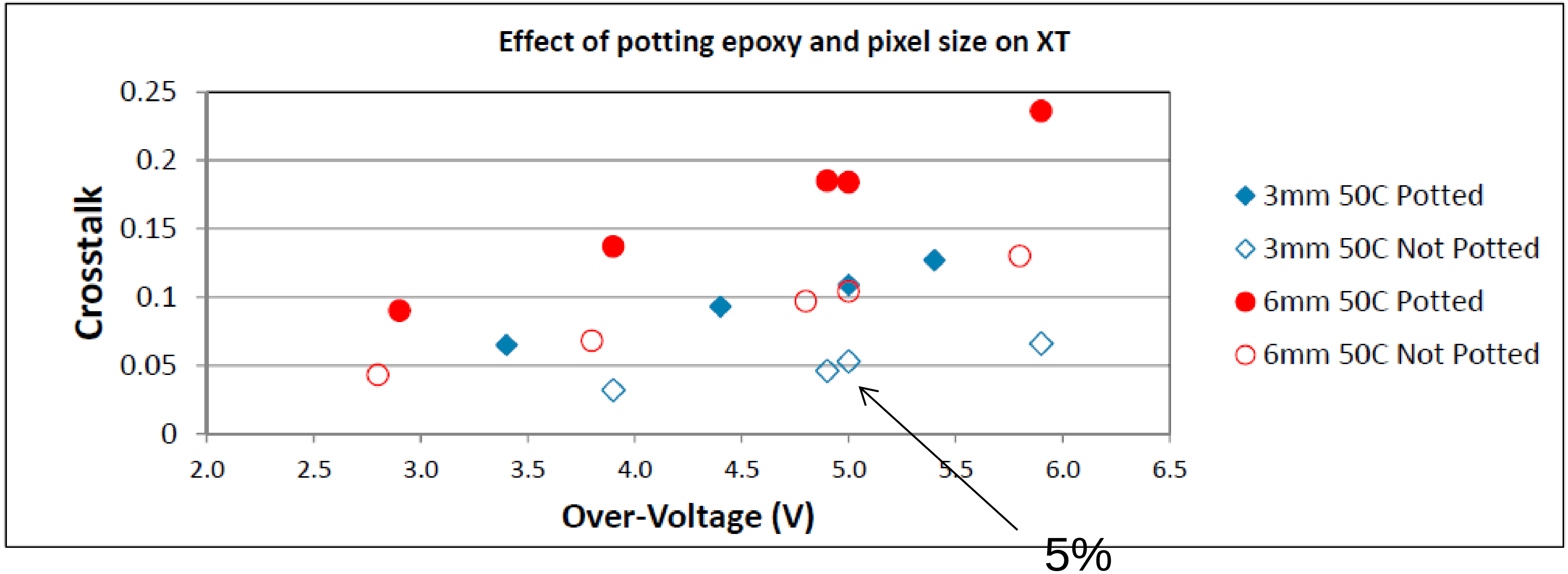


F.Wiest NDIP2014

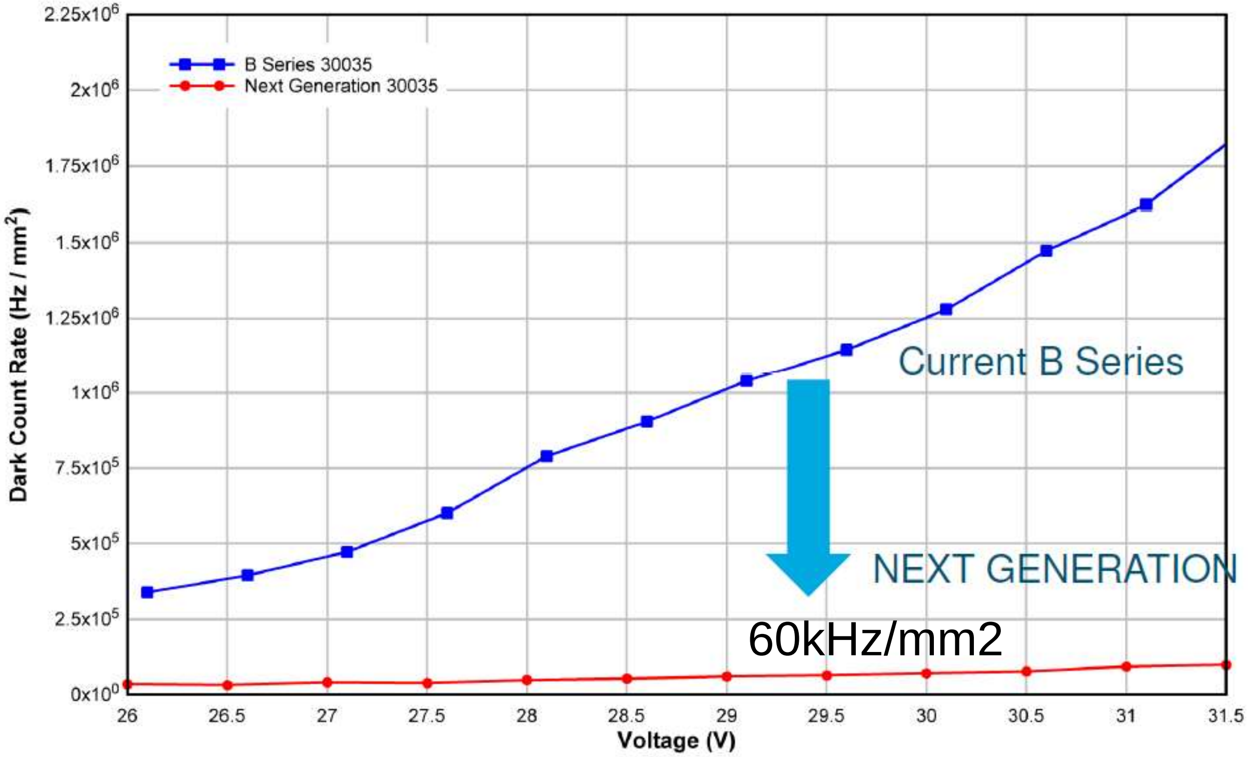
Processing In a Dedicated Detector Production Fab

Excelitas Technologies





Dark Count - 30035 Engineering Samples



sensL sense light

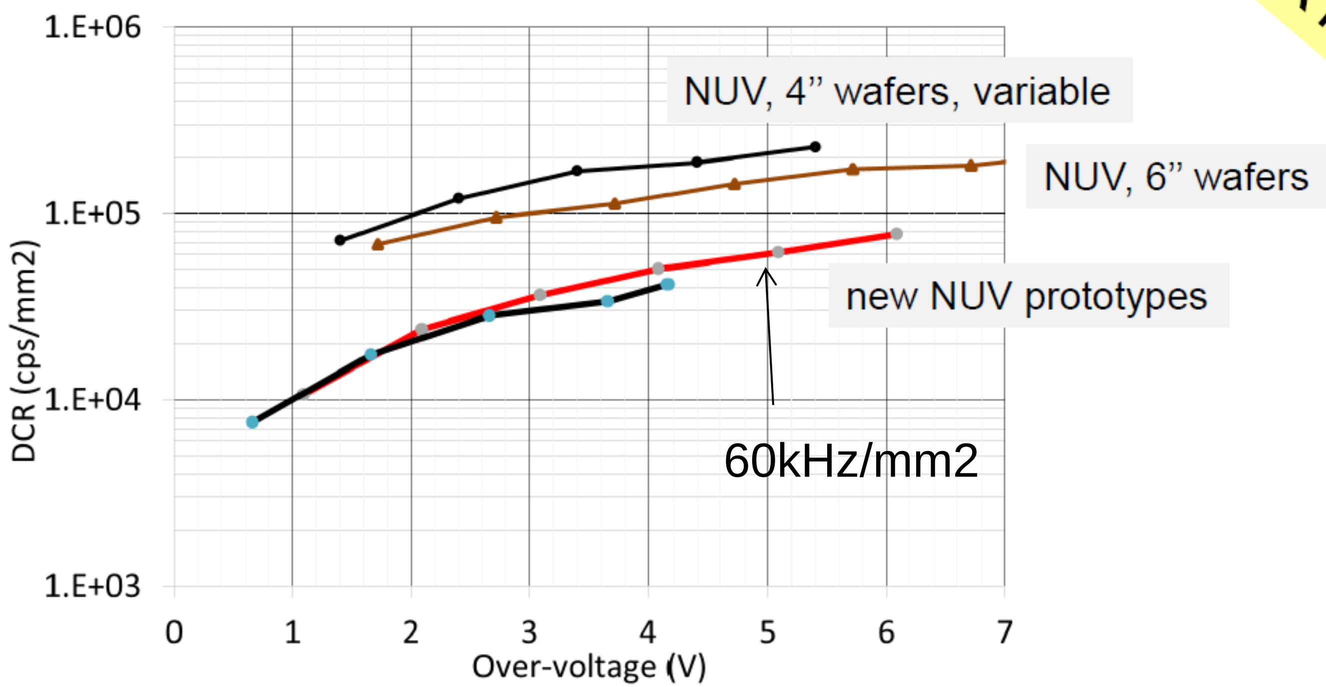
3/24/2014 31

FONDAZIONE BRUNO KESSLER

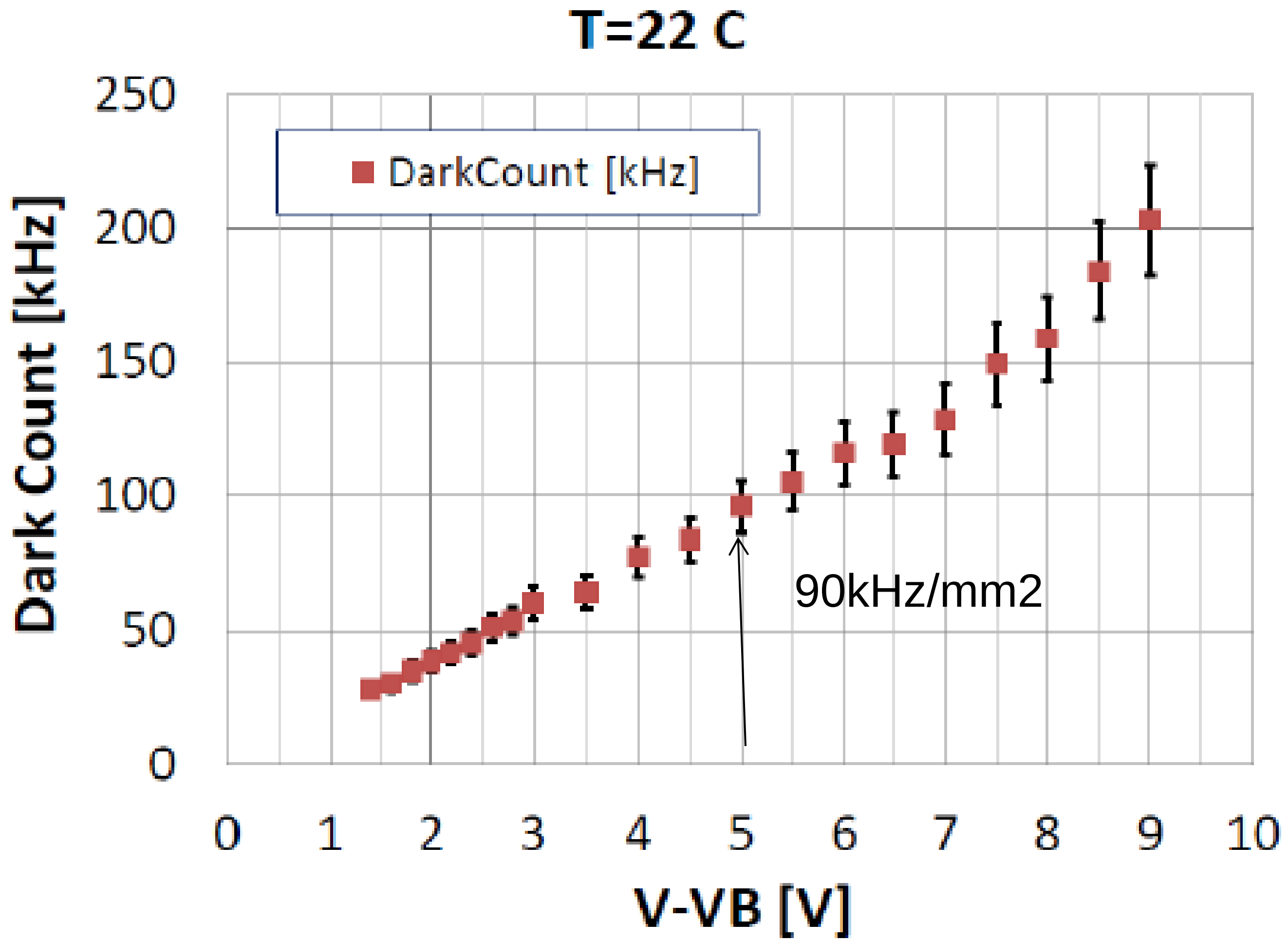
NUV: new developments

Fine technology tuning is ongoing.
New prototypes with:
- Breakdown voltage shifted from 26.5 to 32V.
- lower noise.

PRELIMINARY



New S12651-050C(X) MPPCs, 1mm², 50 μm cell pitch



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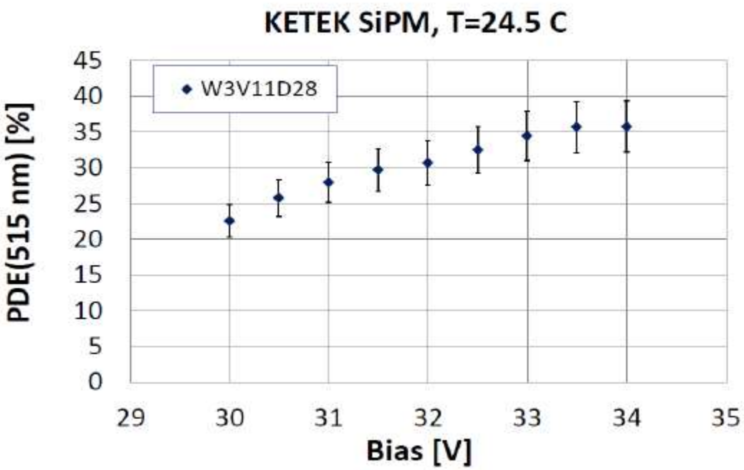
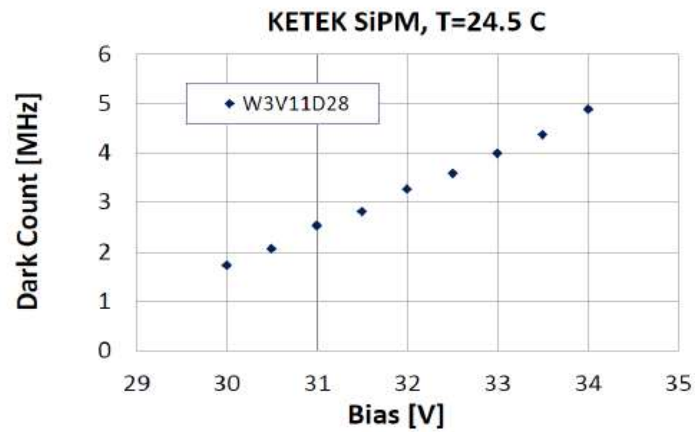
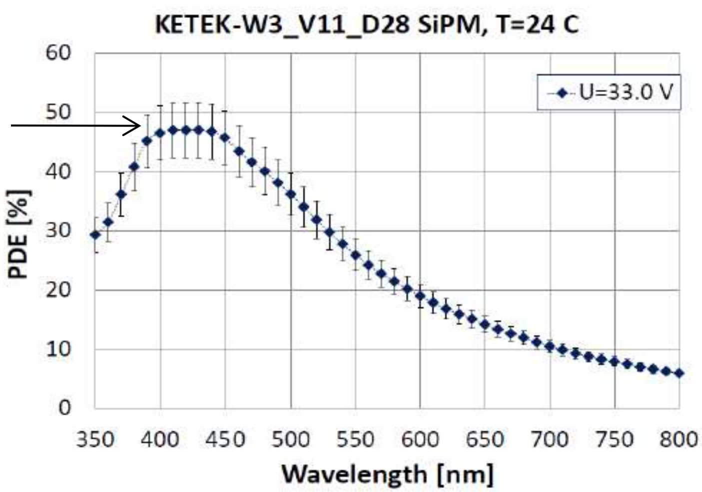
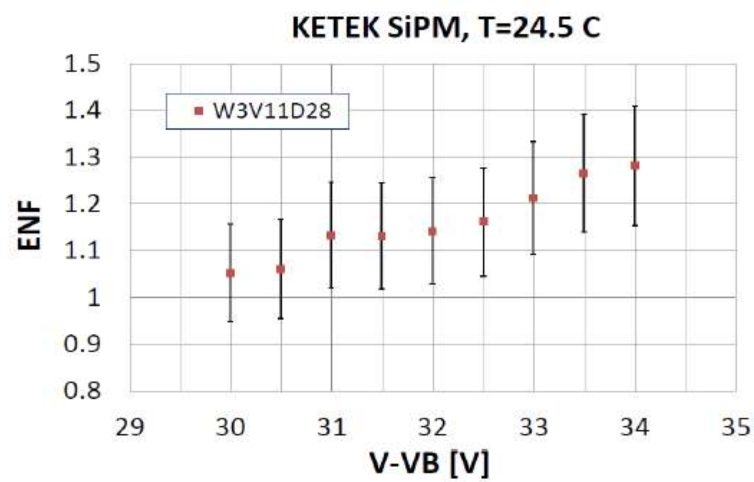
KETEK SiPM, 2.8 mm dia., 15 µm cell pitch





46%





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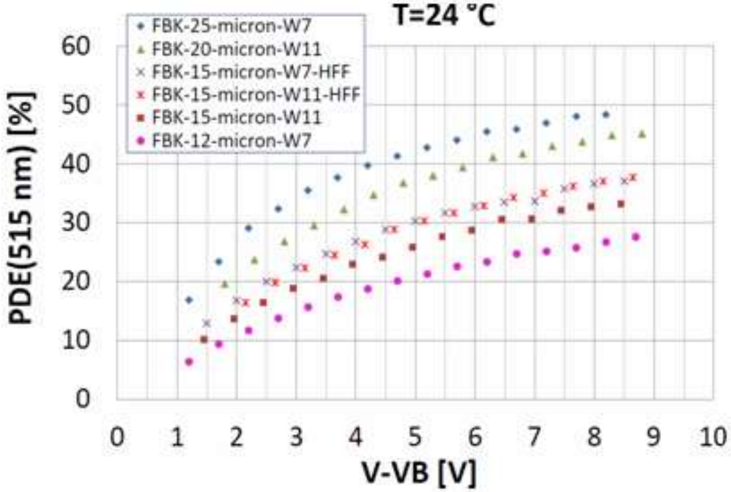
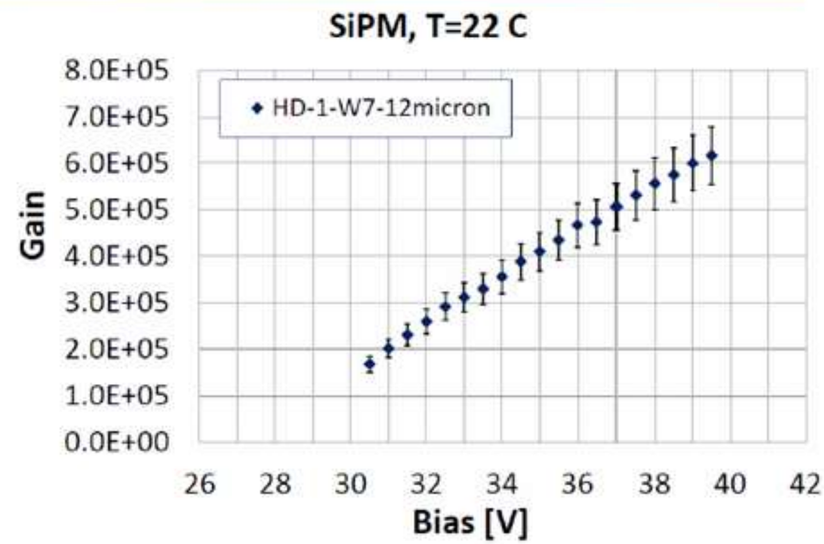
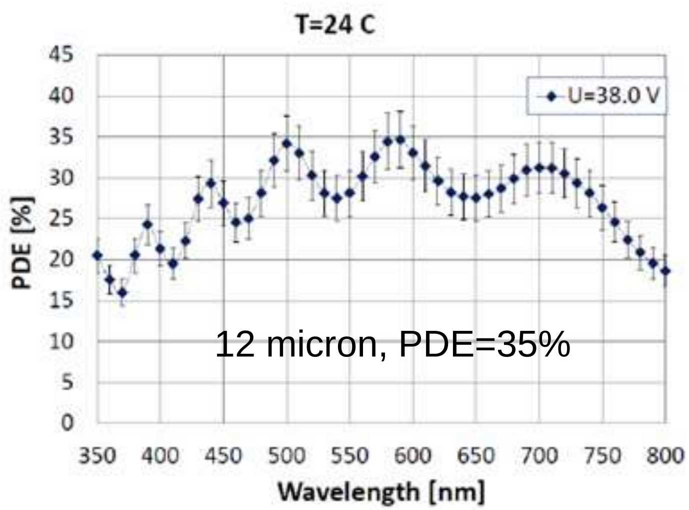
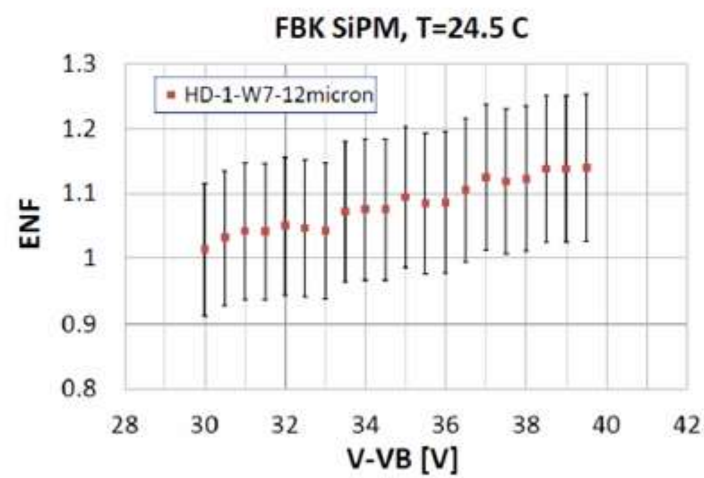
High density FBK SiPMs

Advanced SiPMs









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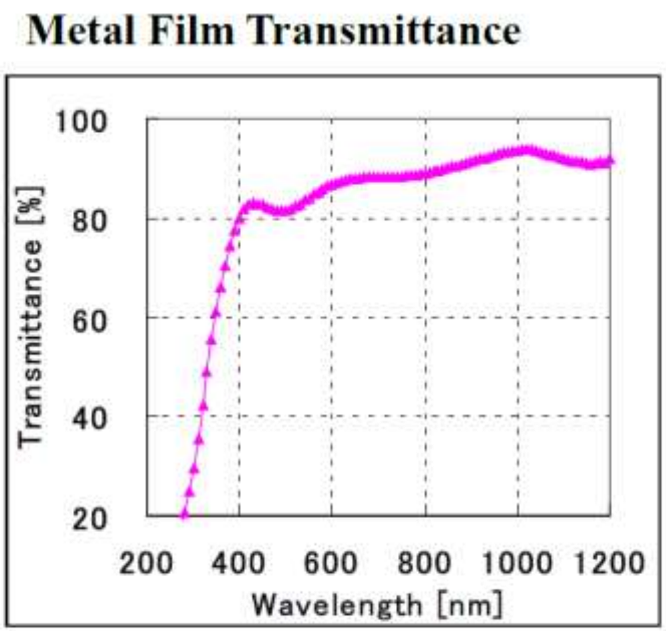
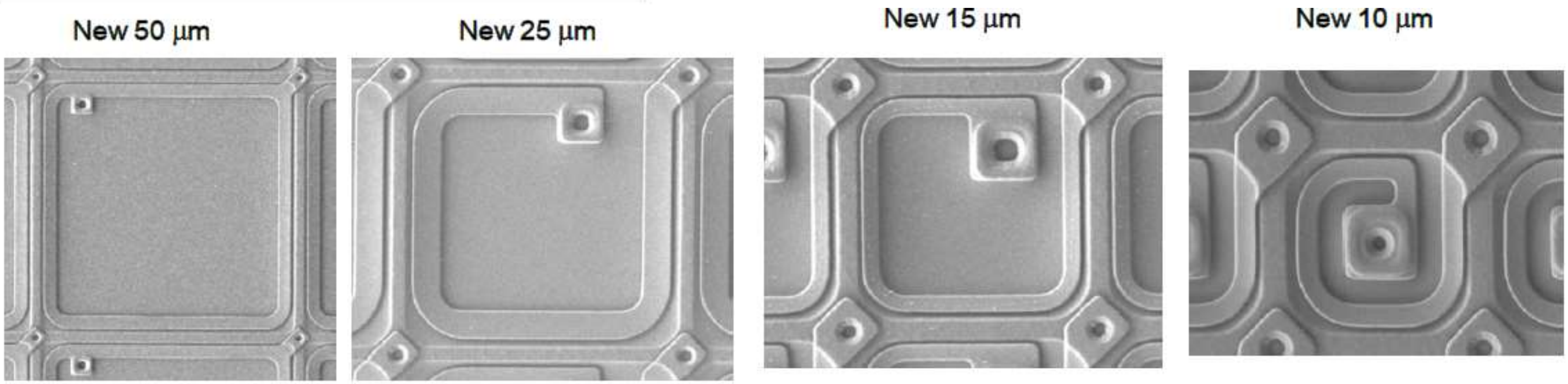
Metal Quenching Resistor



$1x1mm^2$, $\Delta V = 3V$

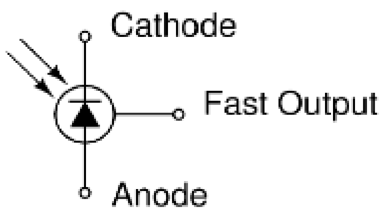
Pixel	N_{total}	PDE
50 µm	400	48%
25 µm	1,600	34%
15 µm	4,489	21%
~~10 µm~~	~~10,000~~	~~5%~~

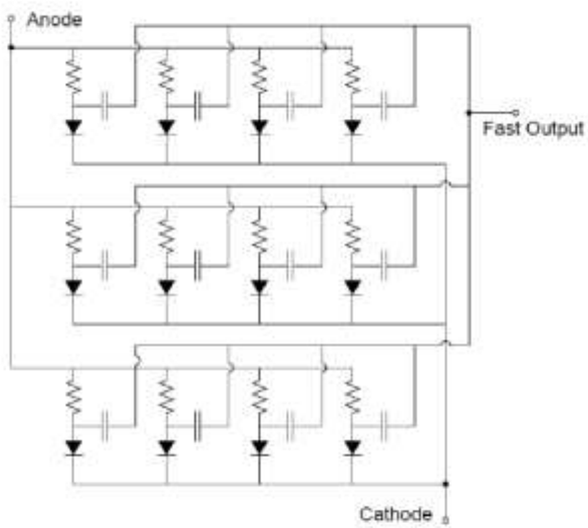


Metal resistor is less sensitive to temperature then polisilicon one

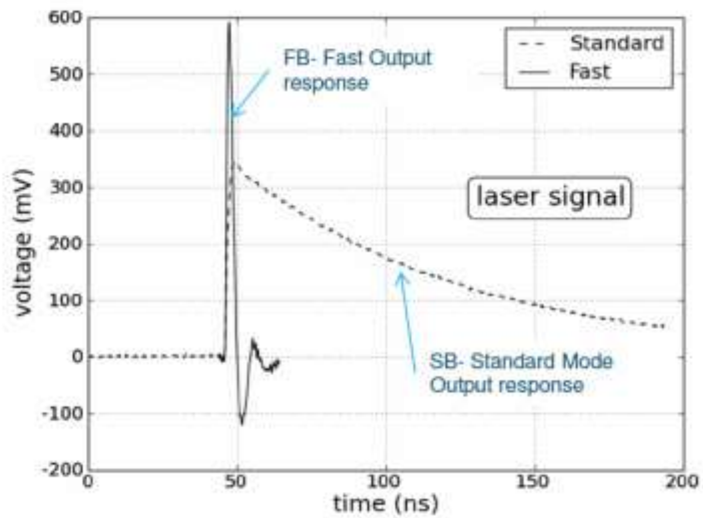
Fast Output Advantages

SENSL





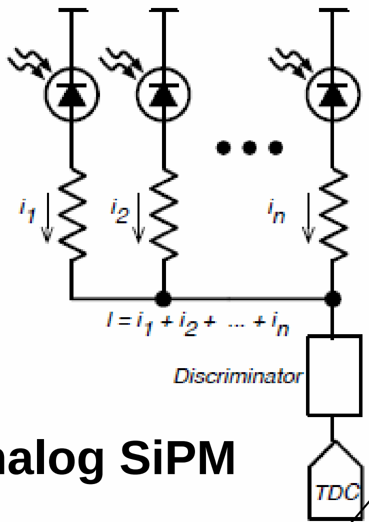
Compatible with
Fast Output (3-terminal) &
Standard Output (2-terminal)



Fast Mode Improvements

- Rise times <100ps; 2ns recovery
- Short impulse response from 1-2ns FWHM
- Reduced signal output capacitance
- Higher count rate resolution ability
- Ability to clearly distinguish the first photon arrival time

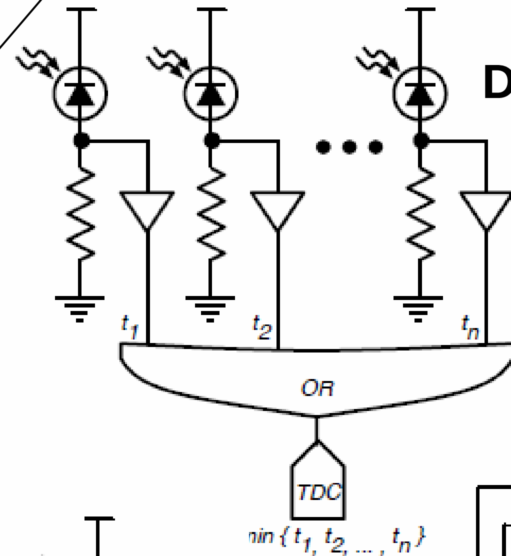
SensL's international patent application no. WO2011117309



Analog SiPM

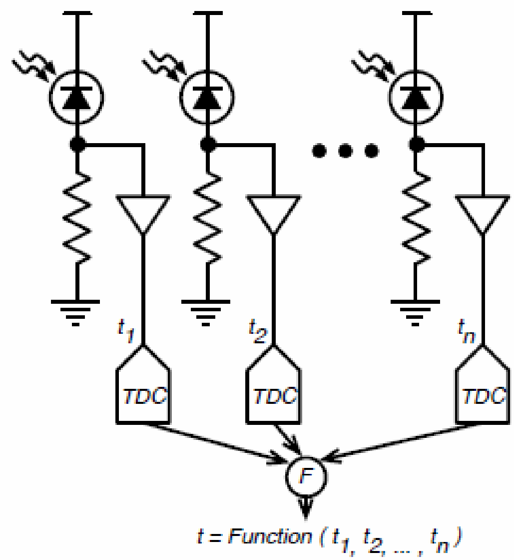
External electronics are required

(a)



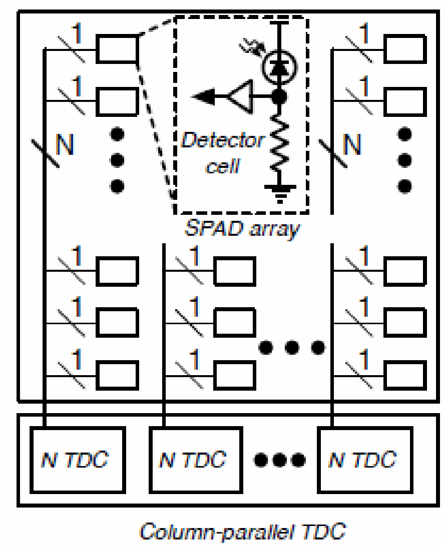
(b)

Digital SiPM (Philips)



(c)

Ideal multidigital SiPM



(d)

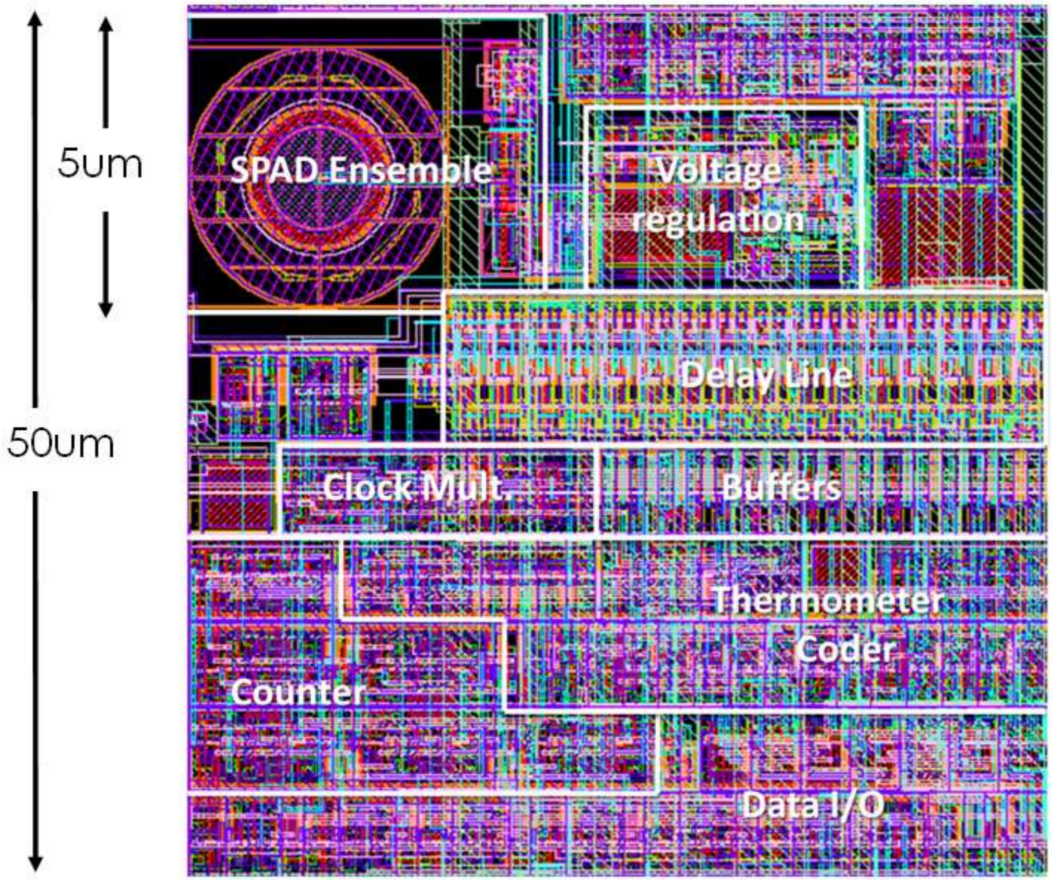
TUI Delft MD- SiPM

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014

Flexibility in digital SPAD design

16/20

- single pixel aspect ratio



Over 500 transistors in 50 x 50 μm^2 can be reduced depending on required functionalities

Typically 50/50 sensitive area to electronics

Gersbach, Charbon, et al., Journal of Solid-State Circuits 2012

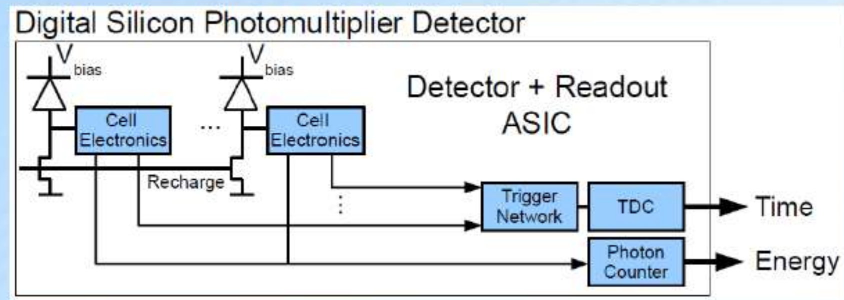
erika.garutti@physik.uni-hamburg.de   Terascale Alliance - Detector workshop, 15/03/12

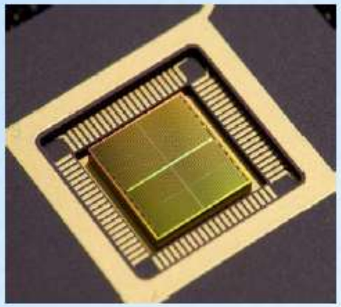
Cell of an "Ideall" multidigital SiPM – too space and power consuming

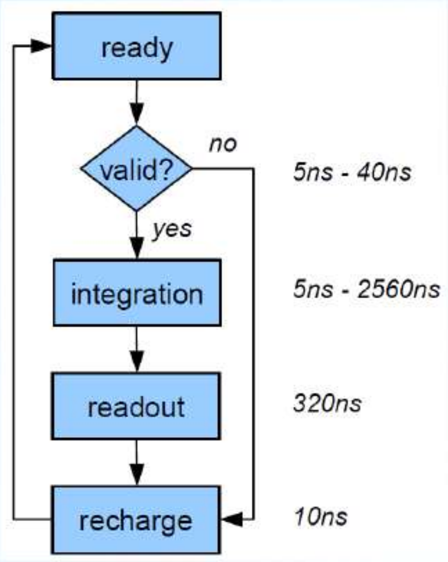
dSiPM-Digital SiPM (Philips)

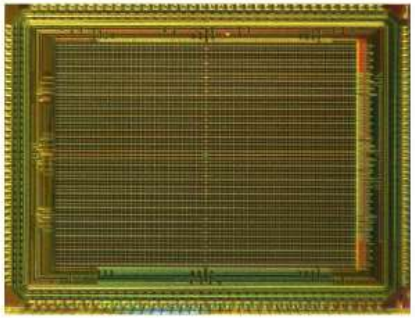
Signal from each pixel is is digitized and the information is processed on chip:

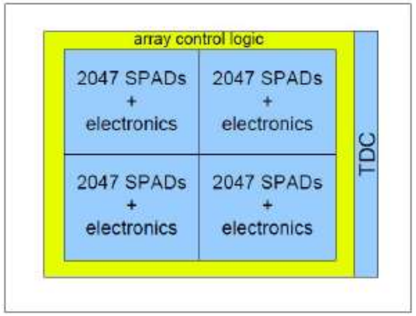
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution











T. Frach (Philips) @ IEEE2009

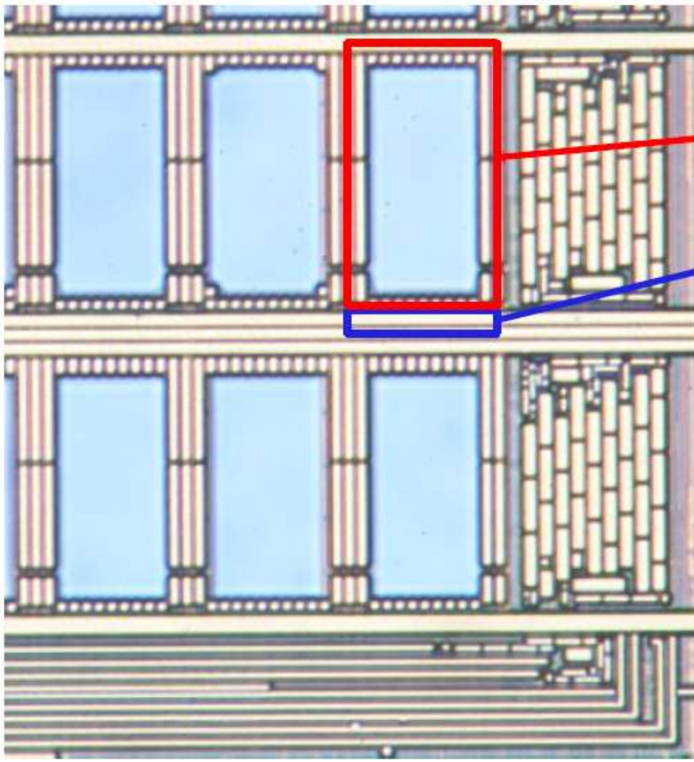
October 6 – 10, 2014
LIGHT14

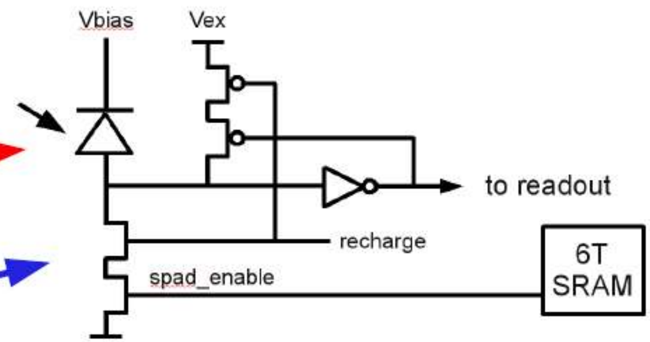
Fast photon detectors for Cherenkov TOF PET (slide 43)

Samo Korpar
Univ. of Maribor and J. Stefan Institute

PHILIPS

Digital SiPM – Cell Electronics



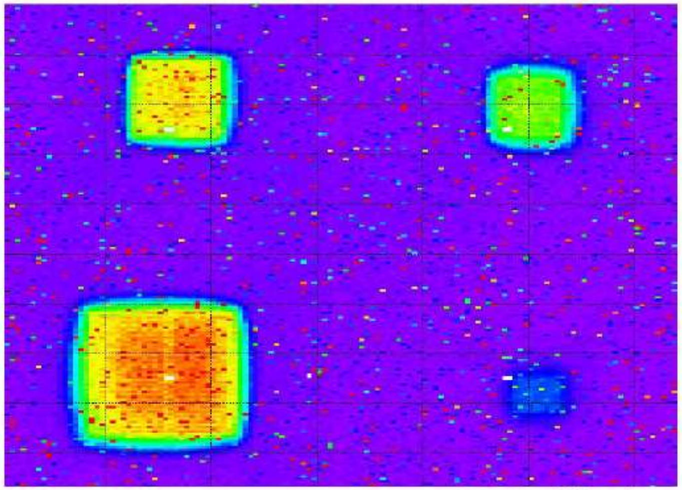


- Cell electronics area: 120μm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18μm 5M CMOS
- Foundry: NXP Nijmegen

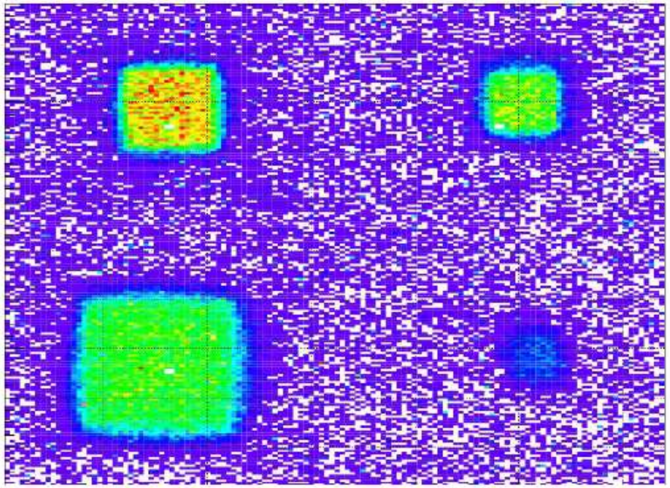
NDIP 2011 3

PHILIPS

Digital SiPM – Slow Scan Imaging Mode

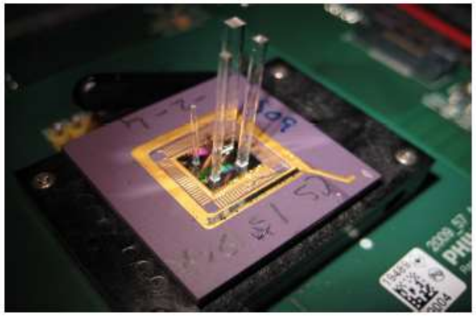


Singles



Coincidences

- *Spatial sampling of the light distribution*
- *Similar to dark count map measurement*
- *Dark count map can be used for correction*
- *Alternatively, use coincidence to reduce noise*
- *Potentially useful for light guide design*

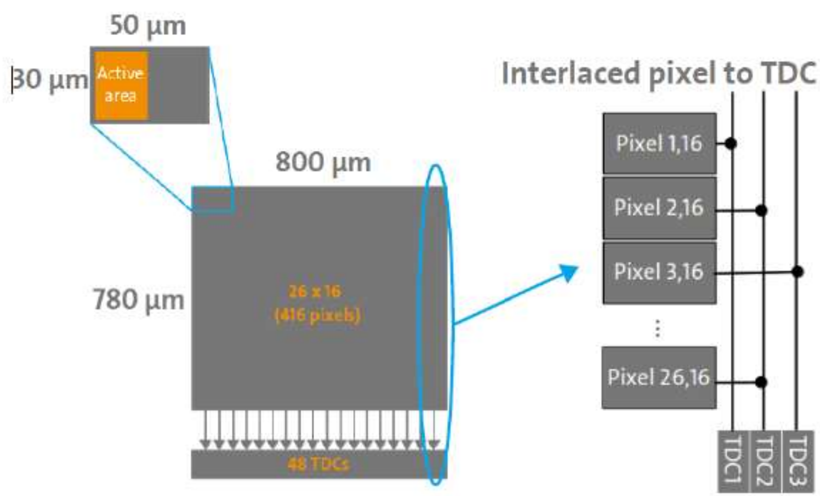


IEEE Nuclear Science Symposium / Medical Imaging Conference, Knoxville, November 4, 2010 14

Inner PET head - Photo-detector - MD-SiPM

TU Delft

- **TU Delft's MD-SiPM prototype specification:**
  - 30x50 μm^2 pixel size with 57% fill factor
  - 416 SPAD pixels (26x16) per cluster
  - 780x800 μm^2 cluster size
  - Photon Detection Efficiency (PDE) up to 17%
  - 48 column-wise shared TDC
  - 45 ps per TDC bin

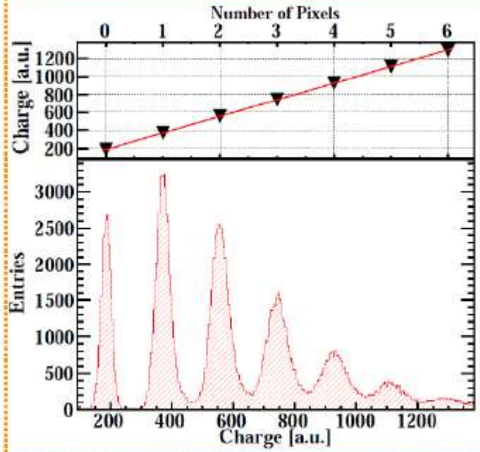


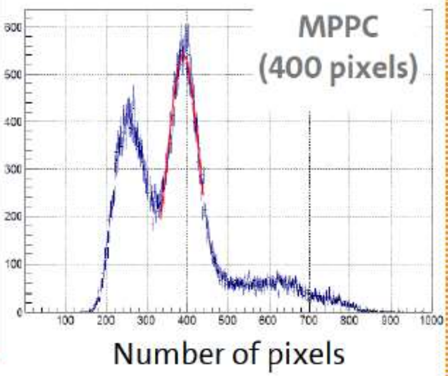
Courtesy of E. Charbon, Delft

Detector response

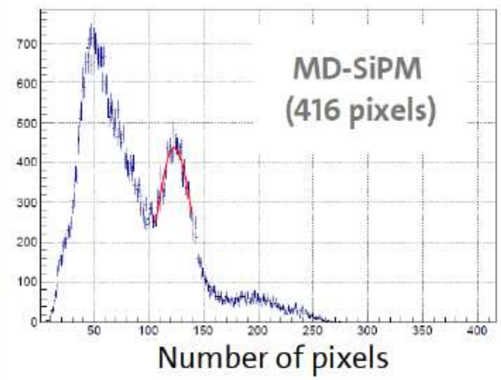
^{22}Na source + 1x1x15 mm^3 LYSO crystal, dry contact, without wrapping

^{22}Na spectrum by MPPC (calibrated to number of fired pixels)





^{22}Na spectrum by MD-SiPM



- 1x1 mm^2 device
- Gain measurement uses blue LED light
- Energy spectrum of ^{22}Na is calibrated to number of fired pixels:

  Number of pixels = Charge/Gain

- 0.78x0.8 mm^2 device

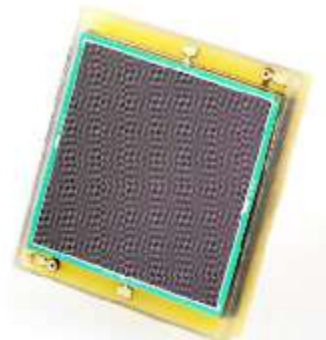
Erika Garutti

ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

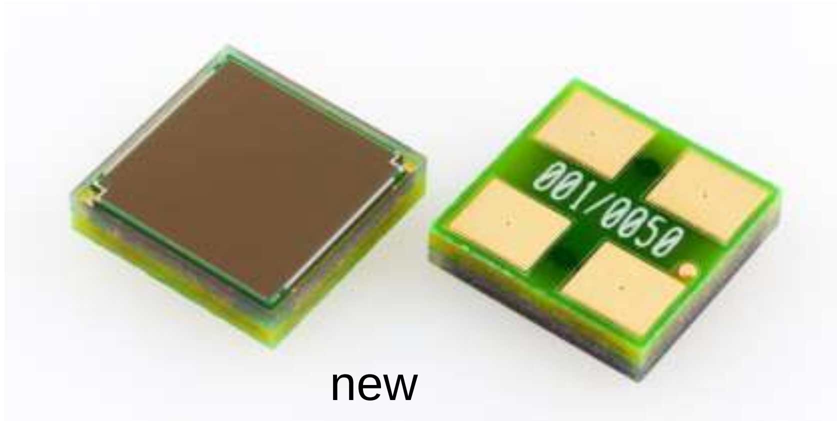
22/38

Tuesday, April 15, 14

KETEK PM5550: 4-side buttable SiPM single channel solution



standart

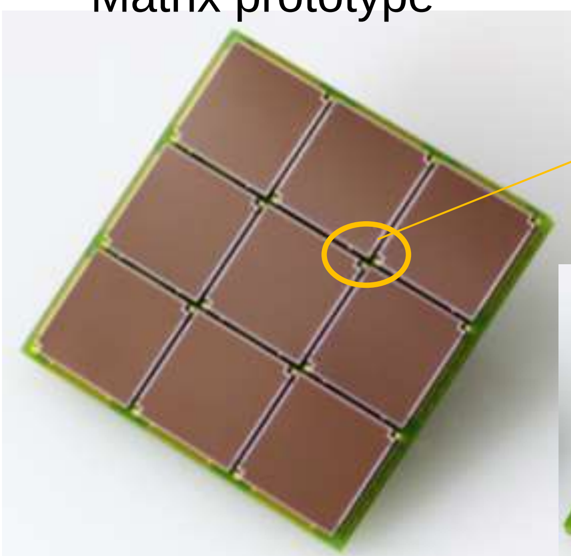


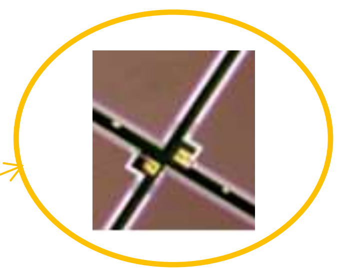
new

PM5550: 4-side buttable SiPM single channel

- Cell type: 50 µm pitch
- Number of micropixels: 11164
- Active pixel area: 0.2791 cm^2 5.2mmx5.2mm
- Chip size: 5.60 mm x 5.60 mm
- Package size: 6.0 mm x 6.0 mm

Matrix prototype





SiPM-Chip

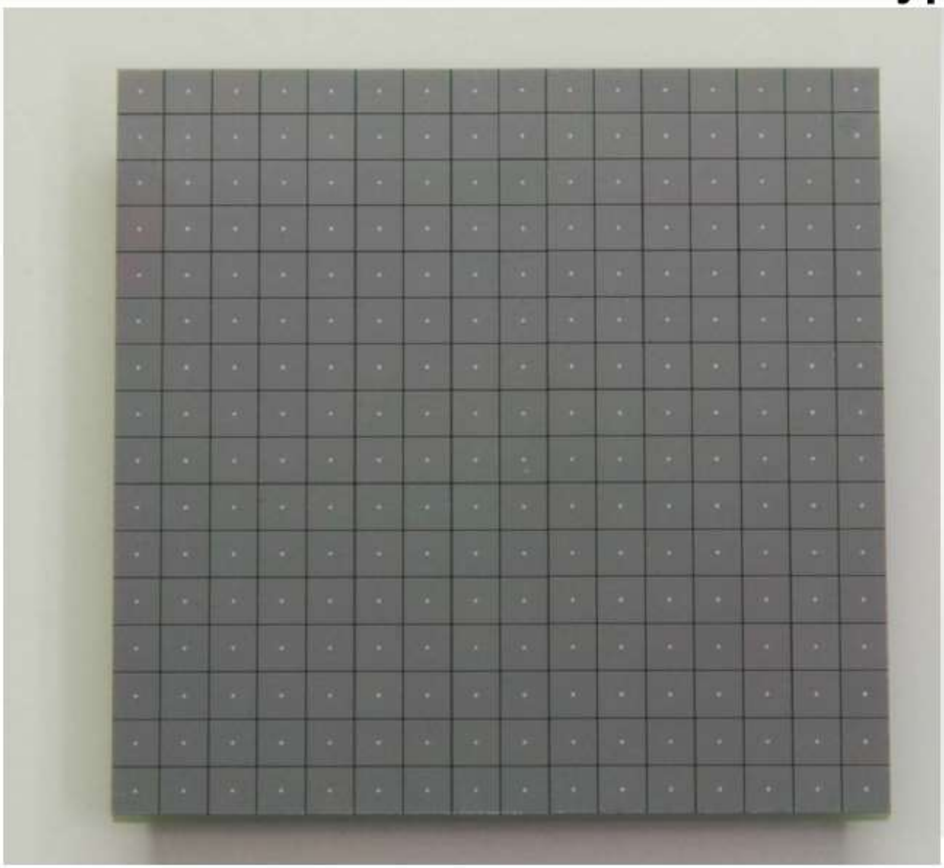
- Based on PM5550

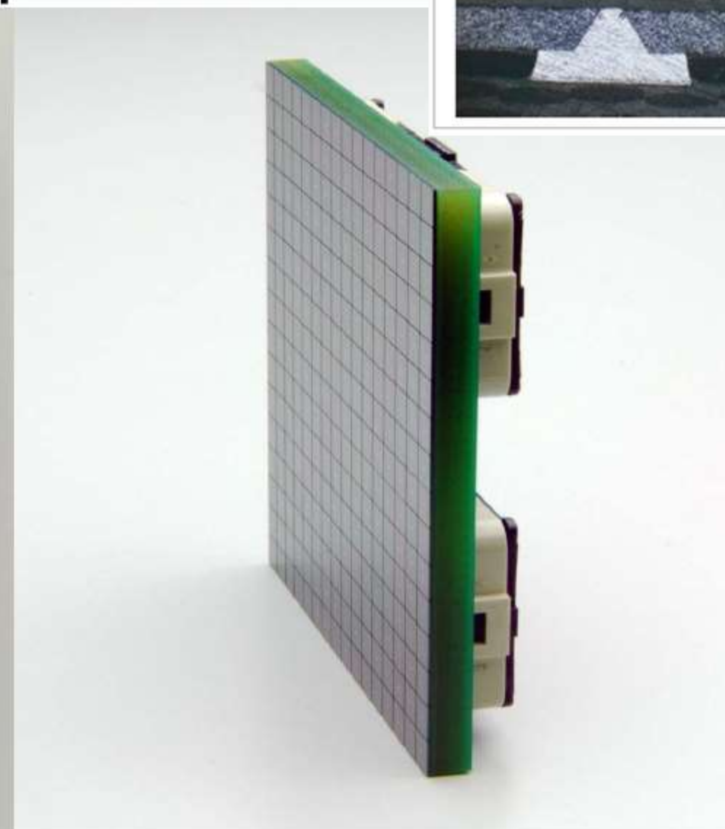
Array Dimensions:

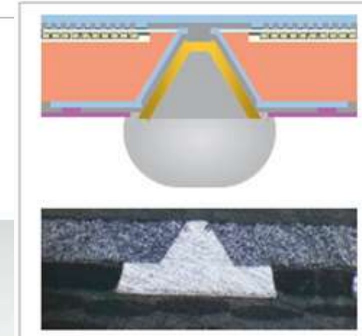
- 3x3 SiPM array
- 9 output signals / 9 bias supplies
- total PCB size: 17.8 x 17.8 mm^2
- total active area: 9 x 27.9 mm^2
- SiPM to package fill factor: **F = 79.3%**
- symmetric package

2D MPPC Array with TSV

50μm pitch, 3x3mm chip,
16x16 channels with Connector type







Packaging and Matrixes

Requests from HEP experiments

2/20

- Higher Photo-detection Efficiency (or Probability)
  - Currently standard 15-20% (green), 30% (blue) **->40% green - 50% blue**
  - Limiting factor = fill factor (fraction of active to total area)
- Larger dynamic range
  - Currently standard ~1000-1500 pixels / mm^2
  - Drawback for larger dynamic range = reduction of fill factor

->10 μm 10,000 pixels/mm^2

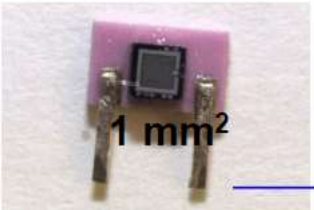
- Single photon counting = lower dark rate (DR) and cross-talk (XT)
  - Currently standard DR ~0.5-1 MHz/mm^2 (dependent on U_{ex}) **30-100 kHz/mm^2**
  - Currently standard XT ~10-15% (dependent on U_{ex}) **<10%**
- Large surface photo-detectors (or photo-detector array)
  - Strong interest also for medical applications **TSV commercially available**

SiPM pioneering experience

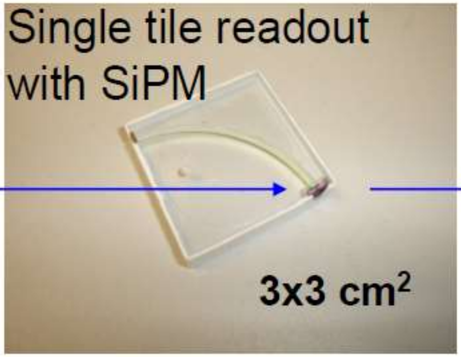
A crucial technology improvement to calorimetry

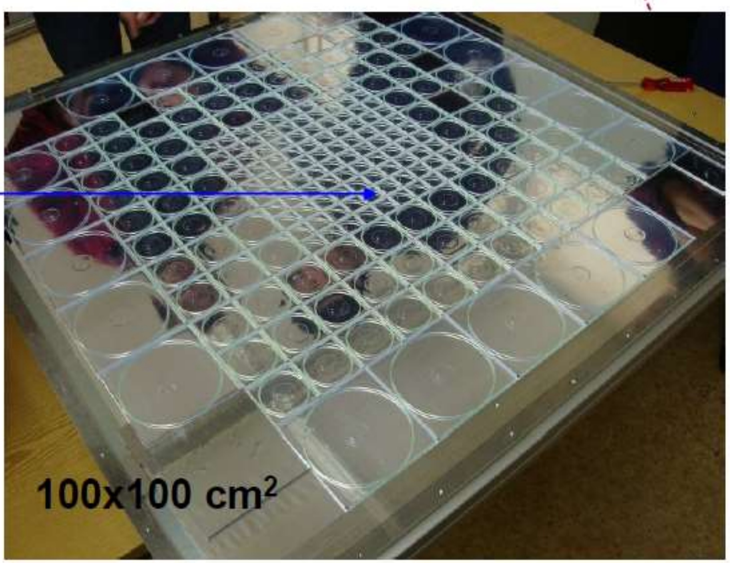
Electron

Hole

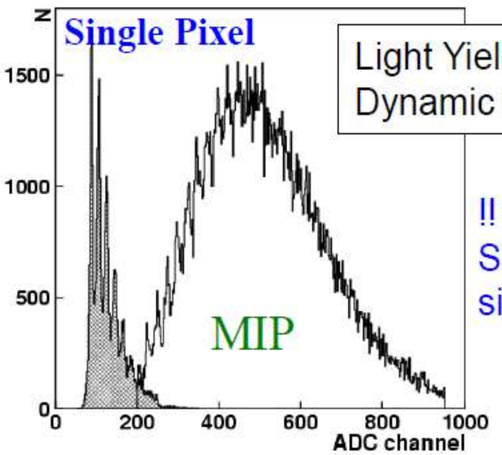


Si-based = insensitive to magnetic field!





1x1m² prototype calorimeter with 8000 channels readout with SiPM (MePHI/Pulsar)



Light Yield = 15 pixels / MIP
Dynamic range ~ 100 MIPs

!! auto-calibration of SiPM gain from single-pixel spectra

Allows unprecedented high granularity

38 layers (~4.5 λ)
Scintillator – Steel sandwich structure (0.5:2cm)

erika.garutti@desy.de

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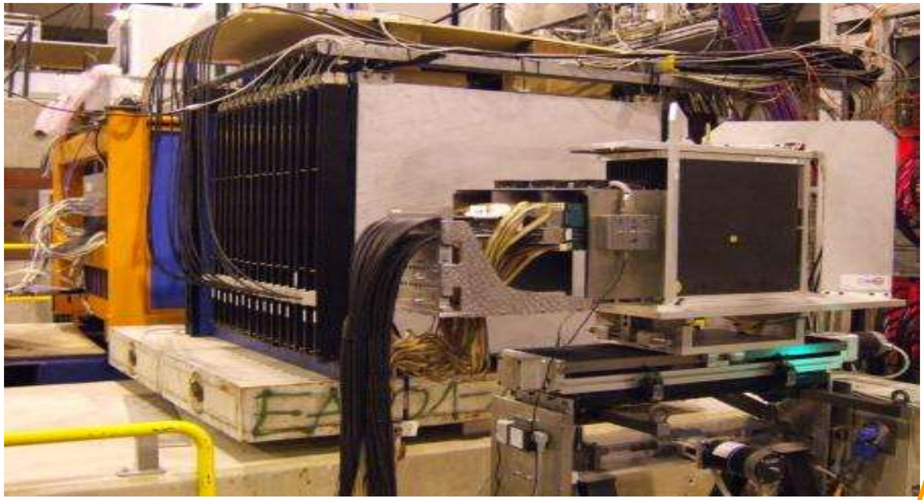
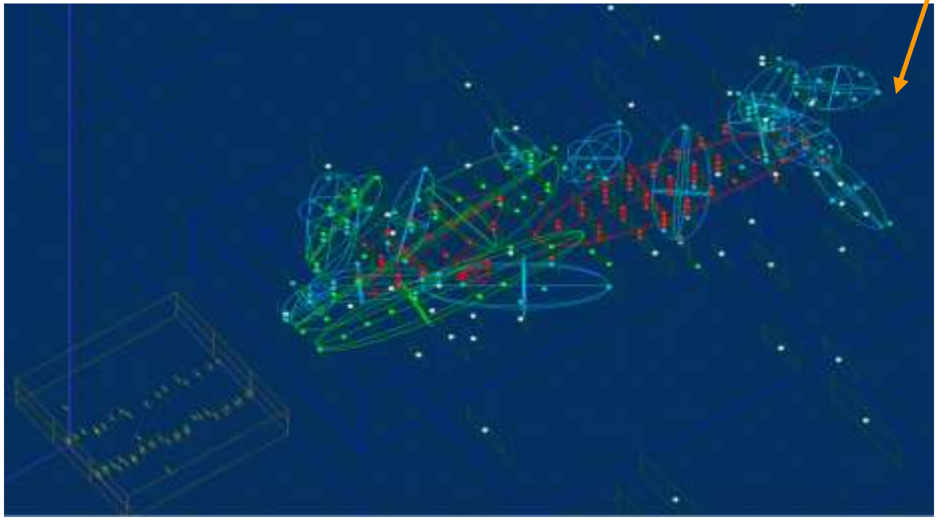
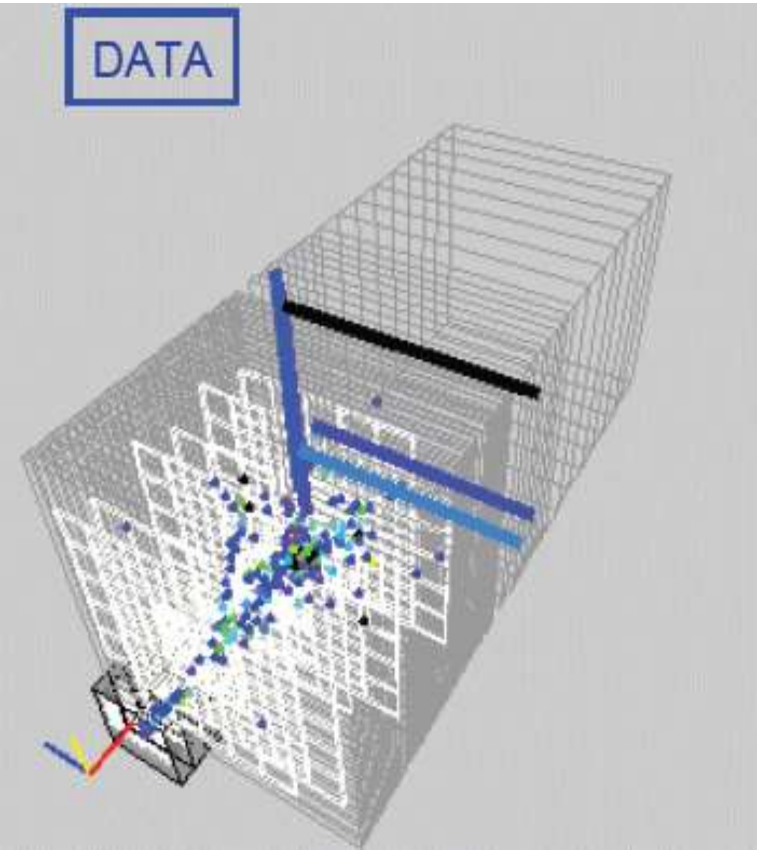
Physical Tile HCAL CALICE Prototype



Event reconstruction



Data monitor

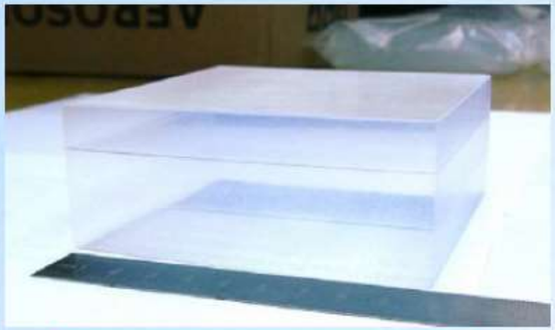


Prototype has been successfully tested at DESY, CERN and FNAL during last years

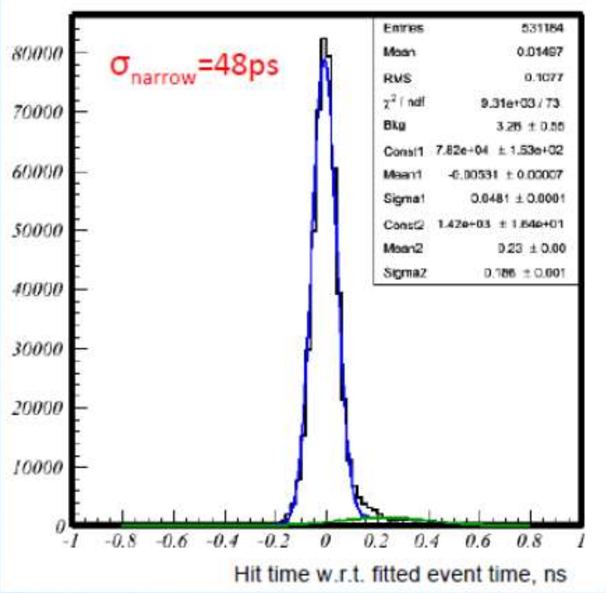
Timing resolution with dSiPM

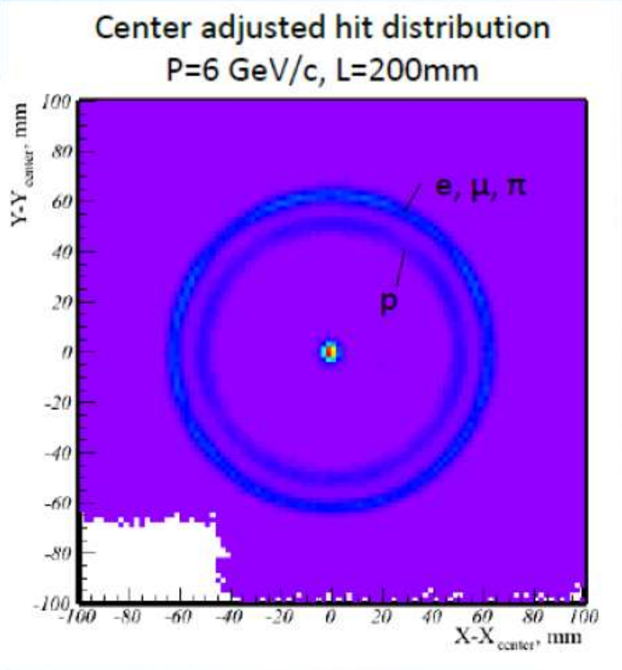
FARICH (Focusing Aerogel RICH) kandidate for ALICE, PANDA, Super c-τ, (SuperB):

- another focusing aerogel development
- SiPM photon detector
- first use of digital SiPMs from Philips
  - tested at CERN
  - excellent timing



S.Kononov @AFAD2013





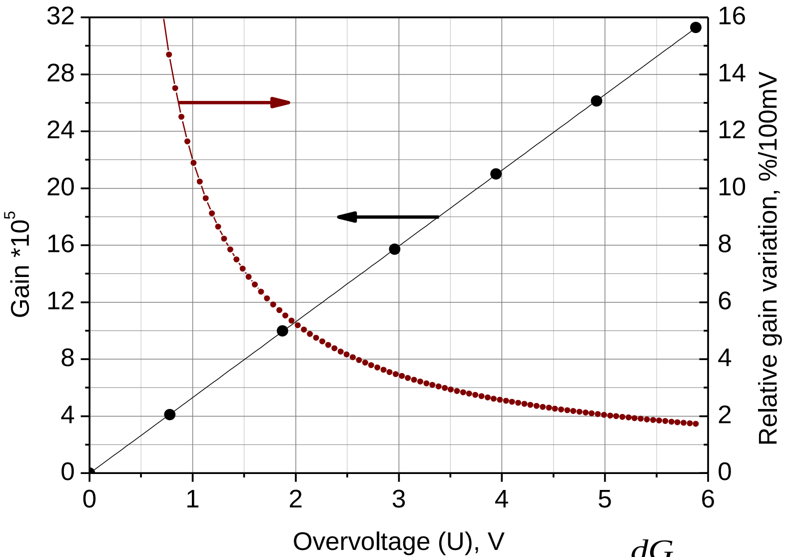
SUMMARY

- Other materials beside of silicon are not presented here
- Different analog SiPM constructions are not presented here
- Different digital and semidigital approaches are not presented here

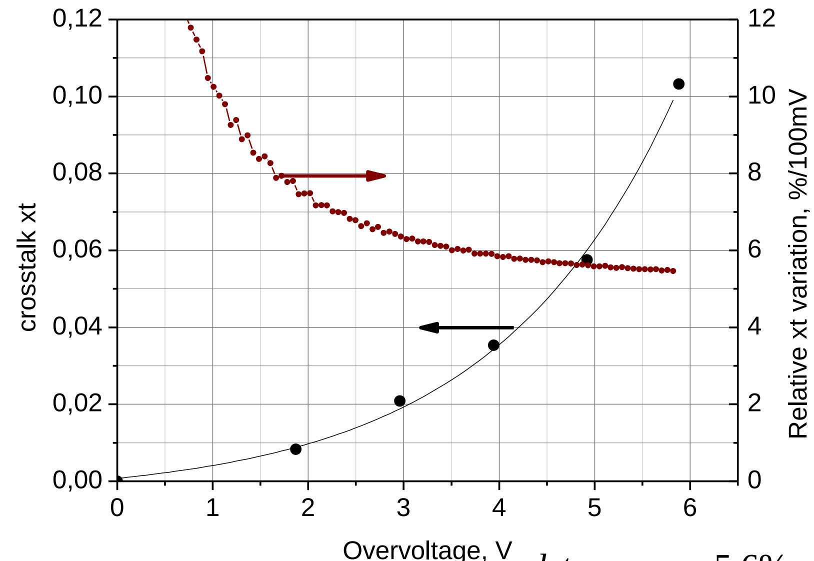
- Noise reduction are ongoing and will be improved further
- Crosstalk reduction continues due to improving of trench technology
- Afterpulsing reduction under way by using new materials, technology improvement
- Detection efficiency for UV and IR light are under development
- Timing will be improved both for analog and digital approaches
- Analog SiPM+electronics – with direct connection to computer is a strong desire of SiPM potential users

Voltage stability SiPM 100B for 5V (15%) overvoltage

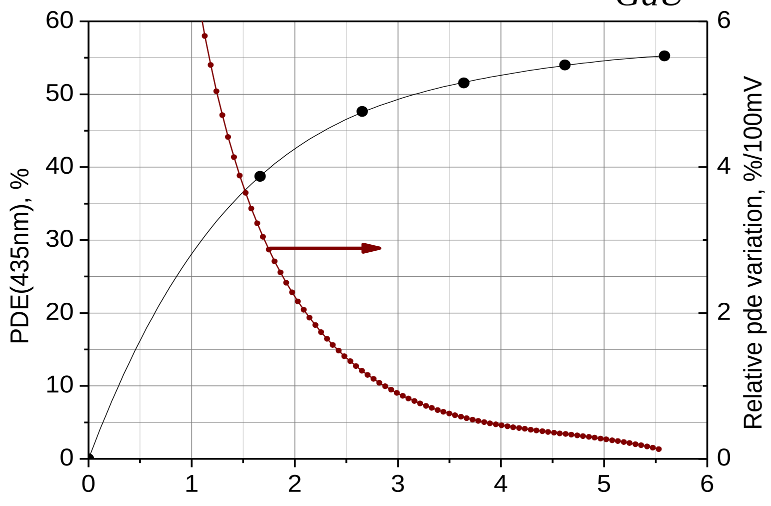
latest MEPhI/MPI SiPM produced in cooperation with Excelitas



$$\frac{dG}{GdU}(5V) = \frac{2.0\%}{100mV}$$



$$\frac{dxt}{xtdU}(5V) = \frac{5.6\%}{100mV}$$



$$\frac{d\varepsilon}{\varepsilon dU}(5V) = \frac{0.25\%}{100mV}$$

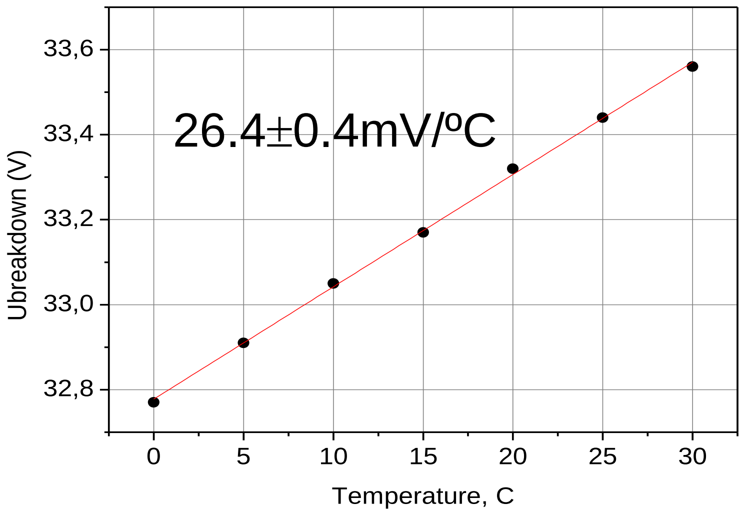
6th NDIP 2011 E. Popova et al.
"Large area UV SiPMs with extremely low cross-talk"

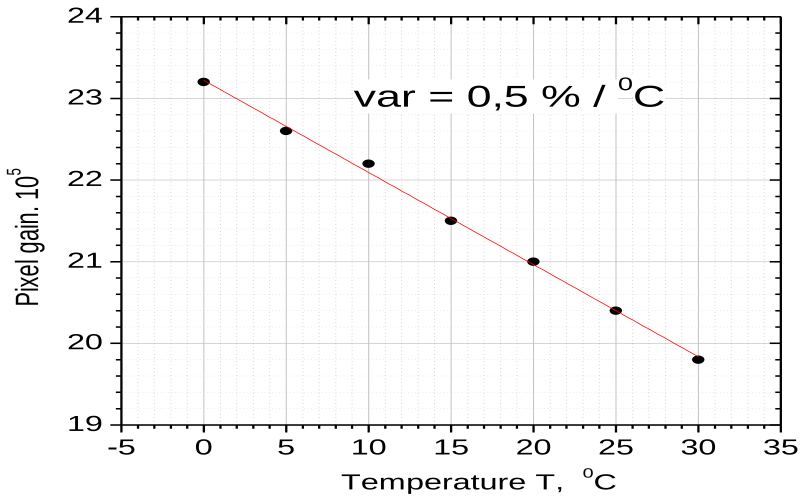
40

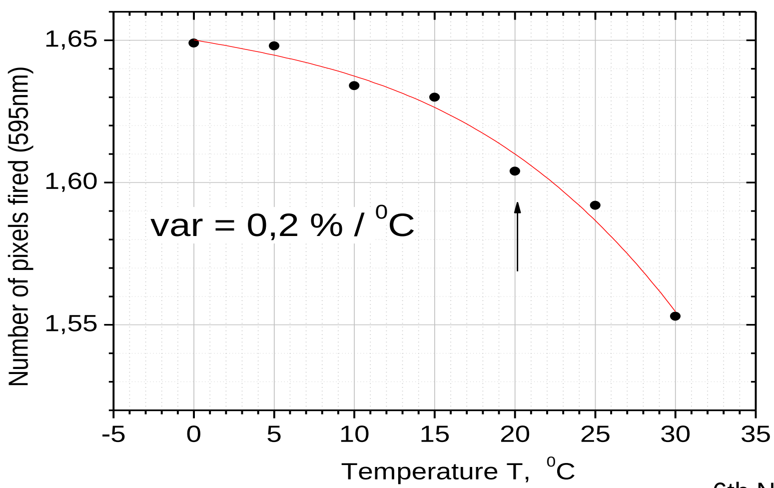
Temperature stability SiPM 100B

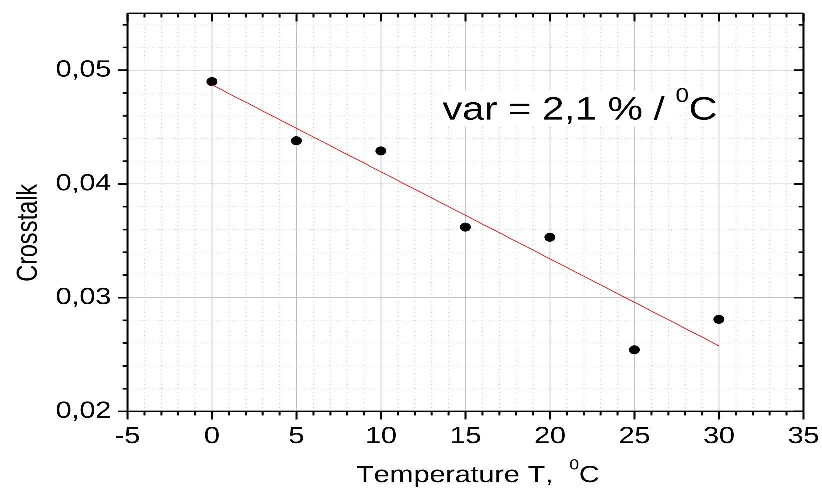
latest MEPhI/MPI SiPM produced in cooperation with Excelitas

ΔV=4V (12%) overvoltage for T=20ºC







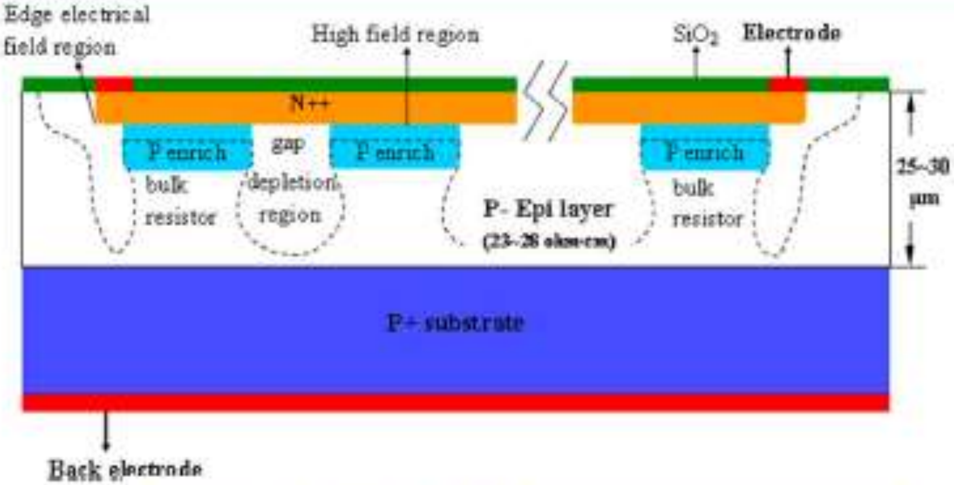


6th NDIP 2011 E. Popova et al.
"Large area UV SiPMs with extremely low cross-talk"

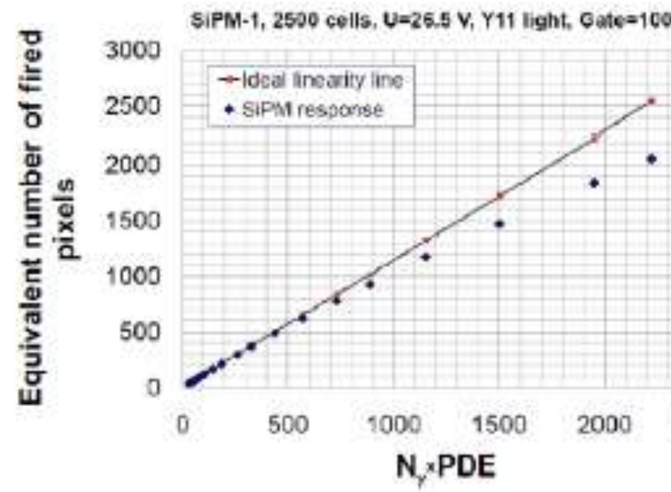
(see NDIP-2011 presentation of Han Dejun "Progress on SiPM with bulk quenching resistor")

Schematic structure of the SiPM with bulk integrated resistors (S=0.5x0.5 mm², 10 000 cells/mm²)

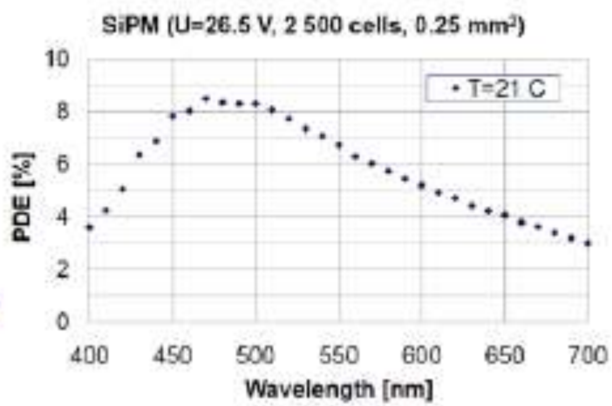
SiPM non-linearity

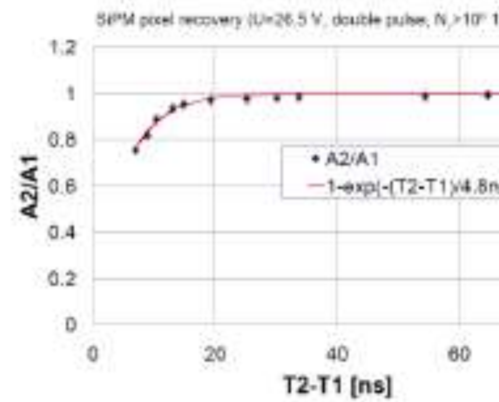


Nuclear Instruments and Methods in Physics Research A 621 (2010) 116–120

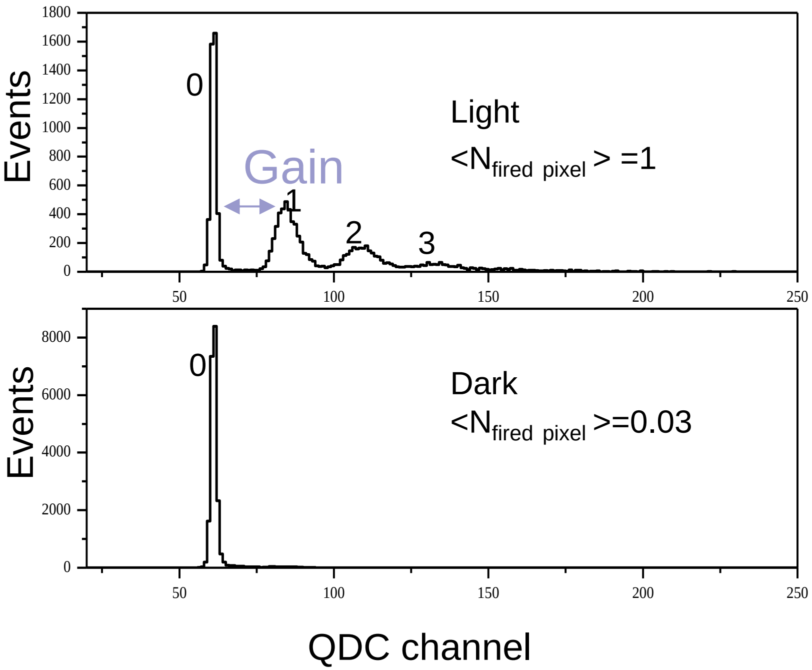


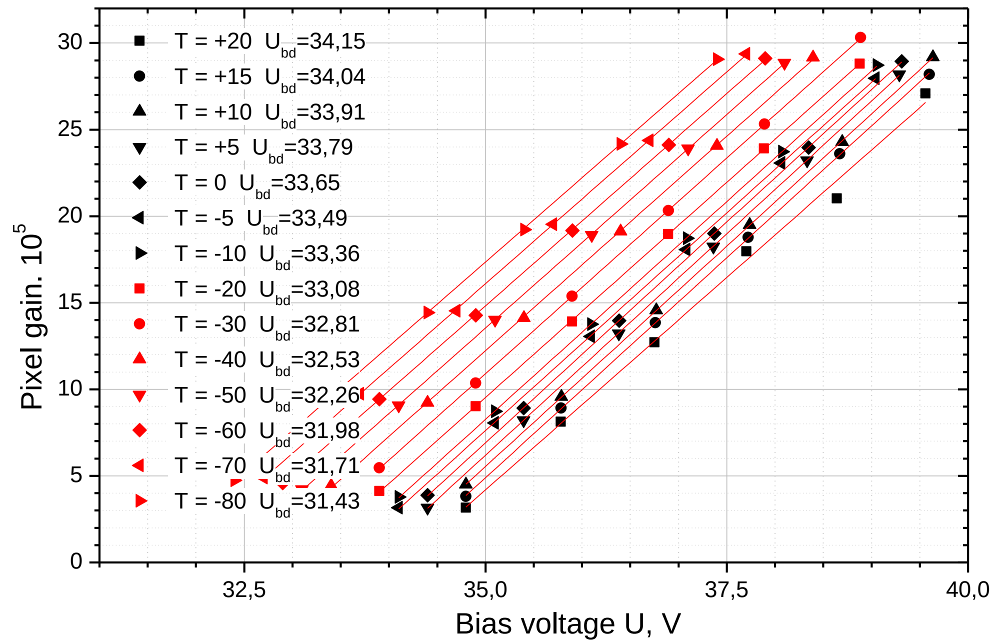
- n on p (structure for green light)
- sensitive area - 0.25 мм²
- number of cells - 2 500
- operating voltage- 26.5 V
- quenching resistor value - 200-300 кОм





Main SiPM's parameters. Gain vs Voltage for different T





$$G = \frac{C_{pixel} \cdot (U - U_{breakdown})}{q}$$

$U_{breakdown} \longrightarrow G=0$

Overvoltage $\Delta U = U - U_{breakdown}$

We need to collect SiPM's spectra for different voltages

With temperature decreasing $U_{breakdown}$ decreases too – temperature sensitivity

Ubreakdown and ΔU–are needed for different type SiPM comparison

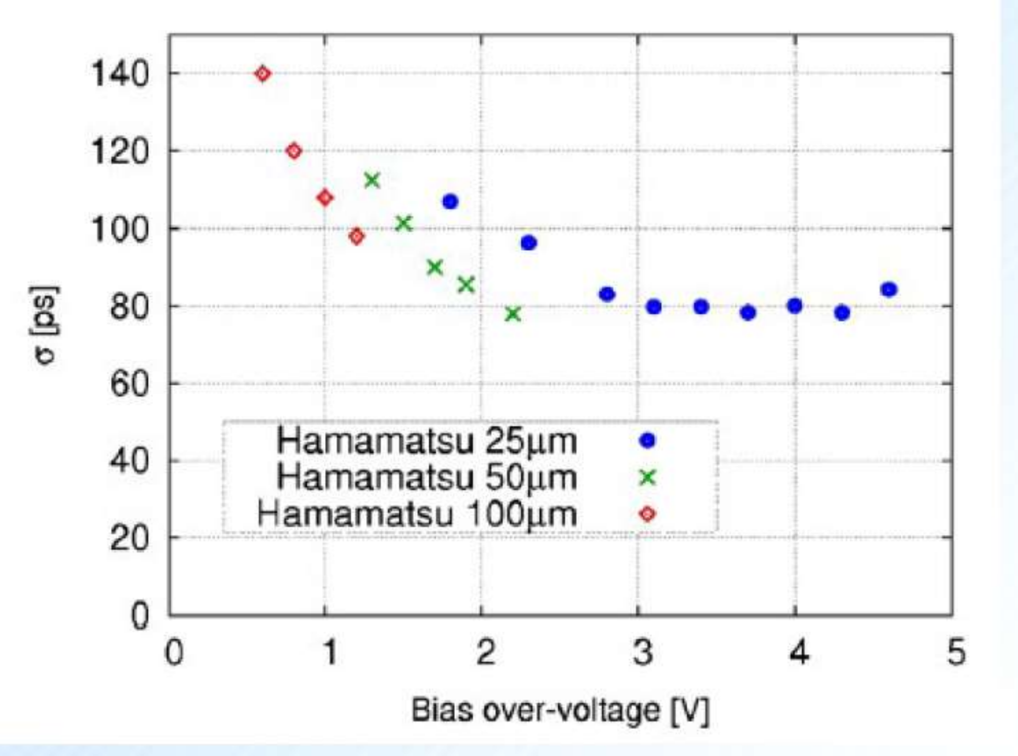
Timing resolution study

- tests of the time response of the same type of MPPCs

Type: S10931	SPAD size (μm^2)	Number of cells	Fill factor (%)	Break down (V)	Opt. bias for PET [2] (V)
–100P	100 × 100	900	78.5	69.3	70.3
–050P	50 × 50	3600	61.5	70.5	72.4
–025P	25 × 25	14,400	30.8	69.2	73

S.Gundacker et.al.NIM A718(2013)569

- NINO chip based readout
- DAQ by oscilloscope
- ~ 200 fs laser pulses
- single photon resolution (TTS) σ ~ 80 ps (~ 190 ps FWHM)



October 6 – 10, 2014
LIGHT14

Fast photon detectors for Cherenkov TOF PET
(slide 29)

Samo Korpar
Univ. of Maribor and J. Stefan Institute

SPTR of a stand alone SiPM cell
min threshold, focused 2 micron spot, <200fs
scope LeCroy WaveRunner 620Zi 2GHz