МОСКОВСКИЙ ИНЖЕНЕРНО-ФИЗИЧЕСКИЙ ИНСТИТУТ
(ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ)

# SiPMs: parameters and applications

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DITANET
December 5-7 2011 DESY

# 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)

Since 1993 Boris developed a new photon detector which he called Silicon PhotoMultiplier (SiPM) in collaboration with DESY and then with Max Planck Institute fur Physics

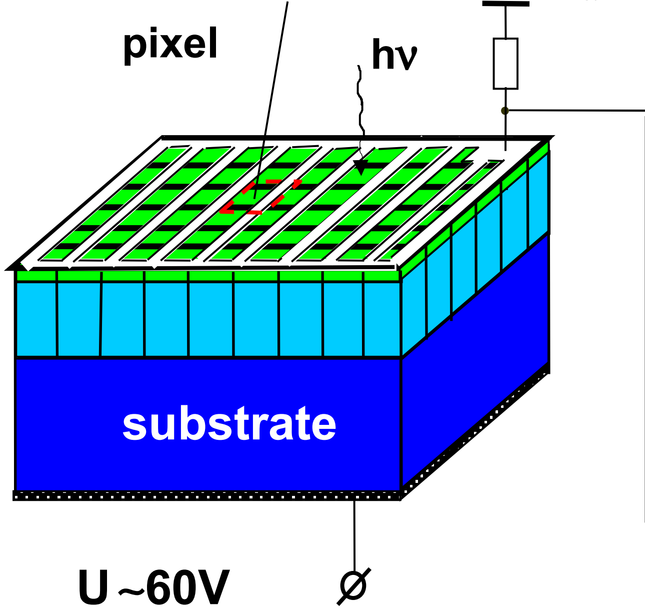
# Outline

- What is it – SiPM?
- SiPM main parameters
- Parameters sensitivity
- Manufacturers and experiments
- Radiation hardness
- Electronics
- Summary

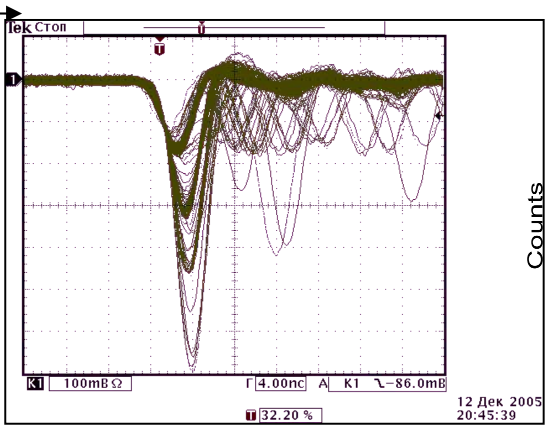
# Silicon Photomultiplier (SiPM)

## The novel type of photon's detector

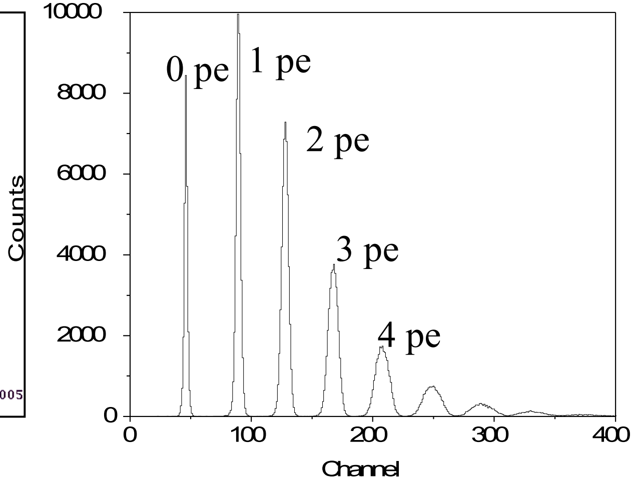
Multipixel device with common readout



Scope signal



Amplitude spectrum



## SiPM – main features:

- Each pixel – p-n-junction in selfquenching Geiger mode
- Pixels number: ~ 1000/mm$^2$
- All pixels are equal
- Pixels are independent from each other
- Signal – is sum of all fired pixels

→

**Pixel signal - 0 or 1**
**But SiPM is analogue device**

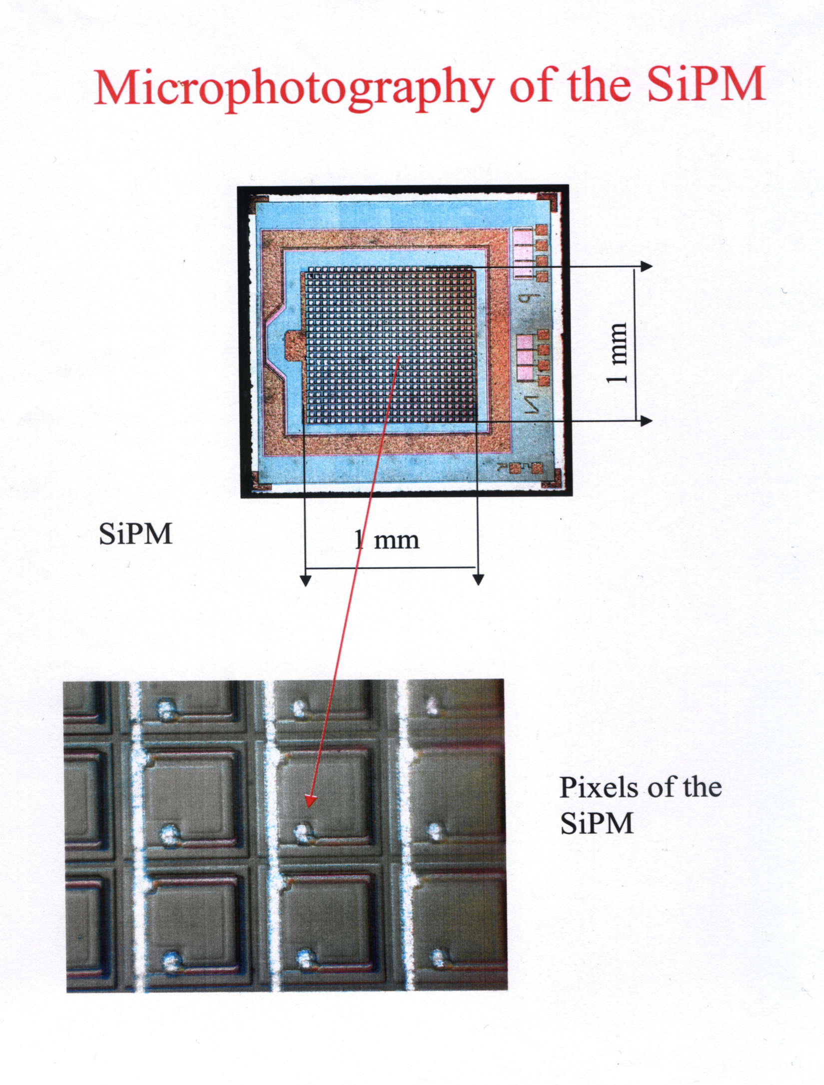
# Silicon Photomultiplier (SiPM)

## *SiPM – main features:*

- **Sensitivity to single photons**
- **Possibility to measure light intensity**
- **Excellent amplitude resolution**
- **Negligible nuclear counting effect**
- **Immunity to magnetic fields up to 7 T**

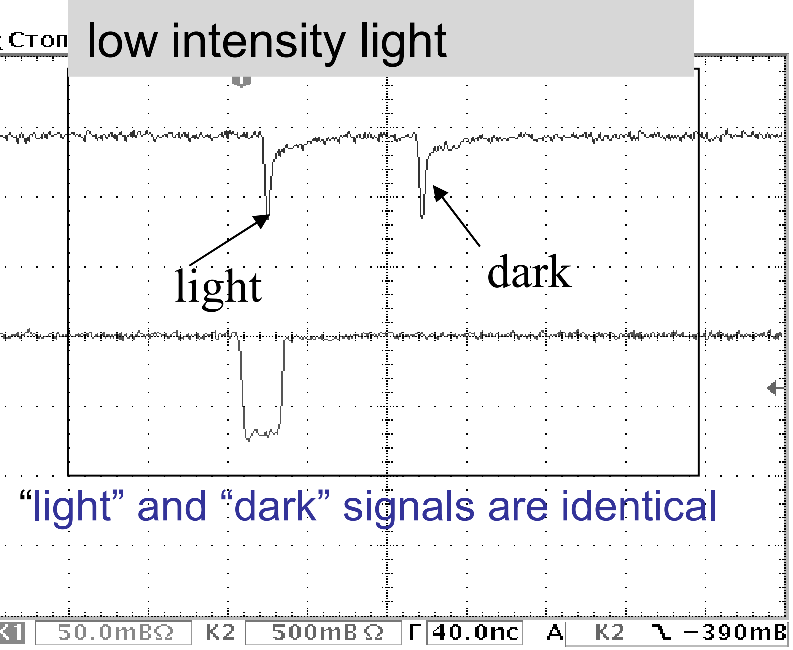
**2008 IEEE Nuclear Science Symposium Conference Record**
Performance Evaluation of SiPM Detectors for PET
Imaging in the Presence of Magnetic Fields S.España, et al.

- **Compactness**
- **Low weight**
- **Low power consumption (~50μW)**
- **Low voltage supply (20-100V)**
- **Fast signal (~1 ns front)**
- **Simple FE electronics**
- **Room temperature operation**

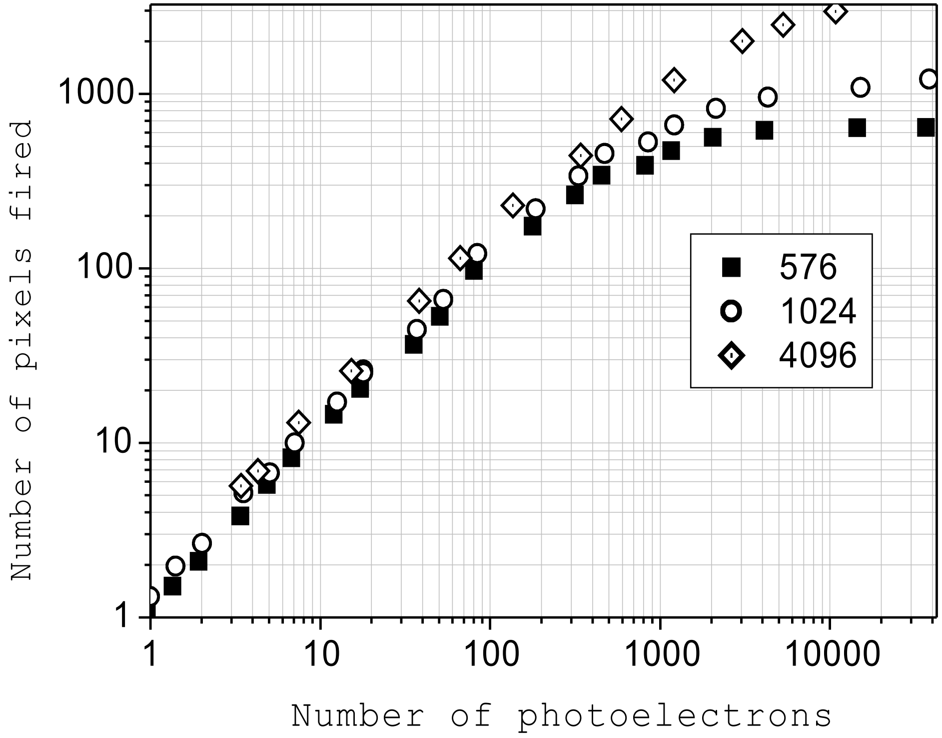


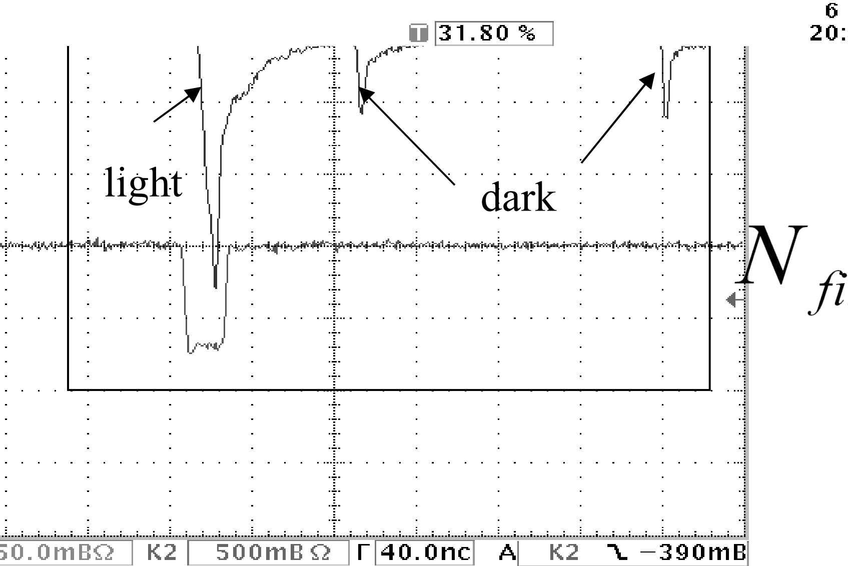
# Silicon Photomultiplier (SiPM)

## Response function for SiPMs with different pixel numbers


low intensity light

“light” and “dark” signals are identical





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

umber of pixels inside SiPM

# 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)*

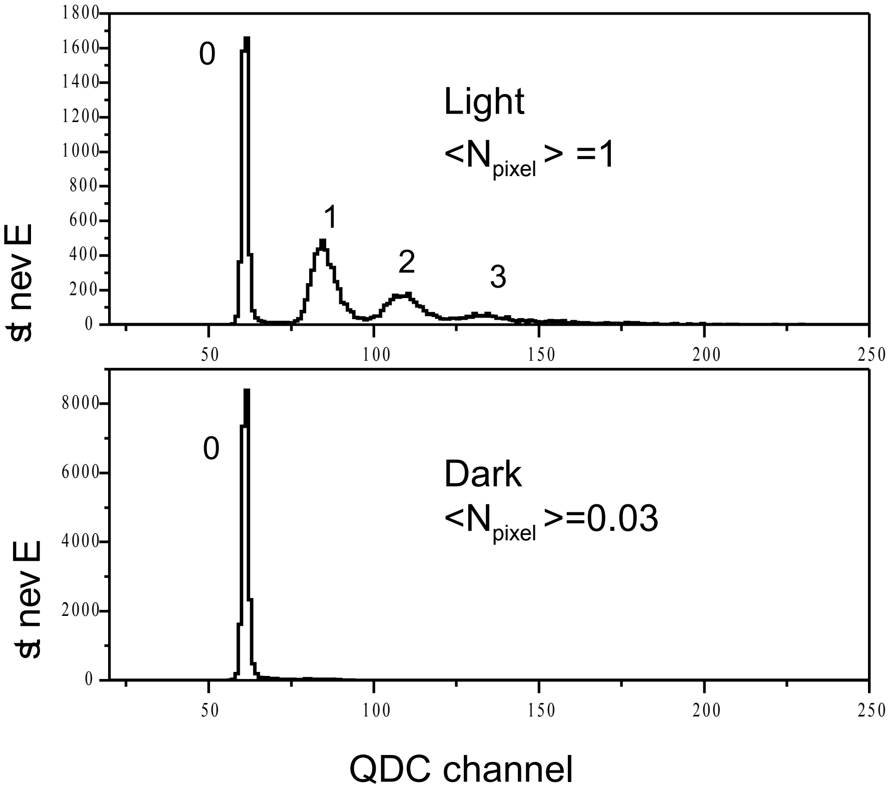
They had :

- 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!

- Department of Elementary Particles headed by prof.Dolgoshein at MEPhI started to investigate such devices since 1993
- Since 2009 MEPHI together with MPI for Physic (Munich) have lisence/collaboration agreement with Excelitas (former Perkin-Elmer) and develop new advanced detectors for different kinds of applications

# Main SiPM's parameters

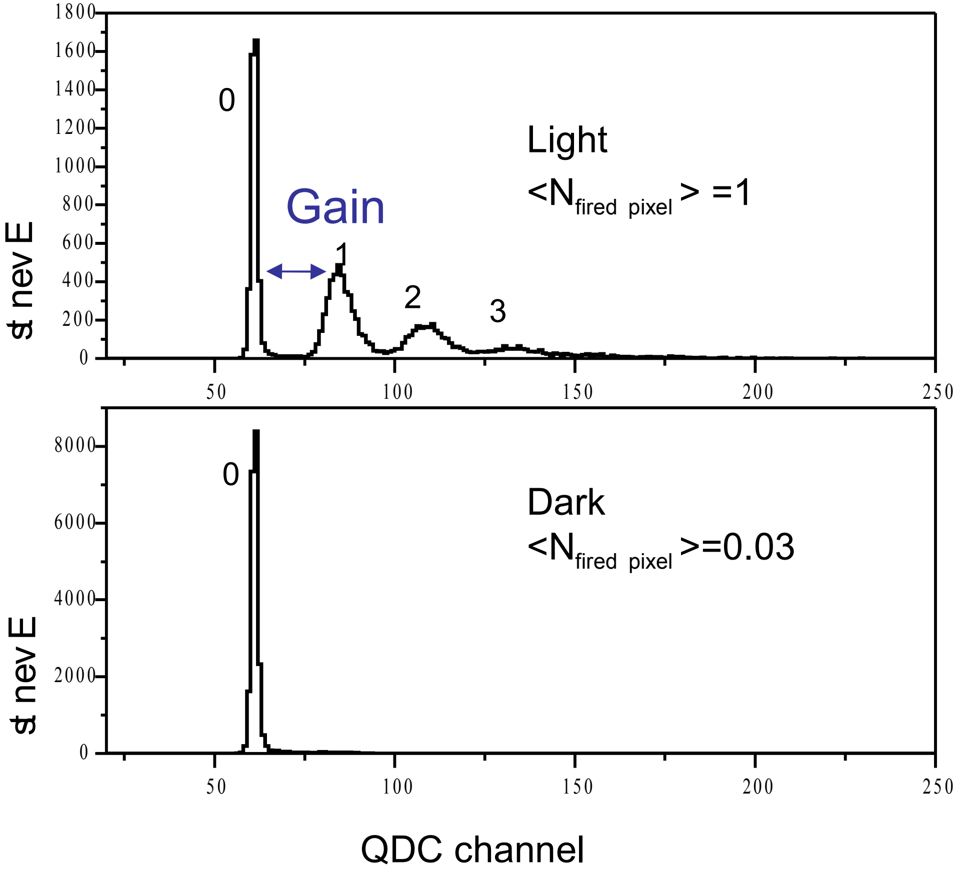


- Photon Detection Efficiency **PDE**
- Gain **G**
- Crosstalk **xt**
- Afterpulsing **ap**
- Dark rate **f**
- Pixel's recovery time $\boldsymbol{\tau}$
- Intrinsic jitter $\boldsymbol{\sigma_t}$

SiPM's single pixel spectra is very useful thing! There are allow us to determine almost all main SiPM parameters.

Quite important – PDE, gain and xt (ap) are measured independently

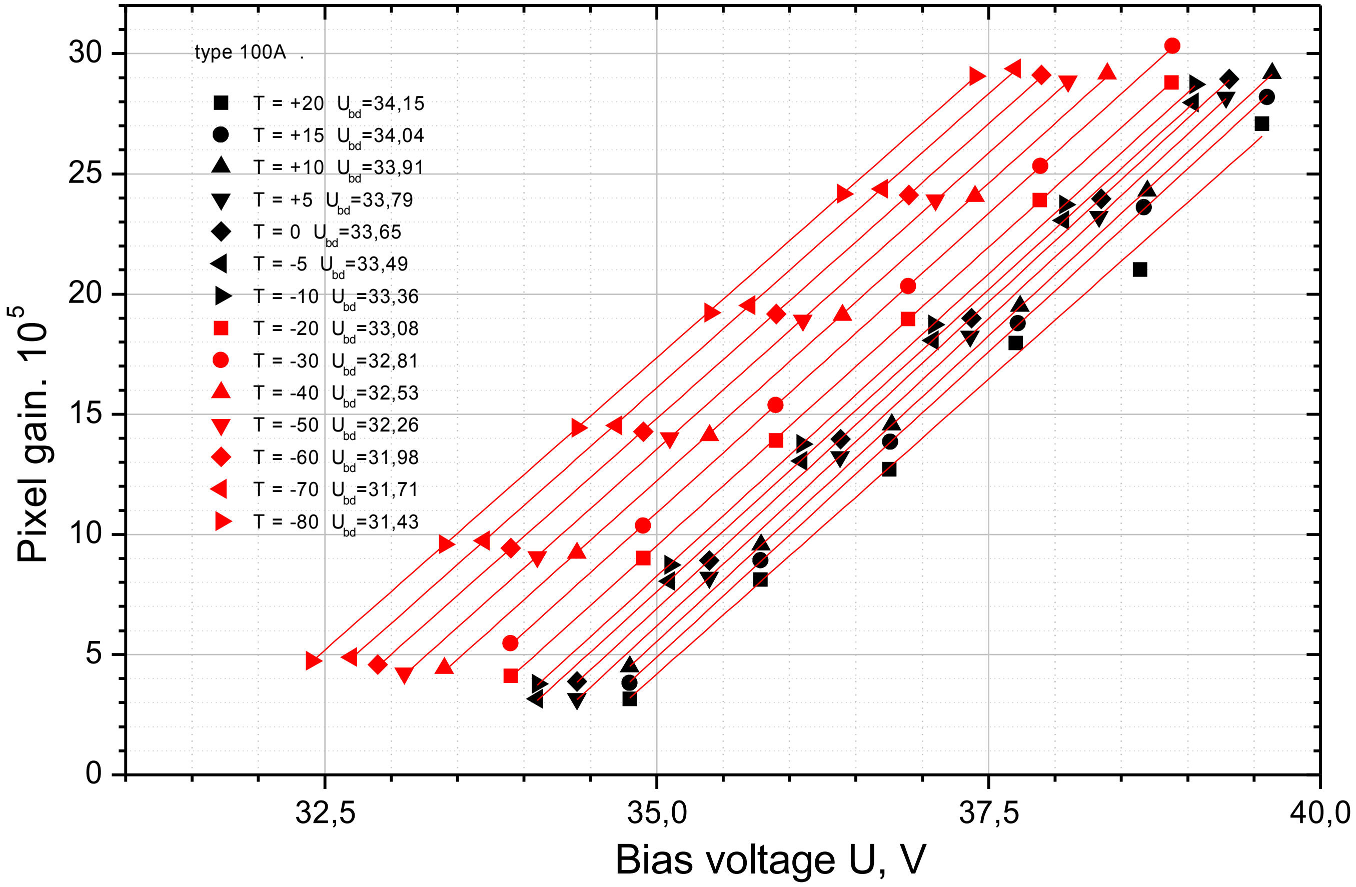
# Main SiPM’s parameters. Gain



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

We need to collect SiPM’s spectra for different voltages

# Main SiPM’s parameters. Gain for different Temperature



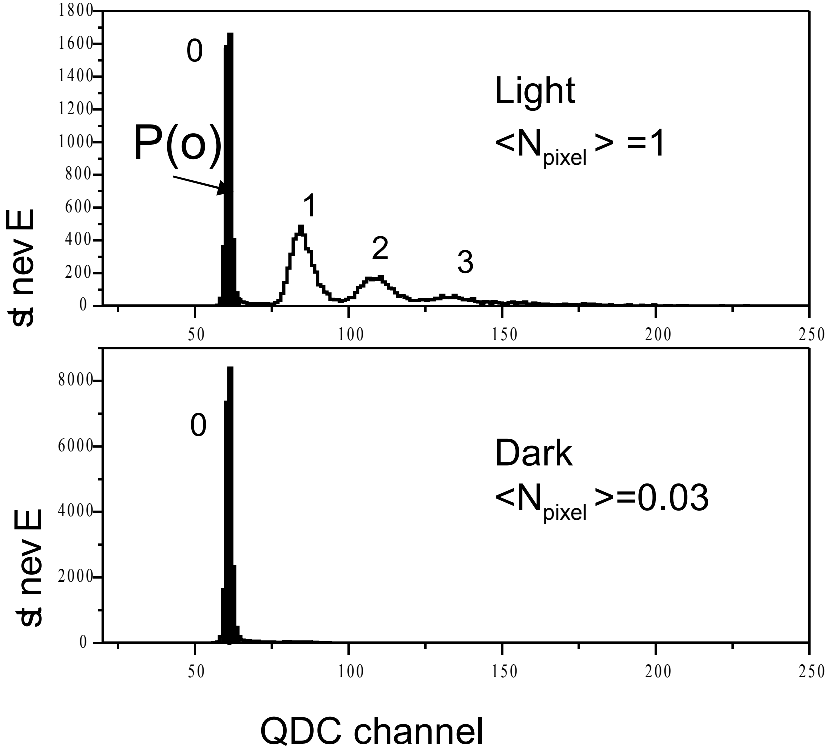
$U_{breakdown} \longrightarrow G=0$

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

$\Delta U$ and $U_{breakdown}$ –are needed for different type SiPM comparison

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

# Main SiPM's parameters. PDE



$$PDE = \frac{< N_{\mathrm{fired\_pixel}} >}{< N_{photons} >}$$

$<N_{photons}>$ - we need a calibrated photodetector

For $<N_{fired\_pixel}>$ assume Poisson distribution of photons:

$$P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

We can find $<N_{pixel}>$ from "zero" peak probability:

$$P(0,< N_{pixel} >) = e^{-< N_{pixel} >}$$

It means that true number of initially fired pixels from light pulse which is free from crosstalk and afterpulsing can be determined as:

$$< N_{fired\_pixel} > = -\ln\left(\frac{S_{ped\_light}}{S_{total\_light}}\right) + \ln\left(\frac{S_{ped\_dark}}{S_{total\_dark}}\right)$$

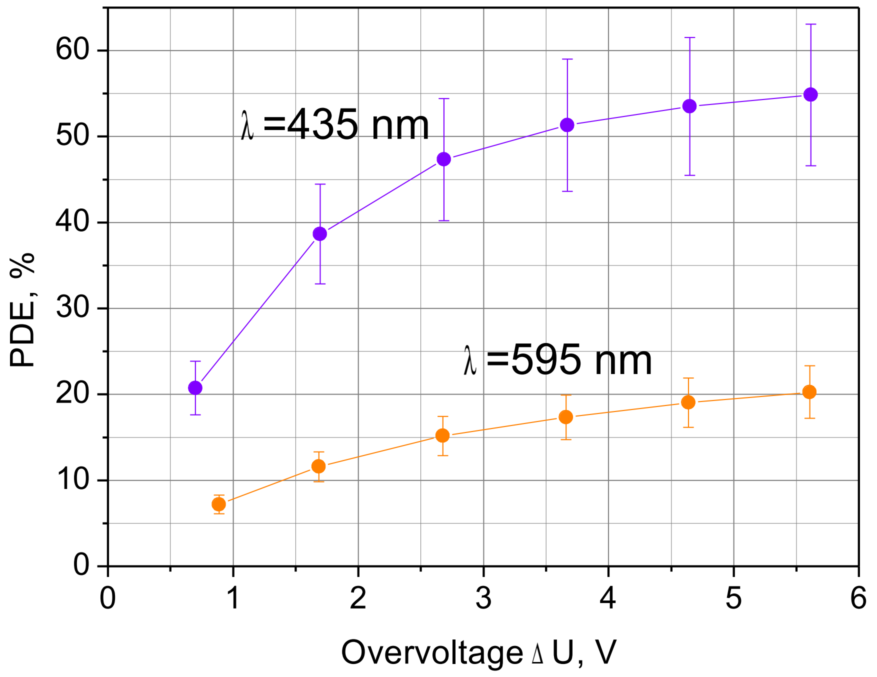
P.Eckert, et al."Characterisation studies of silicon photomultipliers." Nucl. Instr. Meth. Phys. Res. A620 (2009), 217-226

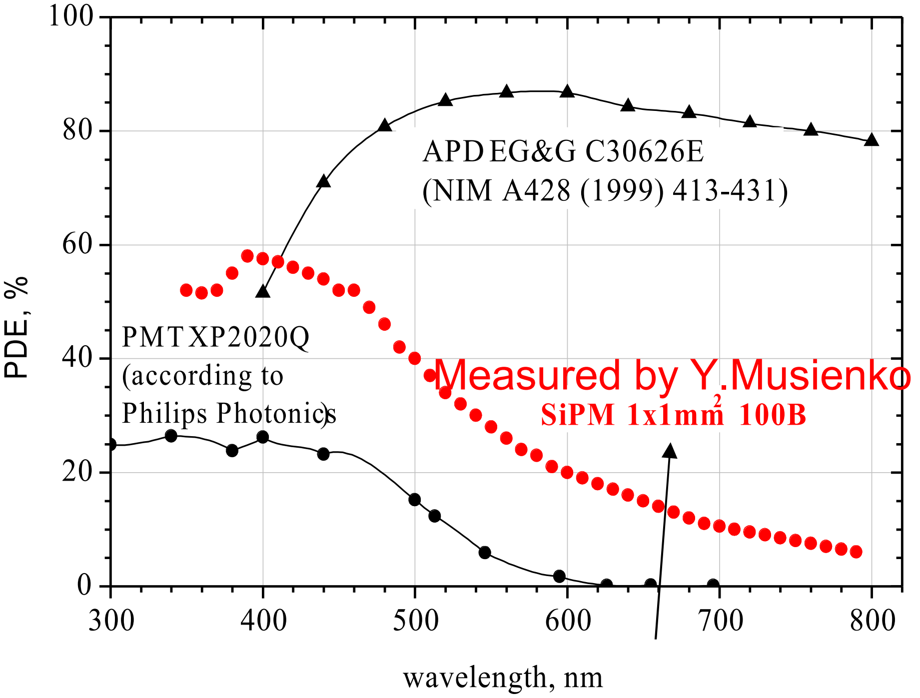
# Main SiPM's parameters. PDE

Spectral PDE for latest MEPhI/MPI SiPM produced in cooperation with Excelitas

100 micron pixel size, geometrical efficiency 80%

MEPhI measurements

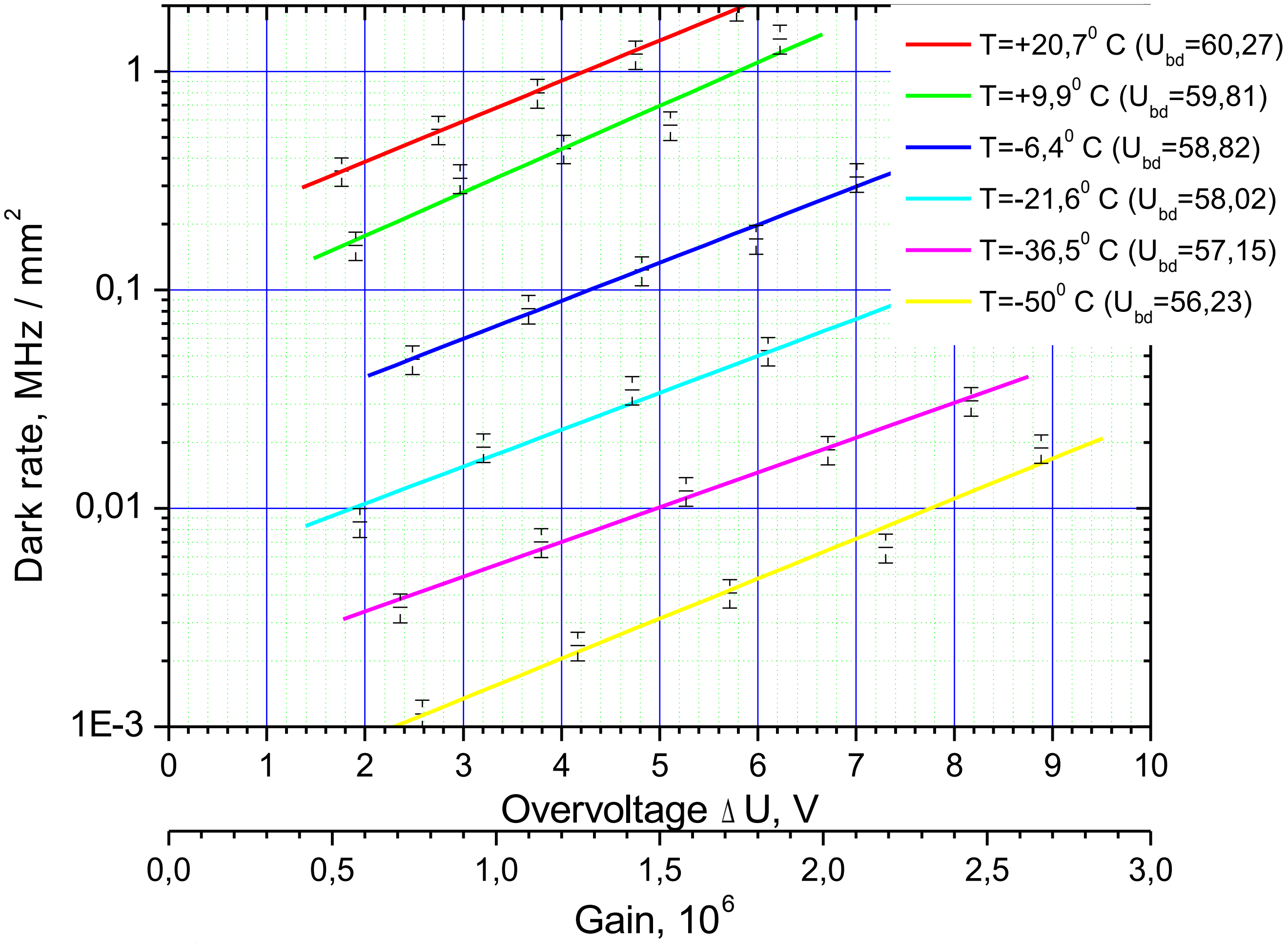




Yury Musienko (Iouri.Musienko@cern.ch)

# Main SiPM's parameters. Dark rate

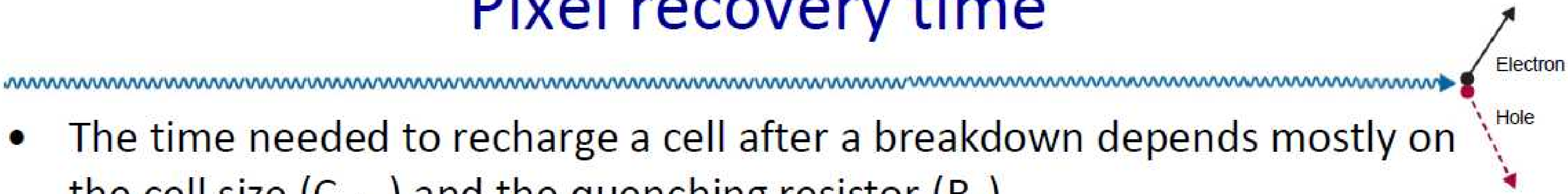
SiPM 1x1 mm$^2$ , 10$^3$ pixels



- ➔ DR typically 10$^6$ 1/mm2 (room T)
- ➔ Cooling helps(-50 C)
- ➔ DR increases with overvoltage(tunneling)->deep cooling does'nt help!

B.Dolgoshein,'Large area SiPM's…'

# Pixel recovery time



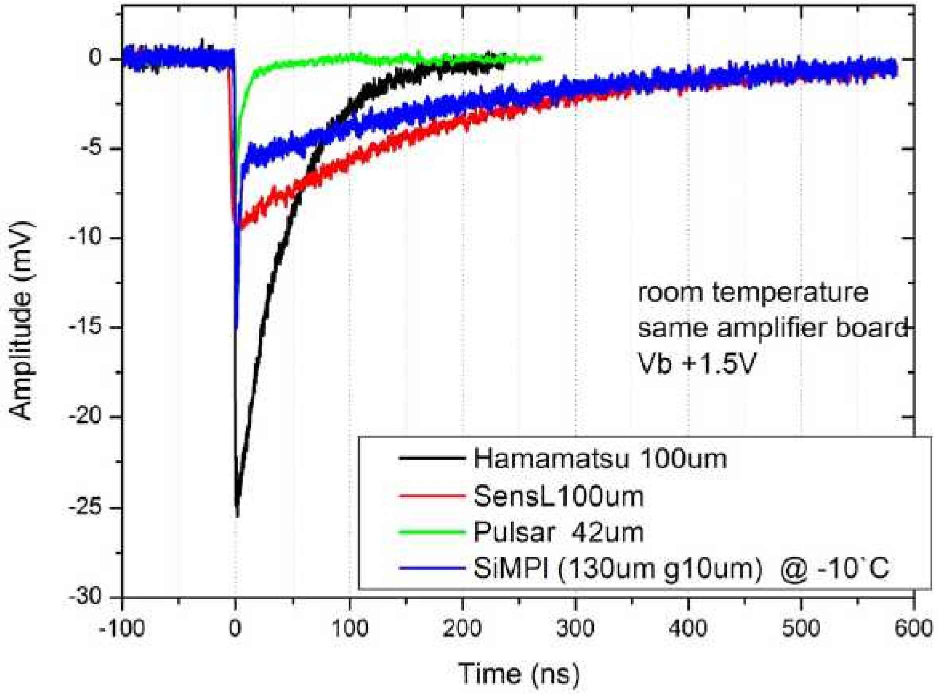
- The time needed to recharge a cell after a breakdown depends mostly on the cell size ($C_{pix}$ ) and the quenching resistor ($R_q$).
  Recovery time of SINGLE pixel:
  τ typical values: $R_q \sim 0.5\text{-}20M\Omega$, $C_{pix} \sim 20\text{-}150fF$

RqCpix $\tau \sim$ 20ns - few μs

! Polysilicon resistors are T dependent
➔ favor high resistivity metal alloy

.

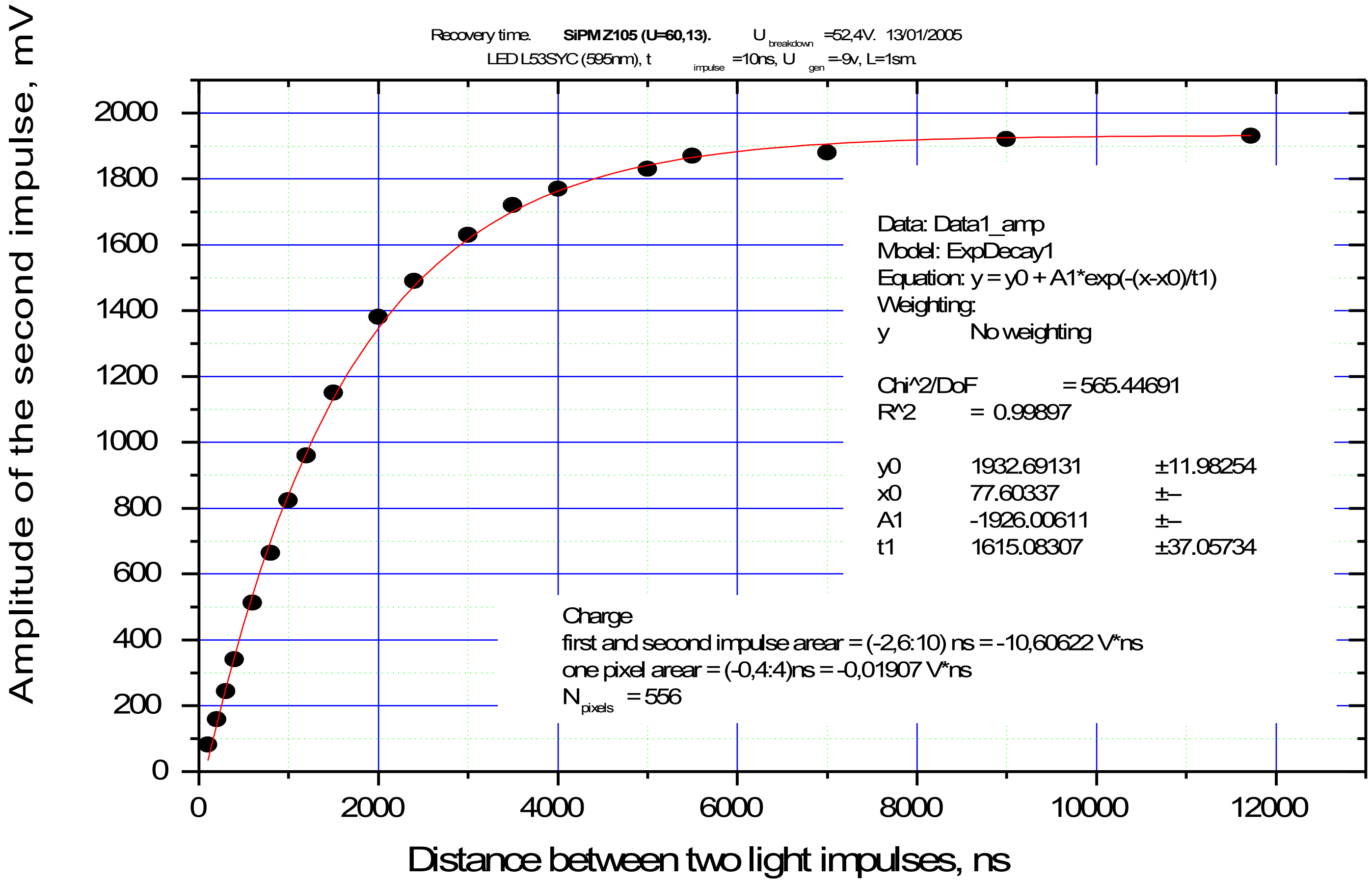
Important for design of readout electronics: Integration or shaping time has to match SiPM signal length, otherwise loss of gain



erika.garutti@desy.de

# Main SiPM’s parameters. Recovery time

Double light pulse method. Possible to use for single pixel and for SiPM itself. Comparison of second pulse SiPM amplitude with first one in dependence from time interval between pulses



Data: Data1_amp
Model: ExpDecay1
Equation: y = y0 + A1*exp(-(x-x0)/t1)
Weighting:
y No weighting

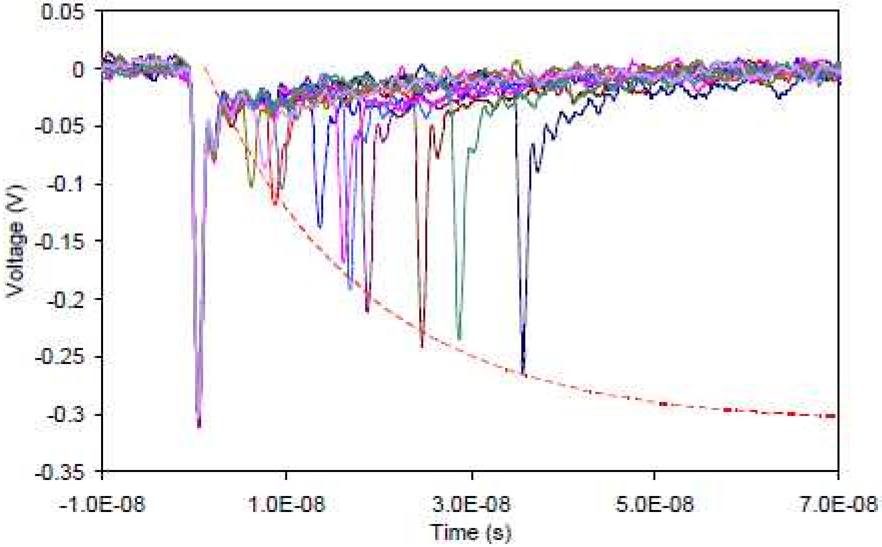
Chi^2/DoF = 565.44691
R^2 = 0.99897

| | | |
|---|---|---|
| y0 | 1932.69131 | ±11.98254 |
| x0 | 77.60337 | ±-- |
| A1 | -1926.00611 | ±-- |
| t1 | 1615.08307 | ±37.05734 |

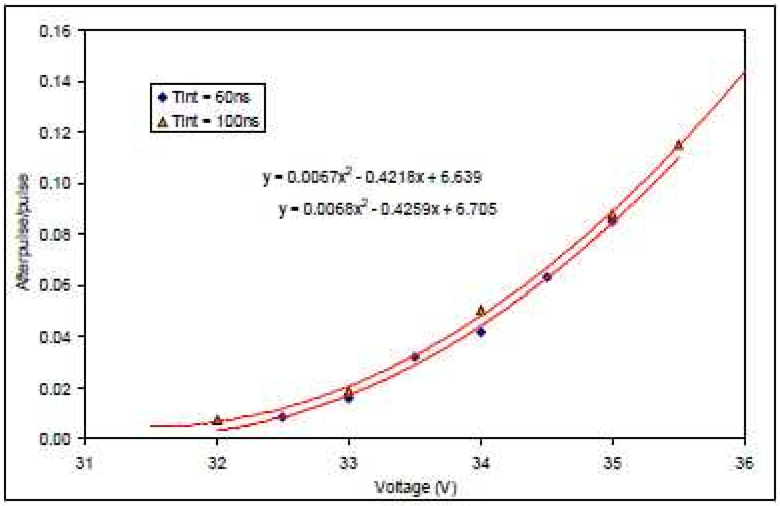
Charge
first and second impulse arear = (-2,6:10) ns = -10,60622 V*ns
one pixel arear = (-0,4:4)ns = -0,01907 V*ns
$N_{pixels}$ = 556

# After-pulsing

Another problem: carriers trapped during the avalanche discharge and then released trigger a new avalanche during a period of several 100 ns after the breakdown



*Events with after-pulse measured on a single micropixel.*



*After-pulse probability increases with the bias*

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

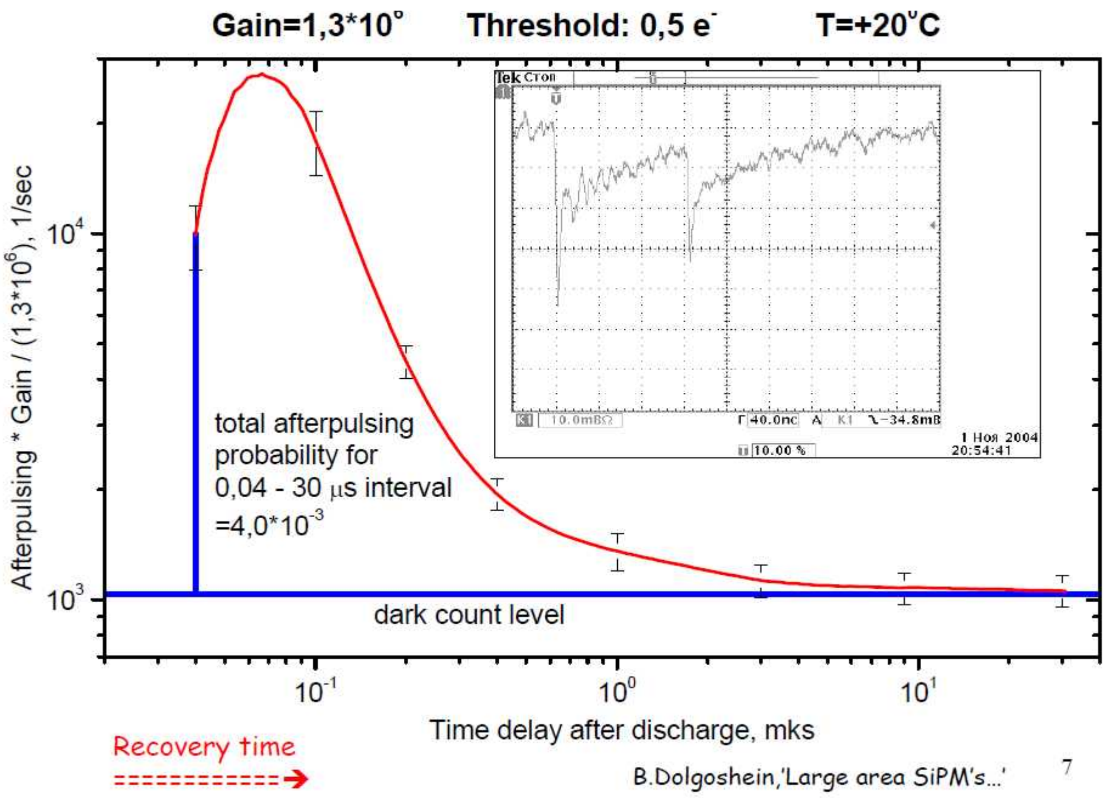
Solutions: "cleaner" technology, longer pixel recovery time and smaller gain

# Main SiPM’s parameters. Afterpulsing

4th NDIP,Beaune-2005

“Large area Silicon Photomultipliers: Performance and Applications”

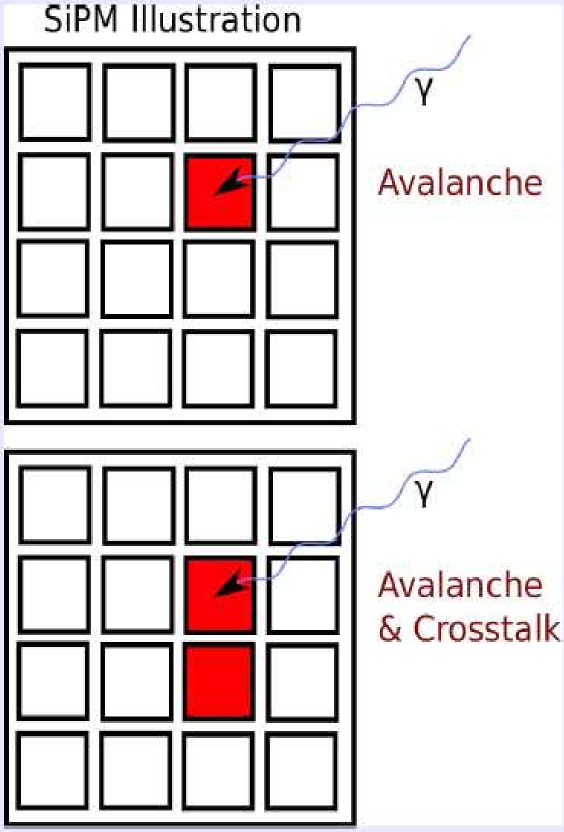
B.Dolgoshein,MEPHI



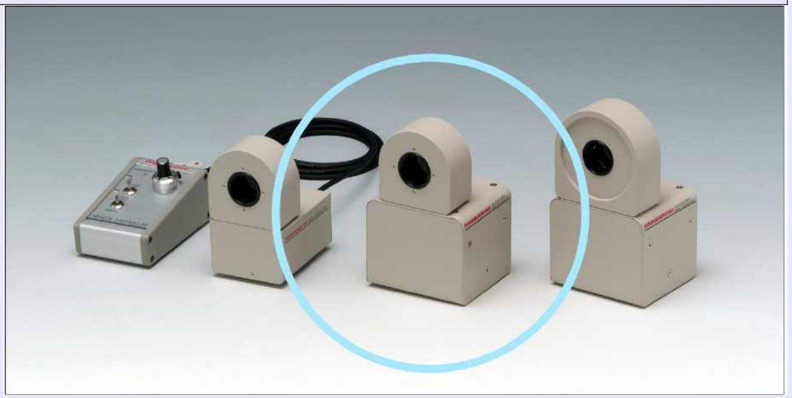
- Afterpulsing AP (trapping of the electrons during discharge and delayed release)-fig.
  - AP is proportional to Gain -typically a few% x Gain/10**6
  - AP increases the Dark Rate
  - AP is high at small delays( < 1 mks)
  - ➔ need a single pixel recovery time of 1-5 mks
  - ➔ Cooling does not help because the increase of trap lifetime

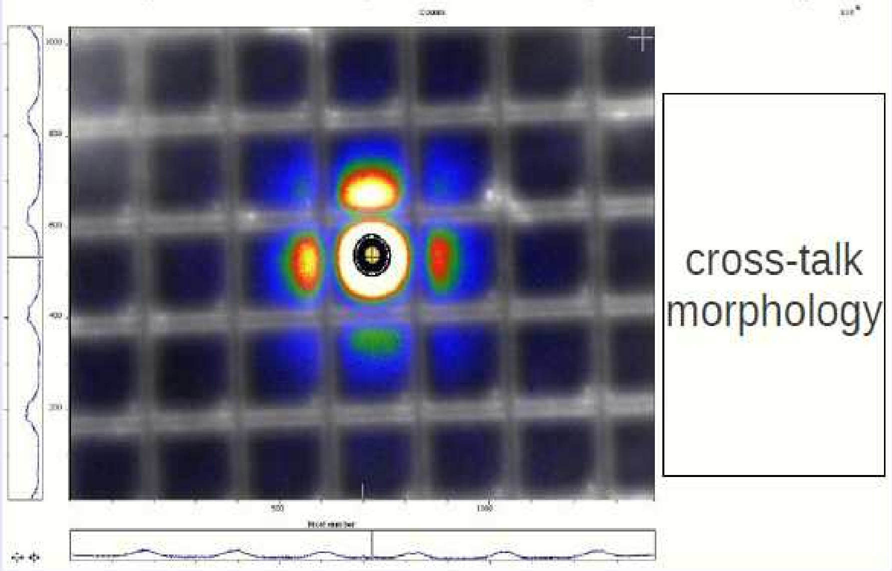
# Main SiPM's parameters. Crosstalk

SiPM cross-talk

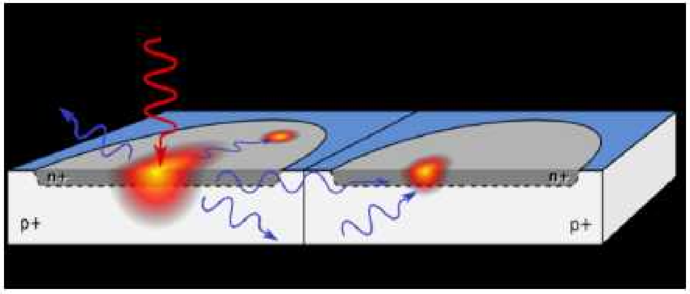


New measurements with high-speed gated image intensifier - 3ns gate
Hamamatsu C9546-05P47L



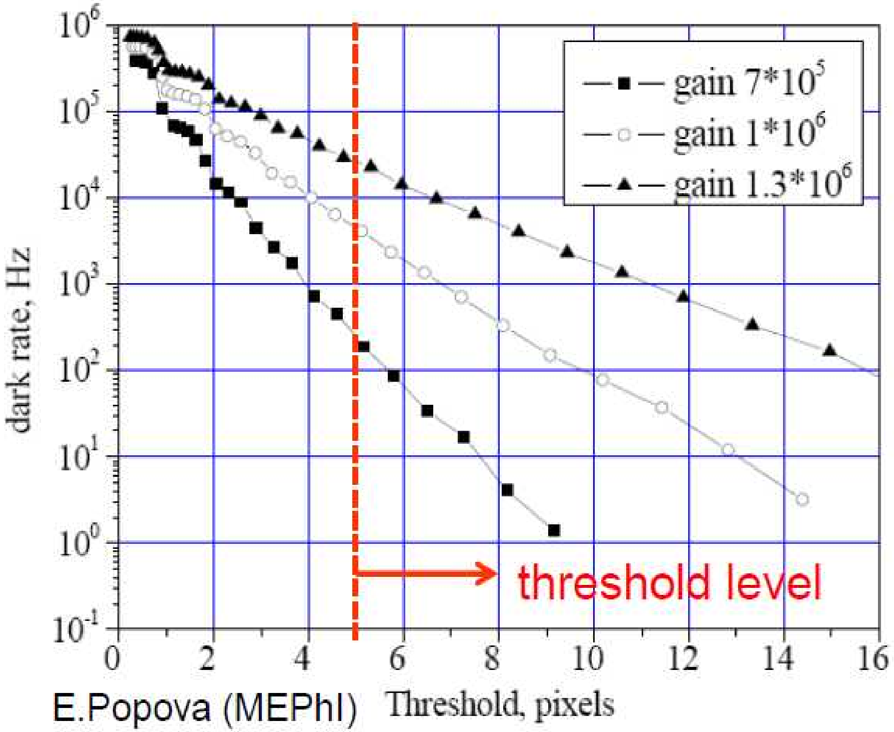


# Main SiPM's parameters. Crosstalk



A p-n junction in breakdown emits photons in the visible range (~ 3 x $10^{-5}$ per charge carrier with a wavelength less than 1 µm*)
If they reach a neighboring pixel additional breakdown can be caused

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



E.Popova (MEPhI)

Optical crosstalk

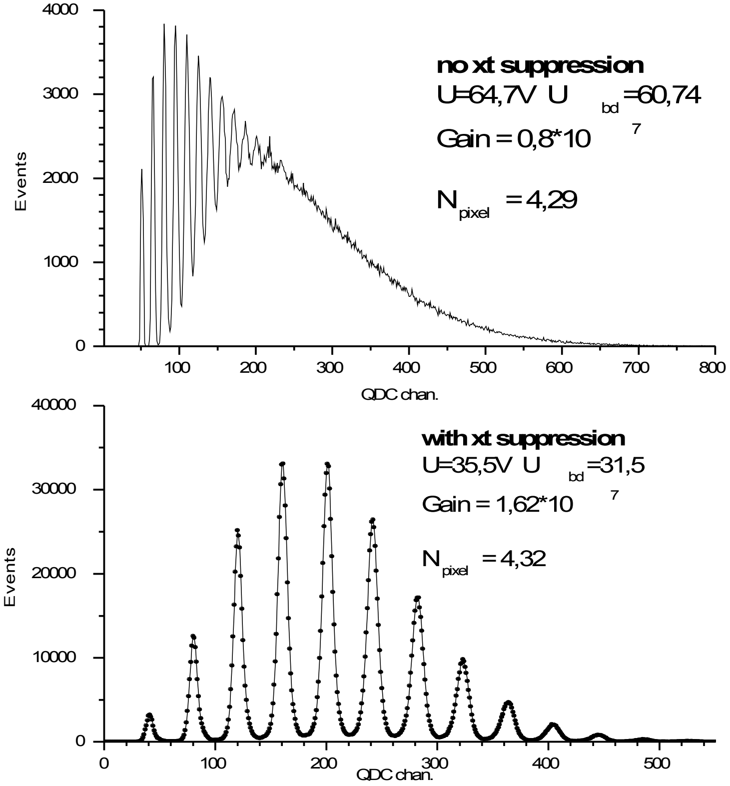
- responsible for the high rate at thresholds >1.5 p.e.
- Increases with overvoltage (or gain)

- Decrease effective dynamic range

Limit to the SiPM sensitivity
Influence on acquisition rate & electronics design

# Main SiPM's parameters. Crosstalk

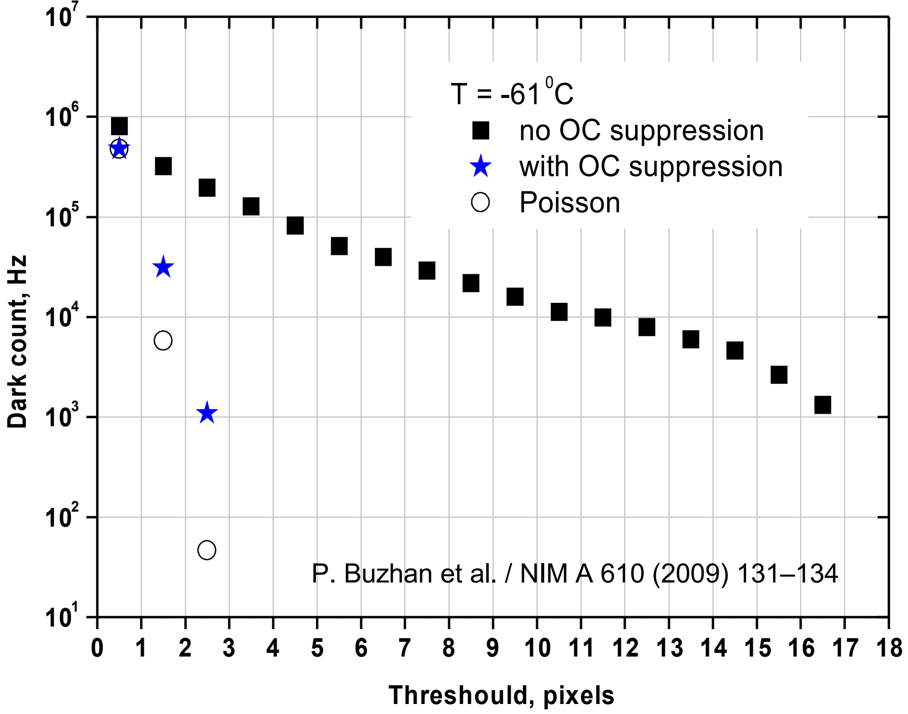
## Xt and light signal



(IMAGING2010 Stockholm, Sweden June 8 – 11, 2010

B.Dolgoshein "Silicon Photomultiplier")

## Xt and dark rate MEPhI/MPI



Main protection from crosstalk – optical trenches between the SiPM pixels
But only trenches are not enough!

# Main SiPM's parameters. Crosstalk

## Crosstalk from light spectra

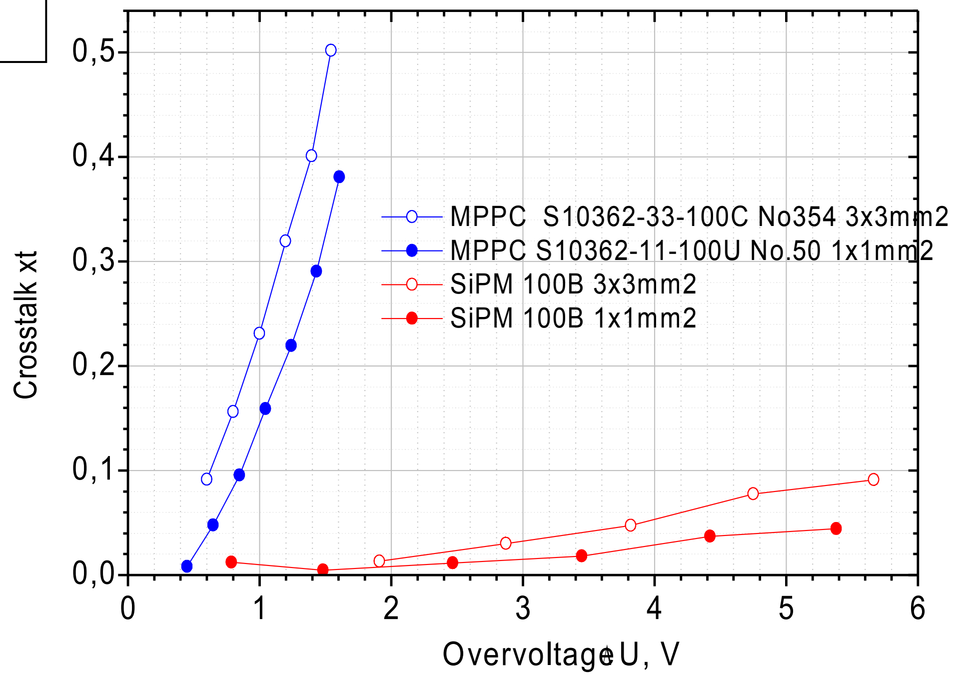
- V.Balagura, et al."Study of Scintillator Strip with Wavelength Shifting Fiber and Silicon Photomultiplier." NIM A564 (2006) 590-596
- S.Vinogradov et al."Probability distribution and noise factor of solid state photomultiplier
signals with cross-talk and afterpulsing ". Nuclear Science Symposium Conference Record (NSS/MIC), 2009 IEEE

## $Xt=N_{>1.5}/N_{>0.5}$ crosstalk from dark rate

P.Eckert, et al."Characterisation studies of silicon photomultipliers." NIM A620 (2009), 217-226

Crosstalk for latest MEPhI/MPI SiPM produced in cooperation with Excelitas and MPPC

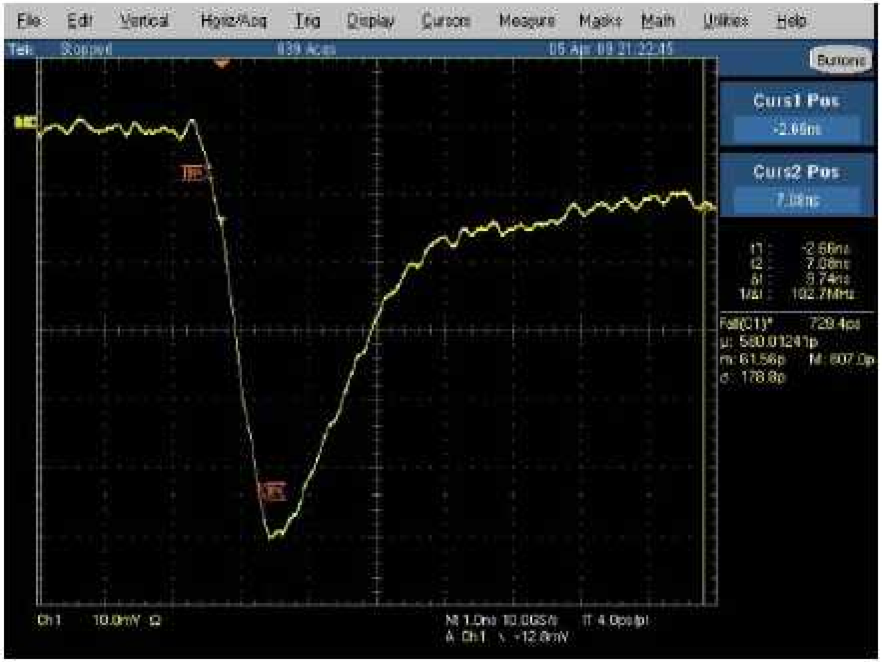
100 micron pixel size, geometrical efficiency 80%



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

# Signal rise time

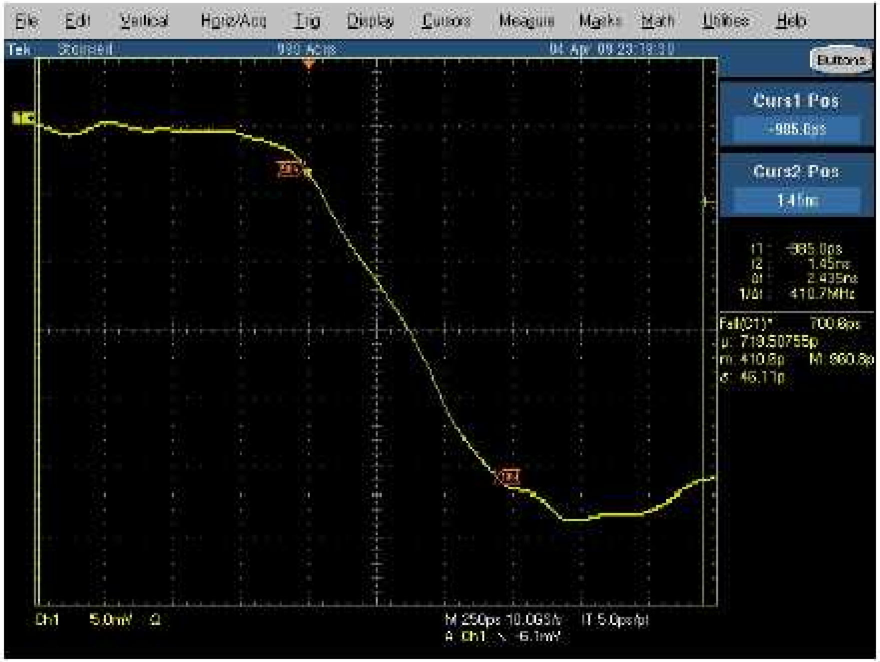
**CPTA/Photonique 1 mm$^2$ SSPM response to a 35 psec FWHM laser pulse ($\lambda$=635 nm)**



```
t1 :   -2.66ns
t2 :    7.08ns
Δt :    9.74ns
1/Δt : 102.7MHz
Fall(C1)*      729.4ps
μ: 580.01241p
m: 61.56p    M: 807.0p
σ: 178.8p
```

```
Ch1   10.0mV  Ω          M 1.0ns 10.0GS/s   IT 4.0ps/pt
                         A  Ch1  ↘  -12.8mV
```

**Zecotek 3x3 mm$^2$ MAPD response to a 35 psec FWHM laser pulse ($\lambda$=635 nm)**



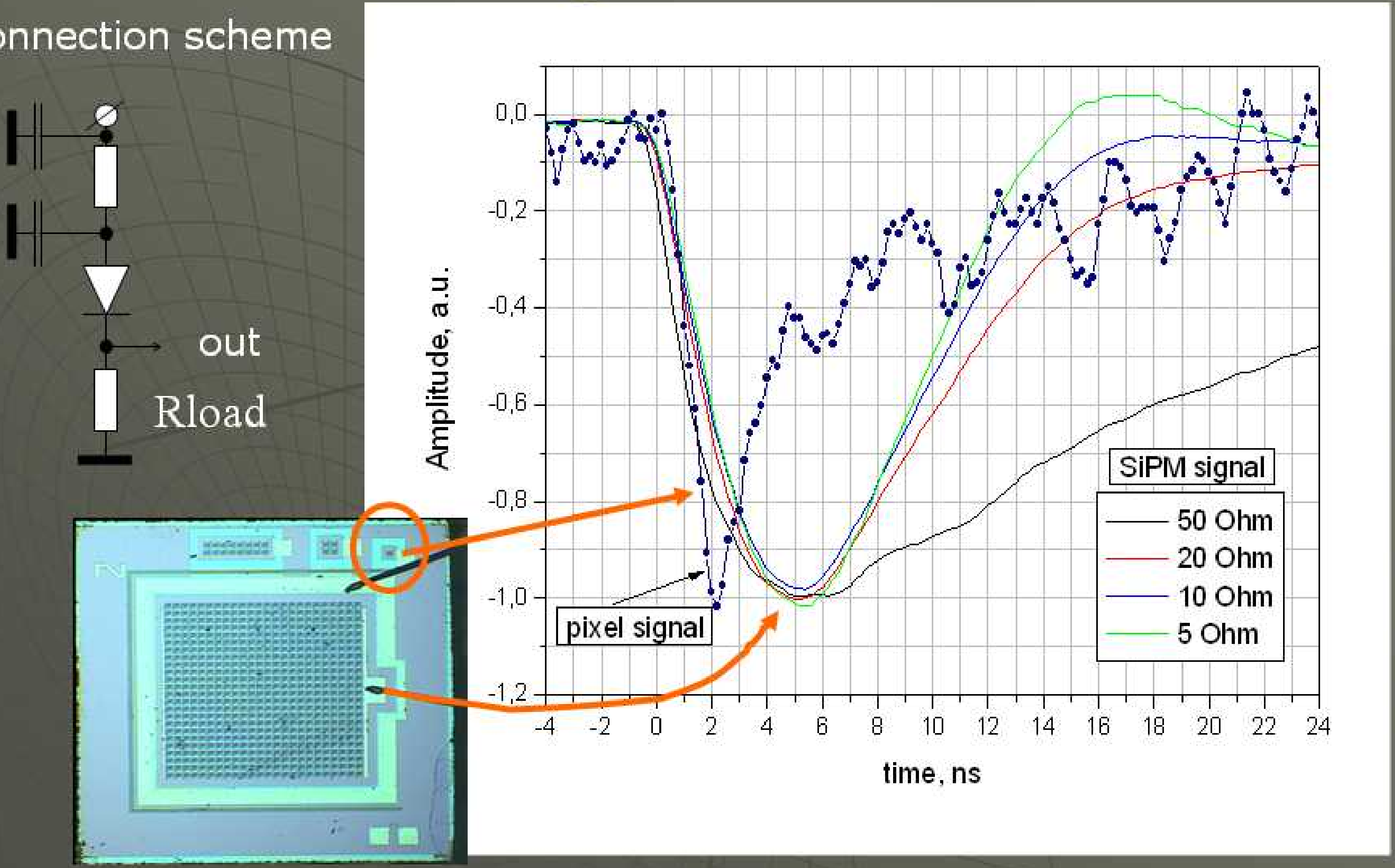
```
t1 :  -985.0ps
t2 :    1.45ns
Δt :   2.435ns
1/Δt : 410.7MHz
Fall(C1)*      700.6ps
μ: 719.50755p
m: 410.8p    M: 960.8p
σ: 46.11p
```

```
Ch1   5.0mV   Ω          M 250ps 10.0GS/s   IT 5.0ps/pt
                         A  Ch1  ↘  -6.1mV
```

~700 psec rise time was measured (limited by circuitry)

# 5x5 mm2 SiPM signal for different Rload

Connection scheme



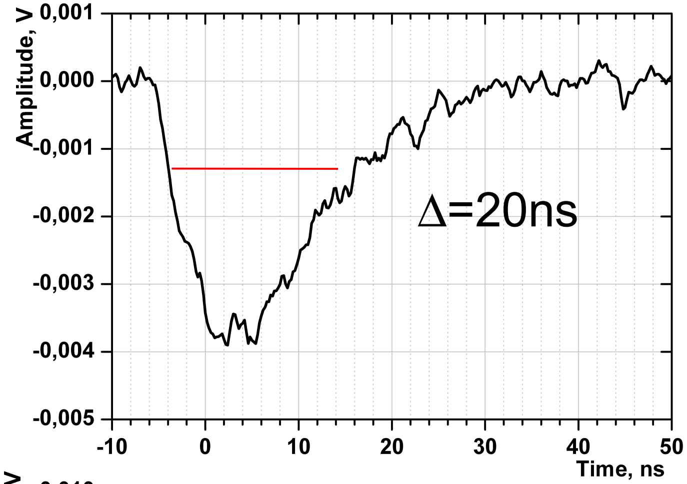
Low input resistivity electronics is needed for fast sipm signal readout

# Cooled SiPM matrixes module for astropartical applications

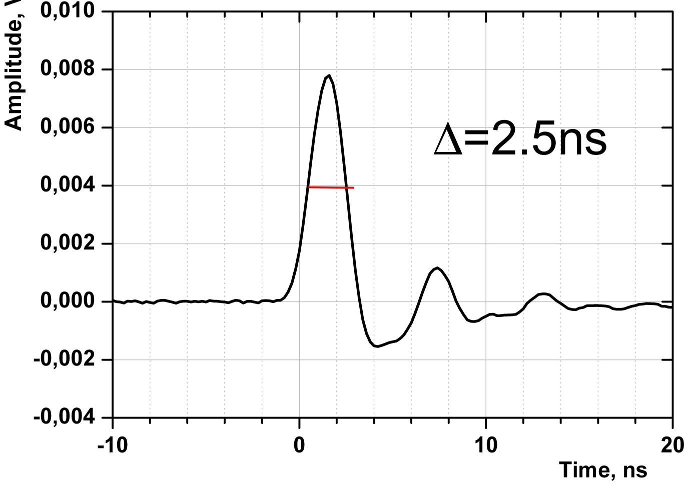
P. Buzhan et al. / NIM A 610 (2009) 131–134

Cooled module with 4 SiPMs 5x5mm2

## SiPM 5x5mm2 signals



50 Ohm load

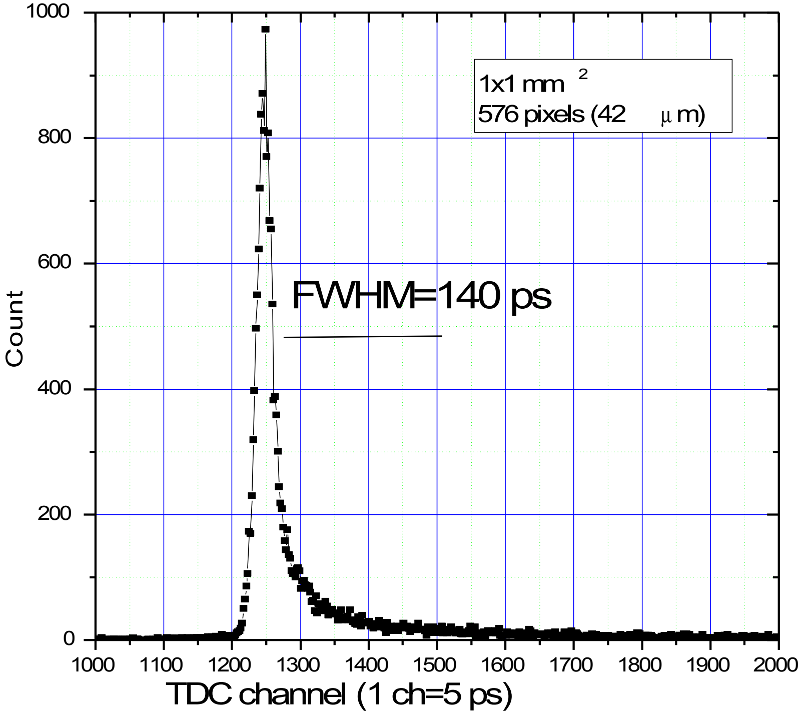


Specially designed FE

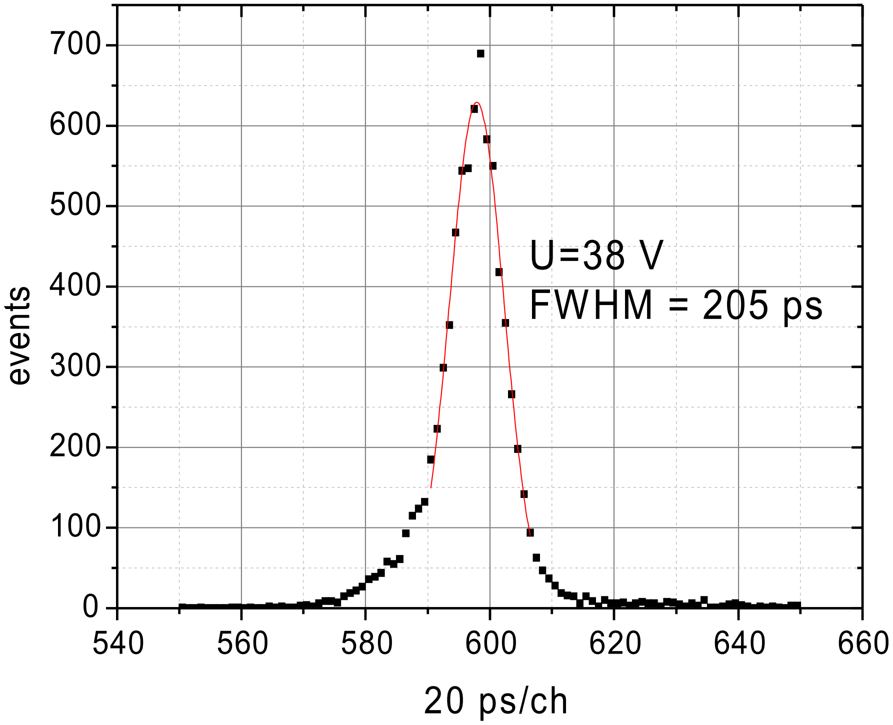
# Main SiPM's parameters. Intrinsic jitter.

Laser in single photon mode

1x1mm$^2$
Room temperature

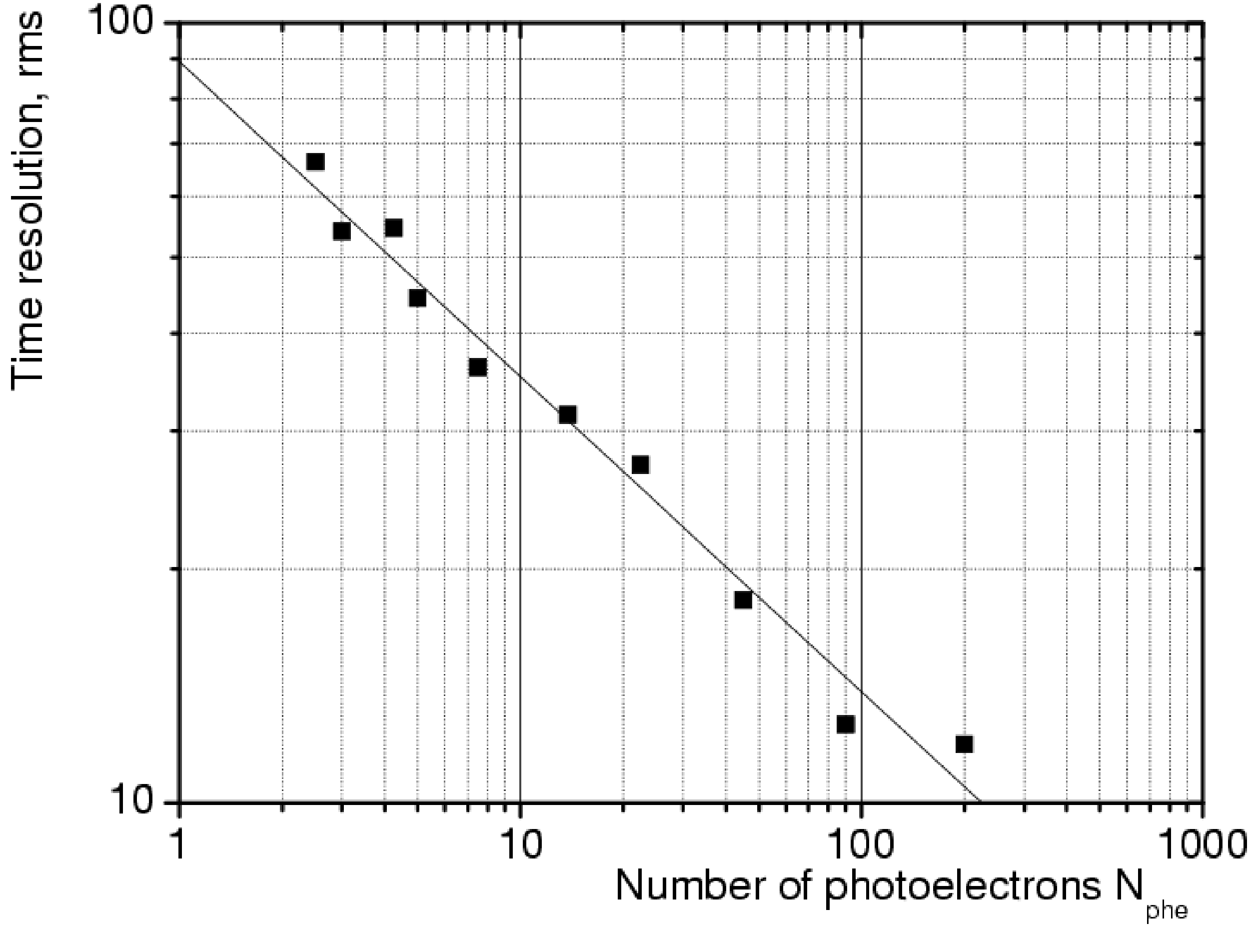


3x3mm$^2$
Temperature -40C



35ps FWHM timing resolution was measured with100µm SPAD using single photons
A.Gulinatti, P.Maccagnani, I.Rech, M.Ghioni and S.Cova

# Main SiPM's parameters. Jitter vs light intensity.



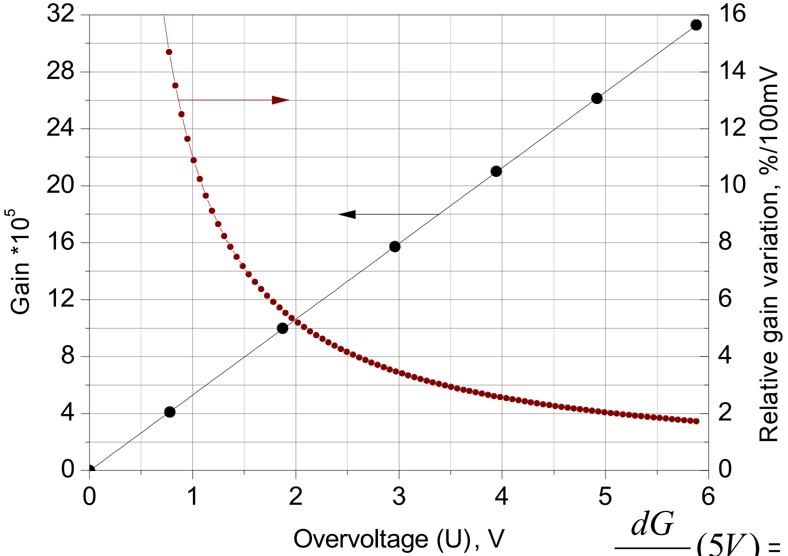
$$\sigma \sim \frac{1}{\sqrt{N_{phe}}}$$

**ADVANCED TECHNOLOGY & PARTICLE PHYSICS Proceedings of the 7th International Conference on ICATPP-7**
*Villa, Olmo, Como, Italy, 15 - 19 October 2001*

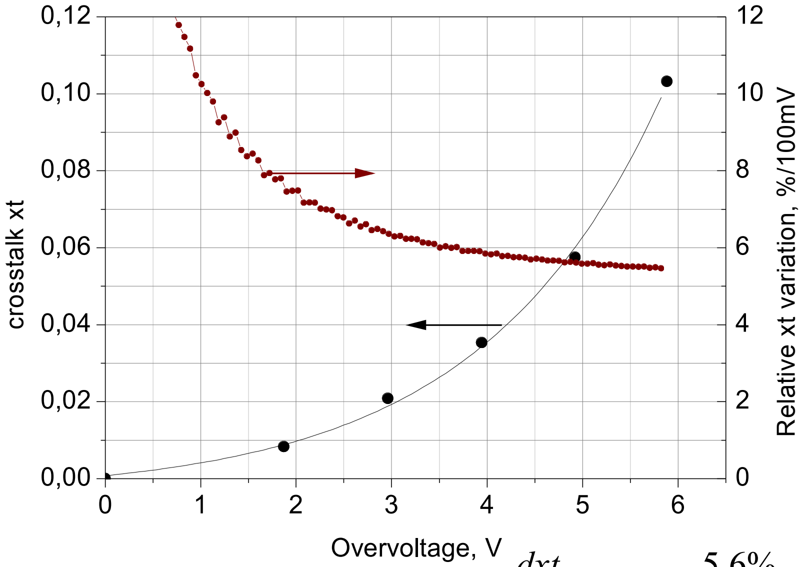
**B.Dolgoshein et al."THE ADVANCED STUDY OF SILICON PHOTOMULTIPLIER"**

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

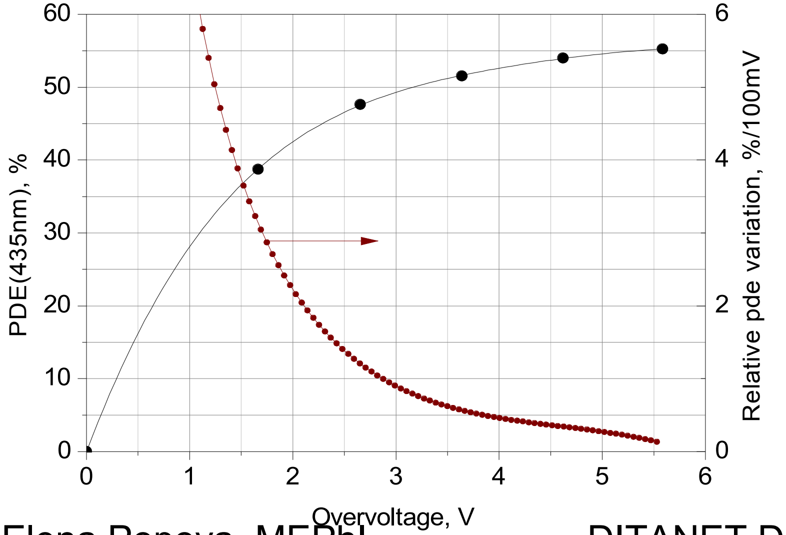
## latest MEPhI/MPI SiPM produced in cooperation with Excelitas



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



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



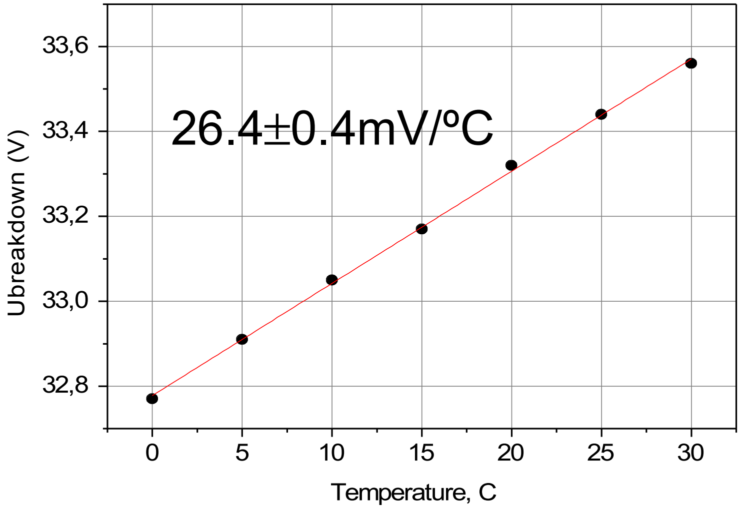
$$\frac{d\varepsilon}{\varepsilon dU}(5V) = \frac{0.25\%}{100mV}$$

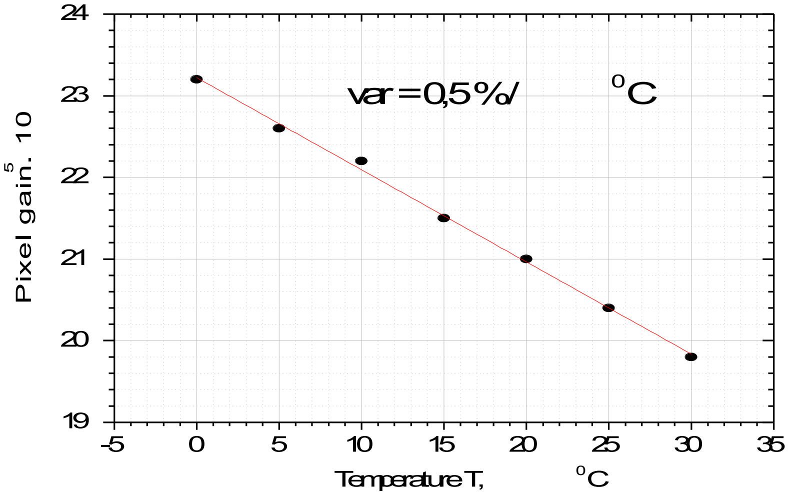
6th NDIP 2011 E. Popova et al.
"Large area UV SiPMs with extremely low cross-talk"

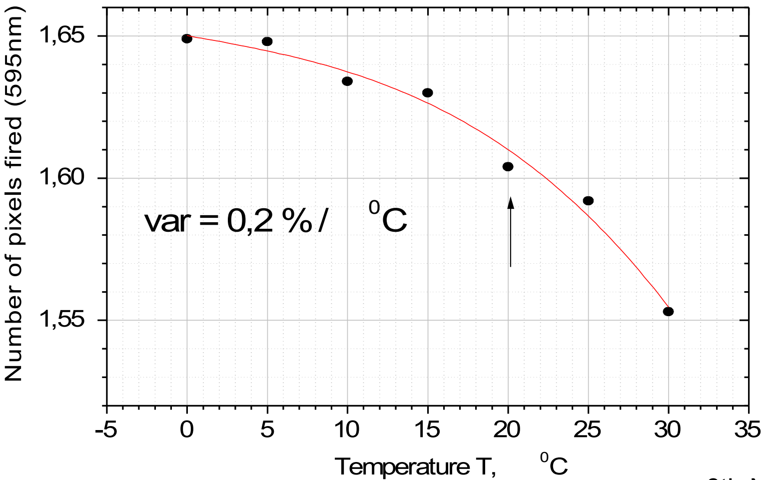
# Temperature stability SiPM 100B

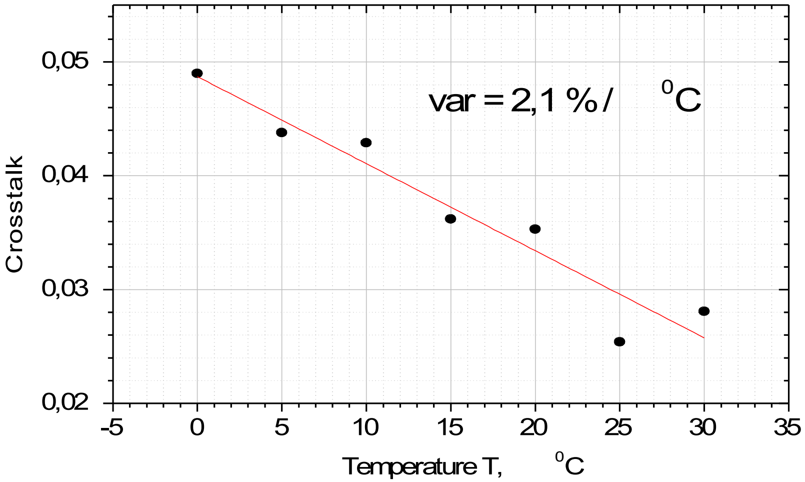
## latest MEPhI/MPI SiPM produced in cooperation with Excelitas

$\Delta V$=4V (12%) overvoltage for T=20ºC









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

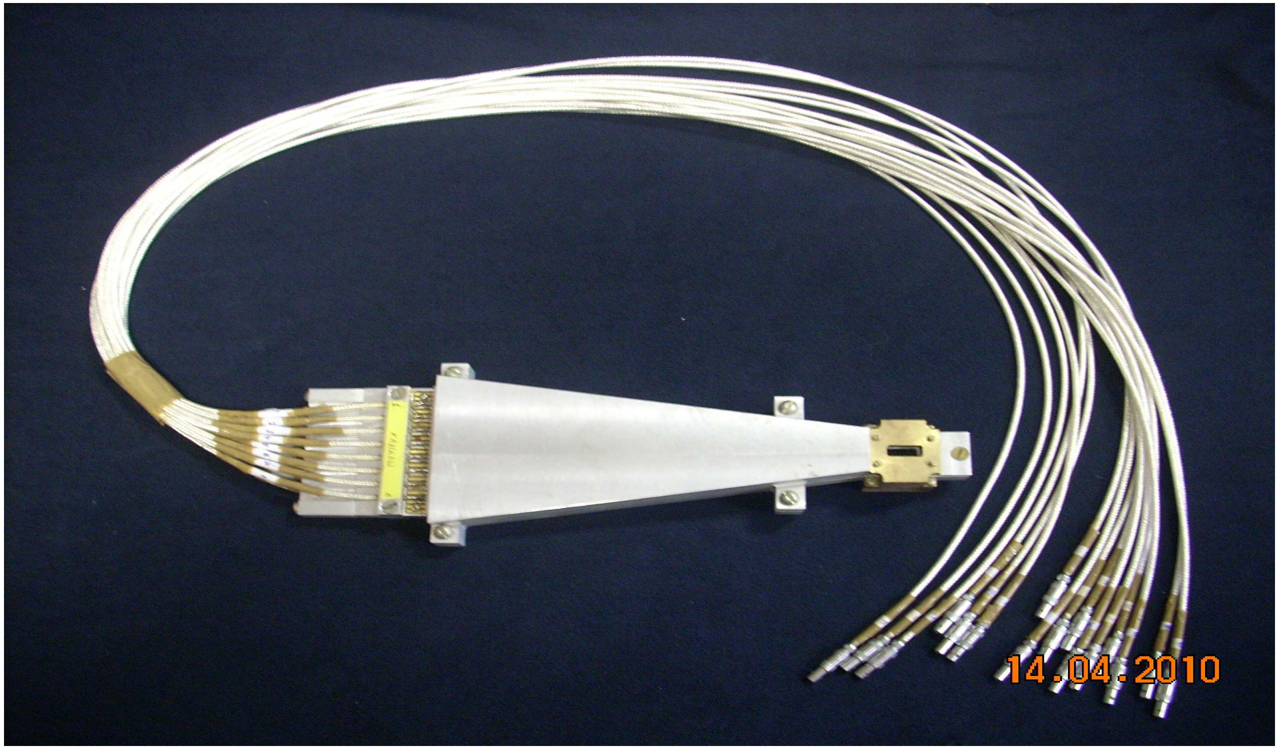
# SiPM applications

*16 channels (SiPMs) tracker on scintillating fibers*

1x1mm2 SiPMs

576 pixels

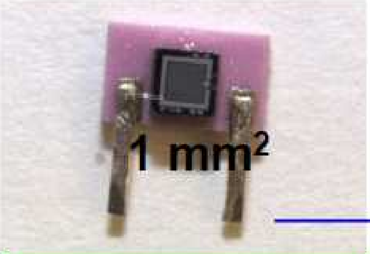
10% light detection efficiency for green light



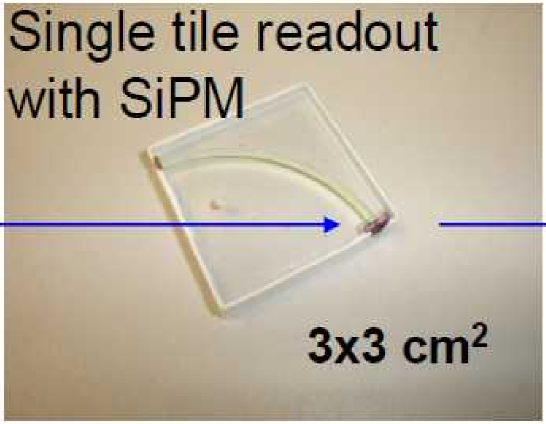
8th Workshop on Electronics for LHC Experiments, Colmar, France, 9 - 13 Sep 2002, pp.380-383
B.Dolgoshein et al.”Scintillation fiber detector of relativistic particles”.

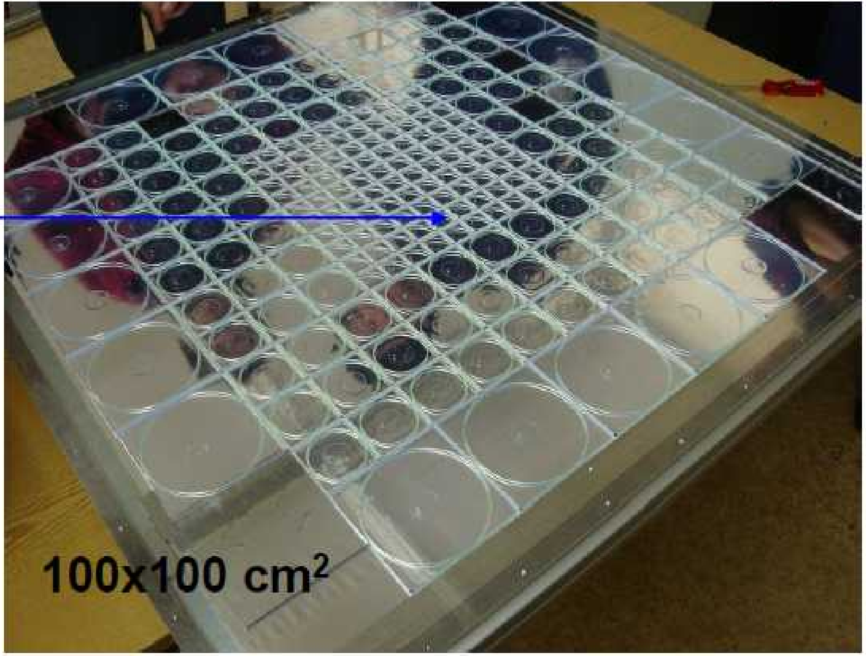
# SiPM pioneering experience

**A crucial technology improvement to calorimetry**

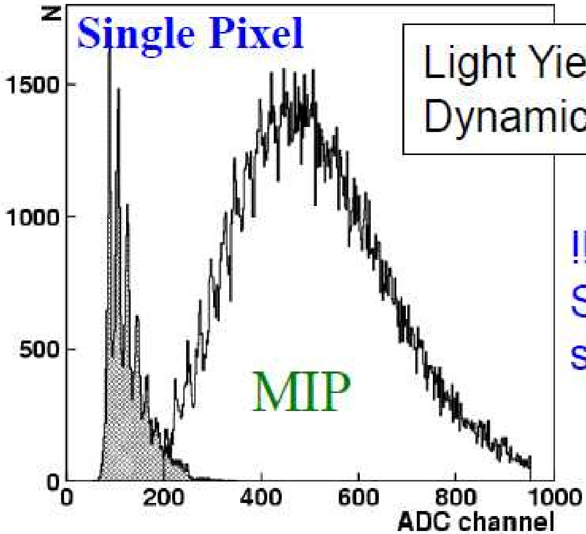


Si-based = insensitive to magnetic field!


Single tile readout with SiPM



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



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

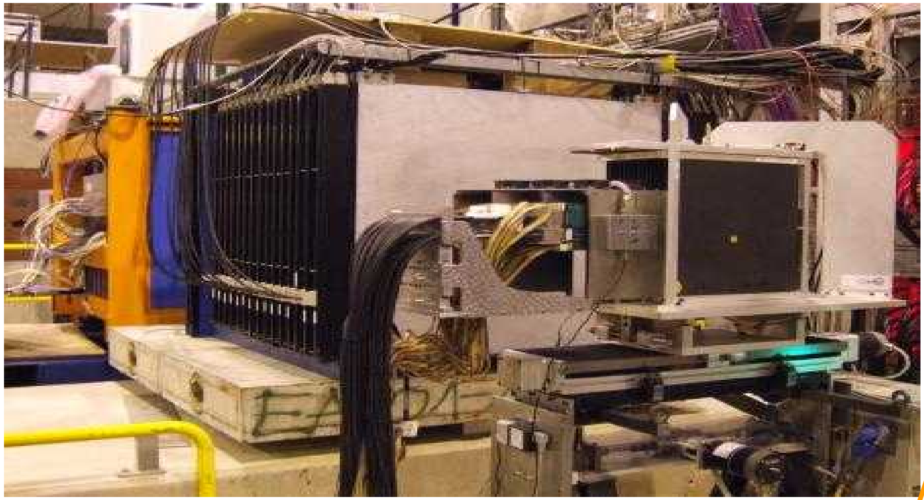
!! auto-calibration of SiPM gain from single-pixel spectra

**Allows unprecedented high granularity**

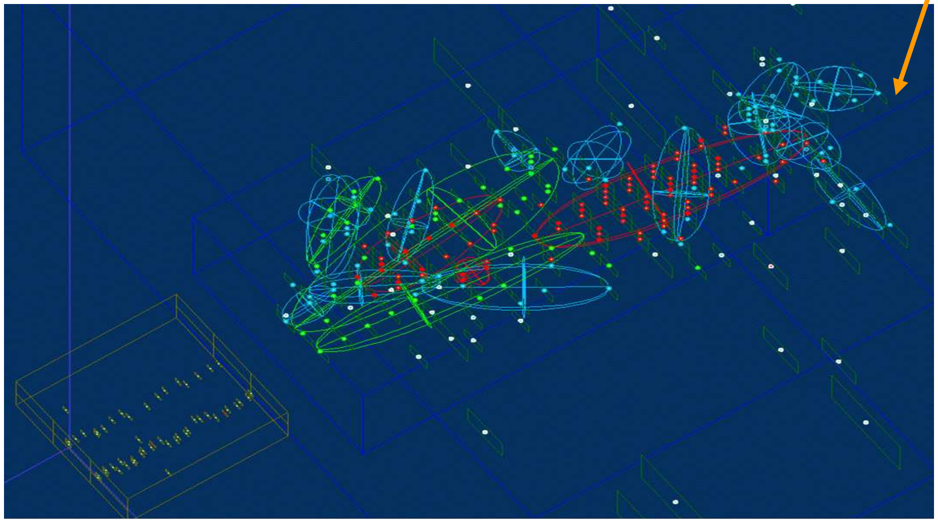
38 layers (~4.5 $\lambda$)
Scintillator – Steel sandwich structure (0.5:2cm)

erika.garutti@desy.de

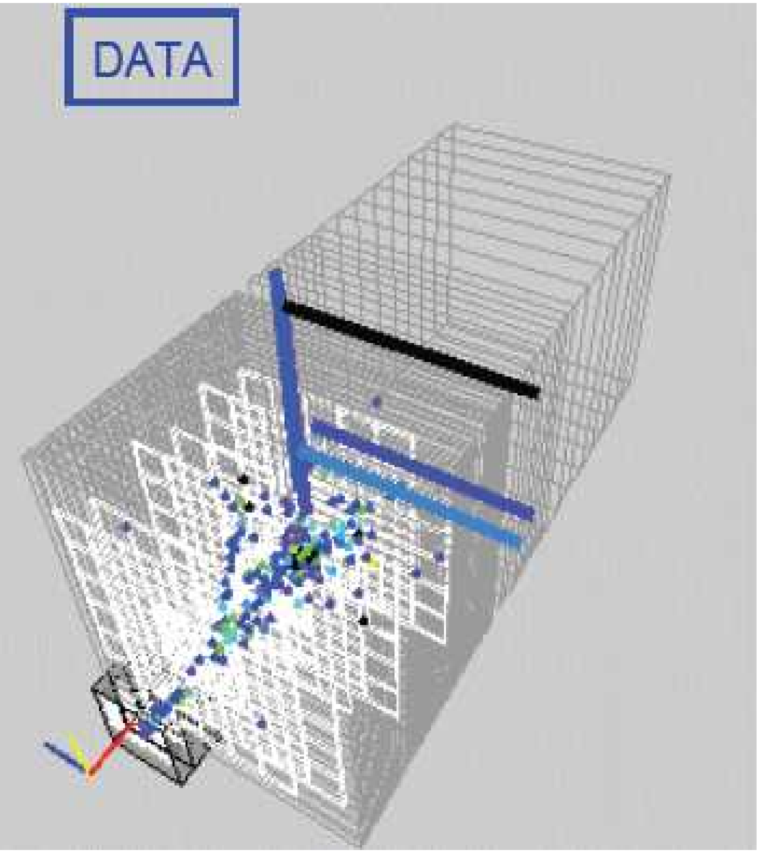
# Physical HCAL Prototype 2005-2007



Event reconstruction



Data monitor

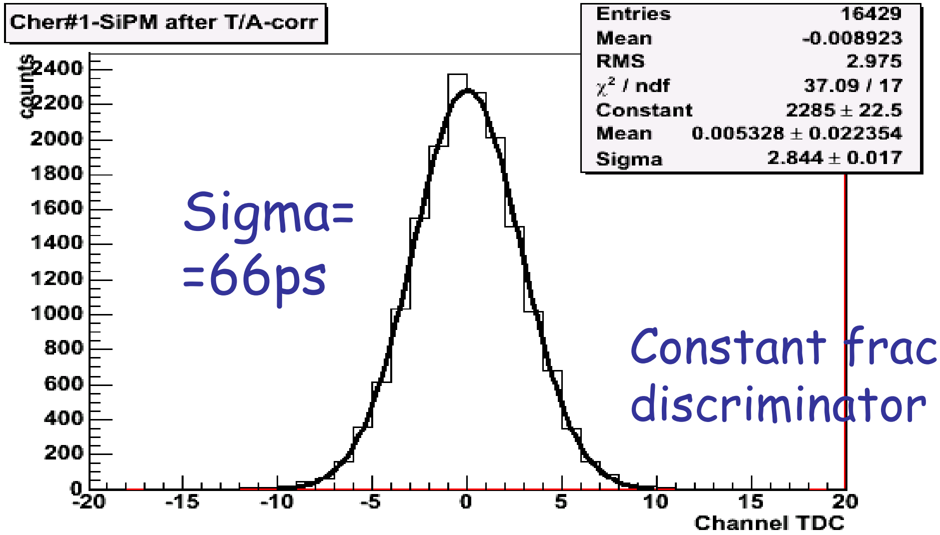


Prototype has been successfully tested at DESY, CERN and FNAL during several years

# 3x3 mm2 SiPM application for TOF

➲ TOF for MIP(3GeV electron beam, DESY)

SiPM: MIP signal is appr.100 mV w/o amplification



Sigma= =66ps

Constant fraction discriminator

Timing resolution between :

PMT(FEU 187)+Cherenkov radiator and SiPM 3x3mm2+BC418 3x3x40 mm3

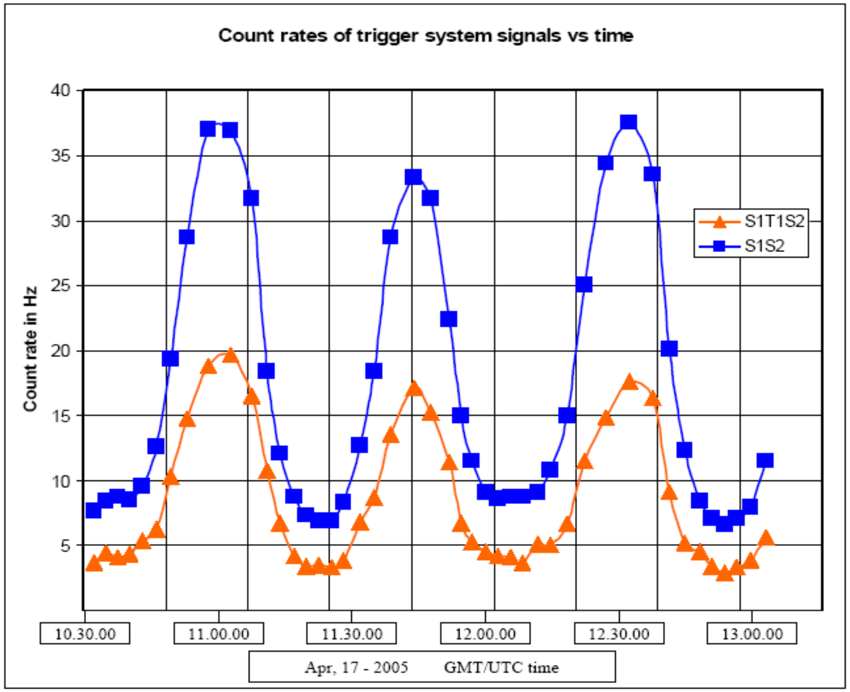
Results:

- sigma(PMT+Ch.rad)=48,5ps
- sigma(electronics) =32ps

➔ Sigma(SiPM+BC418)=33ps

# SiPM's in space ! International Space Station: launched by 15th of April,2005

Space experiment "LAZIO"(MEPHI-INFN Collaboration)



Latitude particle flux dependence

**Scientific goal**:The measurement of low energy particle fluxes and radiation monitoring by apparatus,including sci tile+WLS fiber+SiPM hodoscope system

**Technological goal**: test of SiPM's in space flight conditions

# 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)

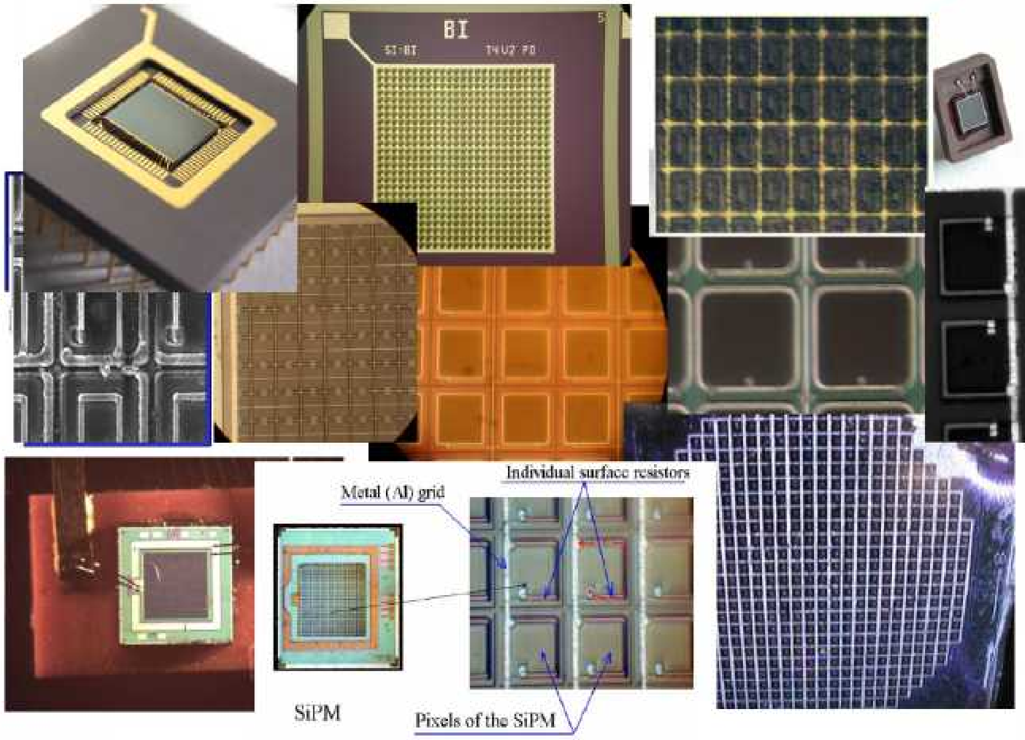
ExcelitasTechnologies (former PerkinElmer)

MPI Semiconductor Laboratory (Munich)

Novel Device Laboratory (Beijing, China)

Philips (Netherlands)

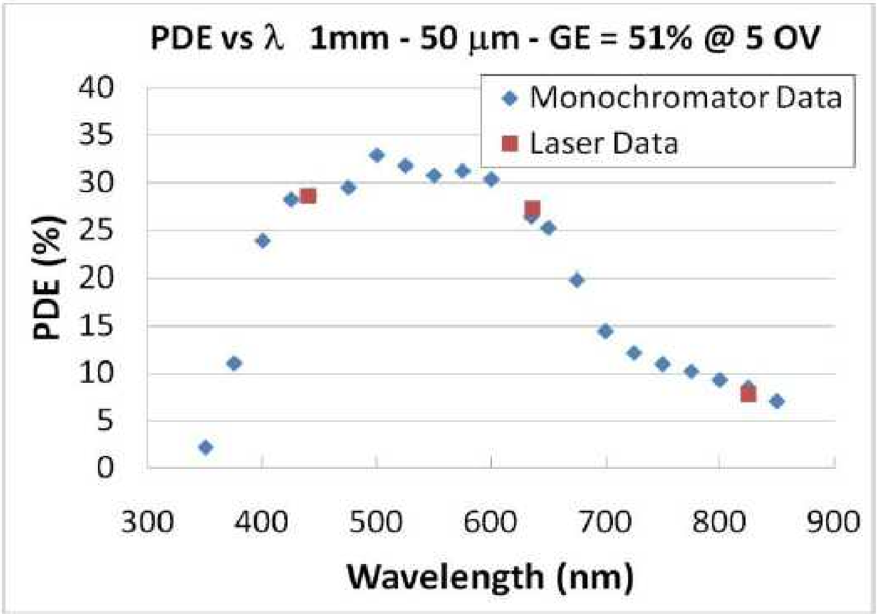
....



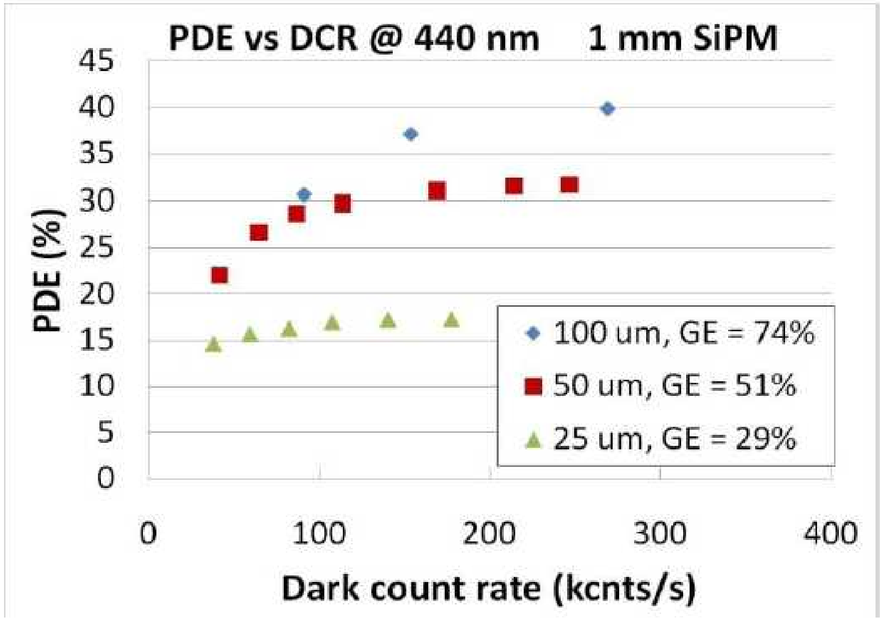
Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, MPPC, SPM, DAPD, PPD, SiMPI , dSiPM…

# Excelitas tecnologies

## 1st Generation SiPM, 2011 – highlights (3)



Broad responsivity spectrum

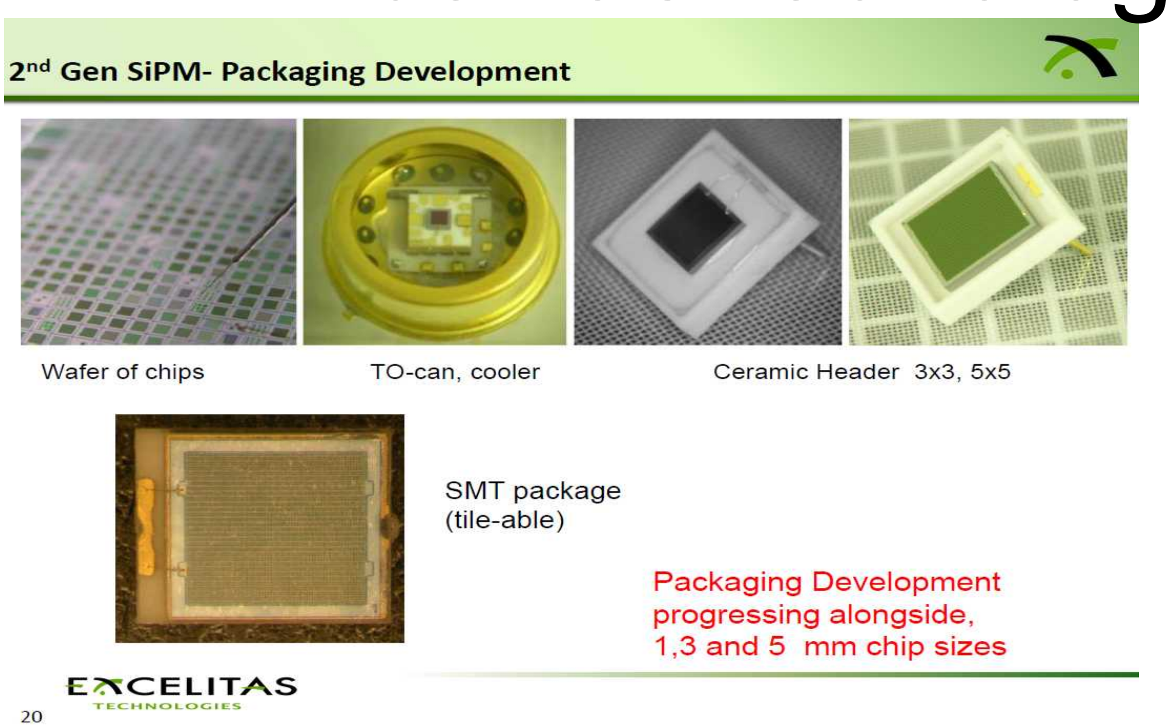


Low dark count even when PDE saturates

P. Bérard et al. "Characterization study of a new UV-SiPM with low dark count rate", *2011 NDIP Conference Record, NIMA*

A Barlow, J Schilz, *"SiPM developments", SiPM Matching Event, CERN, 16-17 Feb 2011*

# Excelitas tecnologies



## 2nd Gen SiPM- Packaging Development

Wafer of chips

TO-can, cooler

Ceramic Header 3x3, 5x5

SMT package
(tile-able)

Packaging Development
progressing alongside,
1,3 and 5 mm chip sizes

EXCELITAS
TECHNOLOGIES

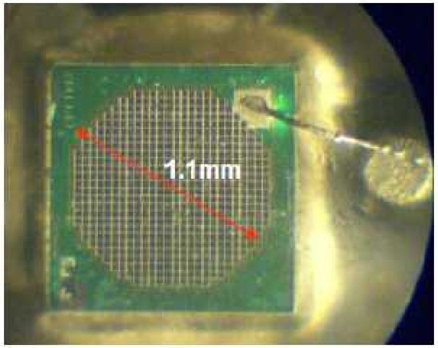
20

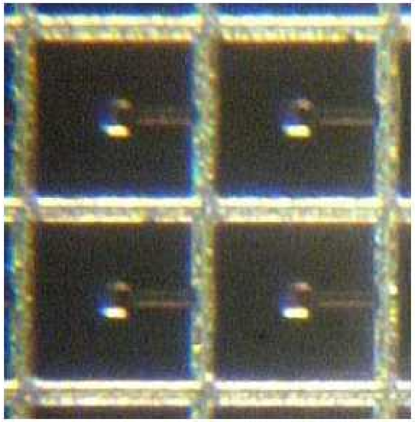
Almost ready for market!

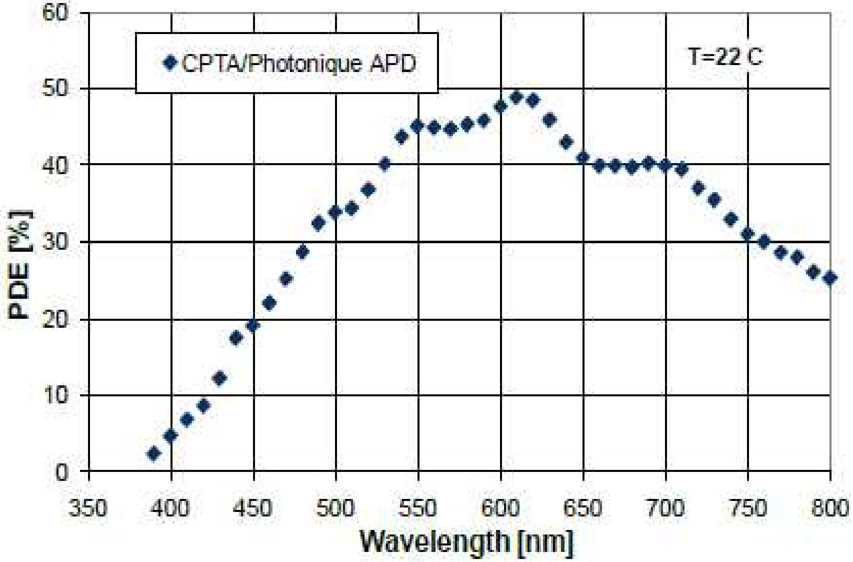
No crosstalk protection yet but is going to implement
Goal – to have the lowest dark rate
Final product in early 2012

***Addressing the needs of molecular imaging and high energy physics communities***

# CPTA(Golovin)/Photonique SSPM



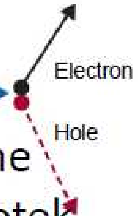




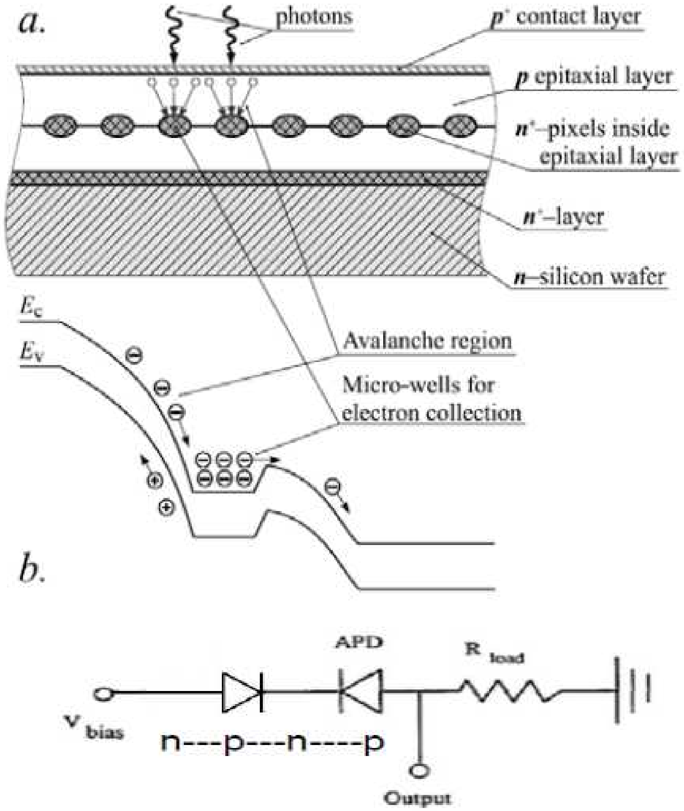
(Y. Musienko, PD-07, Kobe)

SiPMs with 60-80% geometric factor (for 50-100 μm cell pitch) were produced
High sensitivity in green-red region
With optical crosstalk suppression

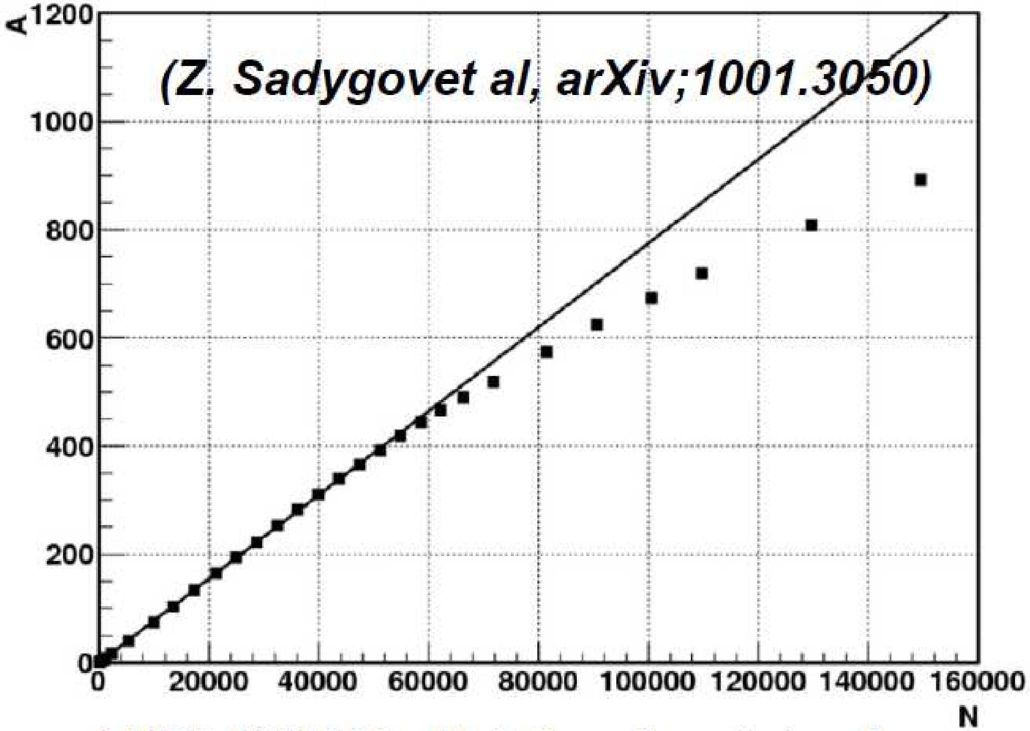
# High dynamic range → MAPD from Zecotek



Micro-well structure at 2-3µm depth with multiplication regions located in front of the wells offer 10000–40000cells/mm$^2$ and up to 3x3mm$^2$ in area were produced by Zecotek



No quench resistors instead specially designed potential barriers are used to quench the avalanches.

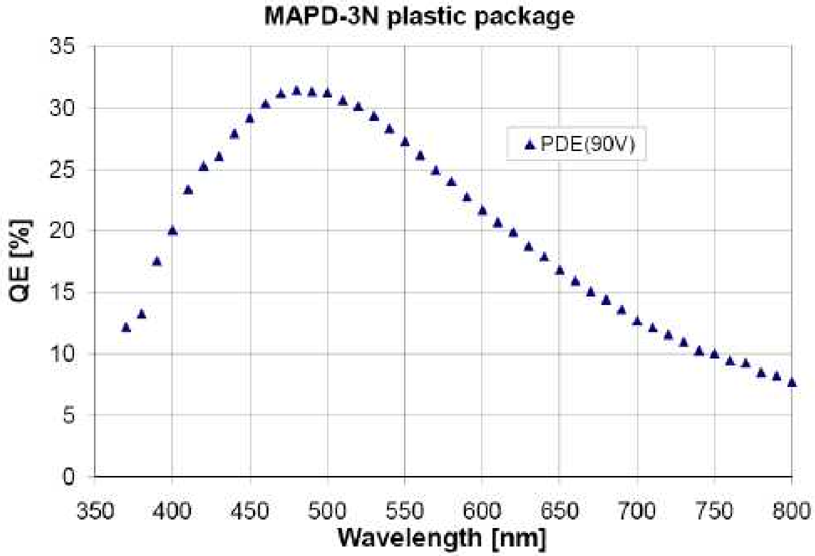


***(Z. Sadygovet al, arXiv;1001.3050)***

MAPD (135000cells,3x3mm$^2$area) signal amplitude A(in relative units) as function of a number of incident photons N

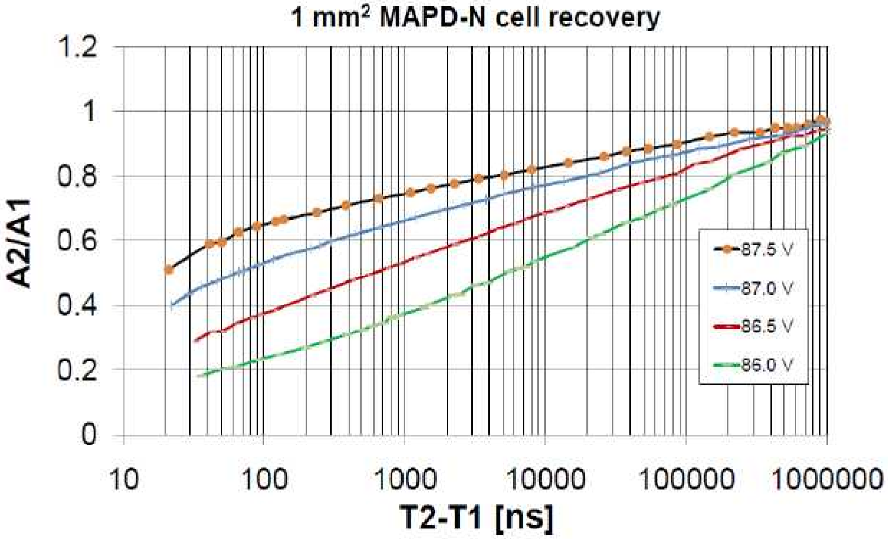
# Zecotek

PDE vs. wavelength



MAPD cell recovery is not exponential

MAPD (3N type) cell recovery (measured using 2 LED technique)

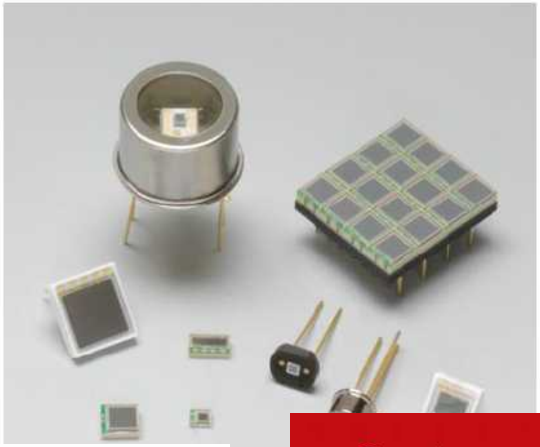


*CERN, SiPM workshop, 16.02.2011*

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

# Multi-Pixel Photon Counter (MPPC)

MPPC® is the solid state photon counter having Multi pixelated Geiger-mode APDs with self-quenching resistance.



ht © Ham

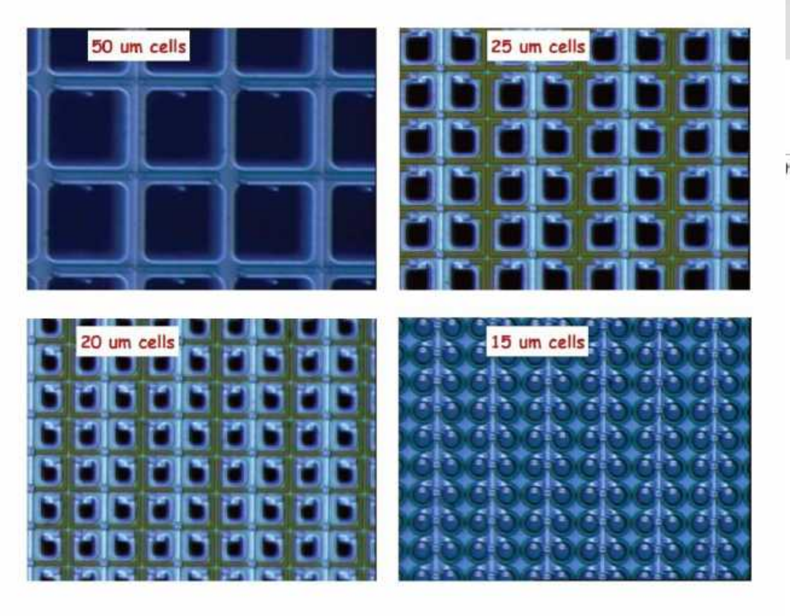
Most widely used SiPM like devices

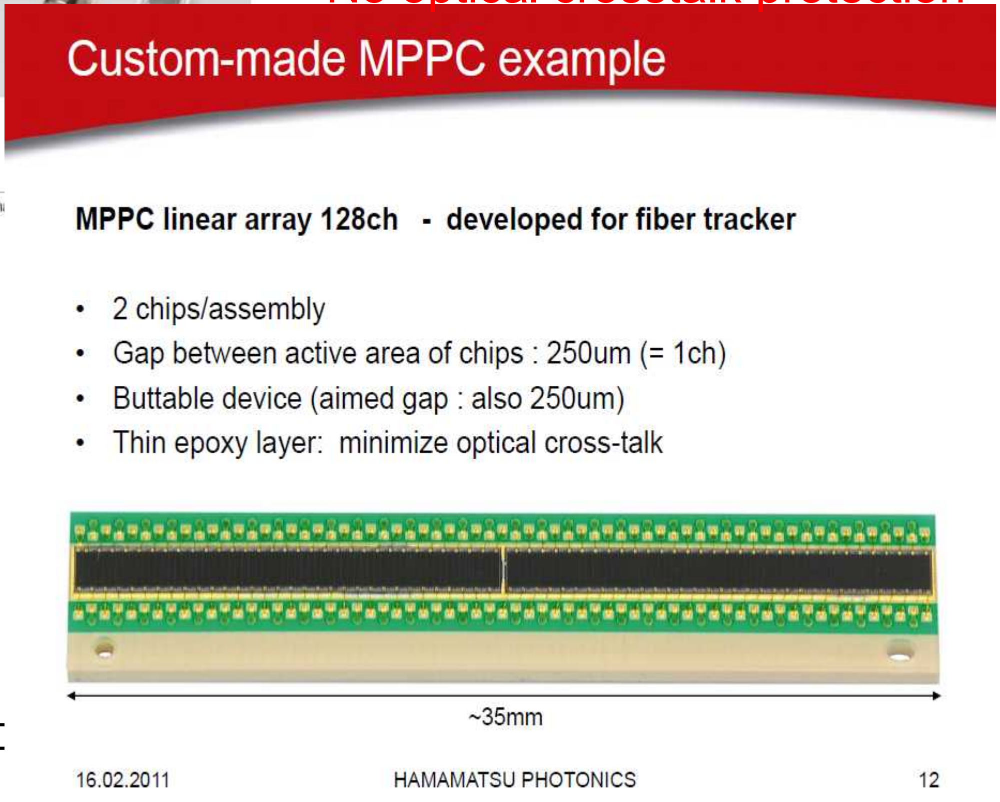
Large dynamic range

Multichannels for tracker

A lot of different modifications but

No optical crosstalk protection





## Custom-made MPPC example

**MPPC linear array 128ch - developed for fiber tracker**

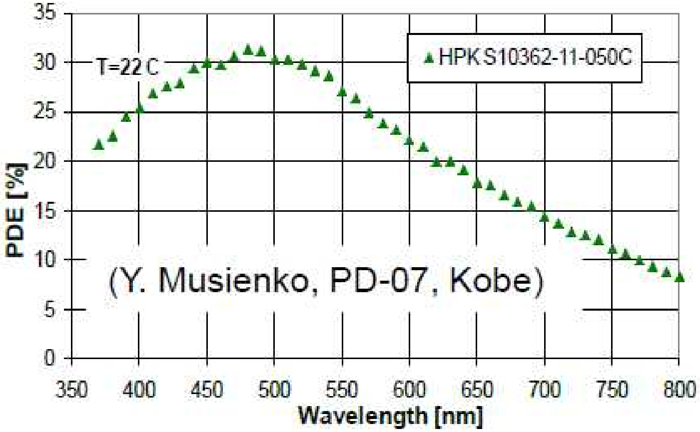
- 2 chips/assembly
- Gap between active area of chips : 250um (= 1ch)
- Buttable device (aimed gap : also 250um)
- Thin epoxy layer: minimize optical cross-talk

~35mm

16.02.2011 HAMAMATSU PHOTONICS 12

# MPPC's PDE without crosstalk and afterpulsing

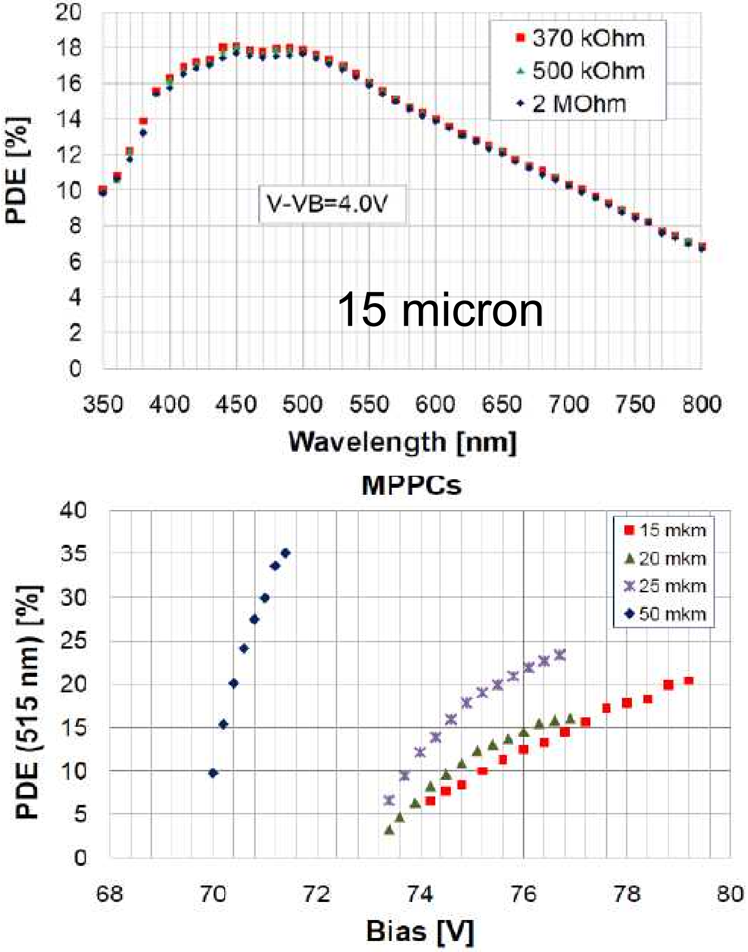
Hamamatsu MPPC (50 µm cell pitch)



(Y. Musienko, PD-07, Kobe)

PDE is lower then specified by Hamamatsu

Y. Musienko *NDIP-2011, Lyon,8.07.2011*



15 micron

# High granularity EM Calorimeter for ILC

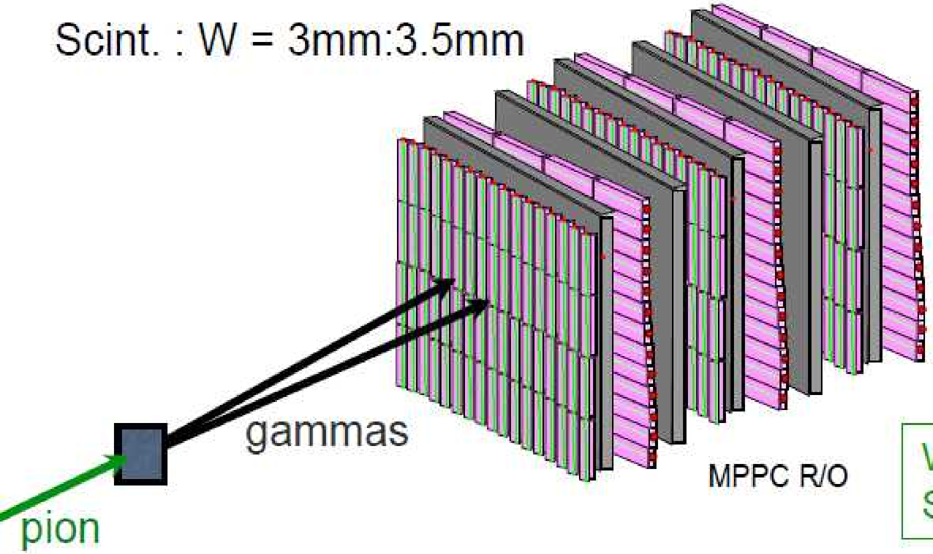
Electron

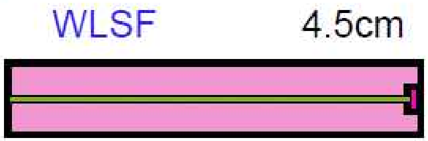
Hole

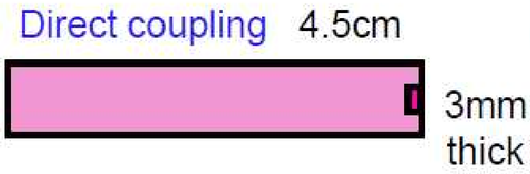
from T. Takeshita, Shinshu Uni., Japan

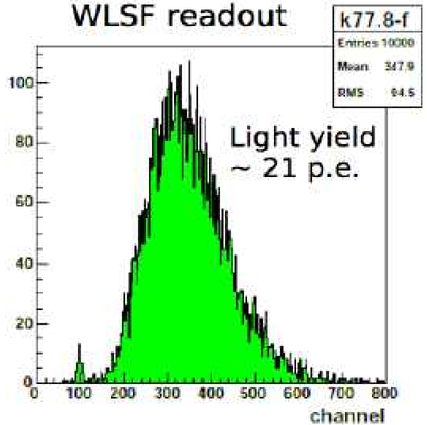
## Scintillator – Tungsten sandwich structure

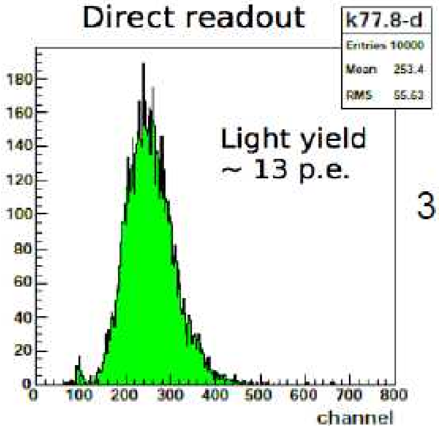
Scint. : W = 3mm:3.5mm





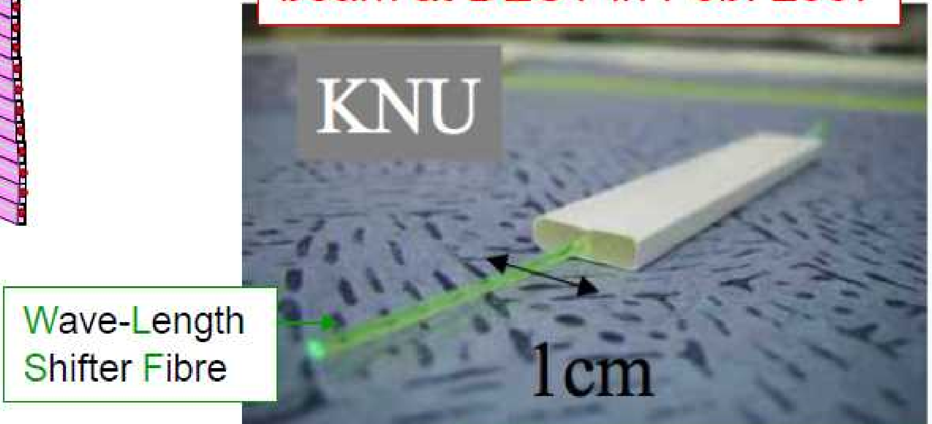


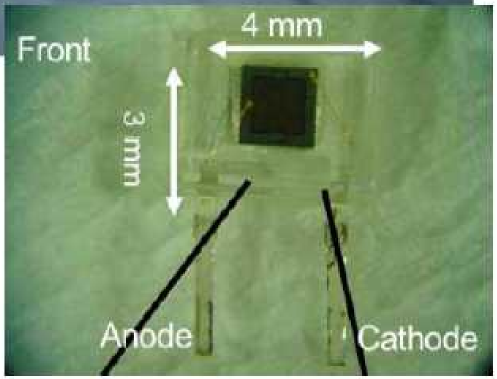




3M R.M.F.

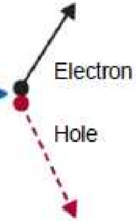
Fist prototype ready for test beam at DESY in Feb. 2007



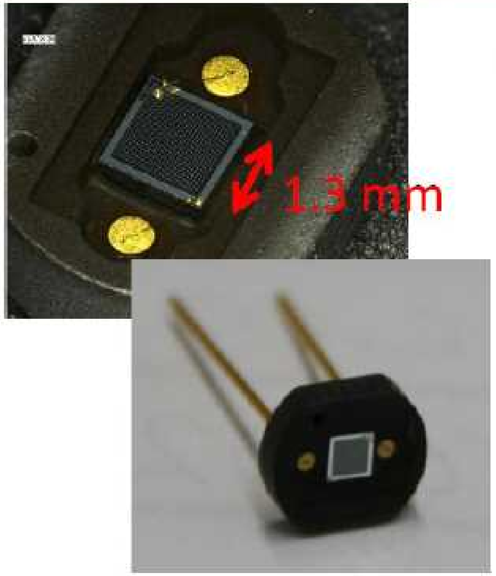


Multi-Pixel Photon Counter from Hamamatsu

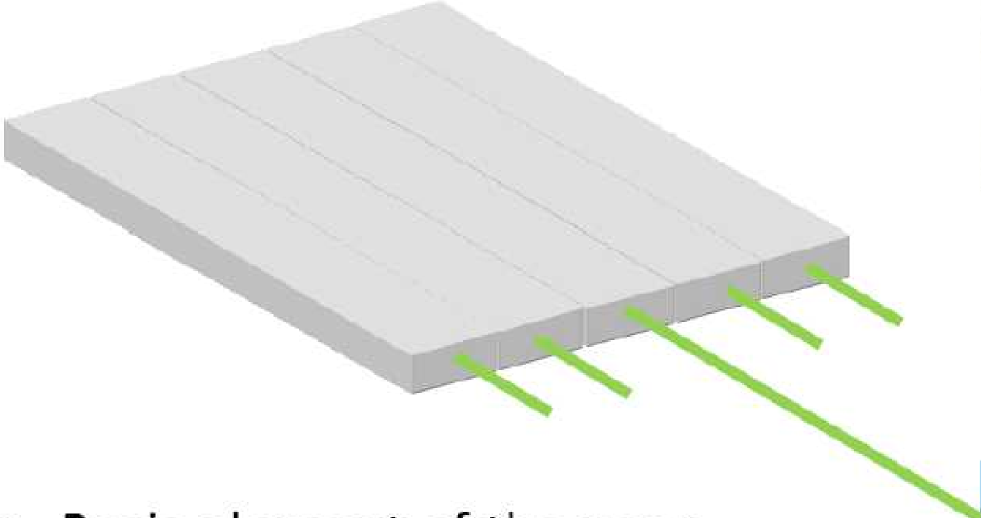
# The design solution



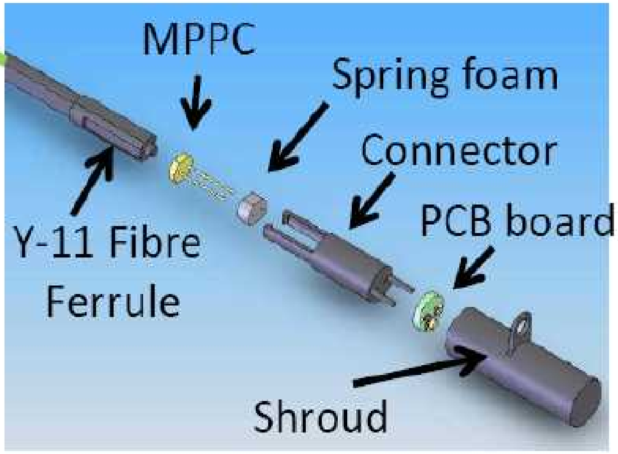
## T2K experiment



MPPC



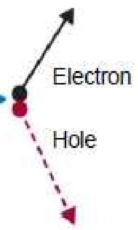
- Basic element of the near detector scintillator subsystem (INGRID, P0D, FGD, ECAL, SMRD)
  - Extruded scintillator bar with embedded Y-11 fibre read out by individual MPPC in coupler
  - 56000 channels in total



Connectors for P0D/ECAL/SMRD

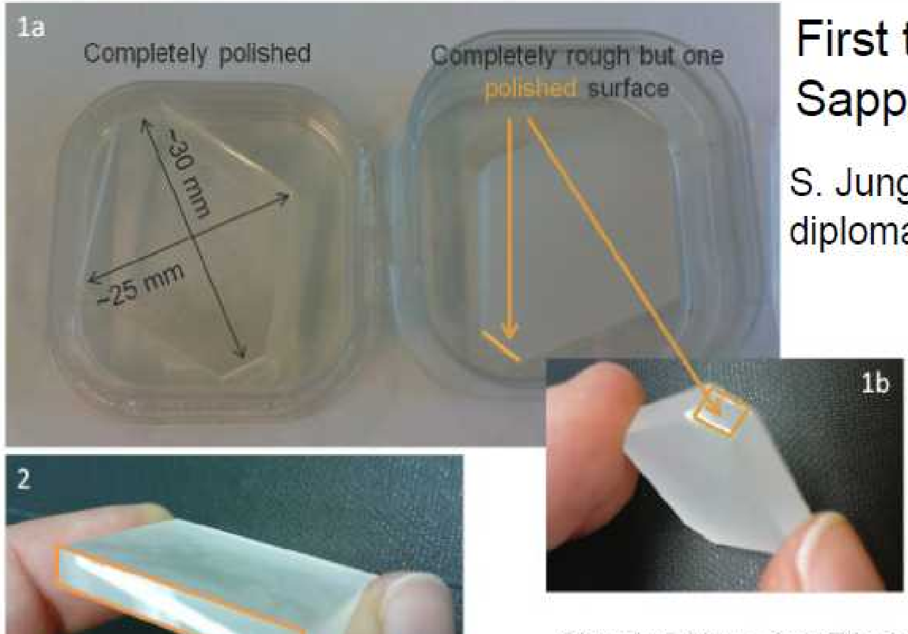
18

# Cherenkov light r/o

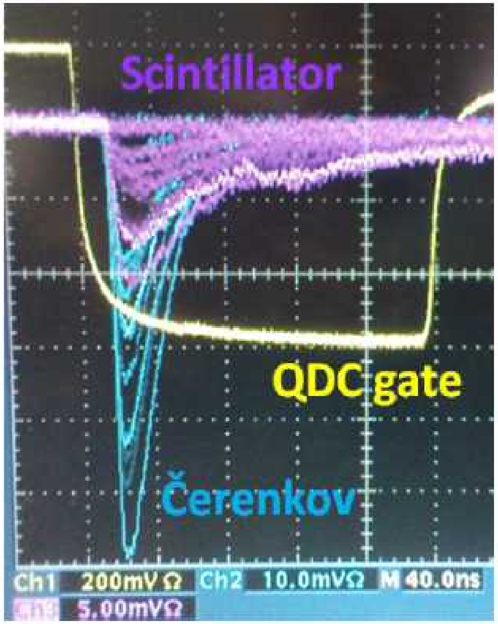


First test of Cherenkov light detection from Sapphire and lead glass tiles

S. Jungmann,
diploma thesis, Heidelberg

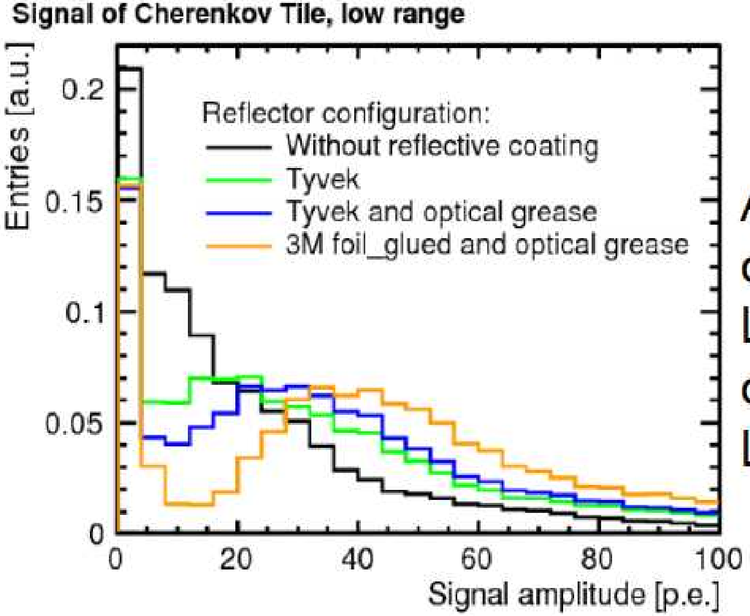


Tested at DESY TB with 3 GeV electrons



Coupled to 3x3 mm$^2$ MPPC, 50um pixel

Possible application in Dual readout calorimetry (CLIC?)



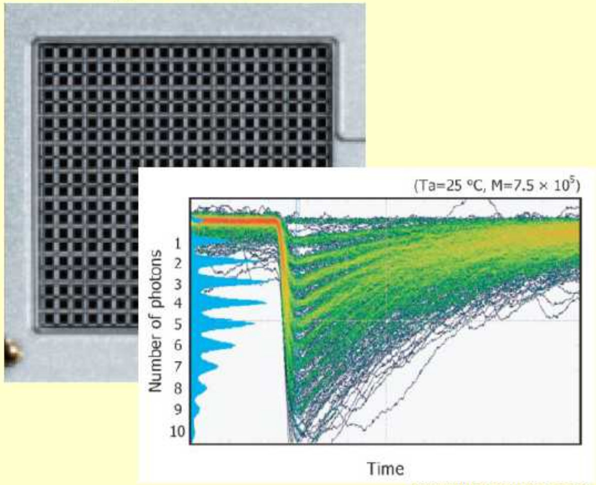
After optimization of coating and coupling
LY sufficient for calorimeter application
LY uniformity under study

# Philips

**PHILIPS**

## Digital SiPM – New Type of Silicon Photomultiplier

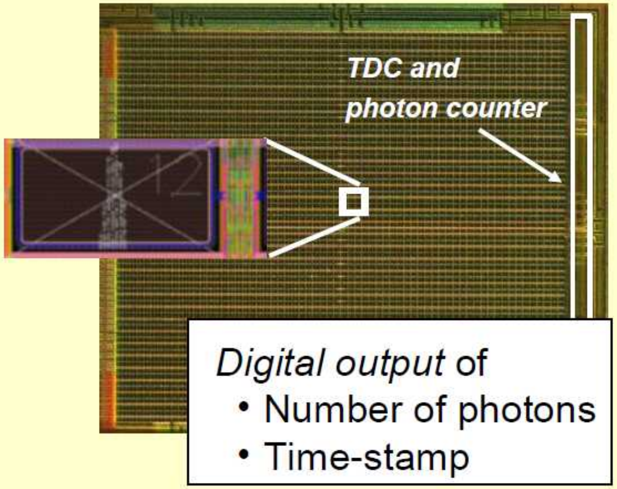
### Analog SiPM



www.hamamatsu.com

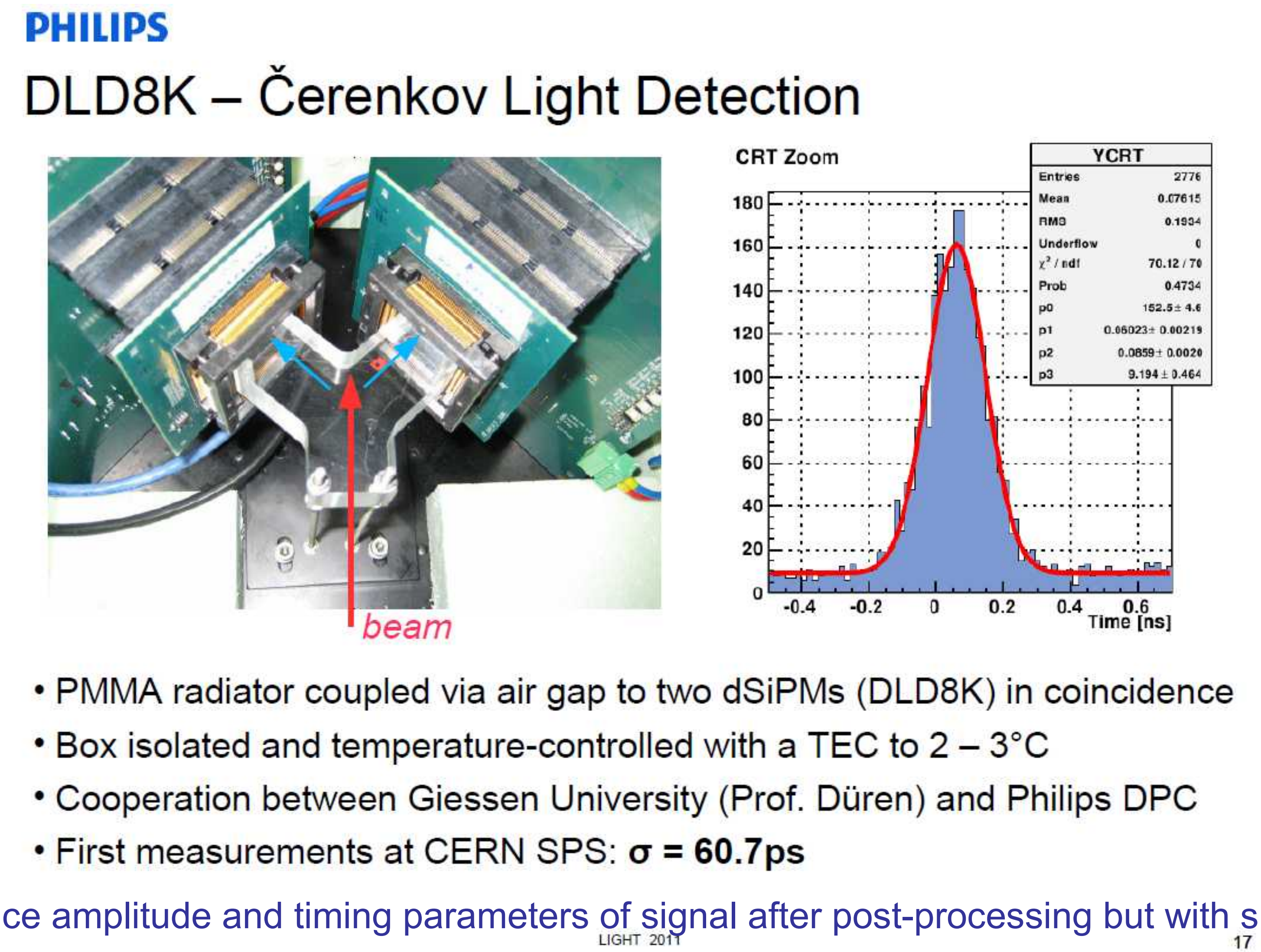
- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

### Digital SiPM



*Digital output of*
- Number of photons
- Time-stamp

- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output



PHILIPS

# DLD8K – Čerenkov Light Detection

- PMMA radiator coupled via air gap to two dSiPMs (DLD8K) in coincidence
- Box isolated and temperature-controlled with a TEC to 2 – 3°C
- Cooperation between Giessen University (Prof. Düren) and Philips DPC
- First measurements at CERN SPS: **σ = 60.7ps**

LIGHT 2011 17

Nice amplitude and timing parameters of signal after post-processing but with slow readout

Radiation hardness?

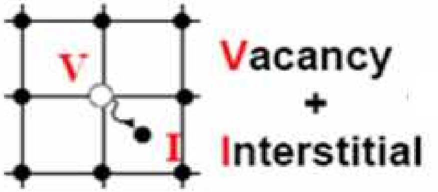
# Radiation Damage in Silicon

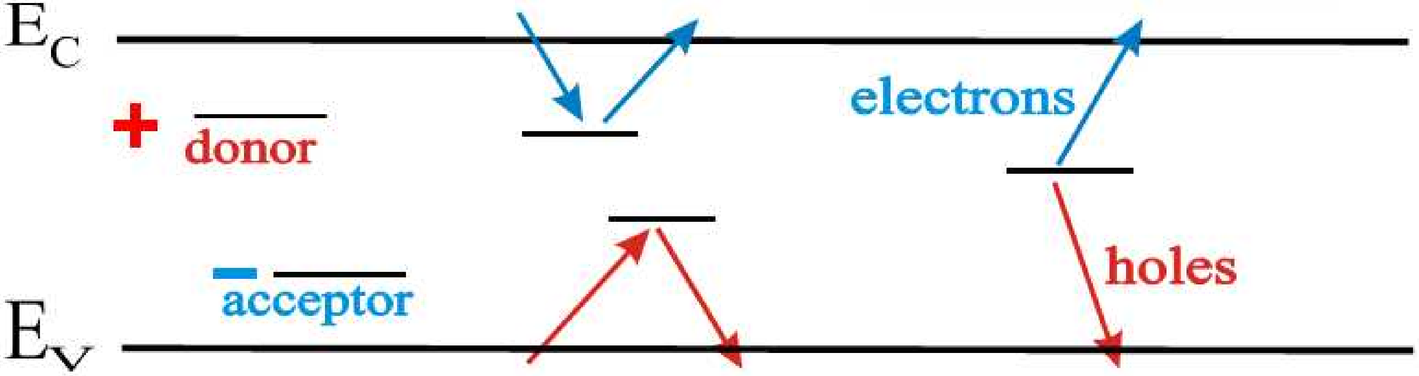
I. **Surface Damage** due to **Ionizing Energy Loss (IEL)**

II. **Crystal (Bulk) damage** due to **Non-Ionizing Energy Loss (NIEL)**

- defects in the crystal
- point defects and “cluster” defects

→ energy levels in the band gap filled

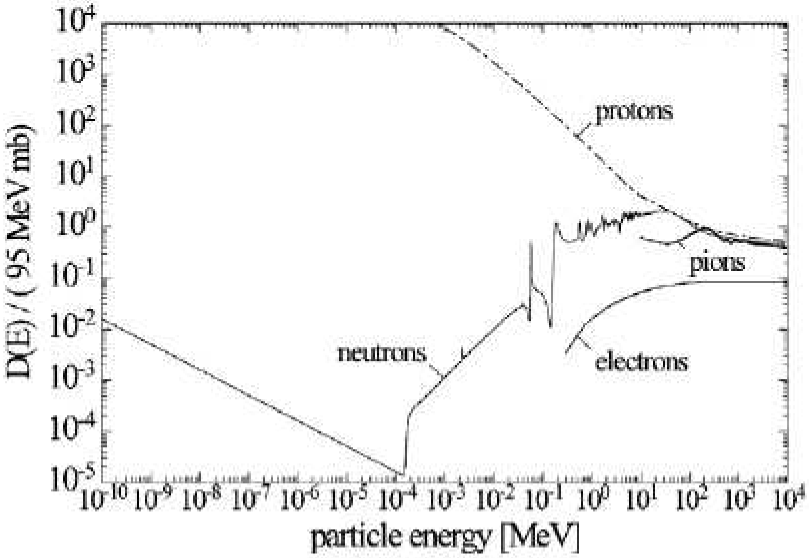




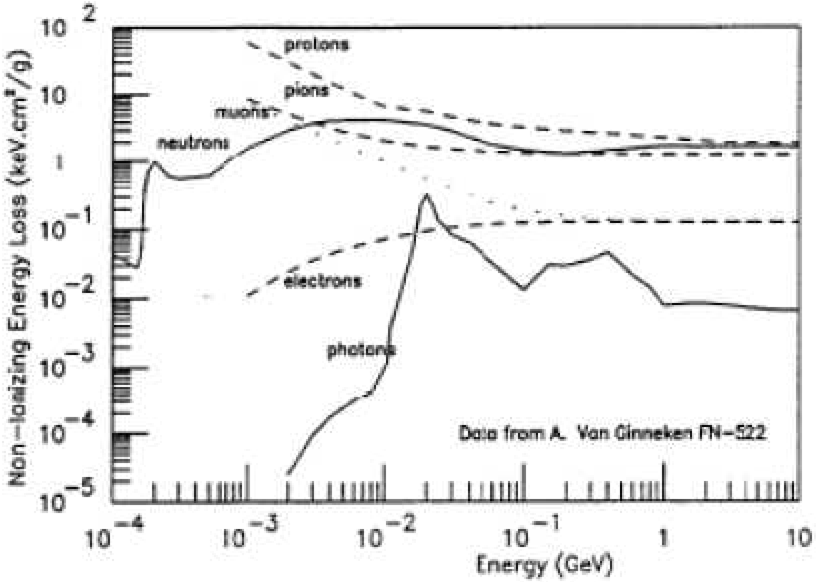
| charged defects | deep traps (e and h), recombination centers | deep traps, generation centers |
|---|---|---|
| ⇒ $N_{eff}$ , $V_{dep}$ | ⇒ Charge Collection Efficiency | ⇒ Leakage current |

# Bulk damage and NIEL function

Bulk damage scales linearly with the amount of Non Ionizing Energy Loss (NIEL hypothesis), which is very dependent on the particle type and its energy



A. Vasilescu, Fluence normalization based on the NIEL scaling hypothesis, 3rd ROSE Workshop on Radiation Hardening of Silicon Detectors, DESY Hamburg 12–14 February 1998, DESY-PROCEEDINGS-1998-02.



A. Van Ginneken, Fermilab Note, FN-522 (1989).

**NIEL(1 MeV gammas) ~ $10^{-5}$ * NIEL(1 MeV neutrons)**

# Bulk damage effects

*Increase of the dark current generated in the silicon bulk*

$$I = \alpha \Phi_{\mathrm{eq}} V$$

***$\Phi_{eq}$ – 1 MeV neutron equivalent total flux***

***V – silicon active volume***

***$\alpha$ – dark current damage constant (~4*$10^{-17}$ A/cm for 1 MeV neutrons after 80 min annealing at 60 C or ~$10^{-16}$ A/cm few day annealing at room temperature)***

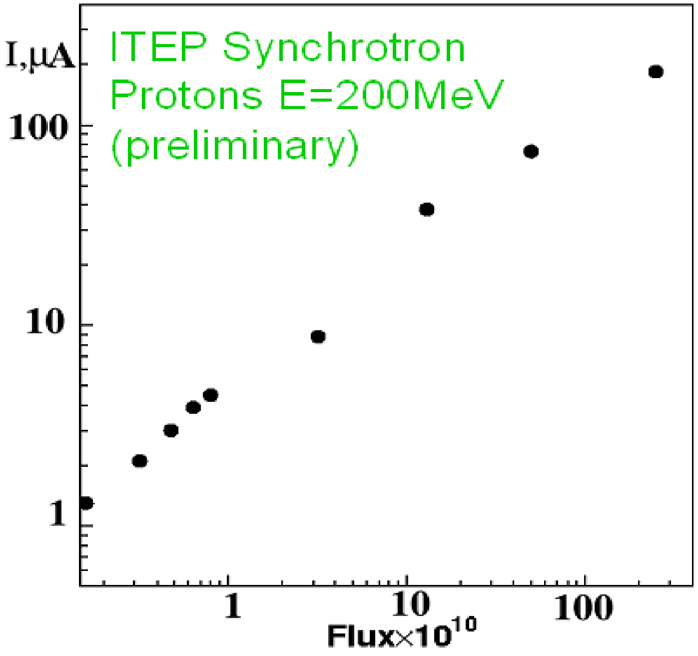
*Changes in the effective doping concentration (creation of acceptor-like states) a few weeks after irradiation:*

$$\Delta N = N_0(1 - e^{-c\Phi}) + b\Phi$$

where $N_0 = 3.36(\pm 0.03) \times 10^{11}\ \mathrm{cm}^{-3}$, $c = 3.58 (\pm 0.2) \times 10^{-13}\ \mathrm{cm}^2$, $b = 0.0171(\pm 0.0001)\ \mathrm{cm}^{-1}$, and $\Phi$ is the total neutron fluence in neutrons/cm$^2$.[5]

HERA-B Design Report, DESY–PRC 95/01, 1995.

# Radiation damage measurements



MEPhI/PULSAR SiPMs

**Dark current increases linearly with flux Φ as in other Si devices:**

**Δ I=α Φ Veff Gain, where $\alpha=6\times10^{-17}$A /cm**

**Veff ~ 0.004mm³** determined from observed **ΔI**
looks a bit too high
(since it includes SiPM efficiency)
but not completely unreasonable

Since initial SiPM resolution of ~0.15 p.e. is much better than in other Si detectors it suffers sooner:
After **Φ**~$10^{10}$ individual p.e. signals are smeared out

However MIP signal are seen even after **Φ**~$10^{11}$/cm²

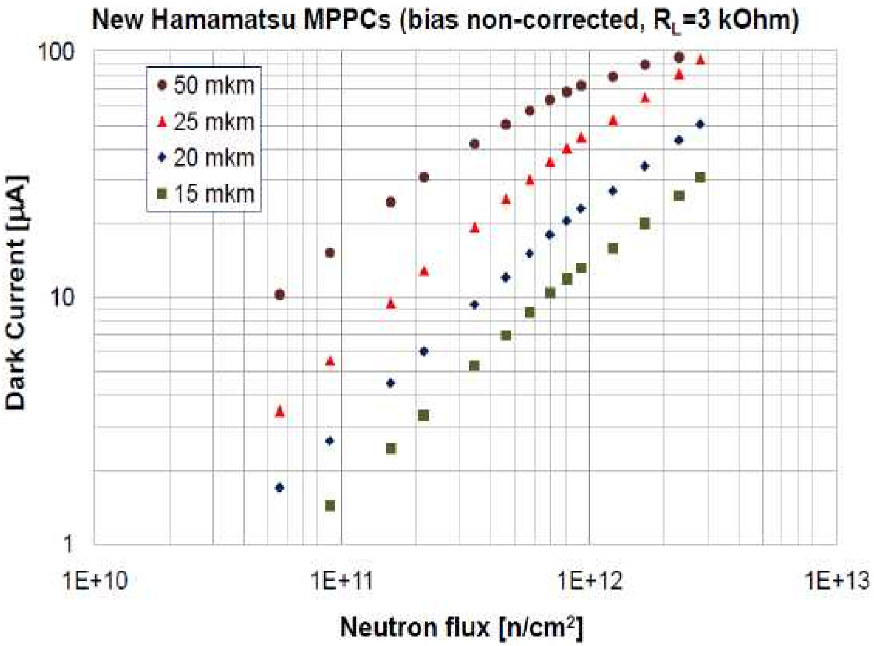
At ILC neutron flux is much smaller than $10^{10}$/cm² except a small area (R<30cm) around beam pipe

**→ Radiation hardness of SiPM is sufficient for HCAL**

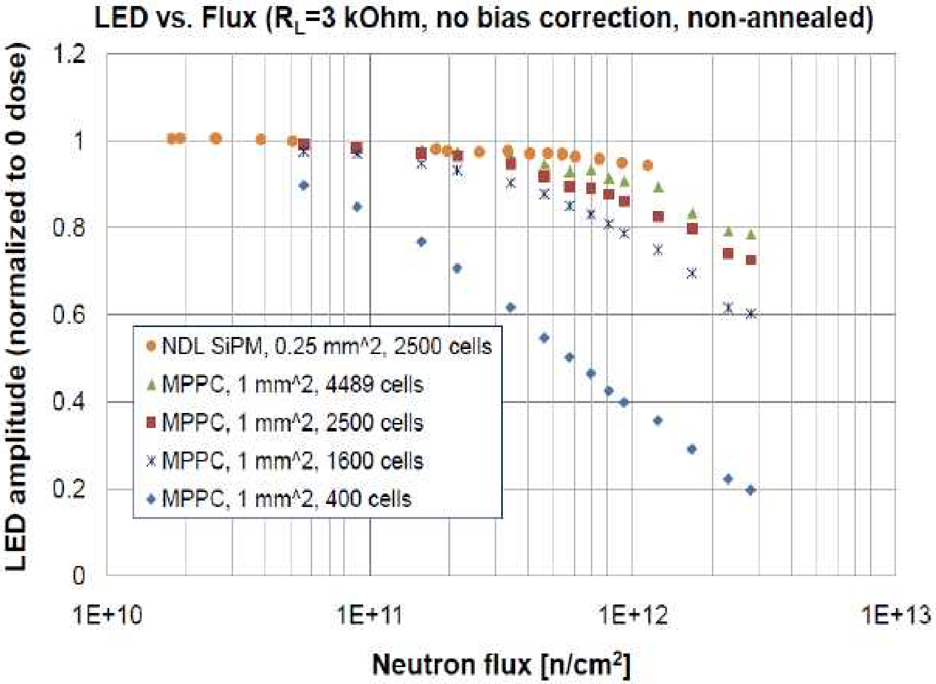
**Vienna Conference on Instrumentation 19.02.2007**
**"A scintillator tile hadron calorimeter prototype with a novel SiPM readout for ILC"**
**M.Danilov, ITEP, Moscow Representing the CALICE Collaboration**

# Neutron irradiation tests

We performed SiPMs' radiation hardness tests using neutrons (E~1 MeV) at CERN IRRAD-6 facility (see NDIP-2011 talk A. Heering et all. " Radiation damage studies of silicon photomultipliers at SLHC at CERN PS")



New Hamamatsu MPPCs (bias non-corrected, $R_L$=3 kOhm)



LED vs. Flux ($R_L$=3 kOhm, no bias correction, non-annealed)

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

# SiPM’s radiation hardness
# 212 MeV proton beam at Massachusetts General Hospital.

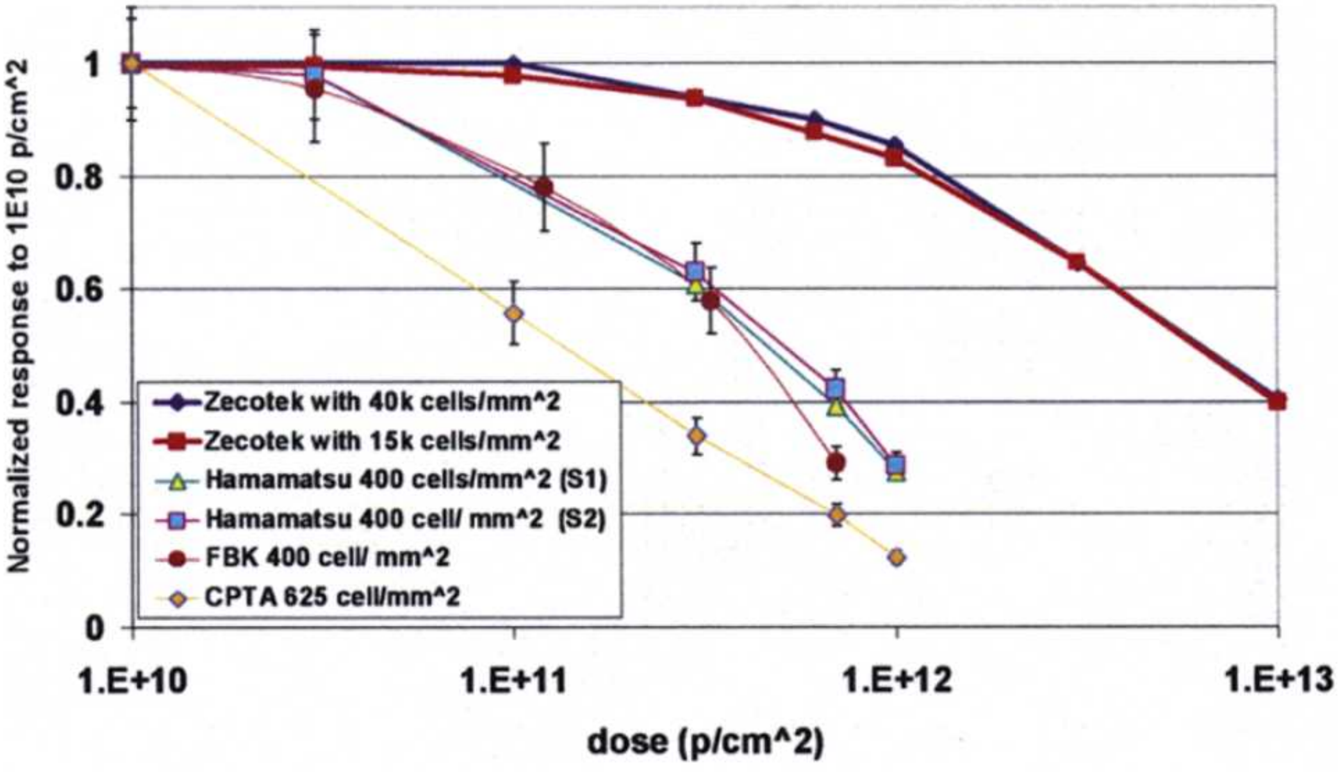


Fig.11. Response vs. radiation fluence for different samples and manufacturers (gain was corrected for voltage drop over the series resistor).

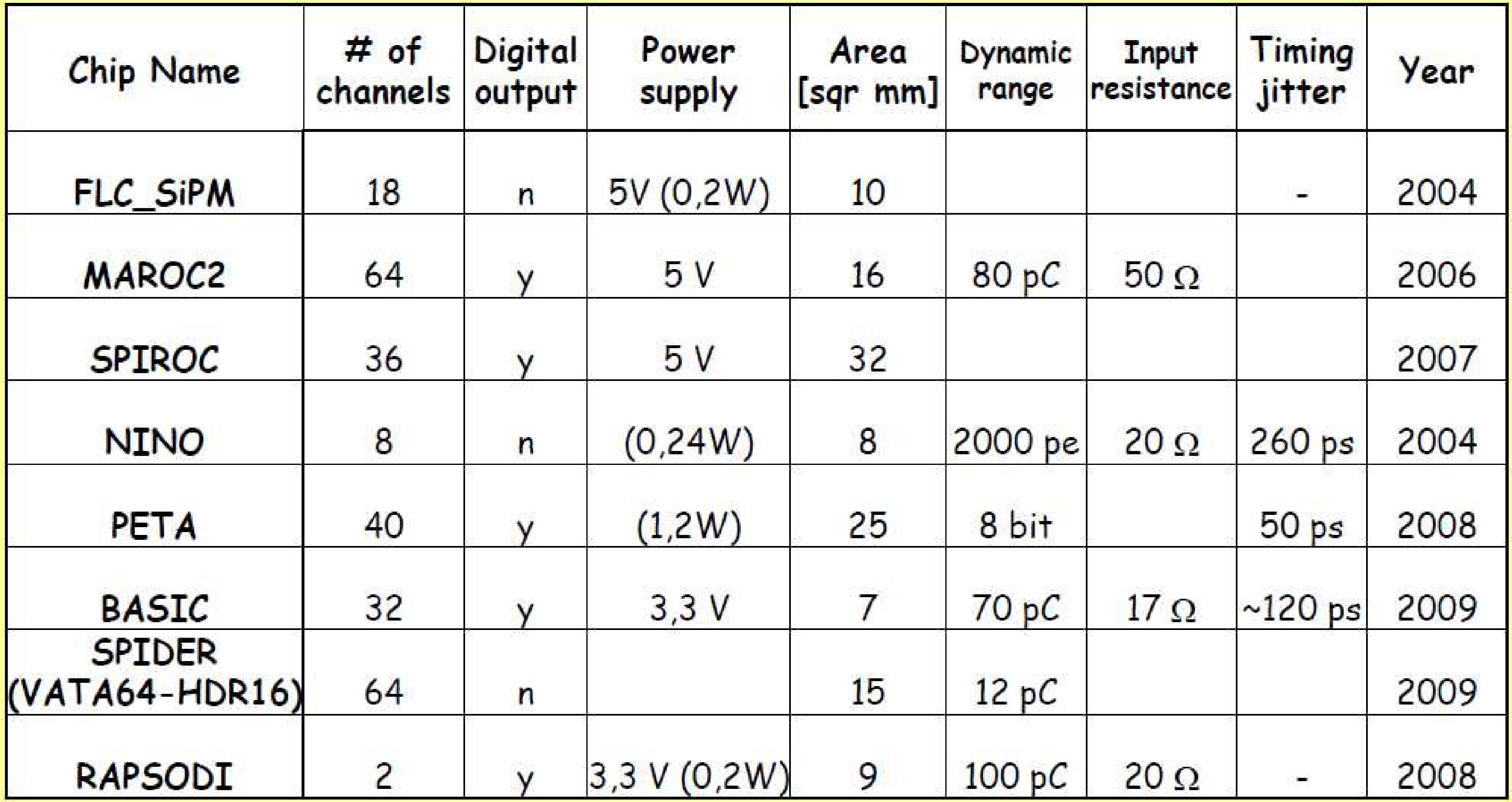
A. Heering et al., Radiation damage studies on SiPMs for calorimetry at the super LHC, IEEE Nuclear Science Symposium Conference Record, vol. 2, 2008.

# Conclusions

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

http://indico.cern.ch/contributionListDisplay.py?confId=117424

# Conclusions



| Chip Name | # of channels | Digital output | Power supply | Area [sqr mm] | Dynamic range | Input resistance | Timing jitter | Year |
|---|---|---|---|---|---|---|---|---|
| FLC_SiPM | 18 | n | 5V (0,2W) | 10 | | | - | 2004 |
| MAROC2 | 64 | y | 5 V | 16 | 80 pC | 50 Ω | | 2006 |
| SPIROC | 36 | y | 5 V | 32 | | | | 2007 |
| NINO | 8 | n | (0,24W) | 8 | 2000 pe | 20 Ω | 260 ps | 2004 |
| PETA | 40 | y | (1,2W) | 25 | 8 bit | | 50 ps | 2008 |
| BASIC | 32 | y | 3,3 V | 7 | 70 pC | 17 Ω | ~120 ps | 2009 |
| SPIDER (VATA64-HDR16) | 64 | n | | 15 | 12 pC | | | 2009 |
| RAPSODI | 2 | y | 3,3 V (0,2W) | 9 | 100 pC | 20 Ω | - | 2008 |

http://indico.cern.ch/contributionListDisplay.py?confId=117424

# Summary

- SiPMs are very promising, fast developing new solid state photodetectors
- Photon detection efficiency at the level of PMT and higher
- A lot of different variations concerned to SiPMs parameters and casings
- SiPMs are commersially available already

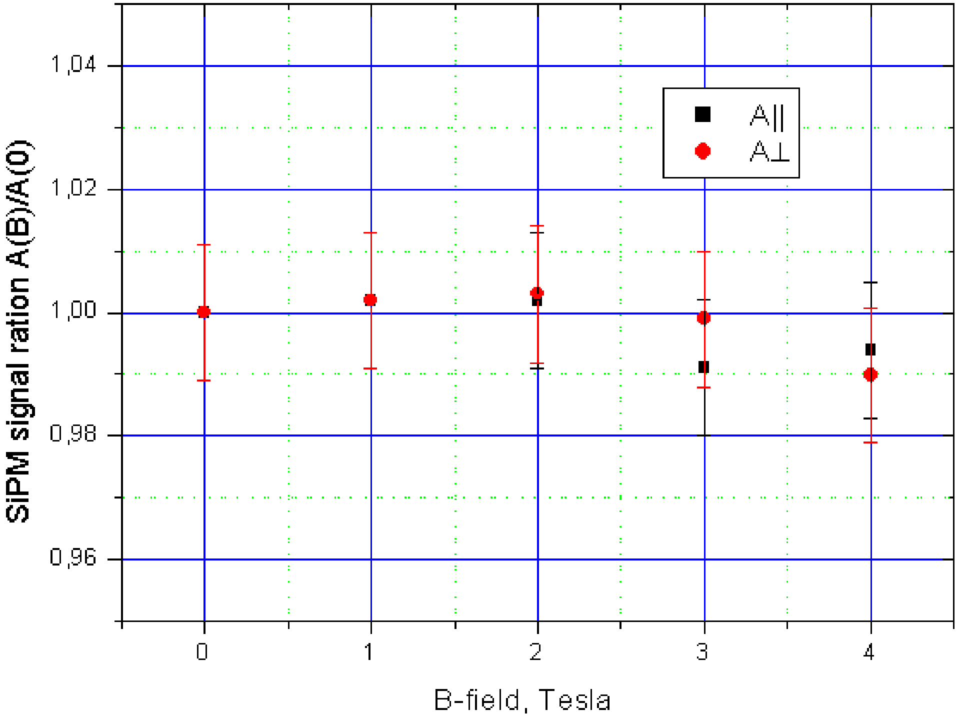
# Backup slides

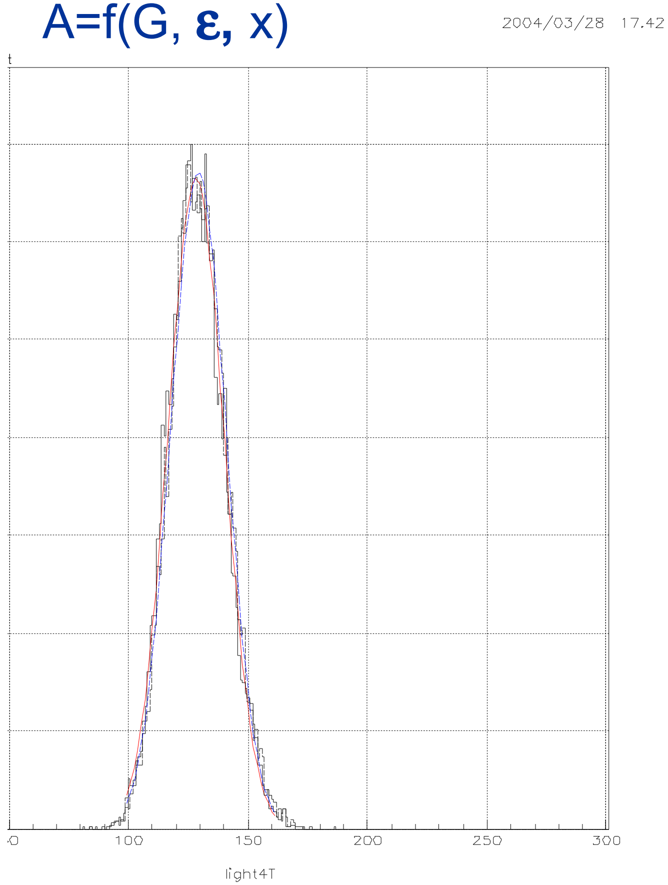
# Comparison of the SiPM characteristics in magnetic field of B=0T and B=4T

# (very prelimenary, DESY March 2004)

LED signal ~150 pixels

A=f(G, **ε,** x)



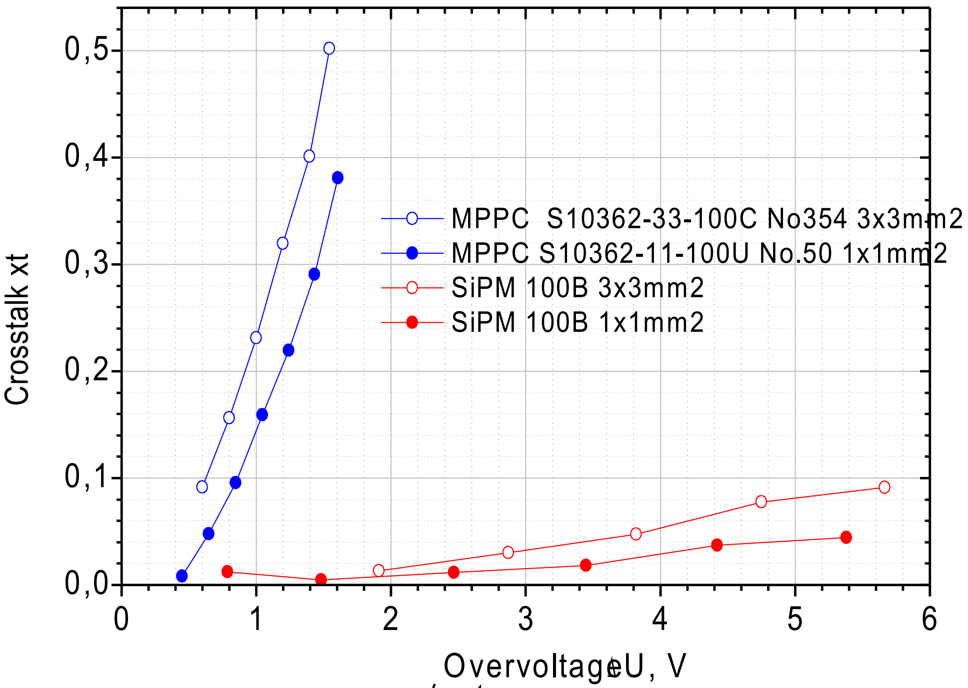


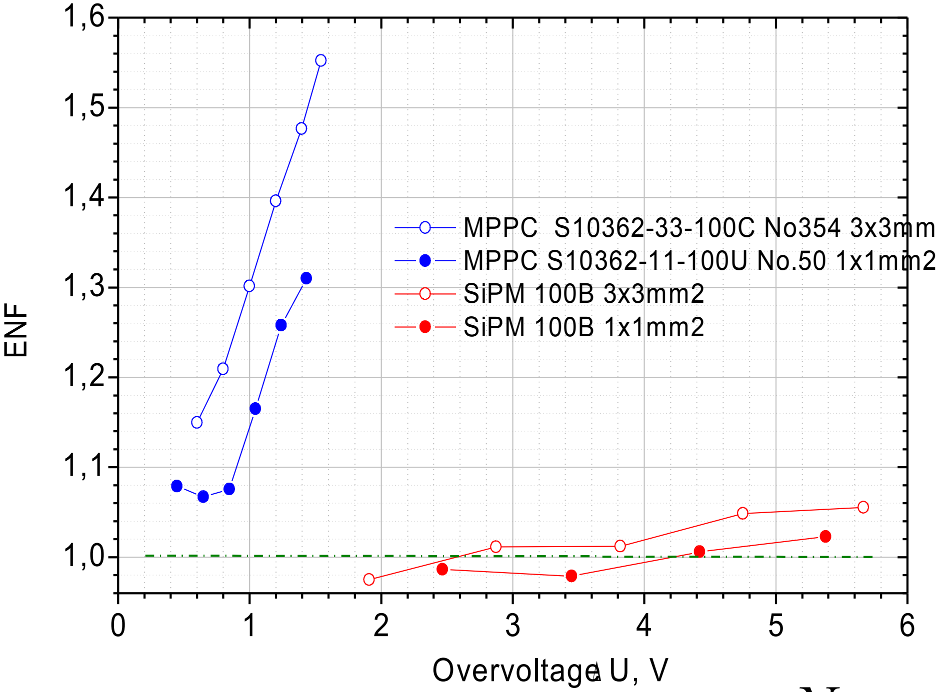
**No Magnetic Field dependence at 1% level**

**(Experimental data accuracy)**

# Crosstalk and Excess noise factor

For light distributed according to Poisson law





$$ENF \equiv \left(\frac{\sigma_{out} / A_{out}}{\sigma_{in} / A_{in}}\right)^2$$

$$ENF = N_0 \cdot \left(\frac{\sigma}{< Mean >}\right)^2_{exper}$$

$$N_{fired\_pixels} = \frac{N_0}{1 - xt}$$

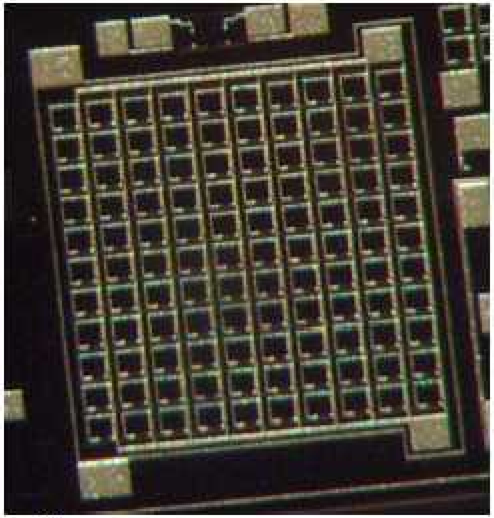
$$N_{fired\_pixels} = \frac{< Mean >}{A_{1e}}$$

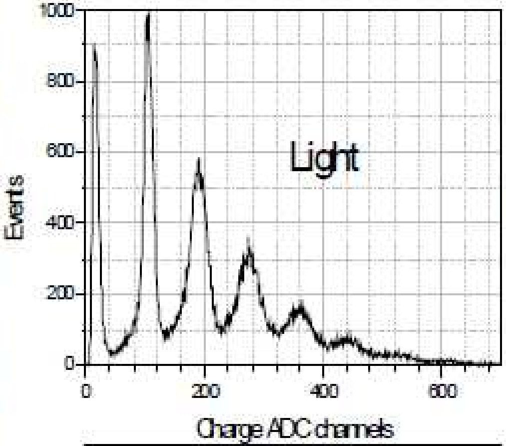
$N_0$ initially fired pixels calculated from “0” probability

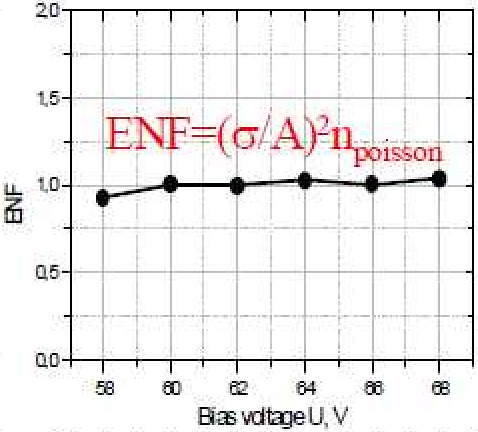
*Xt* crosstalk

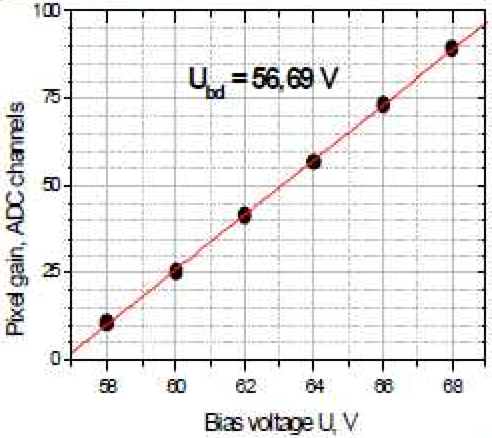
$A_{1e}$ amplitude of single pixel

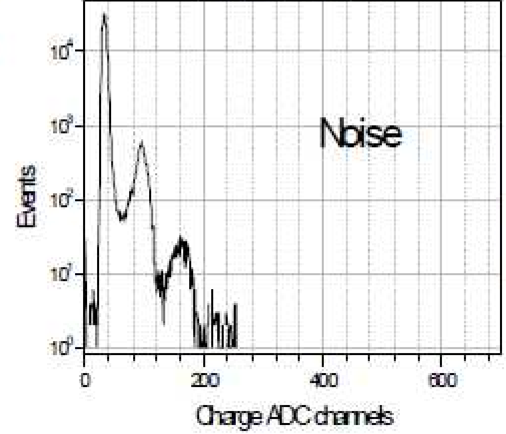
# First step: SiPM 1.4x1.4 mm2 with OC suppression topology

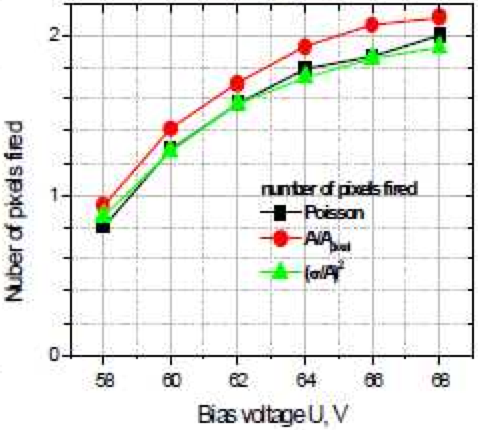










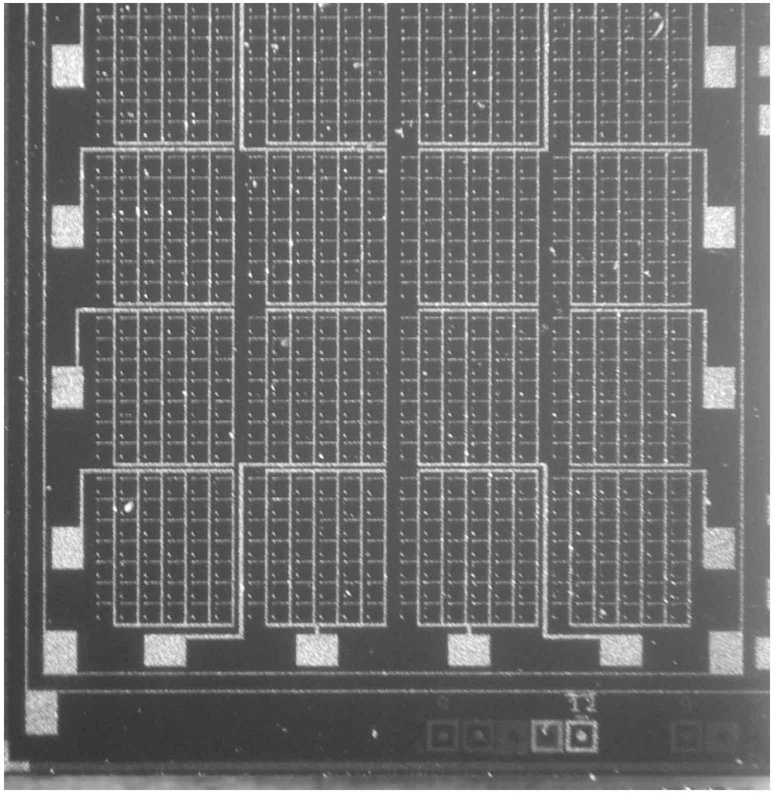


# SiPM matrix

For some applications is very attractive to use monolithic SiPM matrix

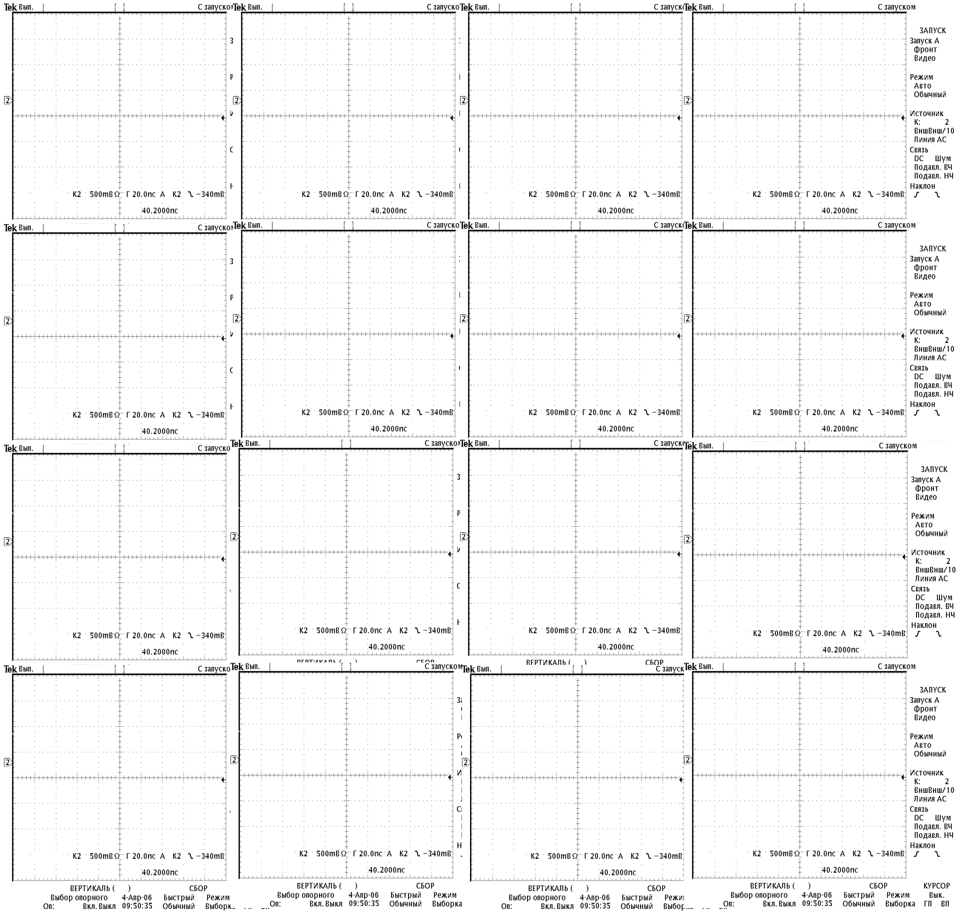
- For decreasing of light losses
- For position sensitivity
- For fast readout

**Common bias voltage U=57.8B**



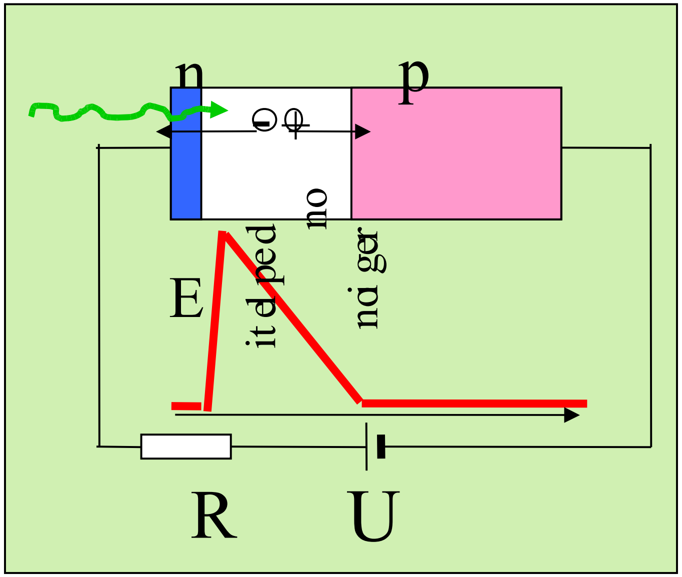
16 SiPMs in matrix

SiPM 0.75x0.75mm$^2$



Signals on scope from LED pulses

# p-n-junction based detectors



**Impact Ionization**

**Avalanche multiplication**

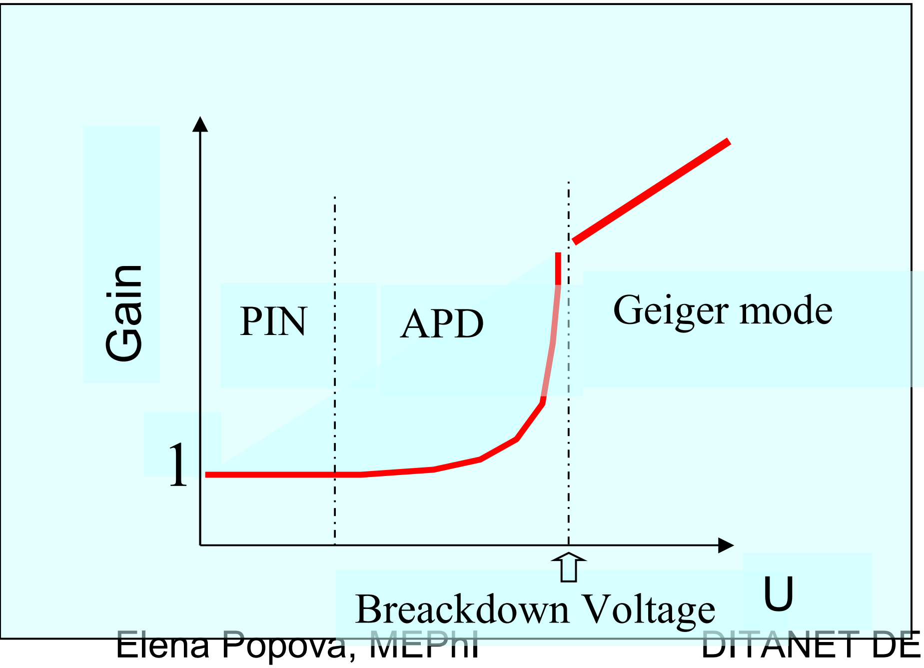
**Geiger discharge**

Geiger mode features

Output signal doesn’t depend from input

Output signal value Q is determined by charge accumulated on pixel capacitance

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



M= Q/e -pixel gain

$M=10^6-10^7$

Discharge duration – of about 1 ns

(selfquenching due to resistor)

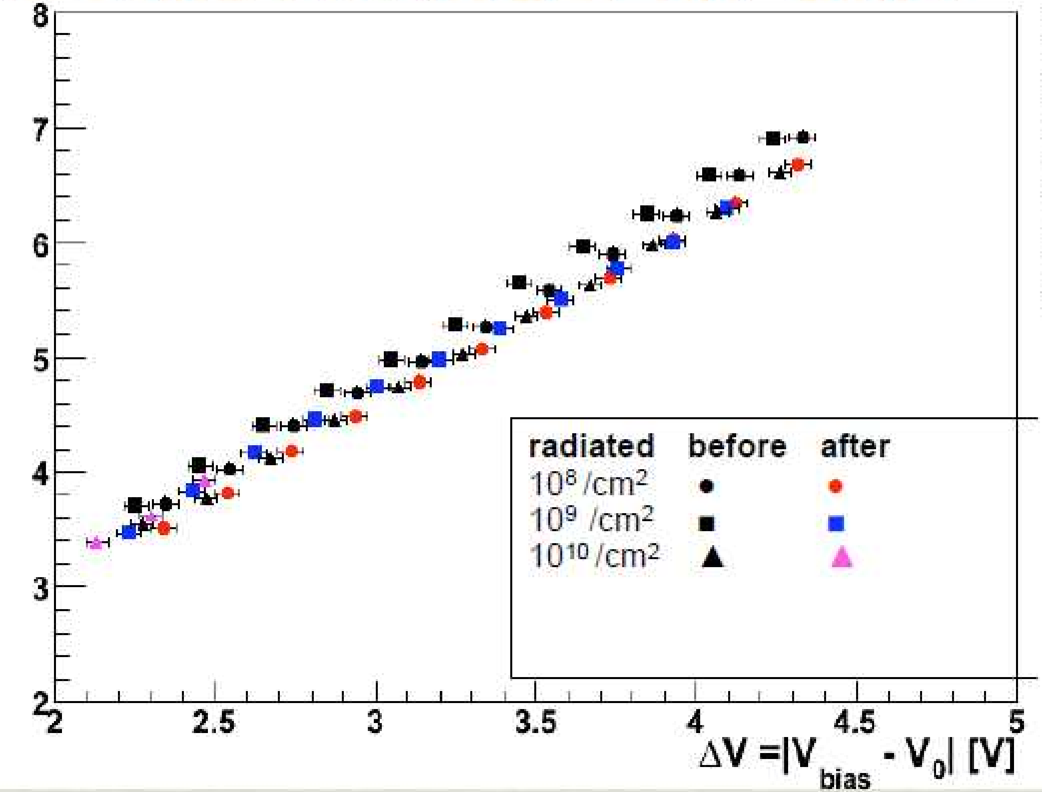
Theoretical and experimental investigations from nineteen sixties

# radiation tolerance of MPPC

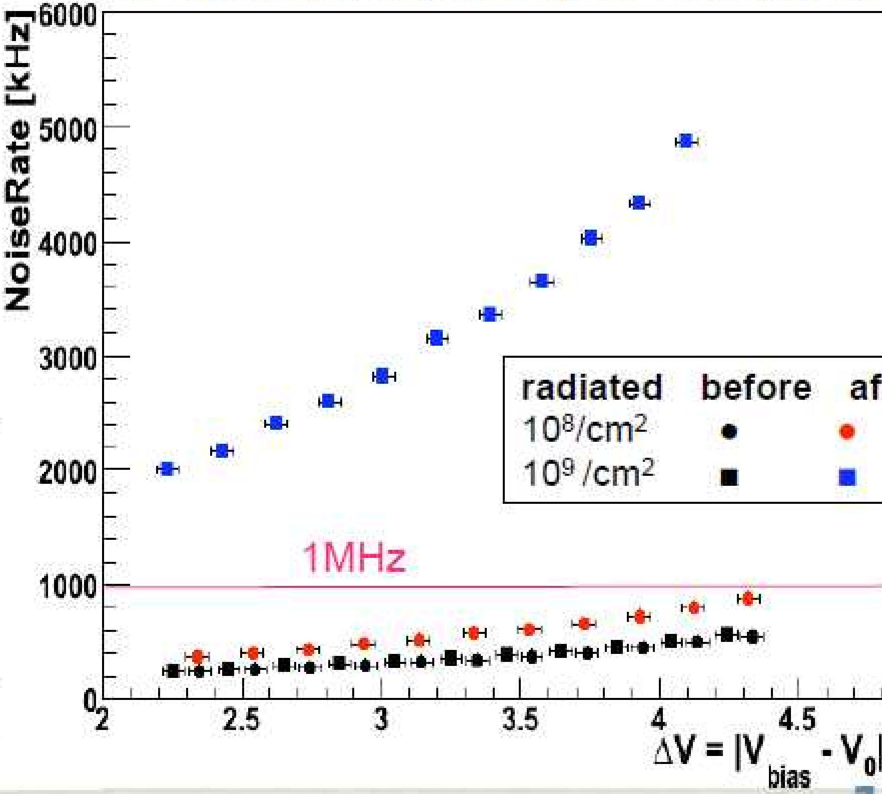
- **neutron** irradiation by reactor

$10^{8-10}$ / CM$^2$

NO SIG. CHANGE FOR GAIN



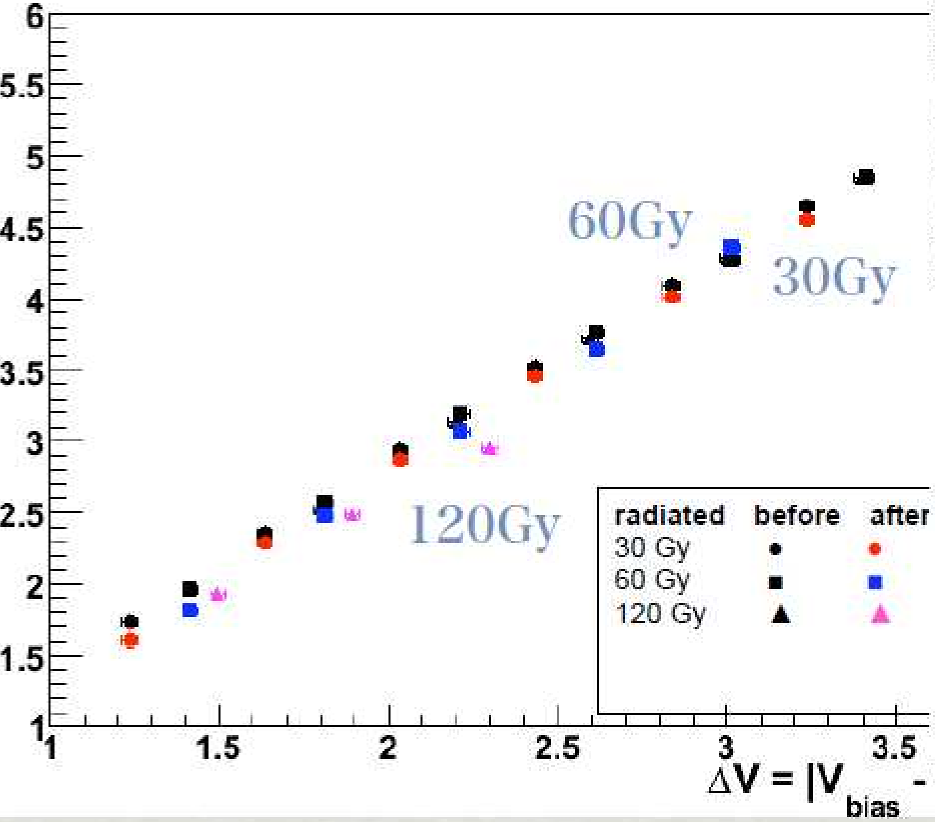
NOISE RATE INCREASE



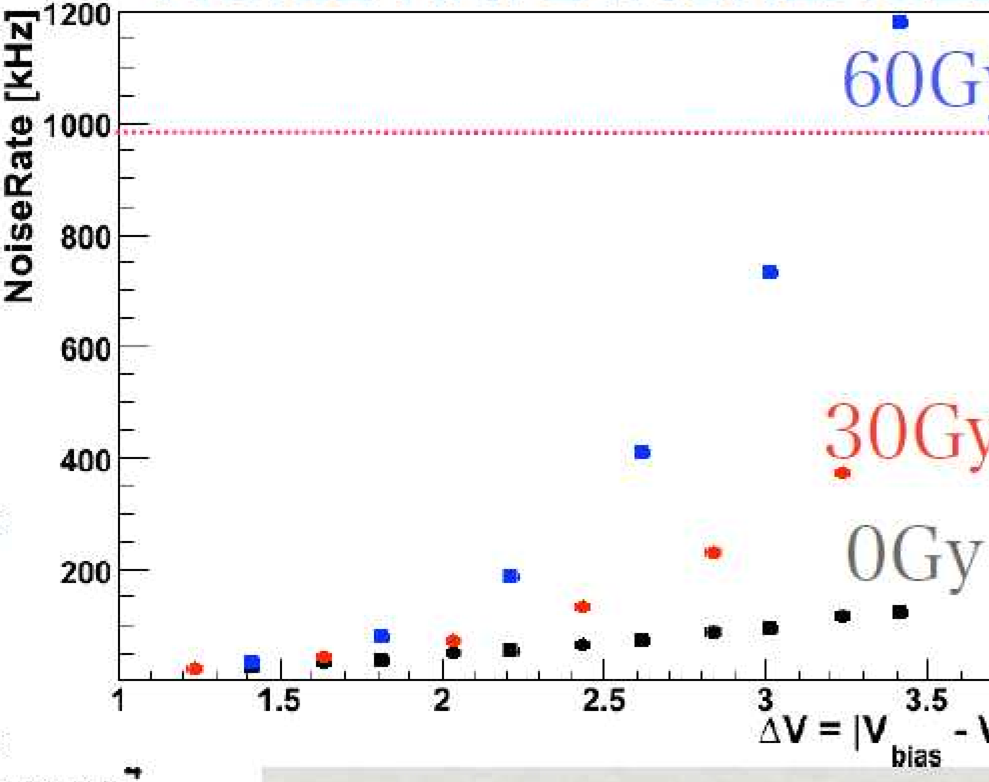
# radiation tolerance of MPPC

- **gamma** irradiation $^{60}$Co

## NO CHANGE FOR GAIN



## NOISE RATE INCREASED



# Dark rate increase per 1E10 n/cm$^2$

| | | | | | | 24C | 20C | annealing (2.5) | |
|---|---|---|---|---|---|---|---|---|---|
| | ΔI / 1E10 (uA/cm2) | A(mm2) | ΔV (V) | PDE 520 nm | Gain at dV (*1E6) | Δ rate (Mhz/mm2 )1E10 | | | thickness (um) |
| | | | | | | | | | |
| Zecotek | 1.6 | 9 | 2.0 | 0.25 | 0.06 | **18.5** | 13.2 | 5.3 | **2.4** |
| HPK 50 um | 5.3 | 1.7 | 1.0 | 0.25 | 0.75 | **26.0** | 18.6 | 7.4 | **3.4** |
| HPK 15 um | 0.4 | 1 | 2.3 | 0.09 | 0.13 | **20.0** | 14.3 | 5.7 | **2.6** |
| FBK (HG) | 30 | 6 | 2 | 0.12 | 0.90 | **34.7** | 24.8 | 9.9 | **4.5** |
| FBK (LG) | 25 | 6 | 2 | 0.07 | 0.60 | **43.4** | 31.0 | 12 | **5.7** |
| NDL | 1.0 | 0.25 | 2.5 | 0.07 | 0.10 | **250.0** | 179 | 71 | **33** |
| KETEK | 7.8 | 1 | 1.9 | 0.14 | 1.40 | **34.8** | 24.9 | 9.9 | **4.5** |
| HPK APD | 0.15 | 25 | | 0.85 | 0.0003 | **125.0** | 89.3 | 36 | **16** |