Development of SiPMs a FBK-irst

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Outline

- Important parameters of SiPM
- Characteristics of FBK-irst SiPMs
- Application of FBK-irst SiPM

General view of the important parameters in a SiPM

- Gain

- Noise

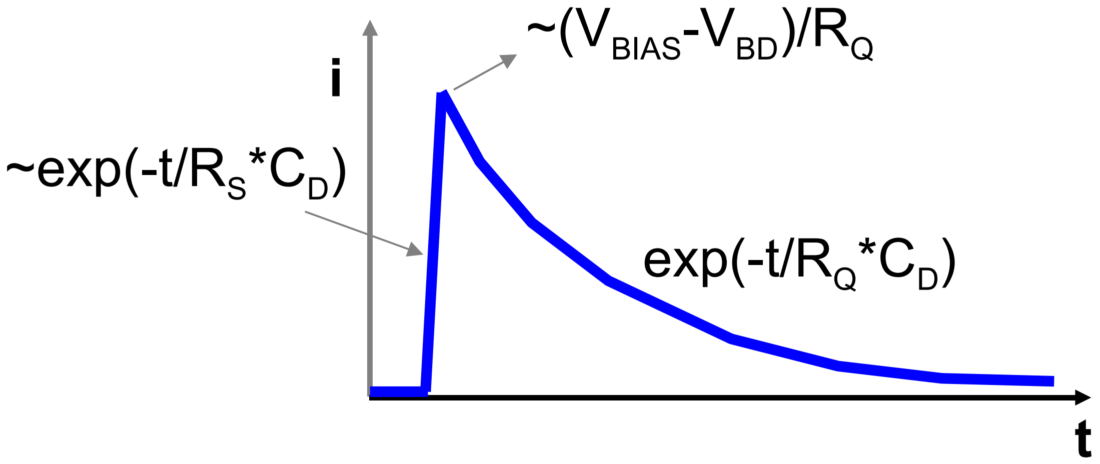
- Photo-detection efficiency

- Dynamic range

- Time resolution

Gain

number of carriers produced per photon absorbed



charge collected per event is the area of the exponential decay which is determined by circuital elements and bias.

$$\text{Gain} = \frac{I_{MAX}{*}\tau_Q}{q} = \frac{(V_{BIAS}-V_{BD})}{R_Q}{*}\frac{\tau_Q}{q} = \frac{(V_{BIAS}-V_{BD}){*}C_D}{q}$$

NOISE

1) Primary DARK COUNT

False current pulses triggered by non photogenerated carriers

Main source of carriers: thermal generation in the depleted region.

Critical points: **quality of epi silicon**; **gettering techniques.**

2) Afterpulsing:

secondary current pulse caused by a carrier released by a trap which was filled during the primary event.

3) Optical cross-talk

Excitation of neighboring cells due to the emission of photons during an avalanche discharge

Photodetection efficiency

$$\mathbf{PDE} = N_{pulses} / N_{photons} = \mathbf{QE \times P_{01} \times FF}$$

1. QE Quantum efficiency is the probability for a photon to generate a carrier that reaches the high-field region.

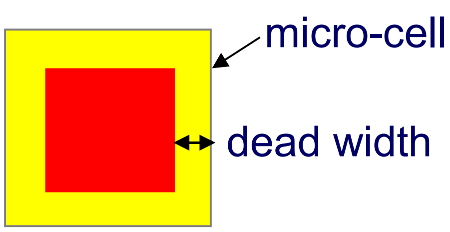
Maximization: anti-reflective coating, drift region location

2. P_{01}. triggering probability probability for a carrier traversing the high-field to trigger the avalanche.

Maximization: 1. high overvoltage
2. photo-generation in the p-side of the junction
(electrons travel through the high-field region)

3. FF. Fill Factor

"standard" SiPMs suffer from low FF due to the structures present around each micro-cell (guard ring, trench)



Time resolution

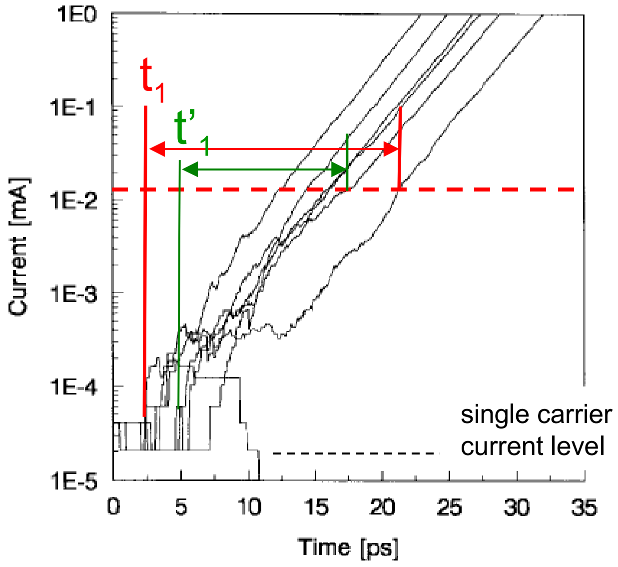
Statistical Fluctuations in the first stages of the current growth:

1. Photo-**conversion depth**

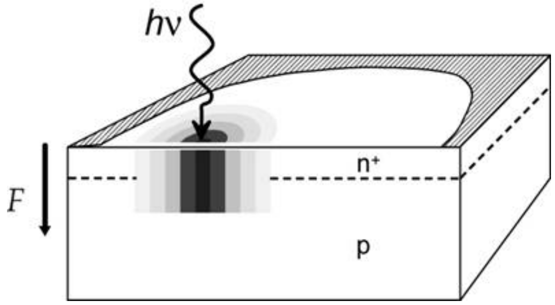
2. ***Vertical*** Build-up at the very beginning of the avalanche

$t=0$	pair generation
$0<t<t_1$	drift to the high-field region
$t>t_1$	avalanche multiplication

* for short wavelength light
the first contribution is negligible



3. ***Lateral*** Propagation



the avalanche spreading is faster if generation takes place in the center

FBK-irst SiPMs

Development of SiPMs started in 2005 in collaboration with INFN.

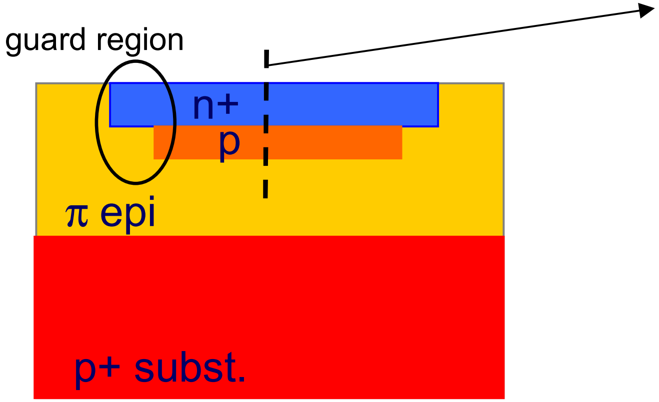
- IRST:
  development of the technology for the production of SiPMs (large area devices/matrices) + functional characterization

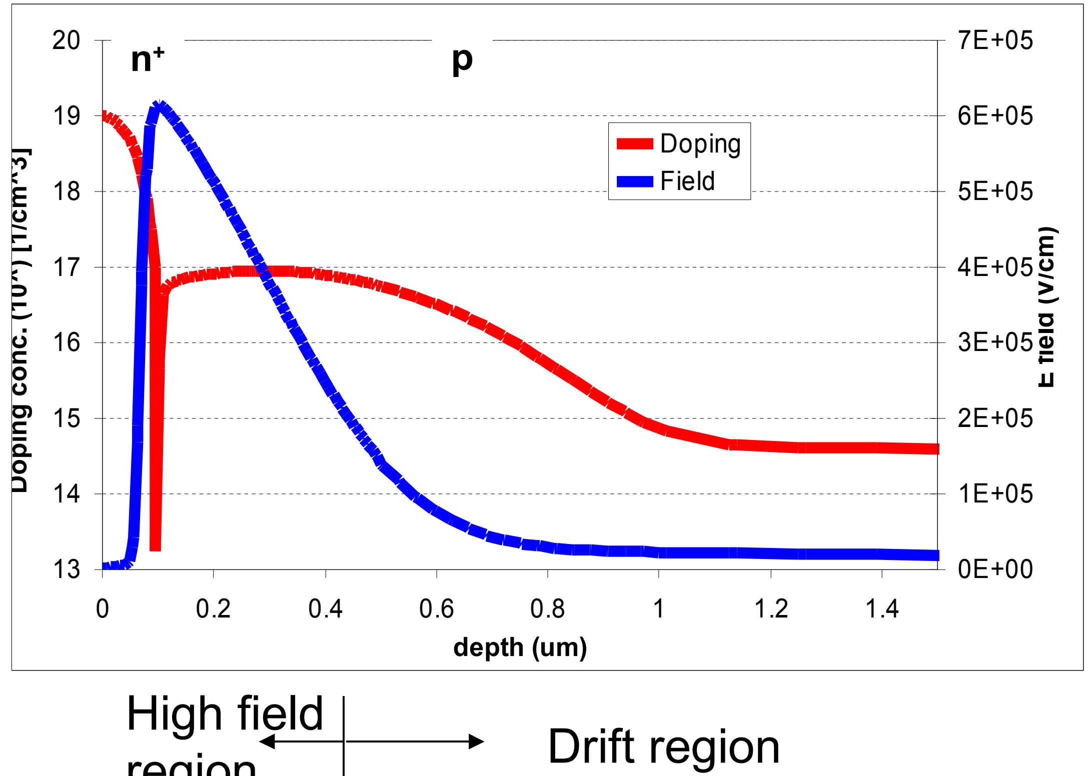
- INFN (Pisa, Bari, Bologna, Perugia, Trento):
  development of systems, with optimized read-out electronics, based on SiPMs for applications such as:
  - tracking with scintillating fibers;
  - PET;
  - TOF;
  - calorimetry

IRST technology

[C. Piemonte
"A new Silicon Photomultiplier structure for blue light detection"
NIMA 568 (2006) 224-232]

Shallow-Junction SiPM

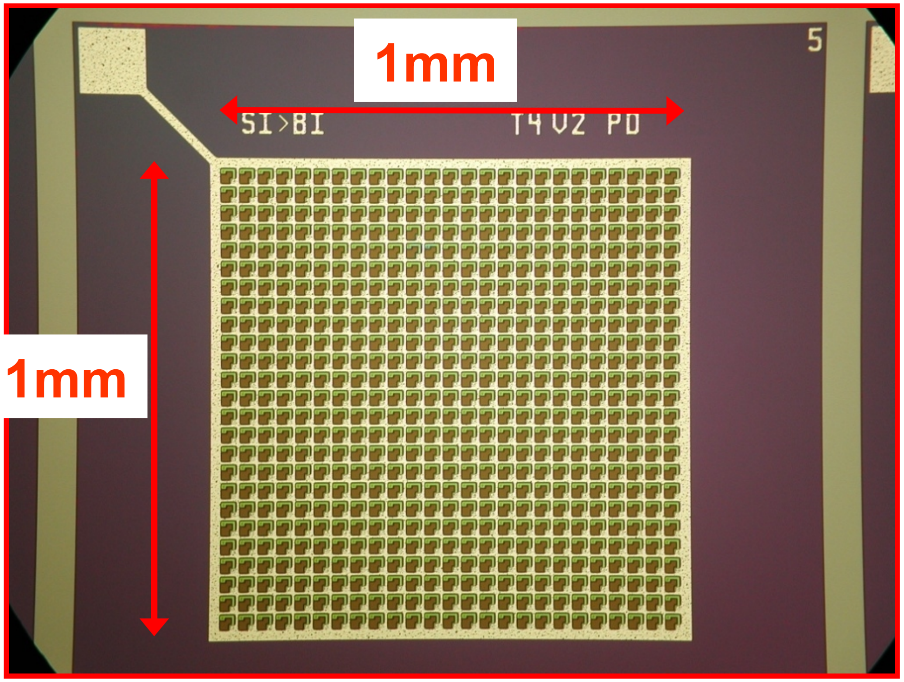




1) Substrate: p-type epitaxial
2) Very thin n+ layer
3) Polysilicon quenching resistance
4) Anti-reflective coating optimized for λ~420nm

Layout: from the first design…(2005)

SiPM structure:
- 25x25 cells
- microcell size: 40x40μm^2

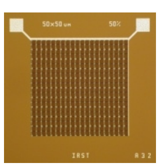


Geometry NOT optimized for maximum PDE (max fill factor ~ 30%)

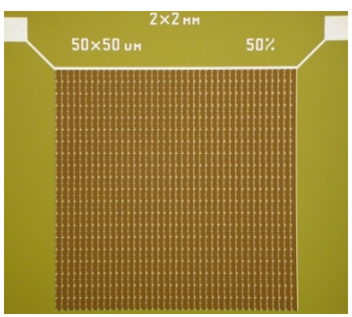
… to the new devices (i) (2007)

Fill factor: 40x40µm² => ~ 40%
50x50µm² => ~ 50%
100x100µm² => ~ 76%

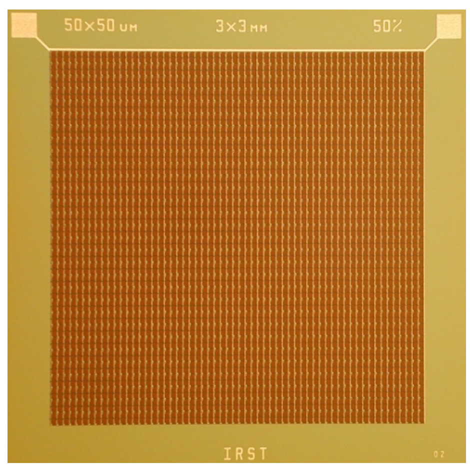
Geometries:



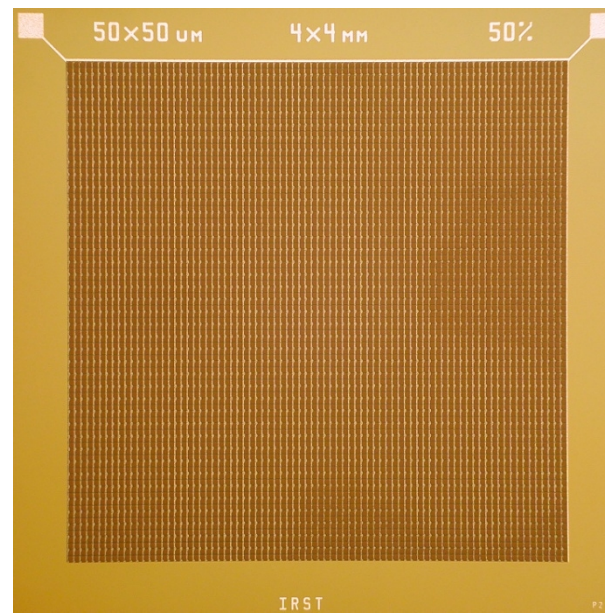
1x1mm²



2x2mm²



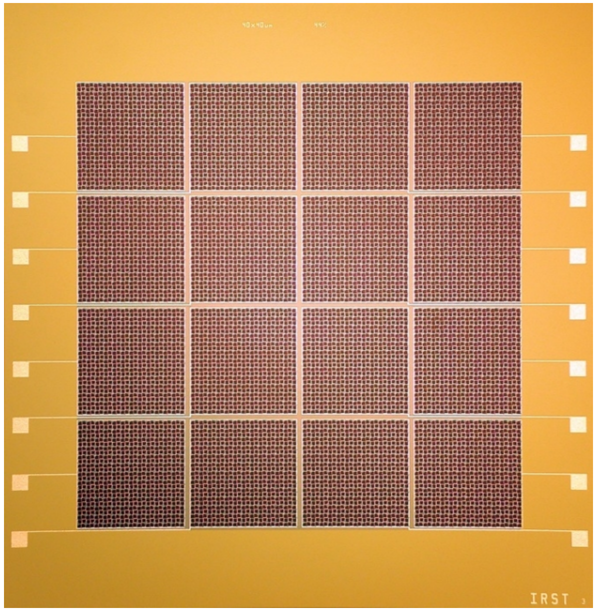
3x3mm² (3600 cells)



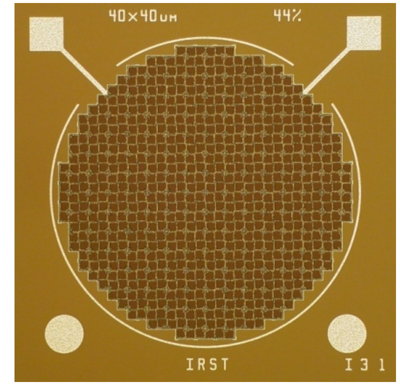
4x4mm² (6400 cells)

FONDAZIONE BRUNO KESSLER

…to the new devices (ii)

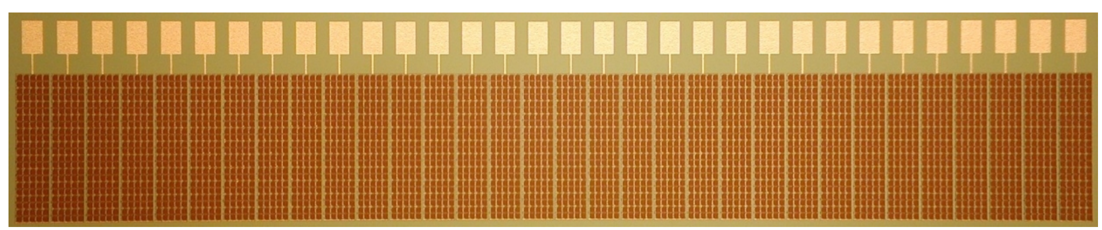


Matrices: 4x4 elements of 1x1mm² SiPMs



Circular: diameter 1.2mm
diameter 2.8mm

Linear arrays:
8,16,32 elements of
1x0.25mm² SiPMs



Tests performed at FBK

- **IV measurement**

  fast test to verify functionality and uniformity of the properties.

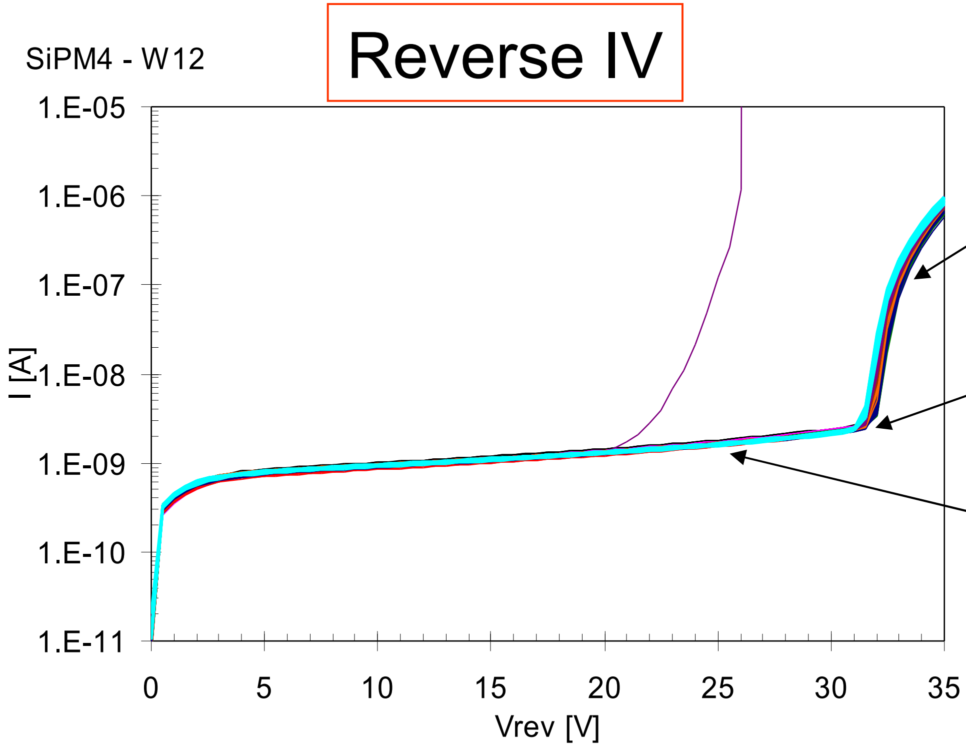
C. Piemonte et al.
"Characterization of the first prototypes of SiPM fabricated at ITC-irst"
IEEE TNS, February 2007

- **Functional characterization in dark**

  for a complete characterization of the output signal and noise properties (signal shape, gain, dark count, optical cross-talk, after-pulse)

- **Photo-detection efficiency**

Static characteristic (IV)



Breakdown current: determined by dark events

Breakdown voltage

Leakage current: mainly due to surface generation at the micro-diode periphery

Very useful fast test. Gives info about:

- Device functionality
- Breakdown voltage
- (Dark rate)x(Gain) uniformity
- Quenching resistance (from forward IV)

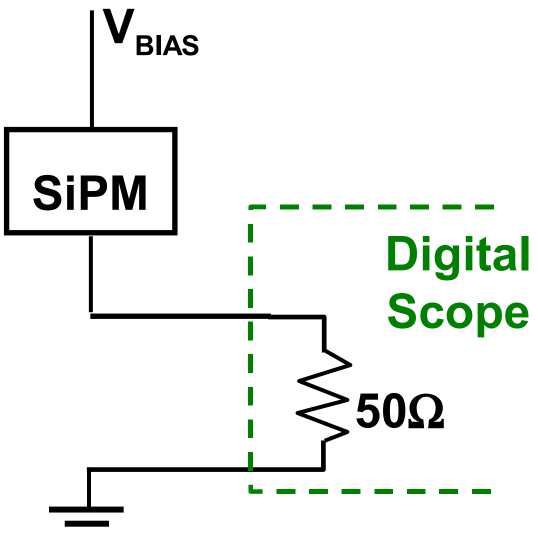
Performed on several thousands of devices at wafer level

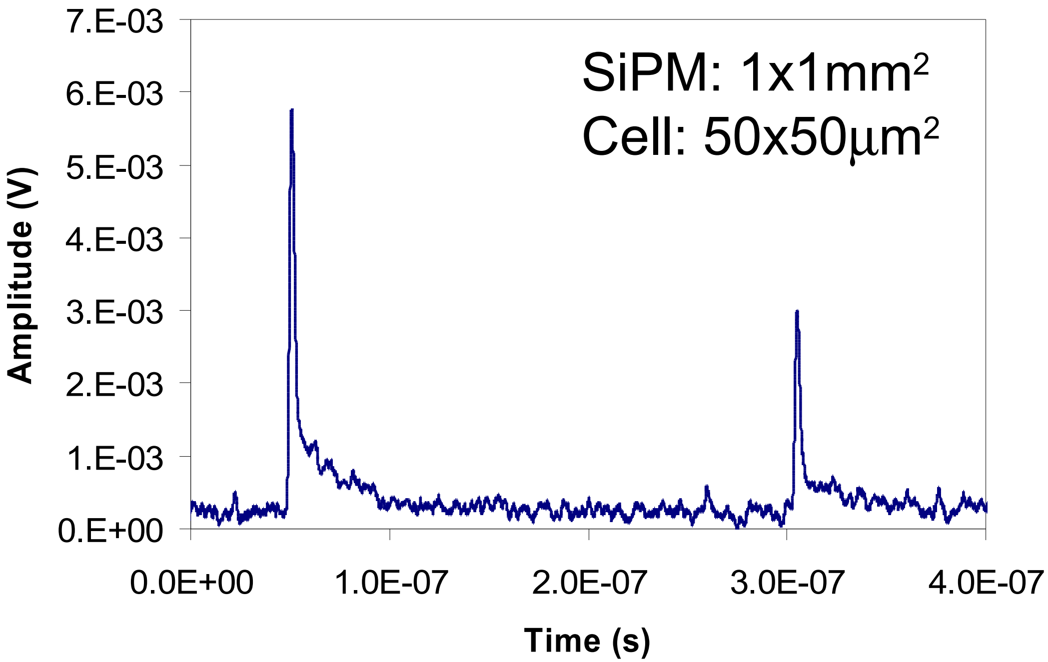
Signal properties – NO amplifier

Dark signals are exactly equal to photogenerated signals

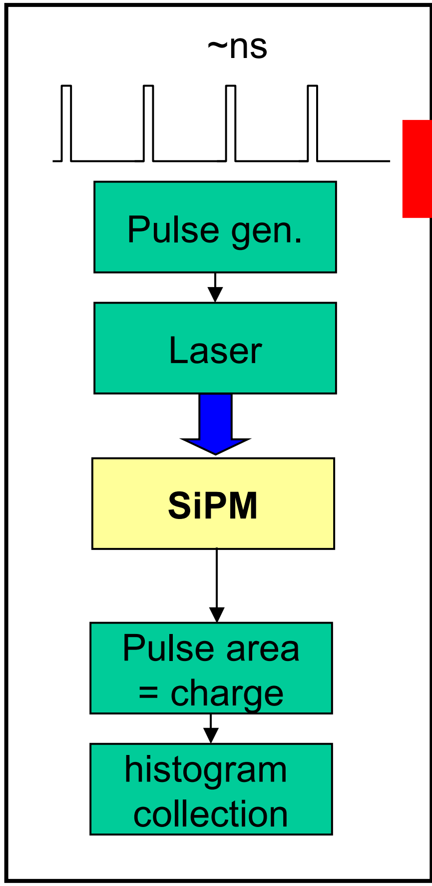
⇨ functional measurements in dark give a complete picture of the SiPM functioning

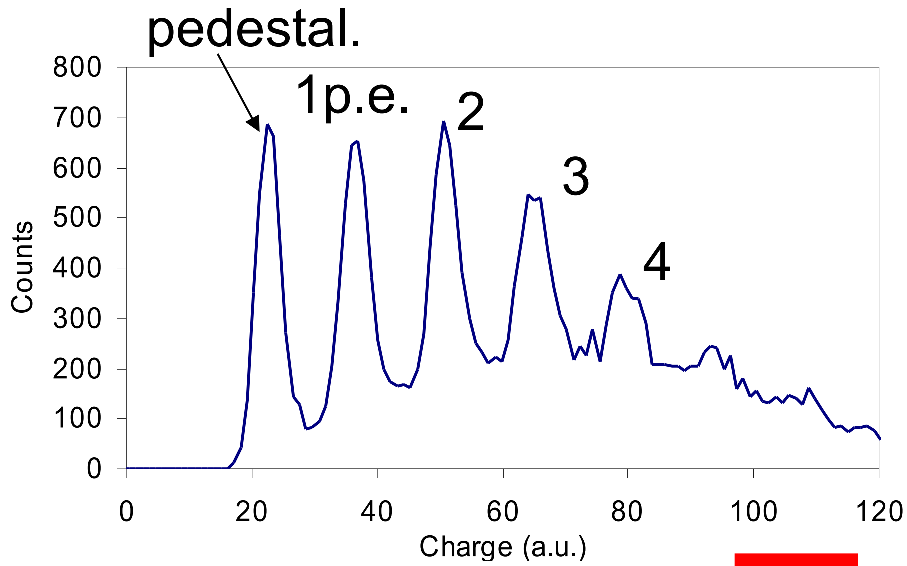
Thanks to the large gain it is possible to connect the SiPM directly to the scope



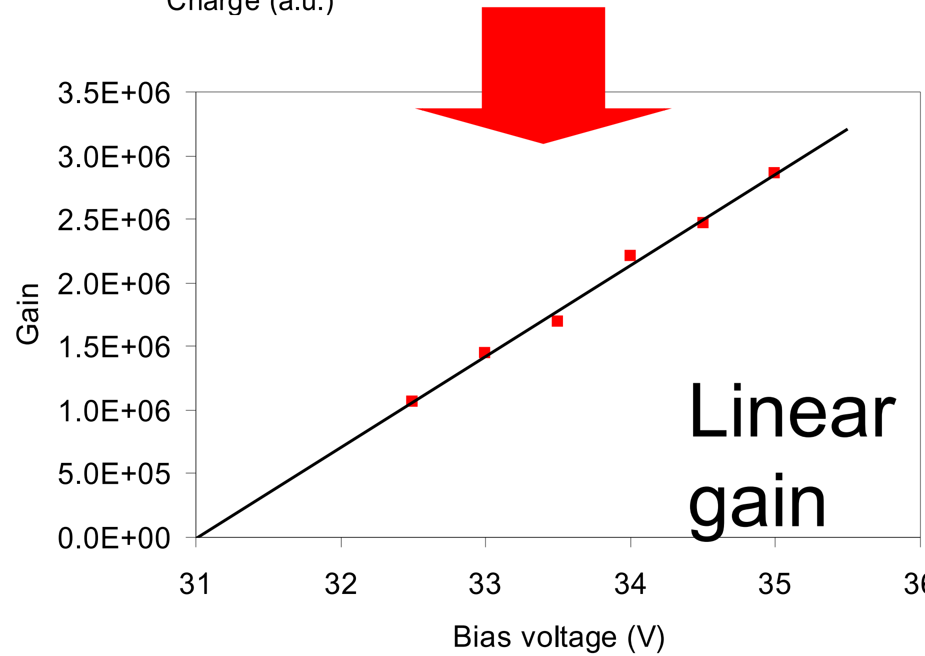


Signal properties – NO amplifier





Excellent cell uniformity



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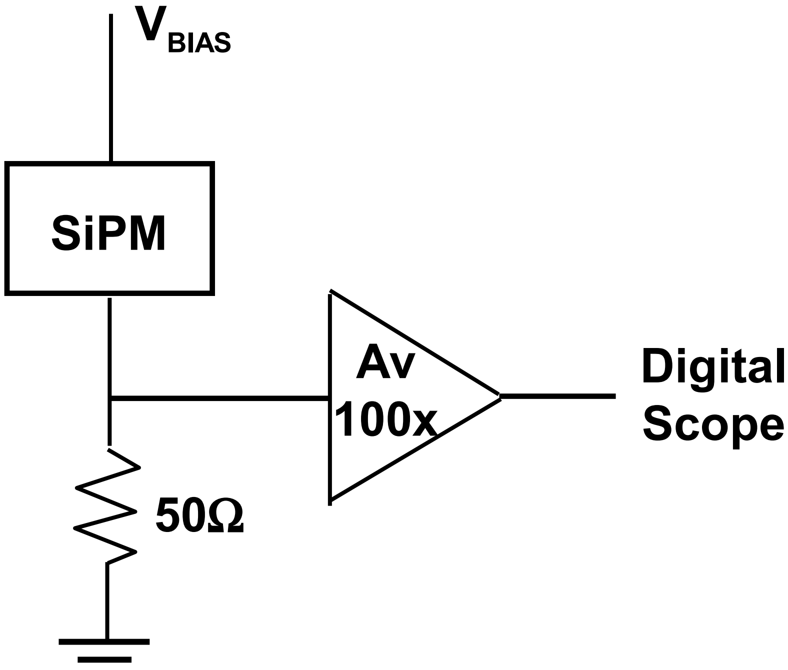
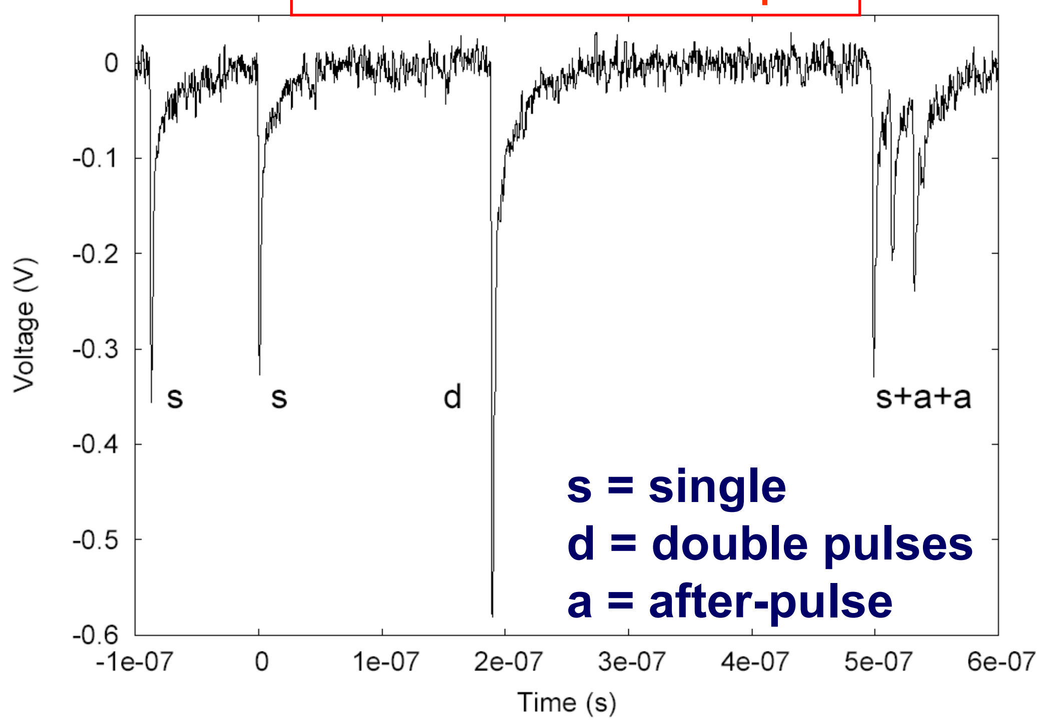
Signal properties – with amplifier

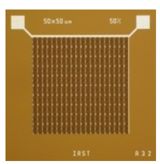
A voltage amplifier allows an easier characterization, but attention must be paid when determining the gain



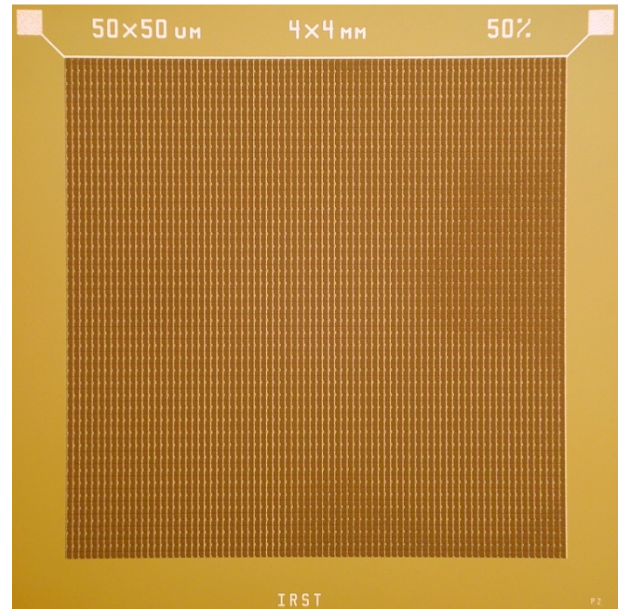
Pulses at the scope.



Let’s look at the electro-optical characteristics of these devices:



$1x1mm^2$ (400 cells)



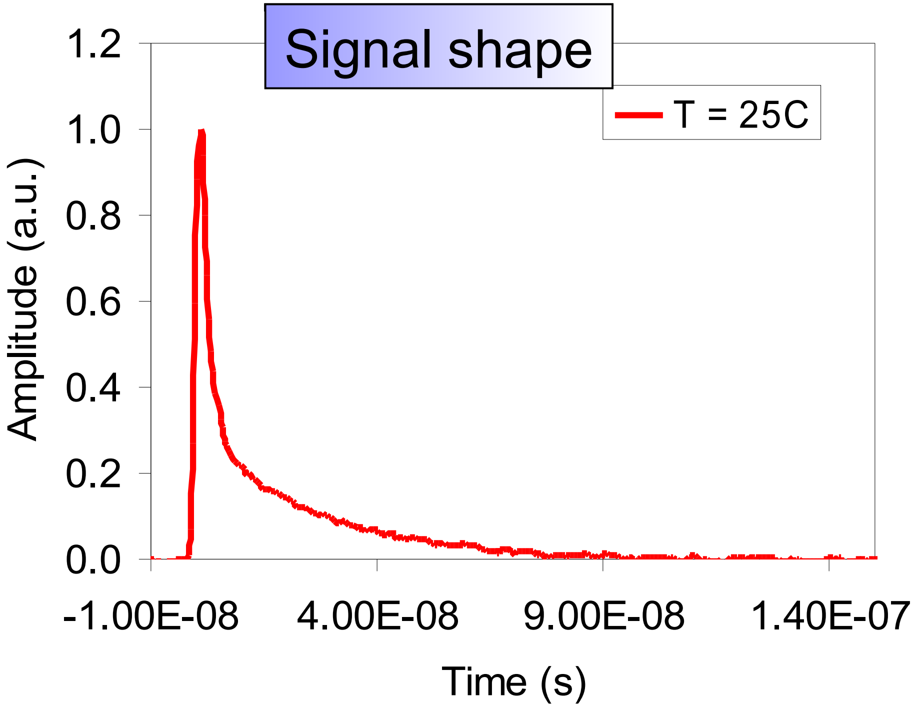
$4x4mm^2$ (6400 cells)

Micro-cell size: 50x50μm^2

1x1mm2 SiPM - 50x50µm2 cell

Set up: SiPM current signal converted into voltage on a 50Ω resistor and amplified with a wide-band voltage amplifier.

Fast transient: avalanche current through parasitic capacitance in parallel with quenching res.

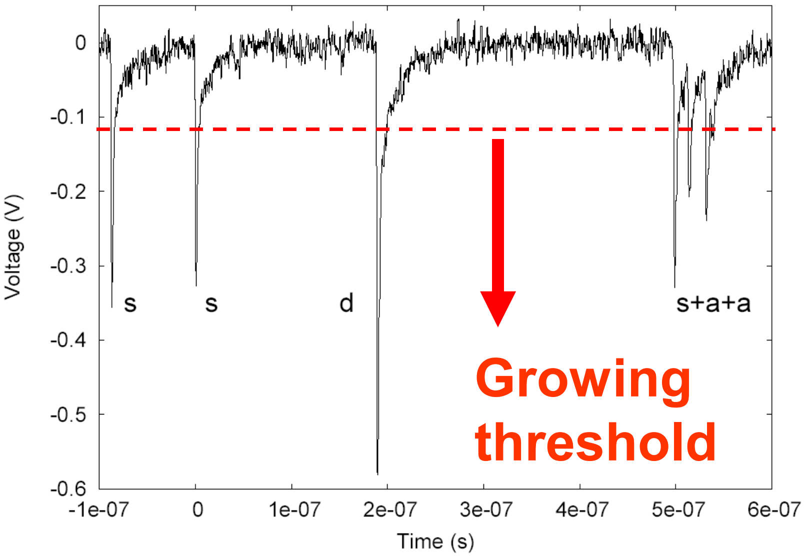


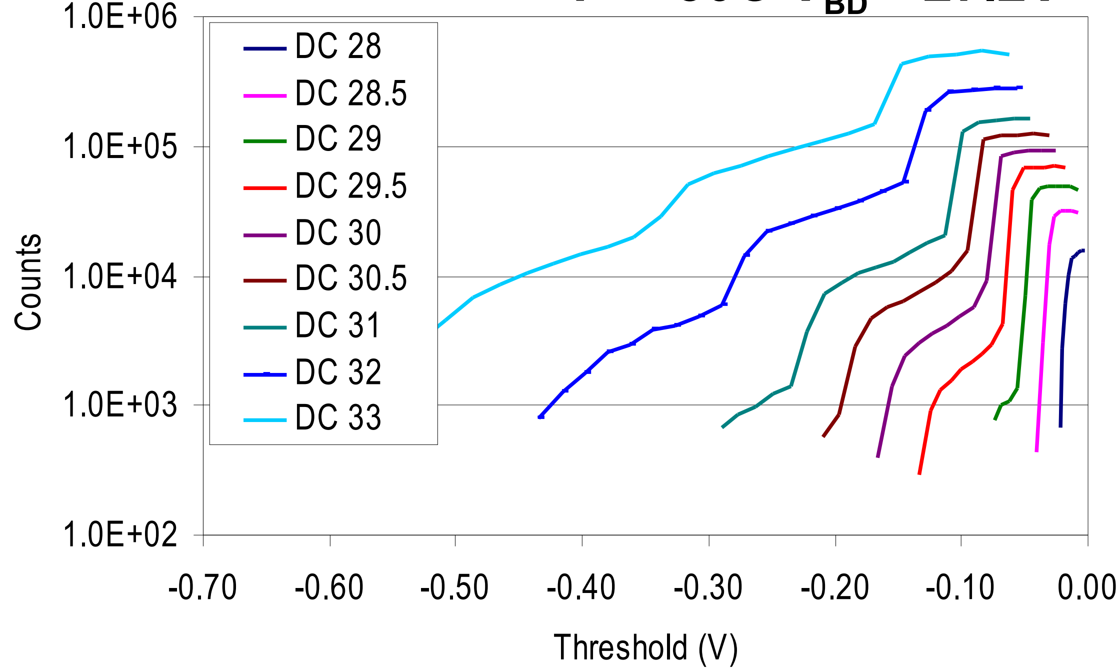
ow transient: xponential recharge the diode capac. rough the ienching resistor

Important to note:

The value of the quenching resistor increases with decreasing temperature and so the time constant follows the same trend

1x1mm2 SiPM – 50x50μm2 cell
Dark count





From this plot we get idea of dark rate and optical cross-talk probability

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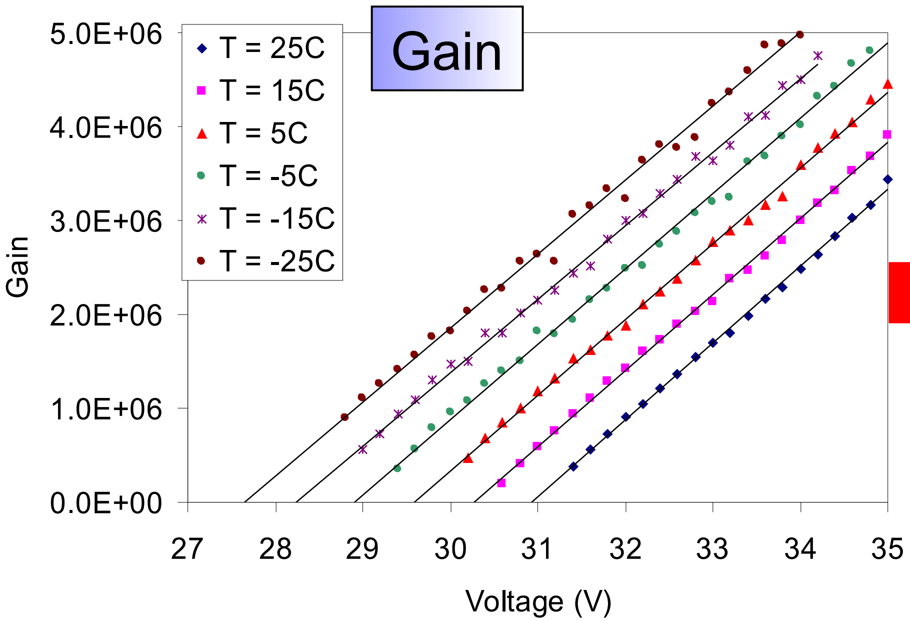
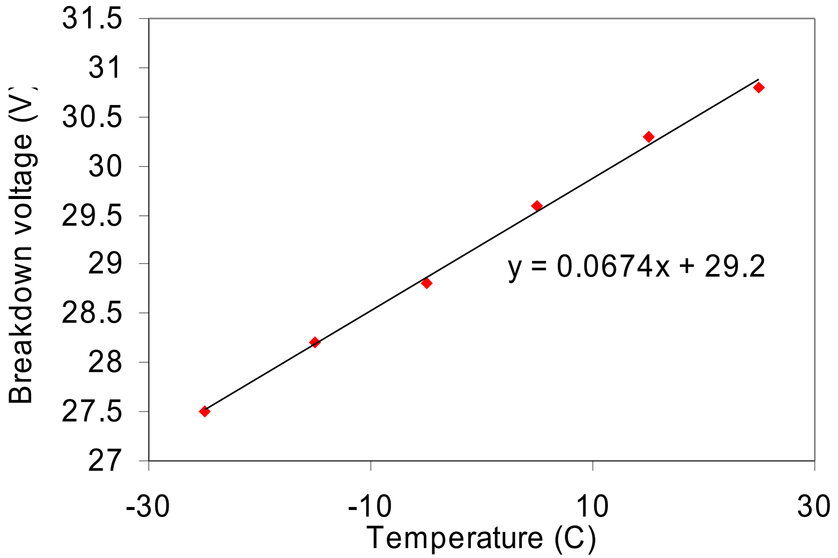
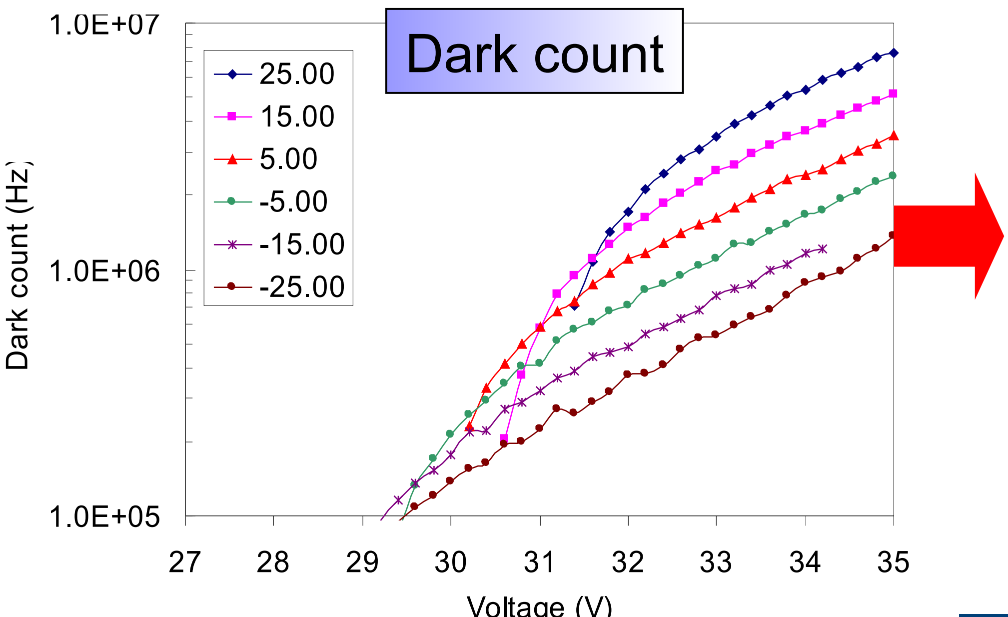
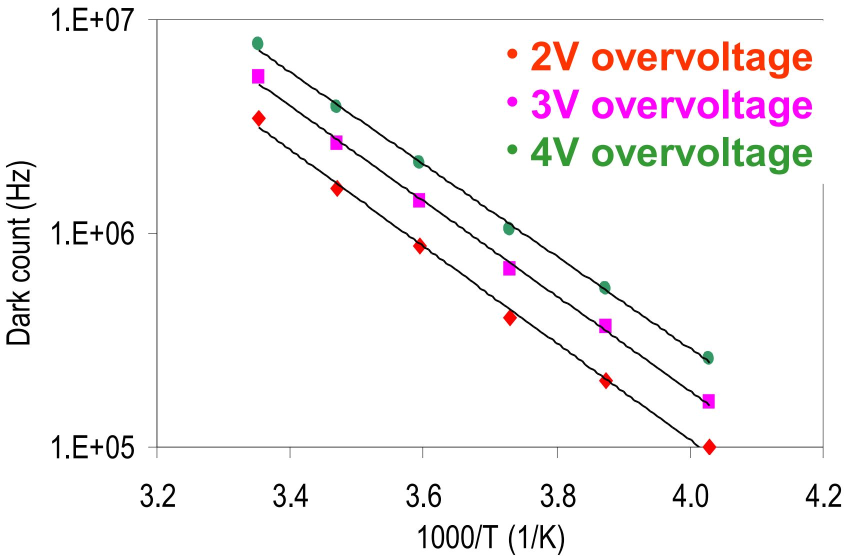
1x1mm^2 SiPM - 50x50µm^2 cell



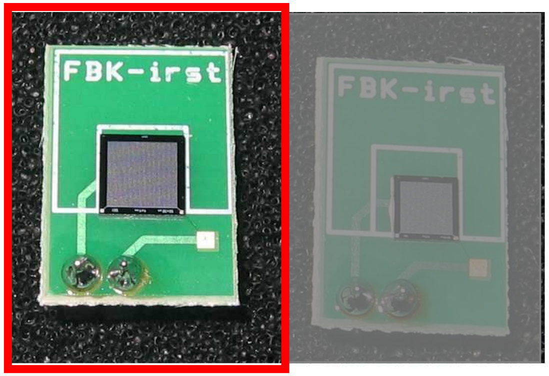


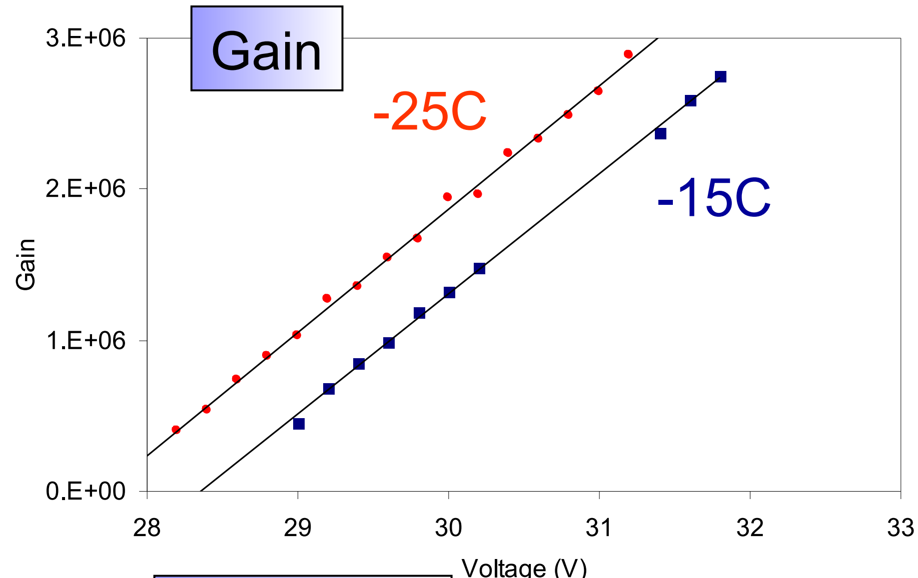


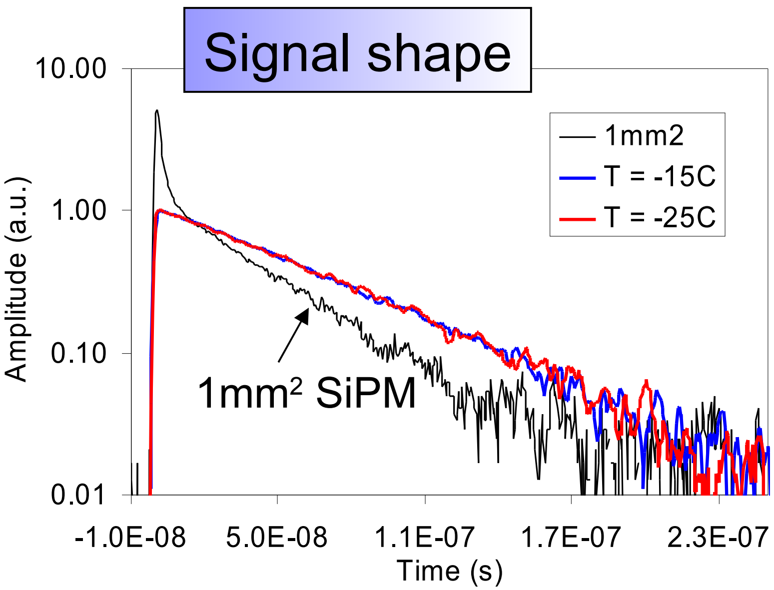


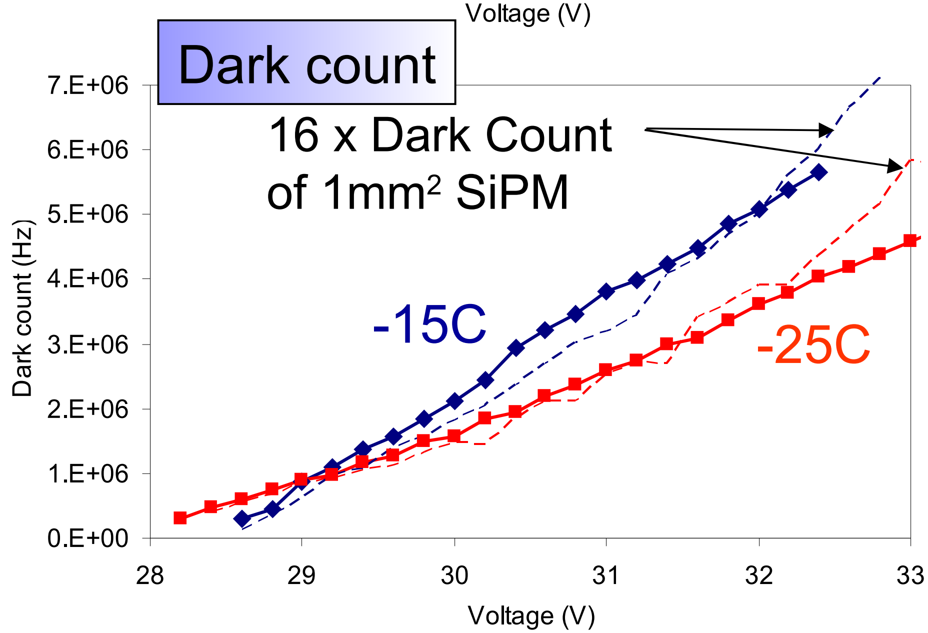
4x4mm² SiPM - 50x50μm² cell

4x4mm²



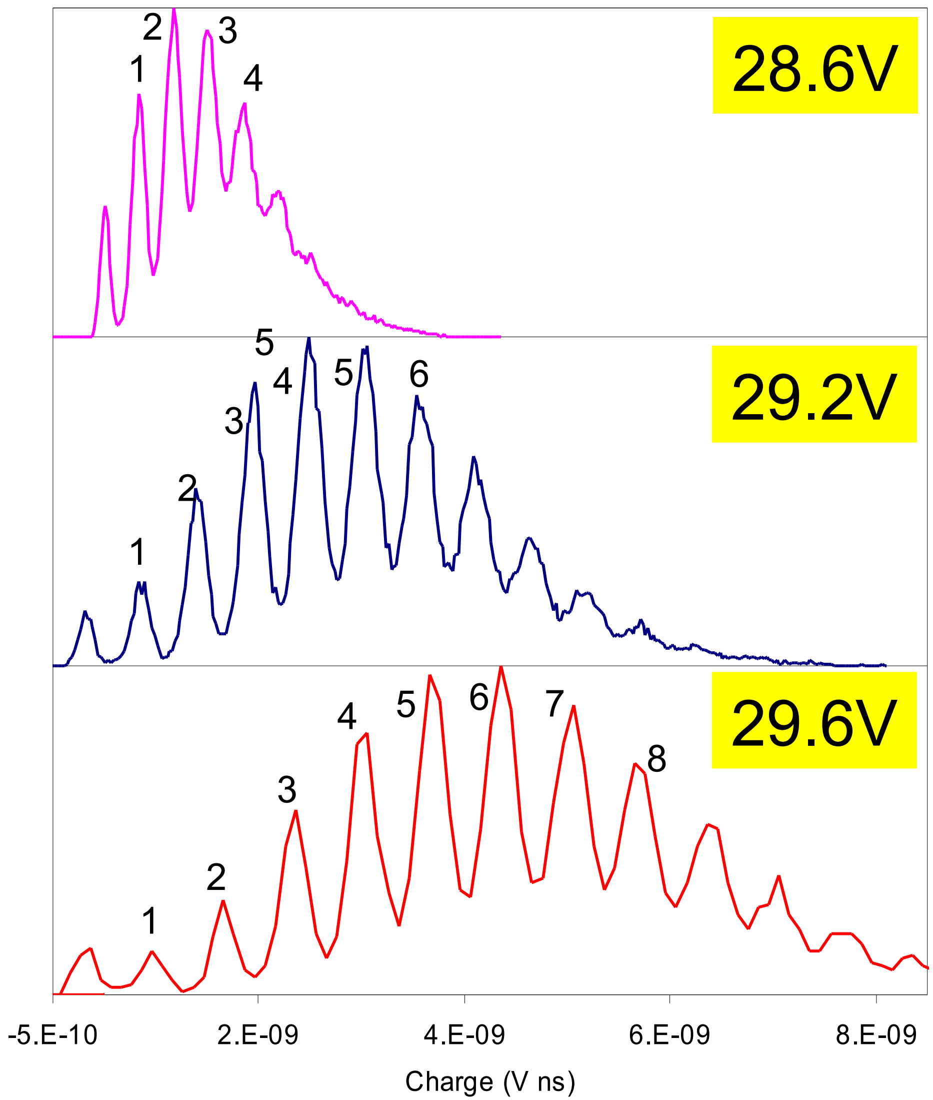






4x4mm² SiPM - 50x50μm² cell

T=-25C   Vbd=27.6V



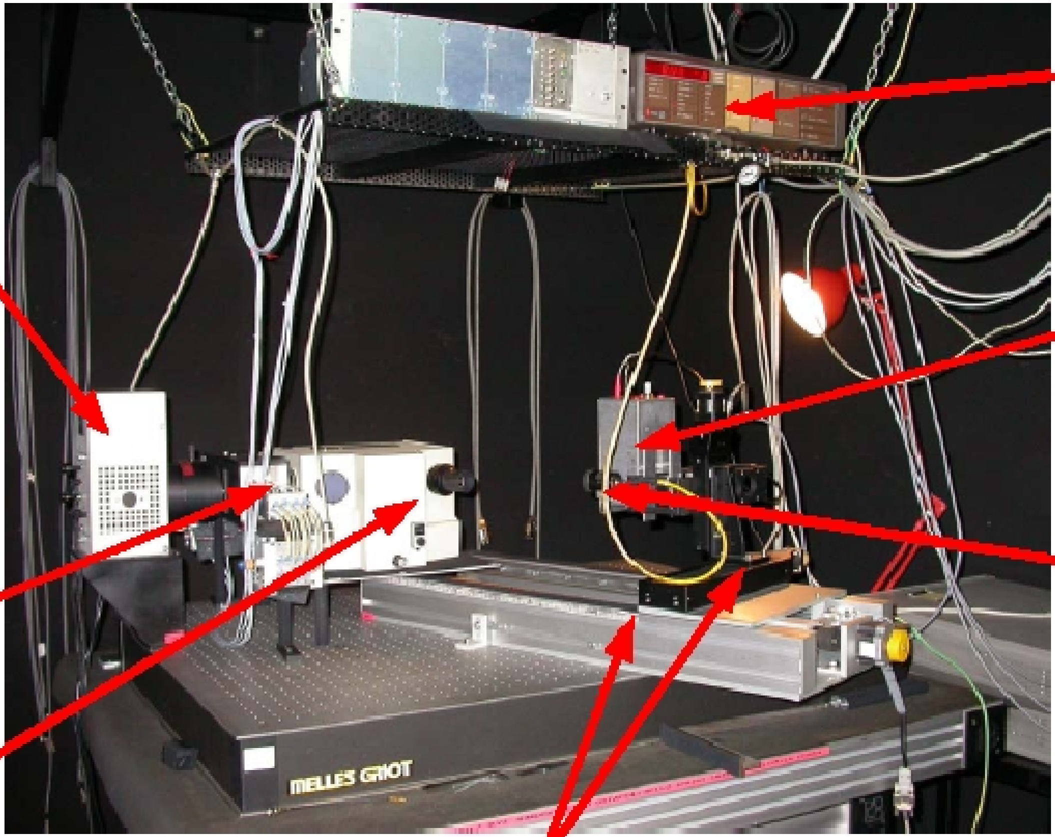
Charge spectra when illuminating the device with short light pulses

Same conclusions as for the previous device:

- Excellent cell response uniformity over the entire device (6400 cells)

  Width of peaks dominated by electronic noise

Photo-detection efficiency (1)



Halogen white lamp

Neutral filters (transmittance 10%)

Monocromator

Optometer

SiPM+ preamplifier

Photodiode UDT221

Stage with 3D micrometers movement (50um precision)

Photo-detection efficiency (2)

Two methods: DC current and Pulses count

$$(1)\quad N_{det.\ photons\ [s^{-1}]} = \frac{I_{light} - I_{dark}}{q \cdot G}$$

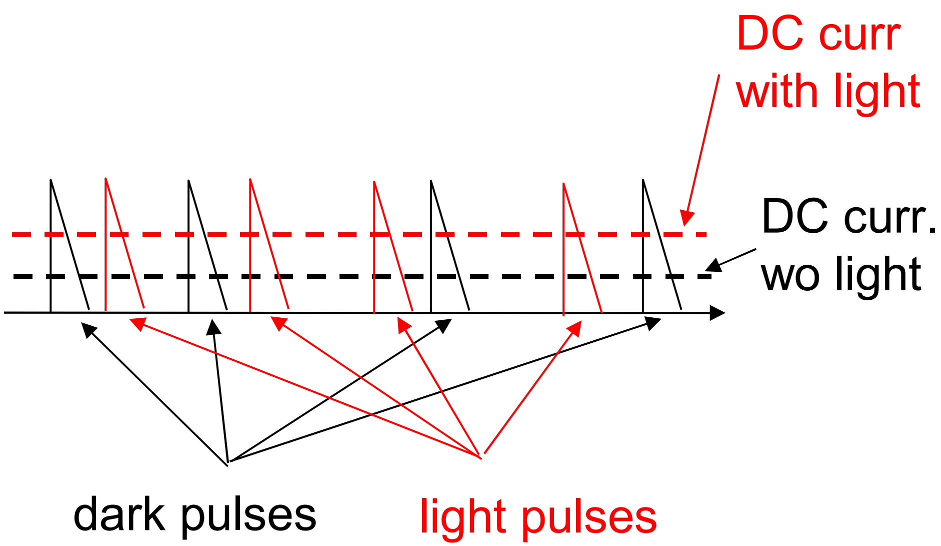
$$(2)\quad N_{det.\ photons\ [s^{-1}]} = Rate_{light} - Rate_{dark}$$

$$PDE = \frac{N_{detected\ photons}}{N_{incident\ photons}}$$

Reference by calibrated detector (photodiode)

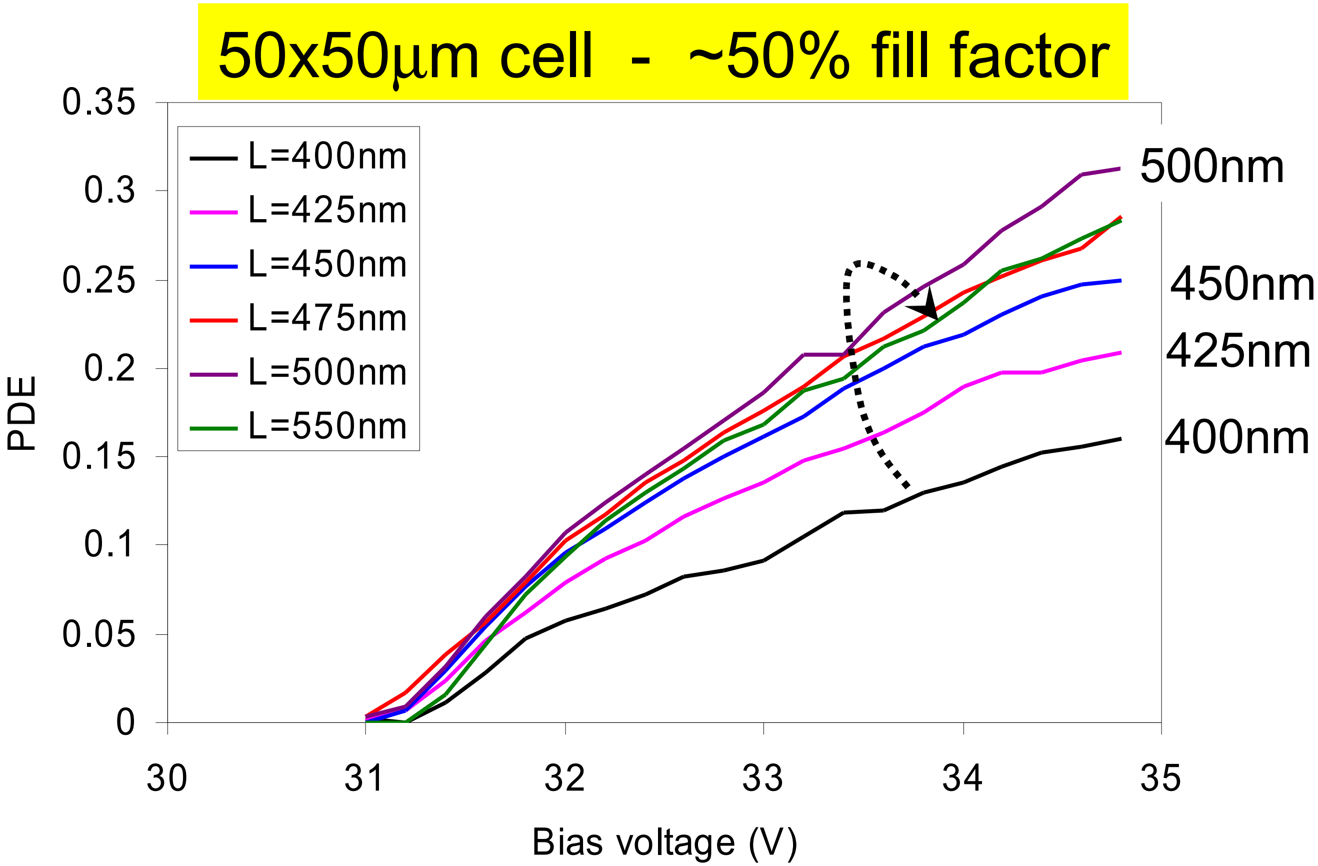
$$N_{incident\ photons\ [s^{-1}mm^{-2}]} = \Phi_{[W/mm^2]} \frac{\lambda}{hc}$$

$$\Phi_{[W/mm^2]} = \alpha_{[W/A]} \frac{I_{[A]}}{S_{[mm^2]}}$$



…what is the PDE of these devices?

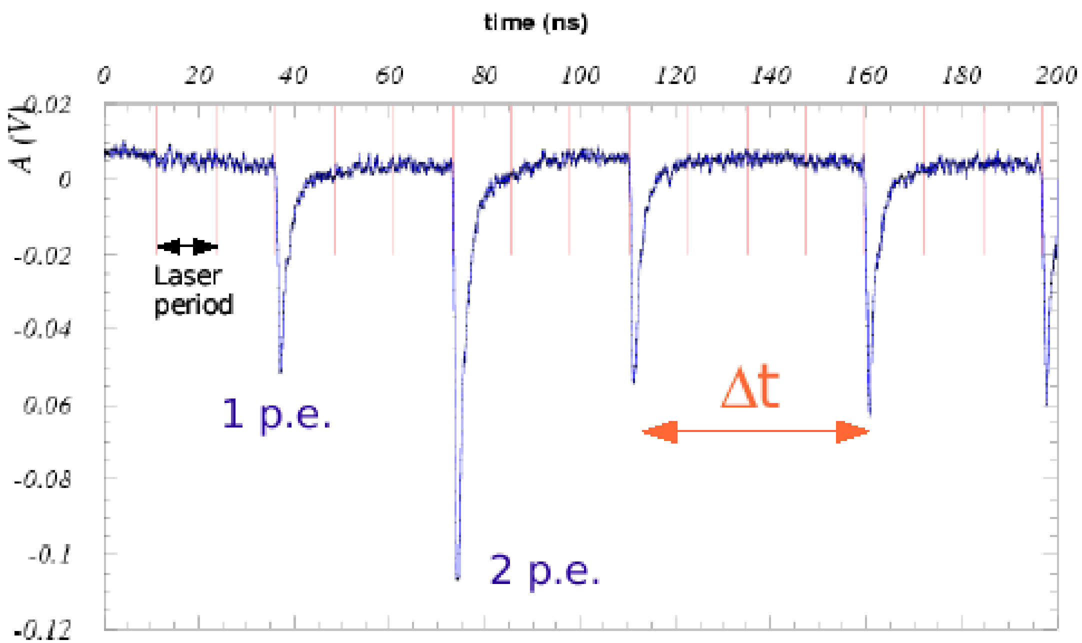
Measured on 1x1mm^2 SiPM using photon counting technique



Broad peak between 450 and 600nm

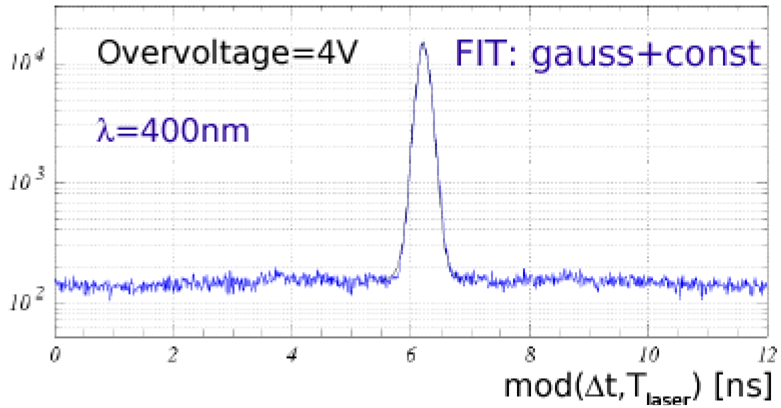
Time resolution (1)

- **Laser:** - wavelength: 400 or 800nm
  - **pulse width: ~60fs**
  - pulse period: 12.34ns with **time jitter <100fs**
- Filters: to have less than 1 photodetection/laser pulse
- **SiPMs:** 3 devices from 2 different batches measured



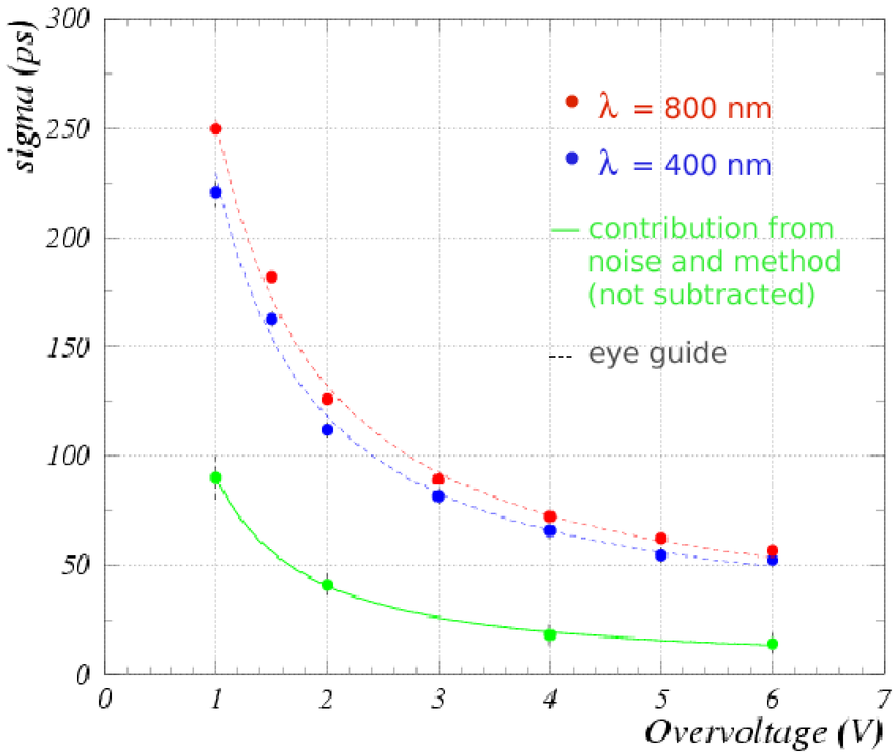
G. Collazuol, NIMA, 581, 461-464, 2007.

Time resolution (2)



Distribution of the time difference

SiPM type without optical trench

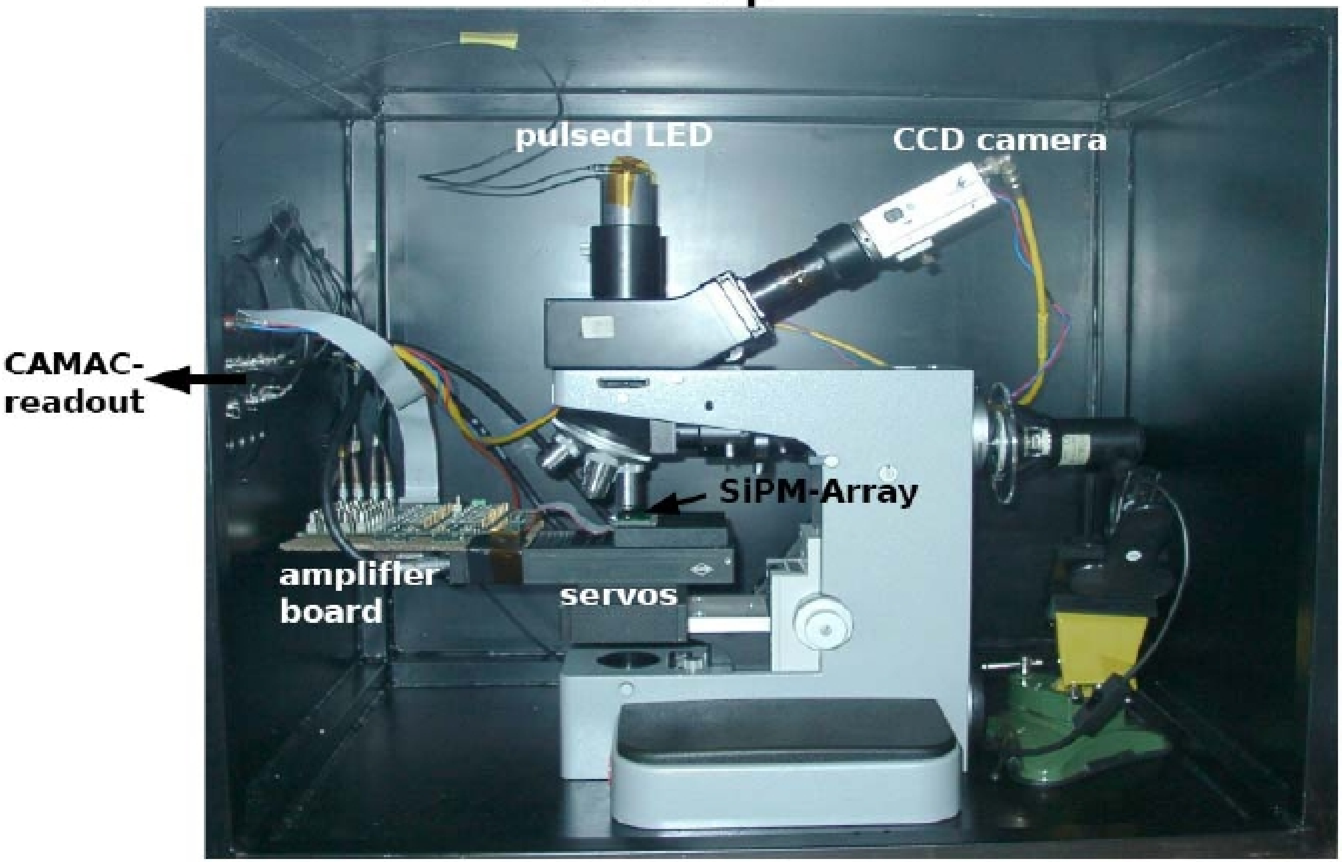


Timing performance (σ) as a function of the over-voltage

Microcell functionality measurement

(measurement at RWTH Aachen)

setup

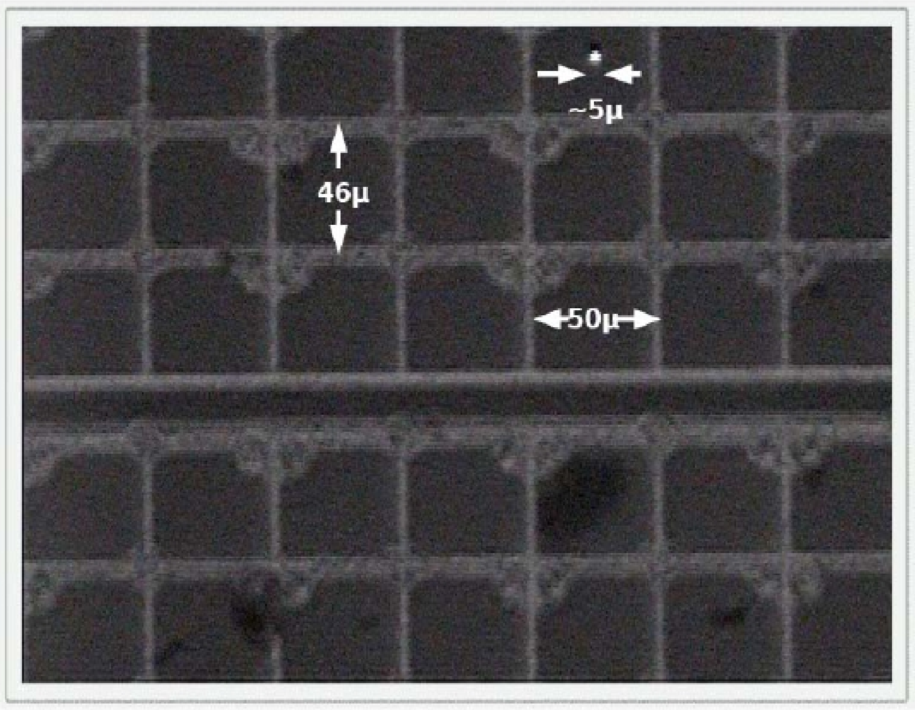


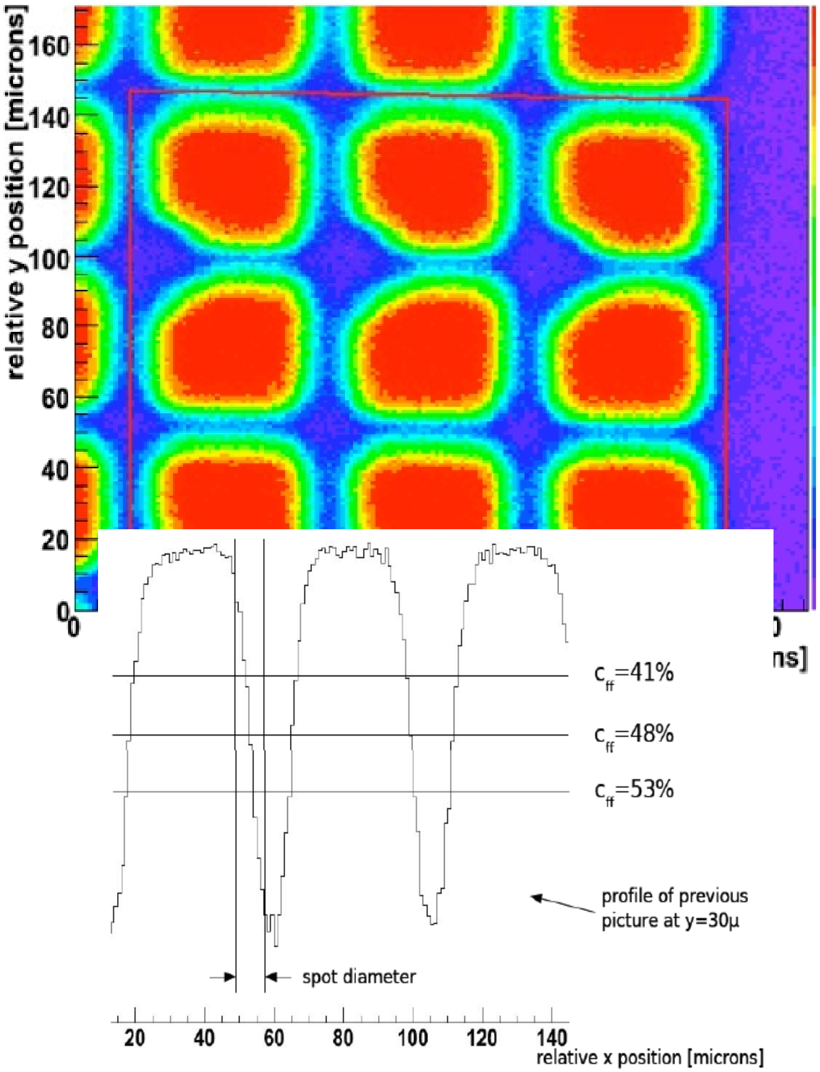
Microcell functionality measurement

fillfactor

Measurement of microcell eficiency with a 5 um LED spot diameter

LED spot diameter





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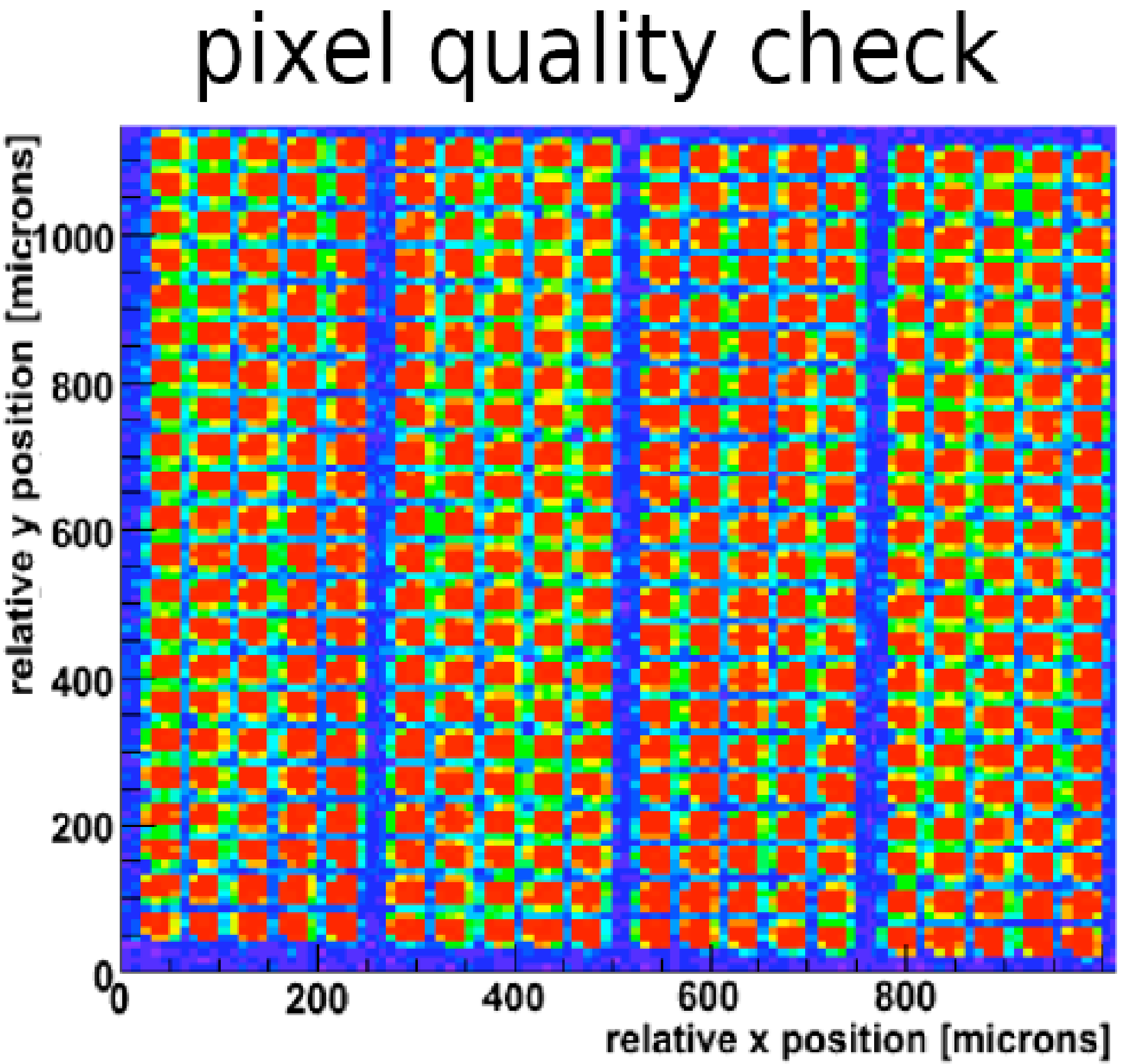
Microcell functionality measurement



step size 10µ, spot diameter ~10µ → all pixels on C15 work fine

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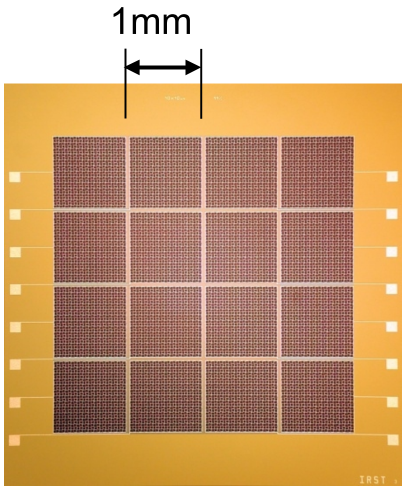
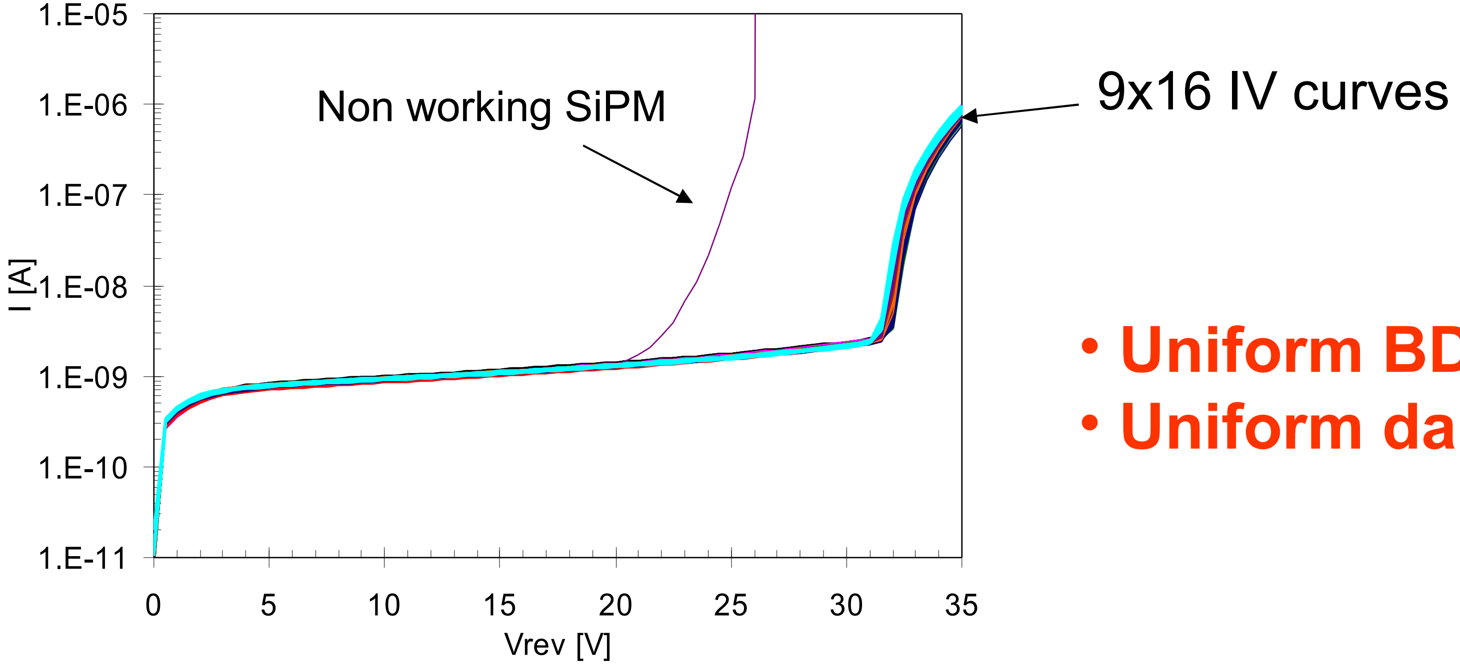
Some applications and projects in which we are involved

SiPM matrix – for PET (1)

First, small monolithic matrix of SiPM:
Element **1x1mm²**
Micro-cell size: **40x40µm²**



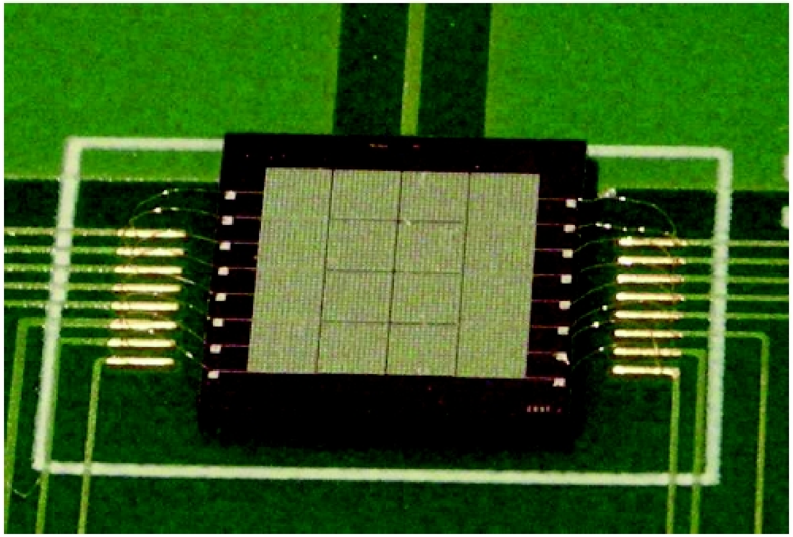
IV curves of 9 matrices of one wafer



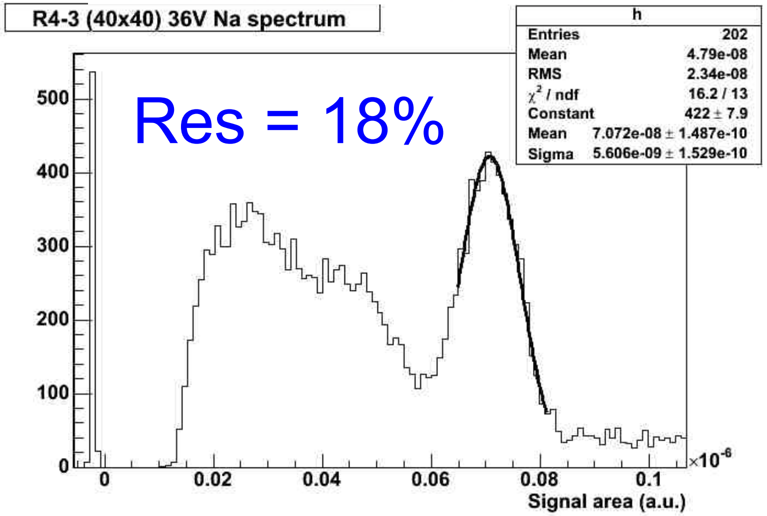
- **Uniform BD voltage**
- **Uniform dark rate**

SiPM matrix – for PET (2)

Tests are ongoing in Pisa
(DASiPM project, A. Del Guerra)
on these devices coupled with pixellated and slab LSO scintillators



Na^{22} spectrum with LSO on a **single** SiPM
(**1x1mm^2, 40x40μm^2 cell**)

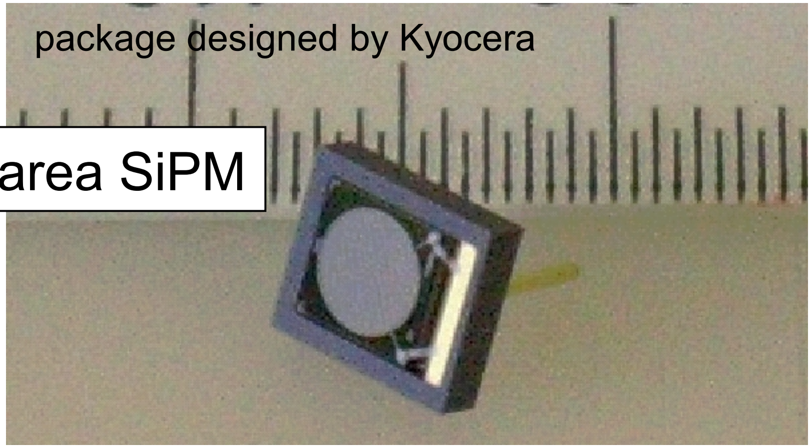


NEXT STEP: Larger monolithic matrices

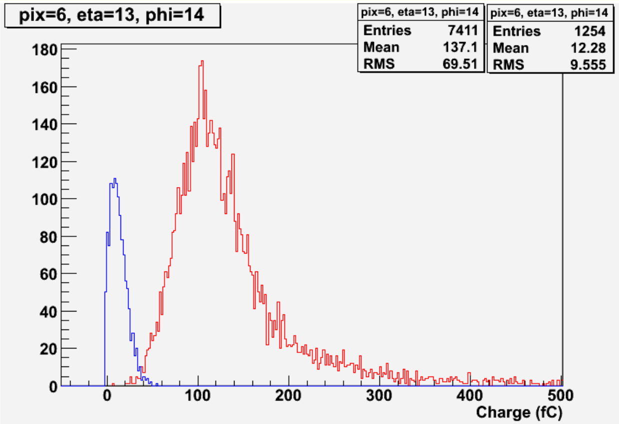
Circular SiPM - 50x50μm² cell

for CMS – Outer Hadron Calorimeter

6mm² area SiPM

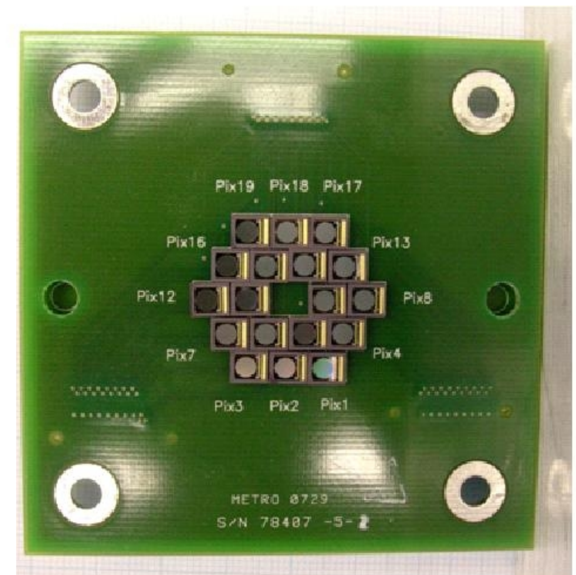


Muon response using SiPMs

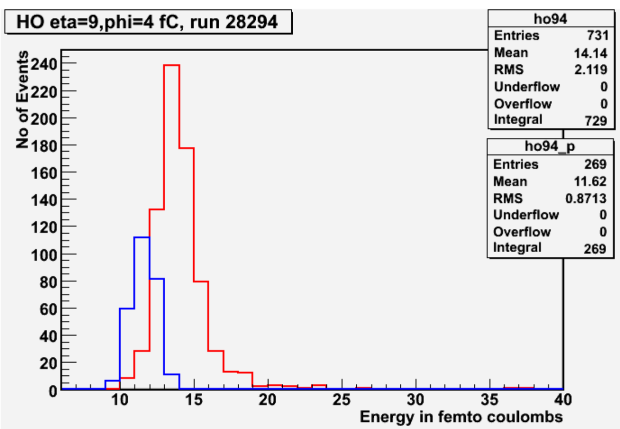


module with
18 SiPMs

Each SiPM
reads a
bundle
of 5 fibers



Muon response using HPD at 8kV

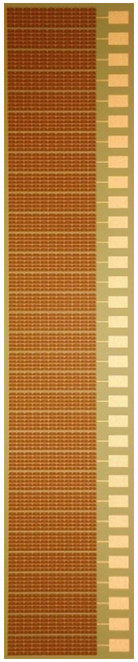


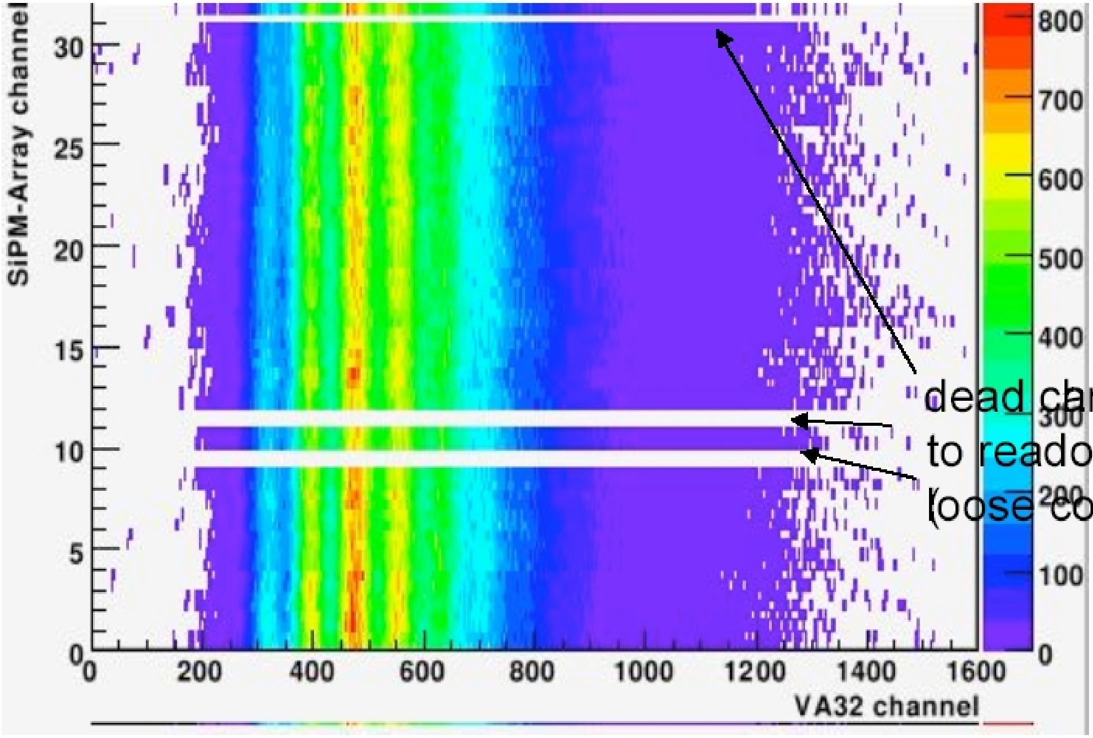
Array of SiPM for Fiber Tracking

INFN PG (R. Battiston) + Uni Aachen

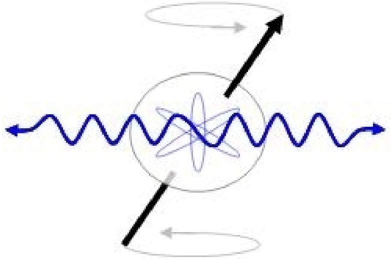
32x array connected to ASIC designed for strip detectors
=> capacitive divider at the input to reduce signal

Response uniformity under LED illumination





HYPERimage project



Seventh Framework programme, FP7-HEALTH-2007-A

	Short name	Country
Philips Research Aachen / Hamburg	**Philips**	DE
University of Heidelberg	**UH**	DE
Foundation Bruno Kessler - Irst	**FBK**	IT
King's College London	**KCL**	UK
Fundación Centro Nacional de Investigaciones Cardiovasculares Melchor	**CNIC**	ES
The Netherlands Cancer Institute - Antoni van Leeuwenhoek Hospital	**NKI**	NL
Universitätsklinikum Hamburg-Eppendorf	**UKE**	DE
IBBT – Gent	**IBBT**	B

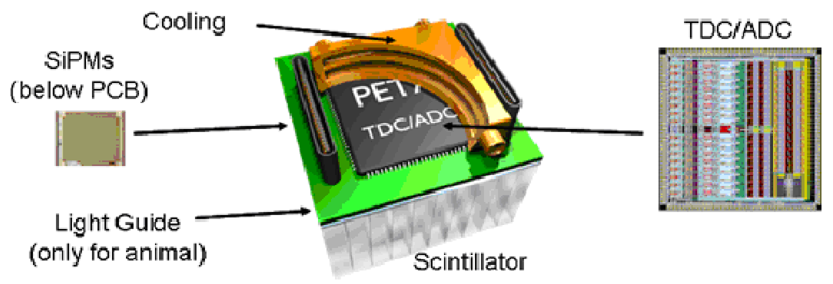
coordinator

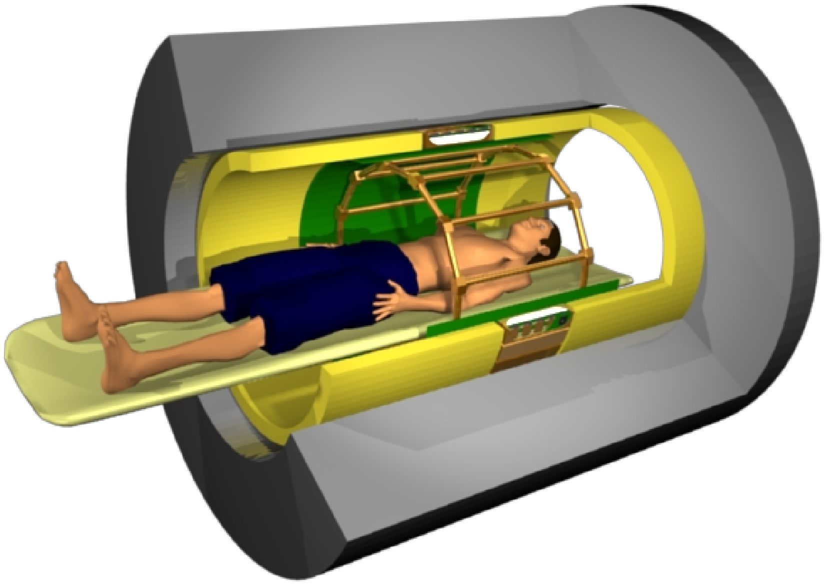
HYPERimage project

Development of **hybrid TOF-PET/MR** test systems with dramatically improved effective sensitivity

First clinical whole body PET/MR investigations of breast cancer

TOF-PET building blocks





Conclusion

- **The SiPM is going to play a major role as a detector for low intensity light, because of:**
  - comparable/better proprieties than PMT;
  - the inherent characteristics of a solid-state det..

- **IRST has been working on SiPMs (GM-APDs) for about 3 years obtaining very good results in:**
  - performance;
  - reproducibility;
  - yield;
  - understanding of the device.