Silicon PhotoMultipliers (SiPM): introductory seminar

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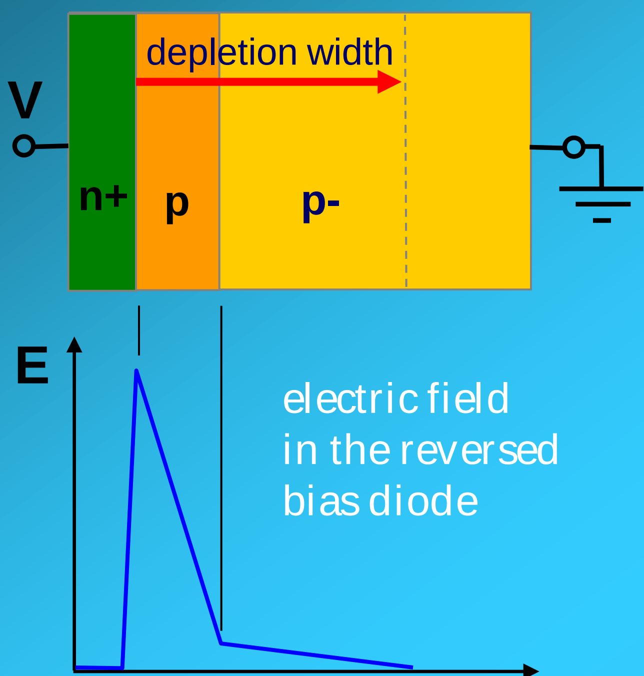
Outline:

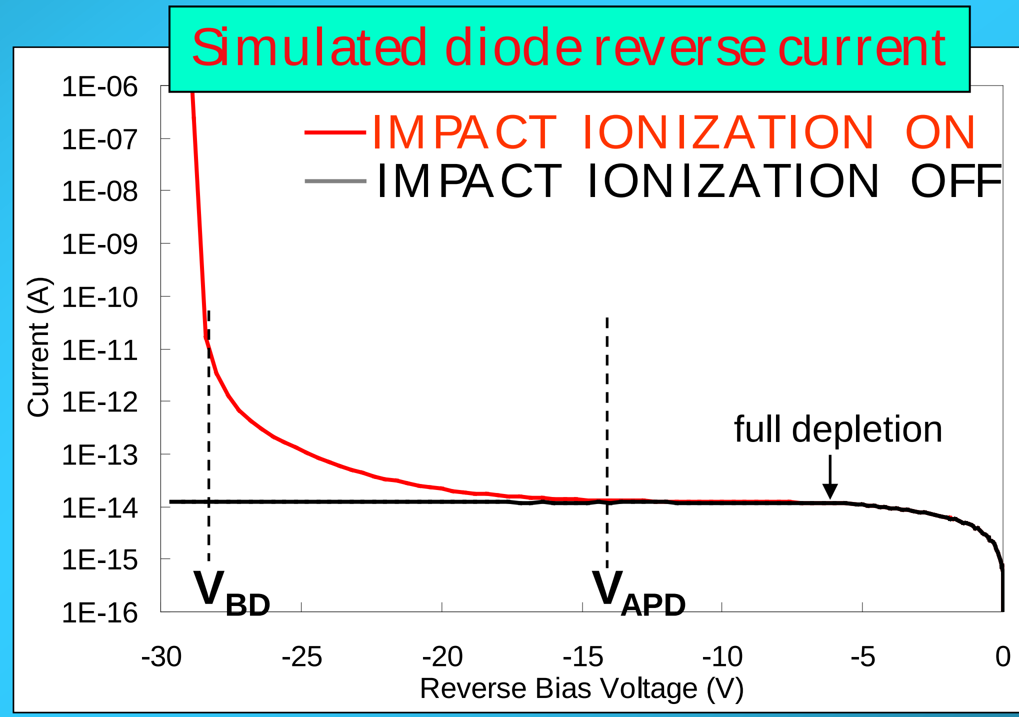
- Silicon Photomultipliers: principles of operation
- Important parameters in a SiPM
- Electrical model of a SiPM
- Some examples of applications
- Laboratory measurement 1: I-V characterization of SiPMs and single-cell APDs and precise gain measurement
- Laboratory measurement 2 : dark count measurements on SiPMs and single-cell APDs
- Laboratory measurement 3: application of large area (16 mm^2) SiPMs to the read-out of a scintillator pad equipped with wls fibers

SiPM: principle of operation - 1

Impact Ionization

diode structure





$V < V_{APD}$ $\Rightarrow$ **photodiode** 1 collected pair/generated pair

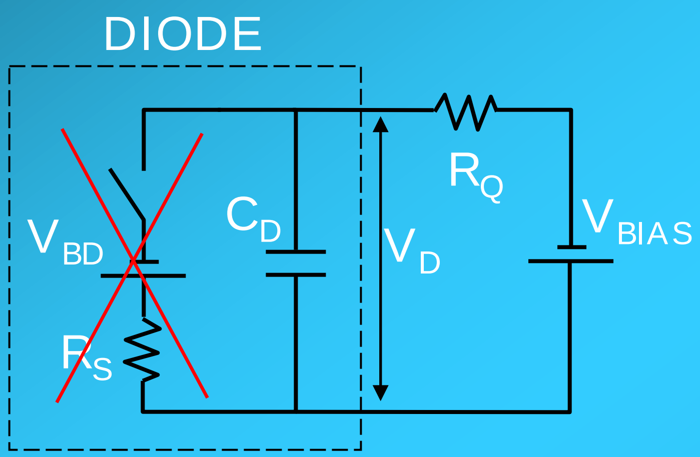
$V_{APD} < V < V_{BD}$ $\Rightarrow$ **APD** $\langle M \rangle$ collected pairs/generated pair

$V > V_{BD}$ $\Rightarrow$ **Geiger-mode APD** ∞ collected pairs/generated pair

SiPM: principle of operation - 2

Studied in detail in the '60 to model micro-plasma instabilities
[R.J. McIntrye, JAP vol.32, n.6 **1961**; R. Haitz, JAP vol.35, n.5 **1964**]

The GM-APD (passive quenched) can be modeled with an electrical circuit and two probabilities.



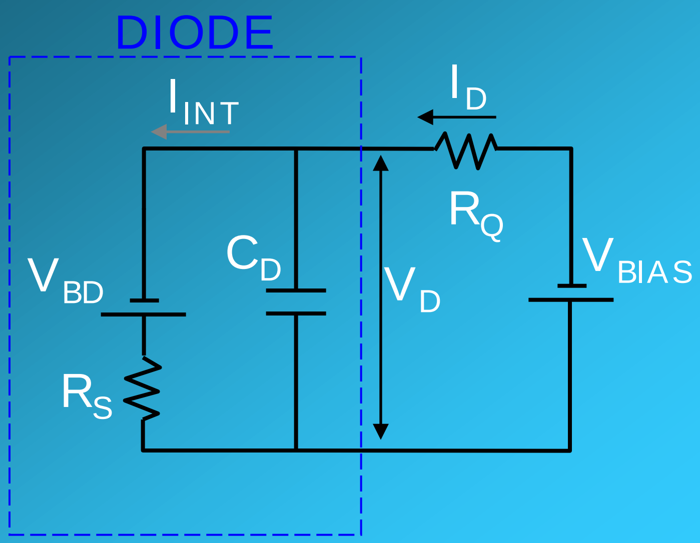
R_Q = quenching resistance
R_S = series resistance (emulates the avalanche spreading)
C_D = diode capacitance
V_{BD} = breakdown voltage
V_{BIAS} = bias voltage

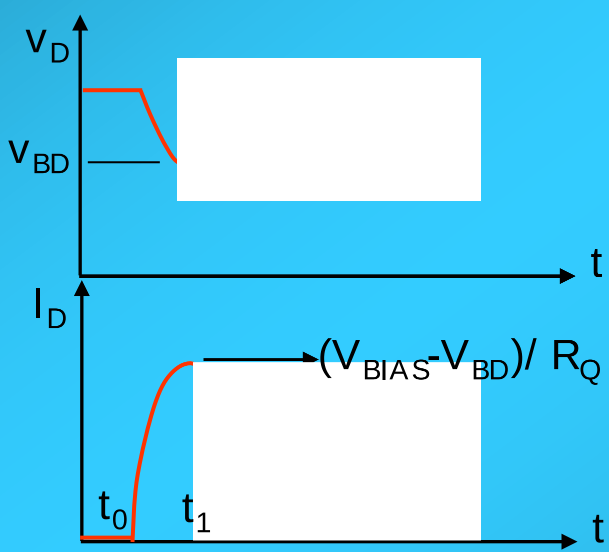
OFF condition:
switch open, capacitance charged to V_{BIAS}, no current flowing

P_{01} = turn-on probability
probability that a carrier traversing the high-field region triggers the avalanche

ON condition

SiPM: principle of operation - 3





ON condition:

avalanche triggered, switch closed

⇒ the capacitance discharges to V_{BD} with a time constant $R_S \cdot C_D$, at the same time the diode current grows to $(V_{BIAS}-V_{BD})/R_Q$

P_{10} = turn-off probability

probability that the number of carriers traversing the high-field region fluctuates to zero.

OFF condition:

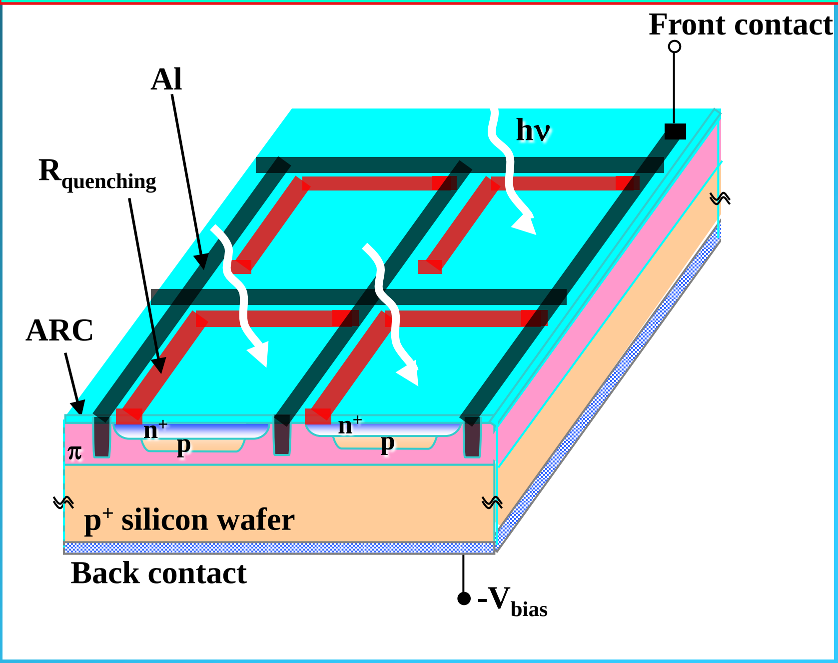
switch open

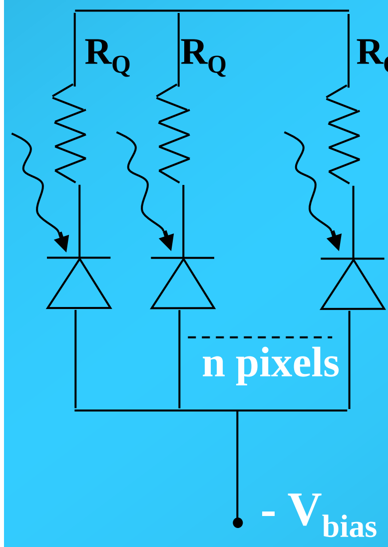
⇒ diode capacitance recharghes from V_{BD} to V_{BIAS} with a time constant $R_Q \cdot C_D$

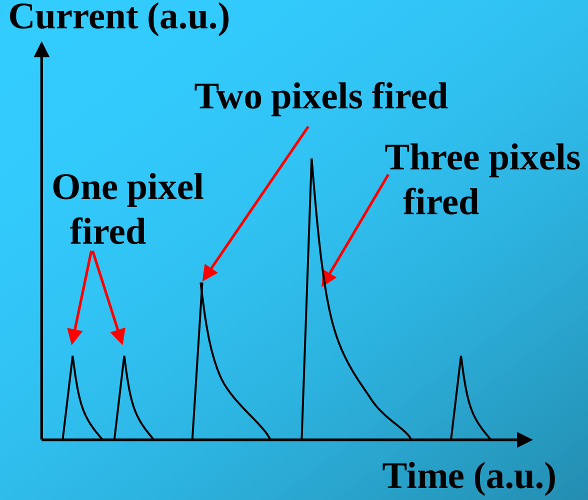
Ready for new detection

SiPM: principle of operation - 4

- Matrix of N micro-cells ("pixels") in parallel, connected to a common output node
- Each micro-cell: GM-APD + $R_{quenching}$
- V.M. Golovin and A. Sadygov (Russian patents 1996-2002)





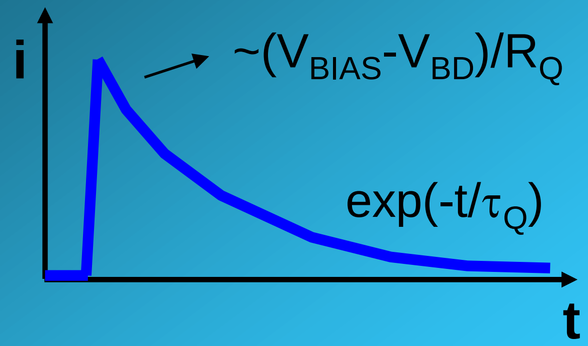


A single GM-APD gives no information about light intensity ⇒ in a SiPM the output charge is proportional to the number of triggered cells, that is (for PDE = 1) the number of photons

Key parameters in a SiPM: Gain, Noise, Photo-detection efficiency, Dynamic range, Time resolution

Important parameters in a SiPM

GAIN



G = number of carriers produced per photon absorbed

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

GAIN = $$I_{MAX} \cdot \frac{\tau_Q}{q} = \frac{(V_{BIAS} - V_{BD})}{R_Q} \cdot \frac{\tau_Q}{q} = \frac{(V_{BIAS} - V_{BD}) \cdot C_D}{q}$$

NOISE

1) **Primary dark count** ⇒ current pulses triggered by non-photogenerated carriers (main source of dark carriers: thermal generation in the depleted region)

2) **Afterpulsing** ⇒ secondary current pulse caused by a carrier trapped during the primary avalanche and released after a certain time

3) **Optical cross-talk** ⇒ excitation of neighboring cells due to photon emission during avalanche discharge

PDE

PDE = Npulses / Nphotons = QE · P_{01} · FF

- QE = device quantum efficiency
- P_{01} = triggering probability
- FF = Fill Factor (geometric efficiency)

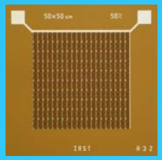
SiPM: comparison with PMTs

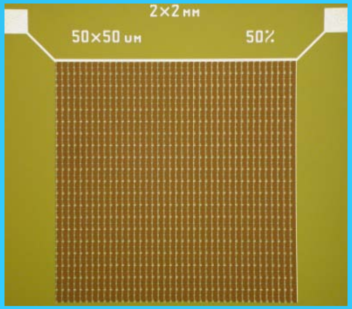
- Main advantages
  - Low bias voltage (~ 50V)
  - Insensitivity to magnetic fields
  - Compact and robust
  - Low cost
  - Simple readout
- Drawbacks
  - Performance degradation after radiation damage
  - Temperature-dependent dark noise
  - Sensitivity of V_{BD} and gain with T
- (Some) Producers:
  - Obnitsk/CPTA (Russia) N.B.: MRS resistors
  - JINR (Russia) N.B.: MRS resistors
  - MEPHI/PULSAR (Russia)
  - Hamamatsu (Japan)
  - Zecotek (U.S.A./Singapore)
  - Novel Device Laboratory (China)
  - SensL (Ireland)
  - FBK-irst (Italy)

FBK-irst SiPMs - 1

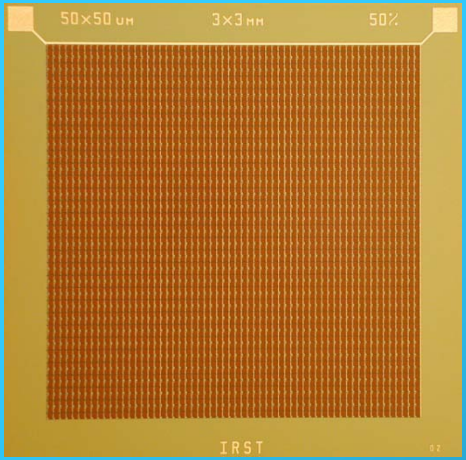
Fill factor (geometrical efficiency): 40x40 μm² ⇒ ~ 40%
50x50 μm² ⇒ ~ 50%
100x100 μm² ⇒ ~ 76%

Geometries:

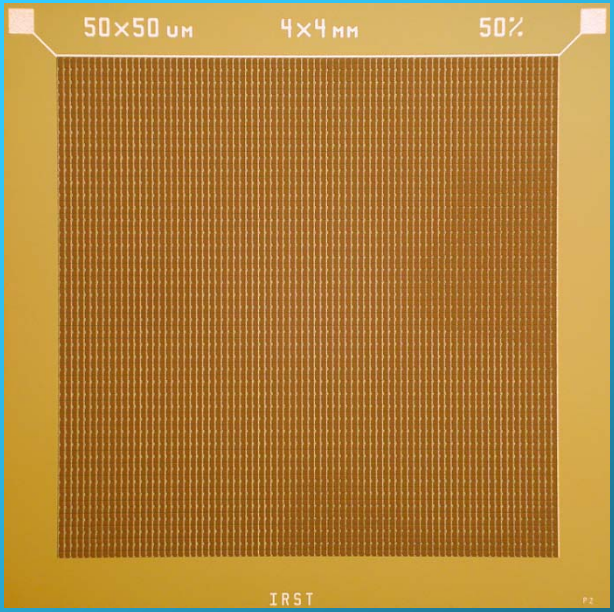

1x1 mm²



2x2 mm²



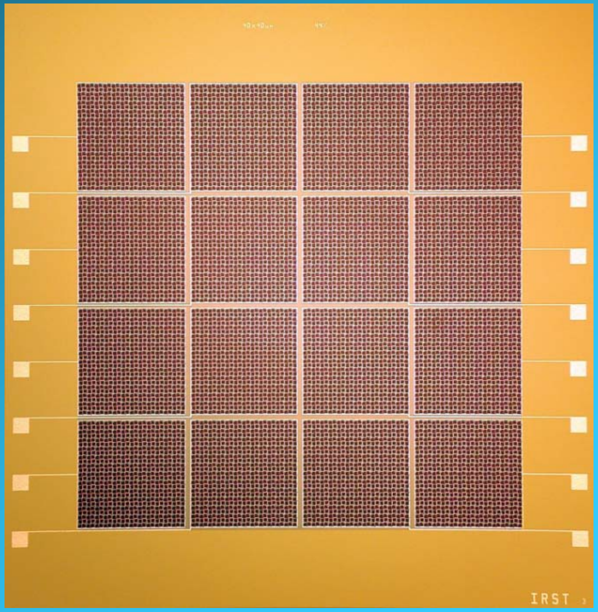
3x3 mm²

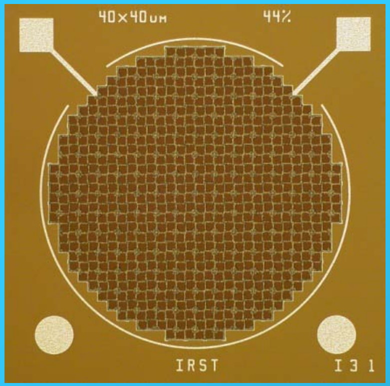


4x4 mm²

FBK-irst SiPMs - 2

Geometries:

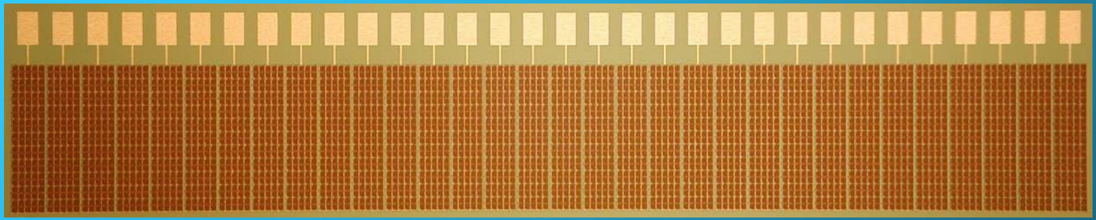




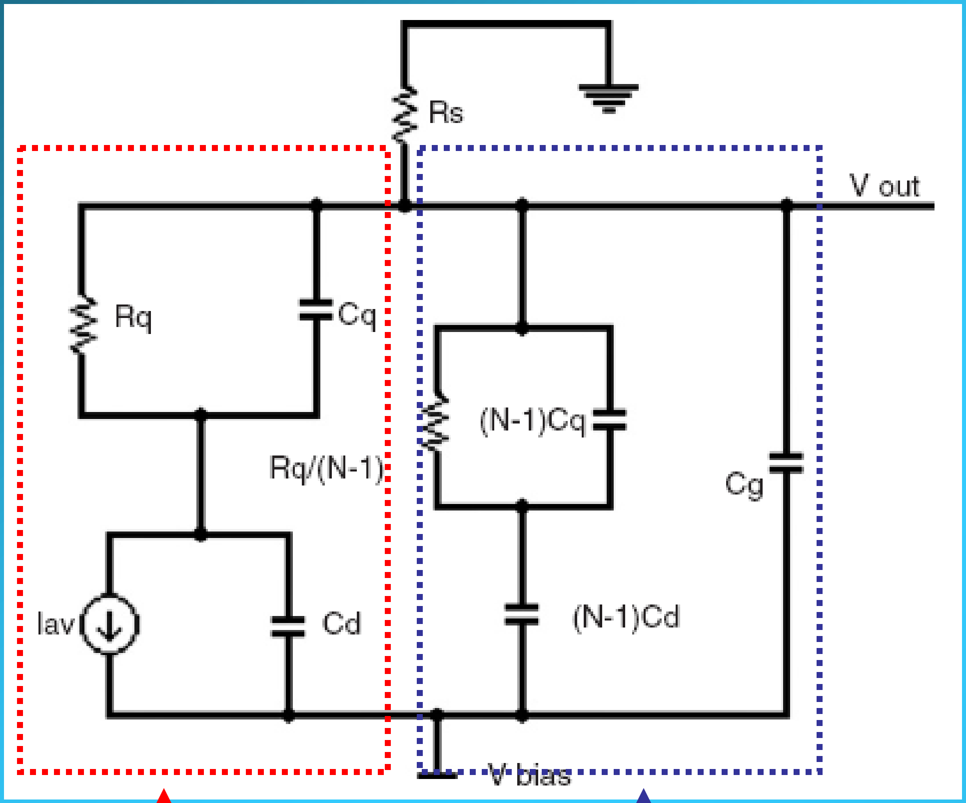
Circular: Ø 1.2 mm
Ø 2.8 mm

Matrices: 4x4 elements of 1x1 mm^2 SiPMs

Linear arrays: 8, 16, 32 elements of 1x0.25 mm^2 SiPMs



Electrical model of a SiPM



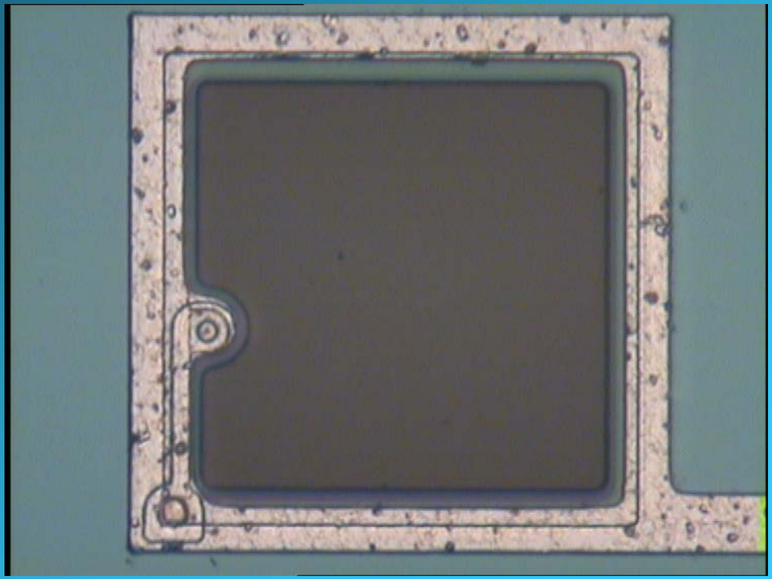
Firing microcell

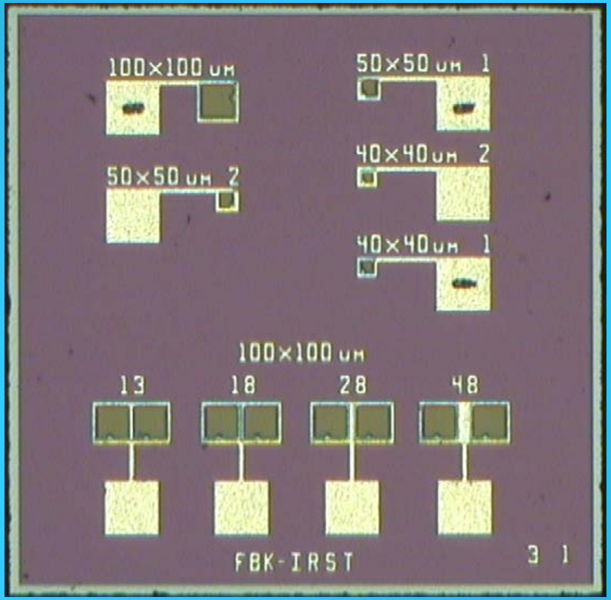
Parallel of the other microcells

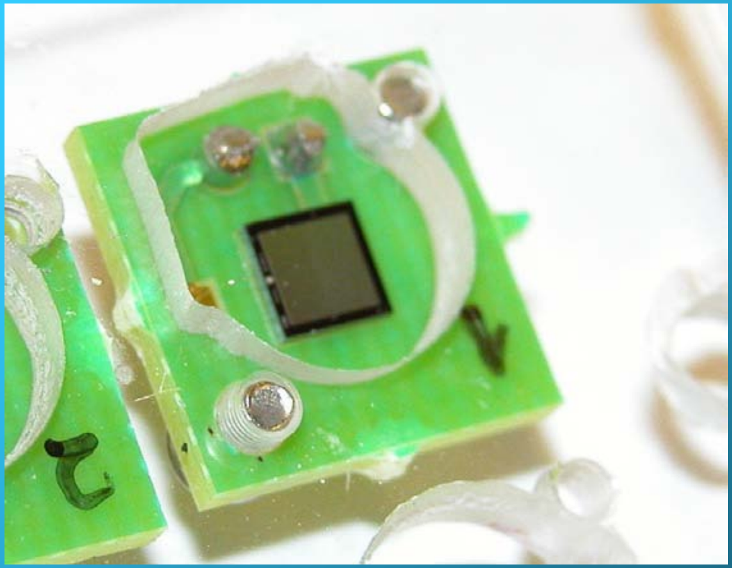
Iav: signal current
Cd: single diode capacitance
Rq: quenching resistance
Cq: parasitic capacitance associated with Rq
Cg: grid and substrate parasitics
Rs: input impedance of the front-end electronics

(F. Corsi et al., Nuclear Instruments and Methods in Physics Research A 572 (2007) 416–418)

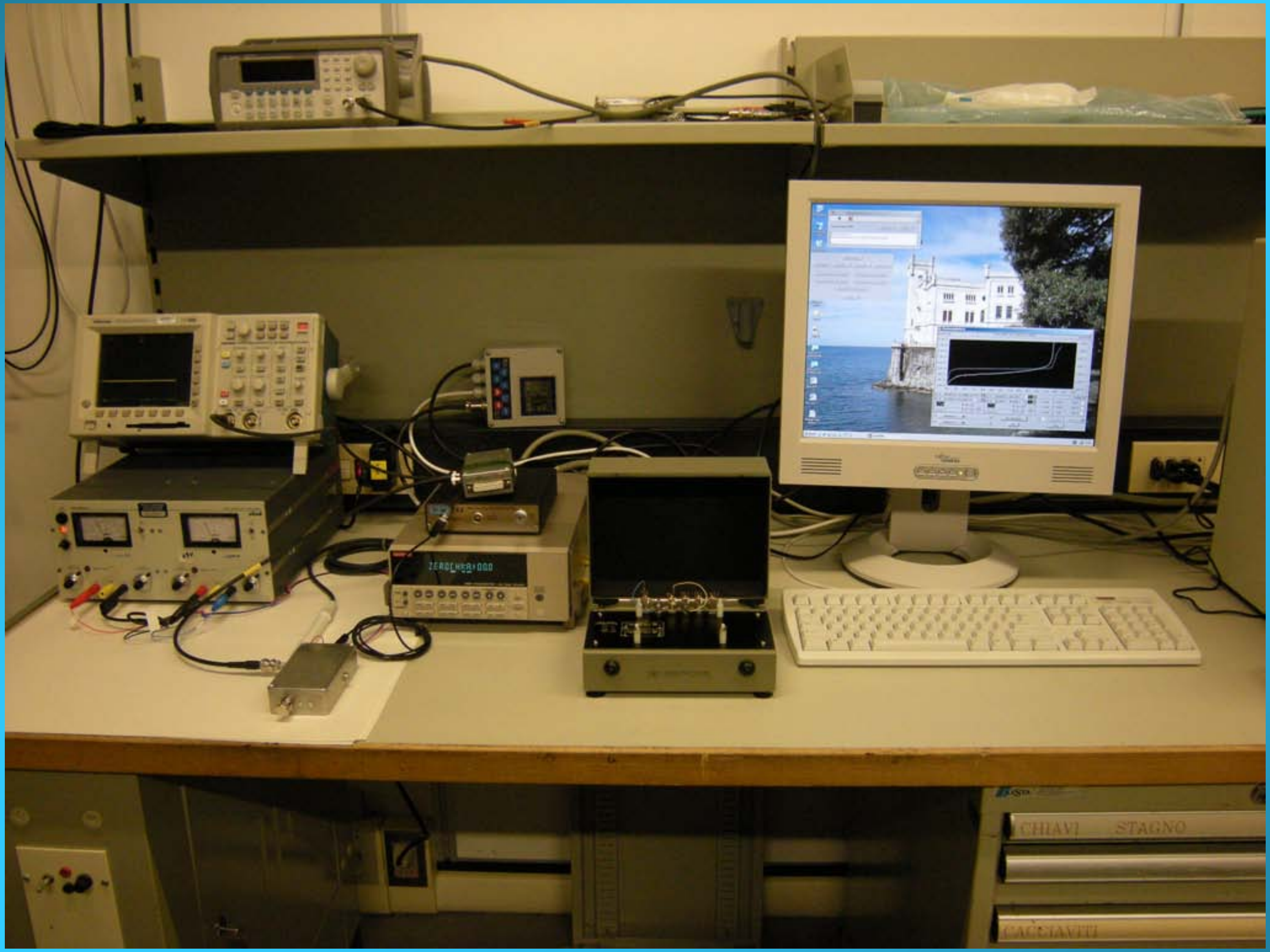
Some pictures of single cells and SiPMs







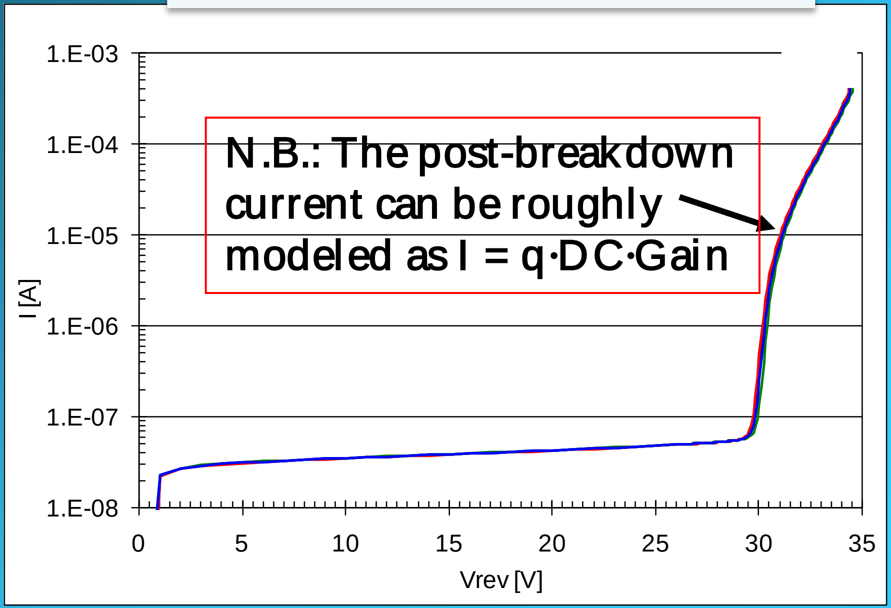
Laboratory set-up n. 1



Laboratory set-up n. 1

Laboratory set-up n. 1

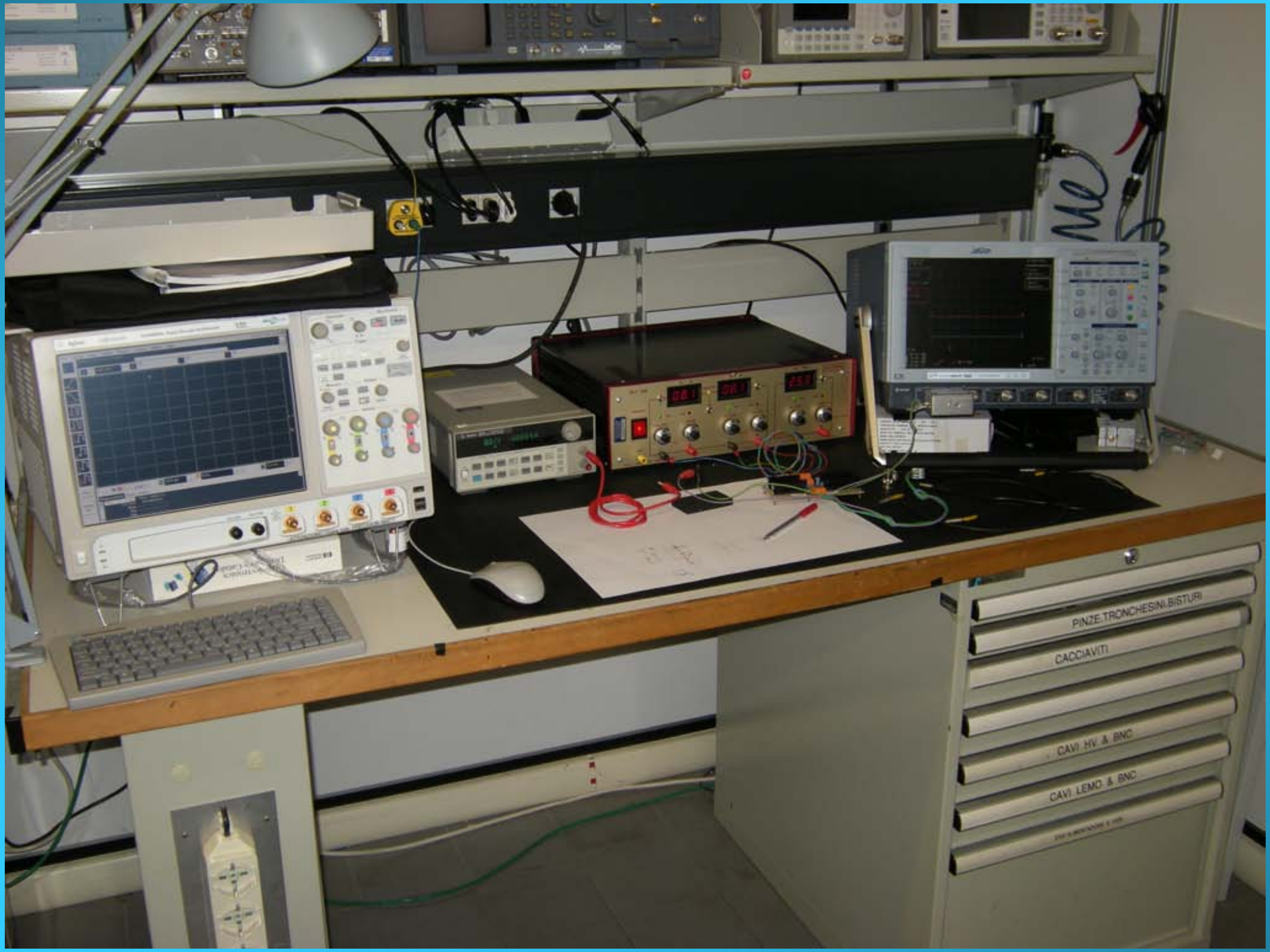
Reverse I-V



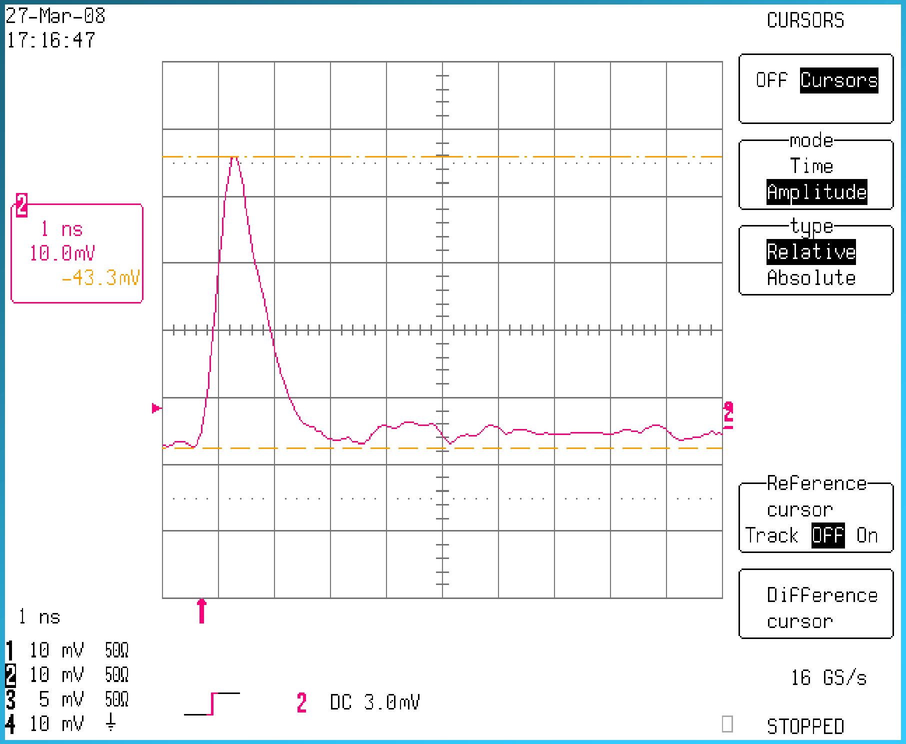
- Functionality of the device
- Breakdown voltage V_{BD}
- Dark count estimate

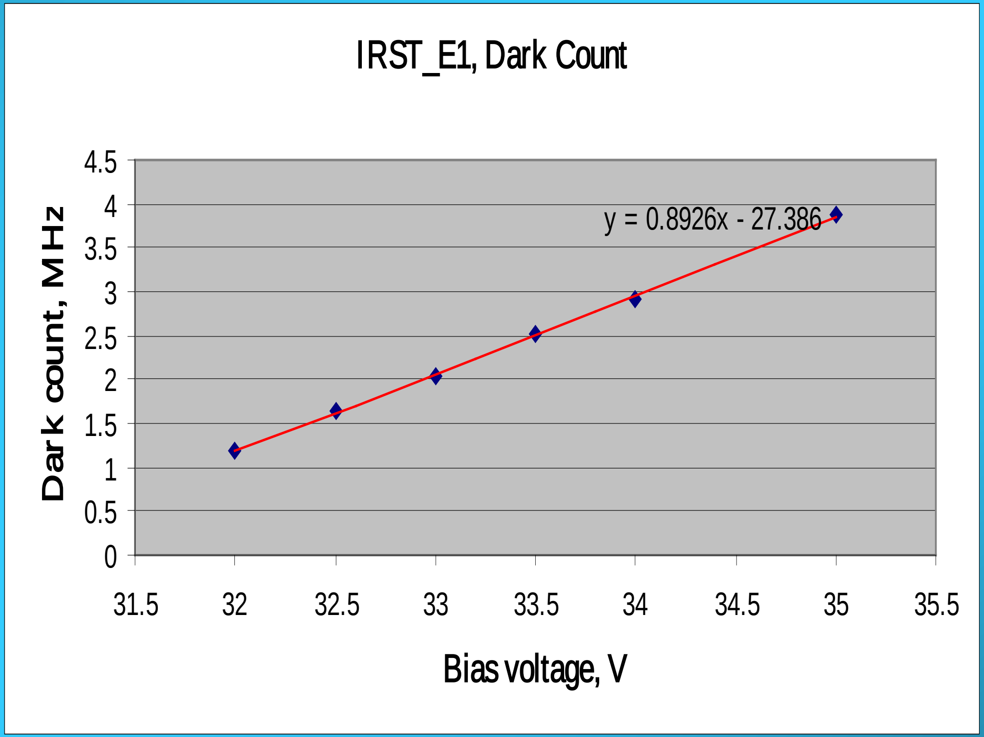
- I-V measurements on single-cell APDs and SiPMs (Hamamatsu and FBK) (Keithley 6487 Picoammeter/Voltage source acquired via GPIB with a LabView program)
- Precise measurement of the gain on single-cells APDs with a CSA (Amptek A250 CSA + Digital Shaper)

Laboratory set-up n. 2



Laboratory set-up n. 2





- Dark count vs Overvoltage measurements with large bandwidth DSO (LeCroy WavePro 960 2 GHz, 16 Gs/s and Agilent 90604 6 GHz, 20 Gs/s)

Laboratory set-up n. 3

Laboratory set-up n. 3

- Application of large area (4x4 mm^2, 6400 microcells) FBK SiPMs to the read-out of wls fibers coupled to a plastic scintillator

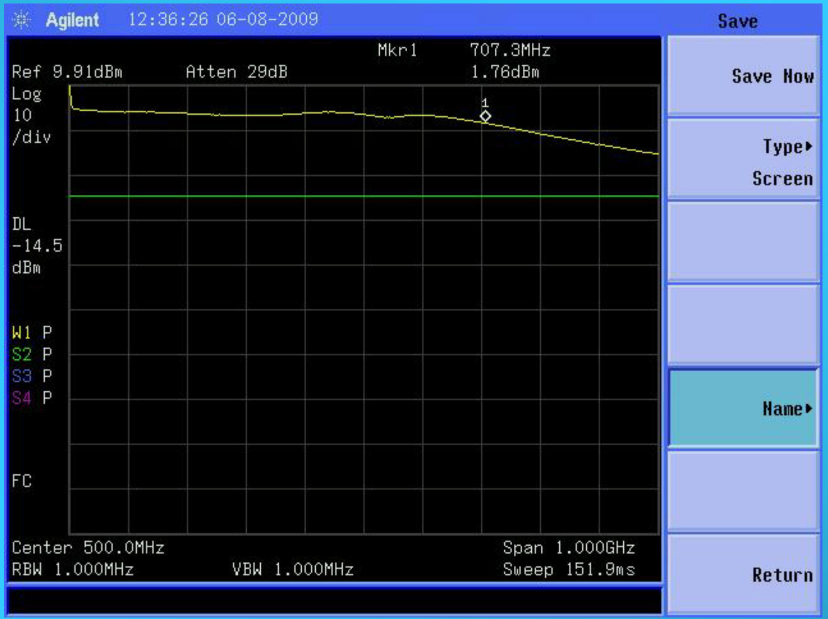
- Fast front-end electronics for the SiPms read-out

- Use of a complete front-end + DAQ chain

- Signals from cosmic rays and γ sources (^{60}Co and ^{137}Cs)

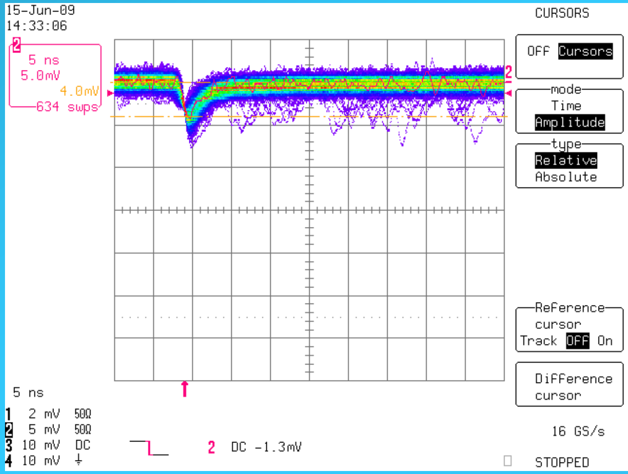
Laboratory set-up n. 3

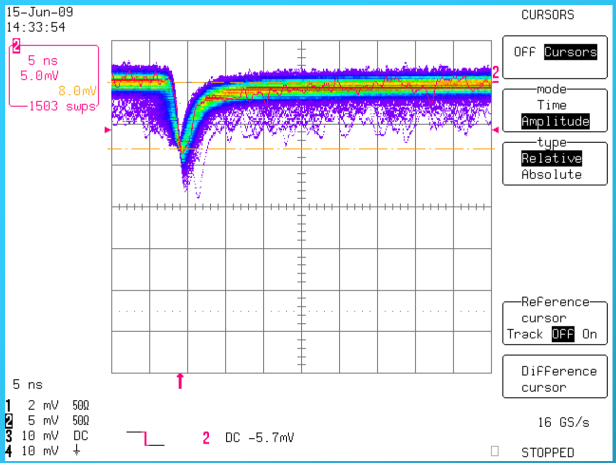
Designed and realized at "El. and Det. Lab" of INFN Trieste

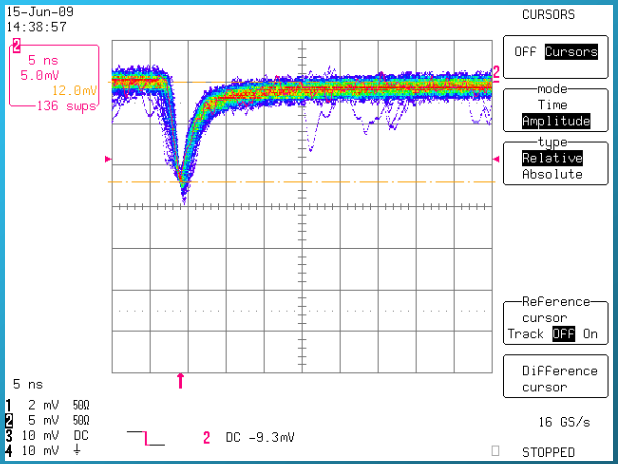


PCB dimensions 4 cm x 3 cm

Bandwidth from DC to 700 MHz, gain 16.3 dB



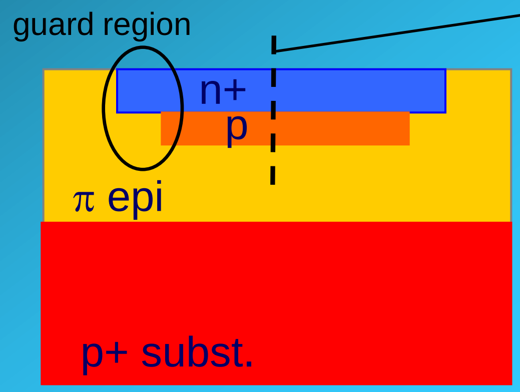


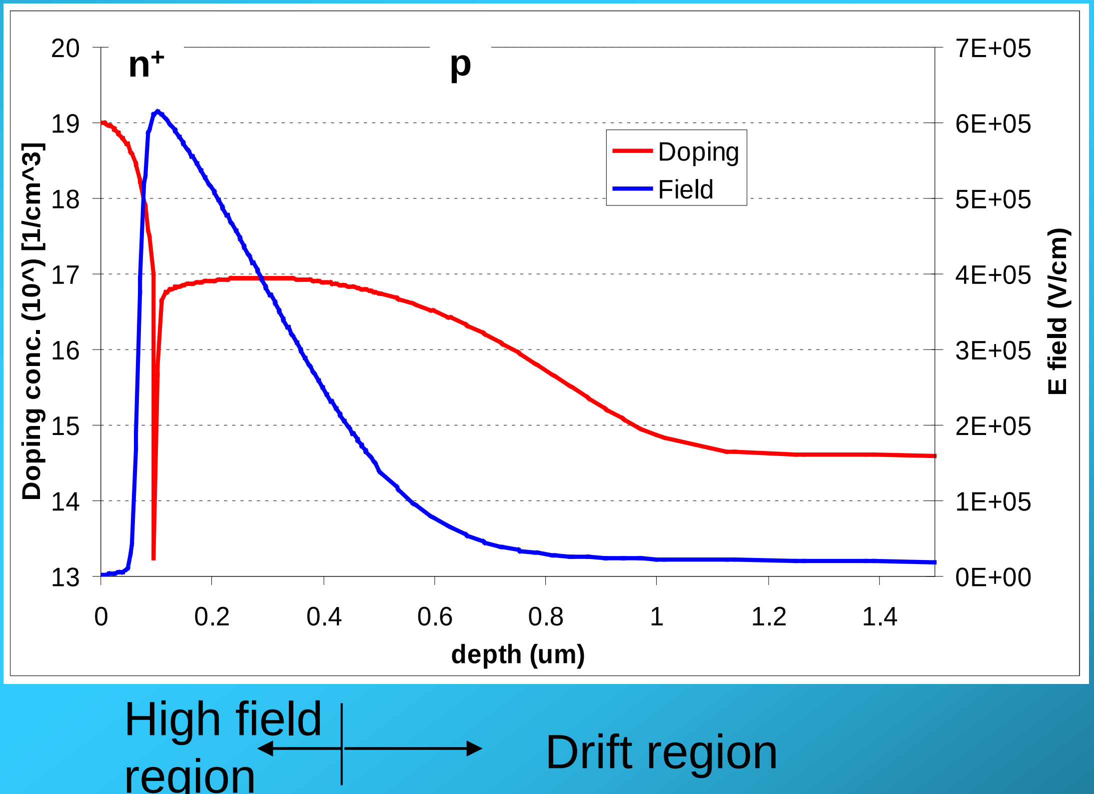


Spare slides

FBK-irst technology

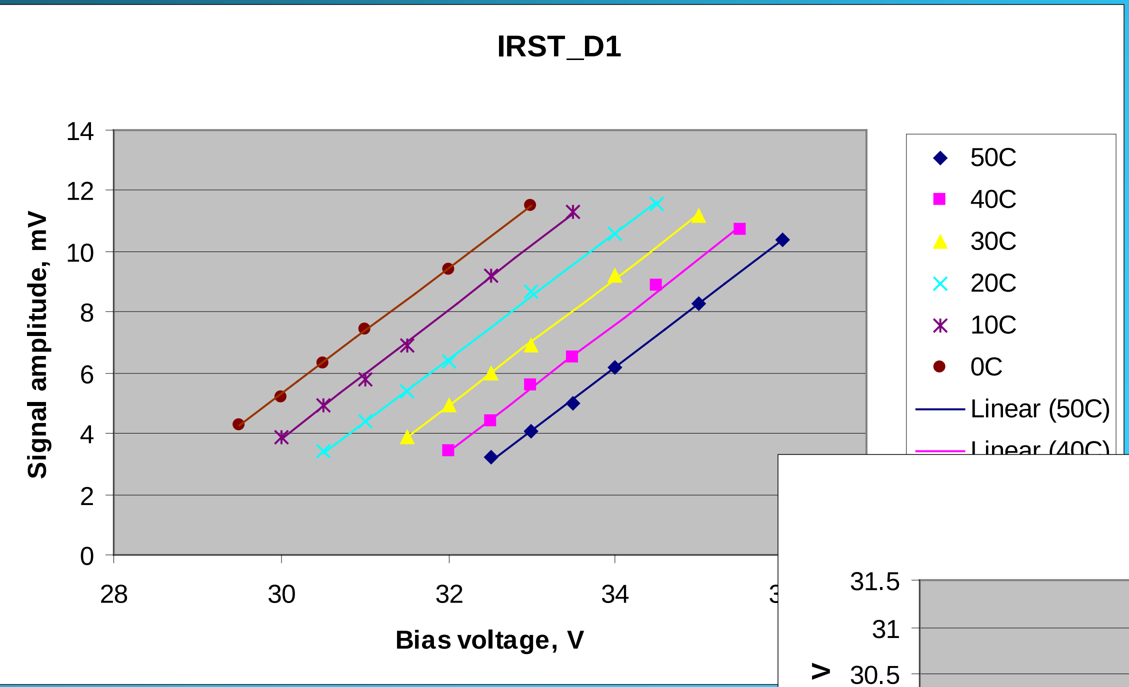
Shallow-Junction SiPM



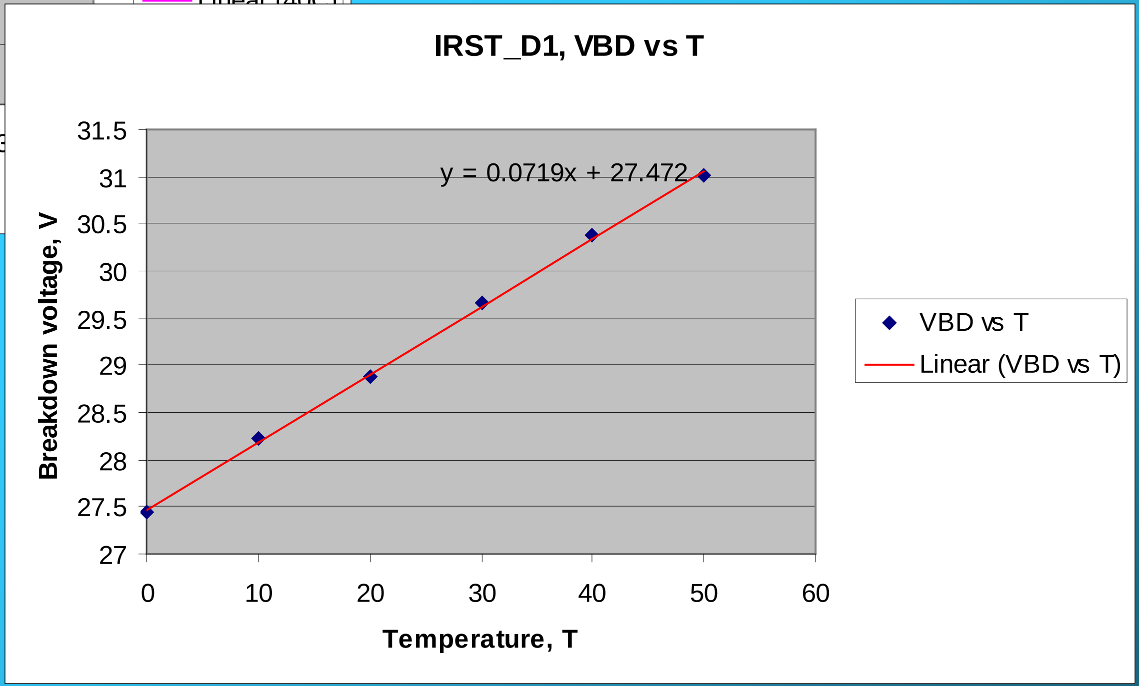


1) Substrate: p-type epitaxial
2) Very thin (~ 0.1 μm) n^+ layer
3) Polysilicon quenching resistance
4) Anti-reflective coating optimized for λ ~ 420nm

Temperature effects



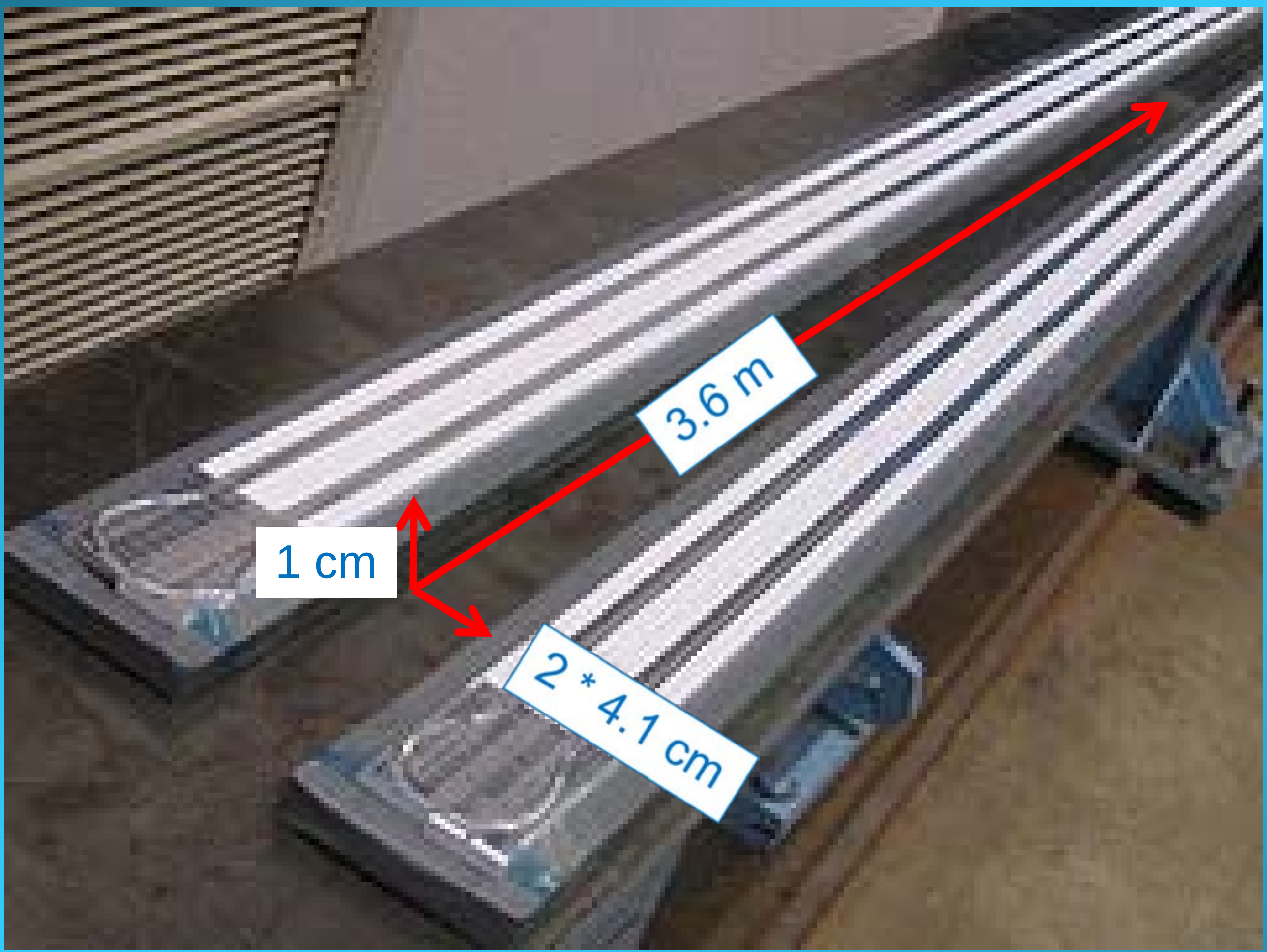
DUT placed in a climatic chamber (with humidity control).
Amplifier located outside the cabinet, connection via a special 18 GHz f_t 50-Ω cable.

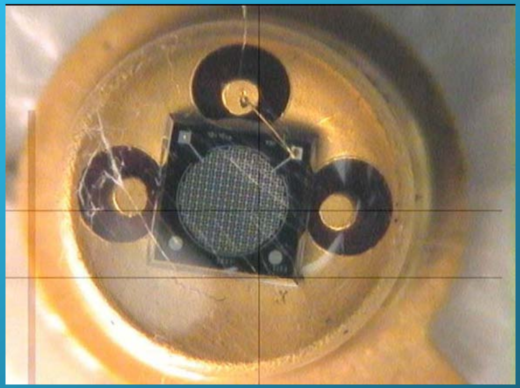


$dV_{BD}/dT \approx 70\ mV/°C$

Application 1: read-out of large extruded scintillators for muon detectors tail-catchers - 1

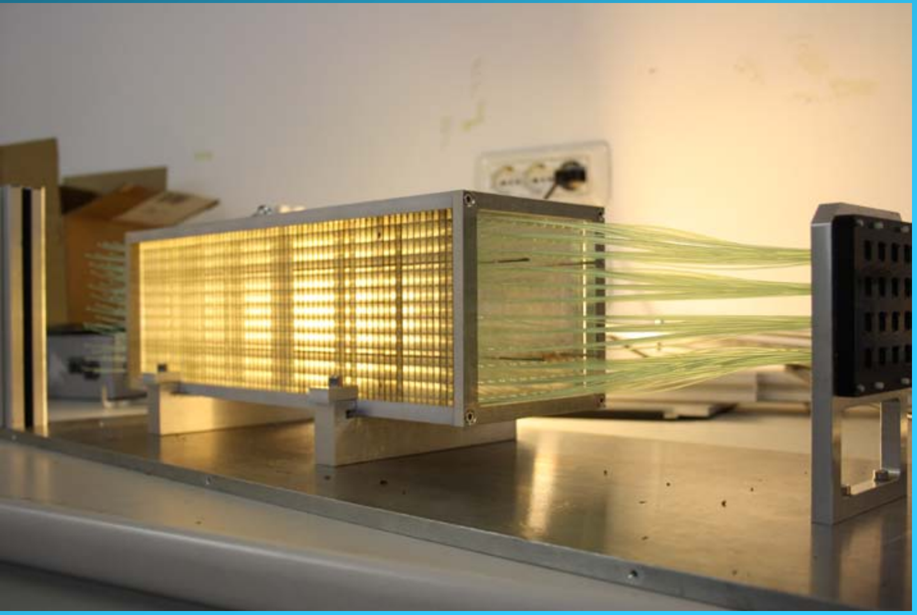
INFN FACTOR Experiment

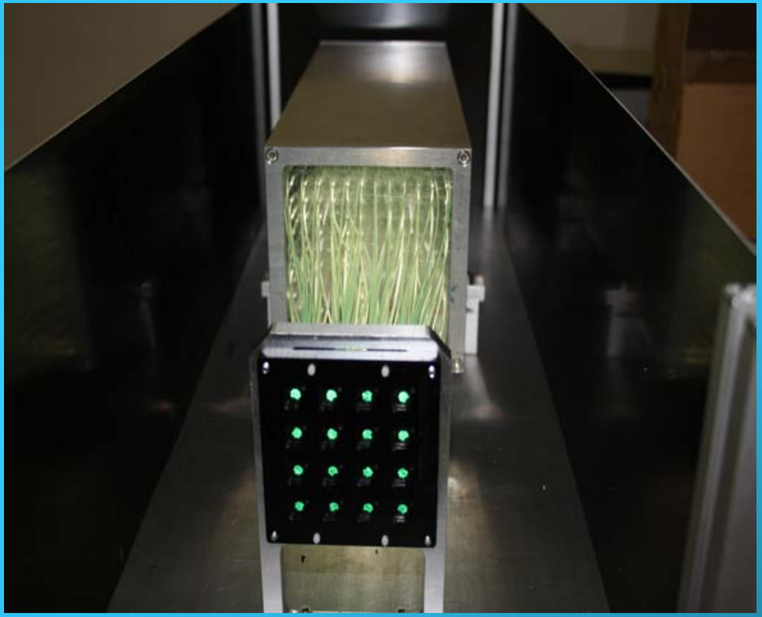




Application 2: read-out of prototype "Shashlik" calorimeters

INFN FACTOR Experiment





- 70 tiles of scintillator 12x12 cm^2, 4 mm thick and 69 tiles of lead (1.5 mm thick), 19 X_0
- 144 1.2 mm WLS fibers for the readout grouped in 36 bundles of 4
- Read-out with 36 large area (16 mm2, 6400 microcells) SiPMs by FBK-irst
- Test beams foreseen in October 2010
- **Each SiPM will be equipped with a front-end/driving amplifier (Ampli 2)**

Irradiation tests of SiPMs - 1

The radiation resistance of SiPMs is crucial in view of their application in "real" experimental conditions (especially in harsh radiation environments like LHC and SLHC).

FACTOR started a systematic measurement campaign in order to study the resistance to radiation effects of **SiPMs produced by different manufacturers**

: to study both surface and bulk damage in the devices

: **X-rays (up to 50 keV) and neutrons**

- X-rays

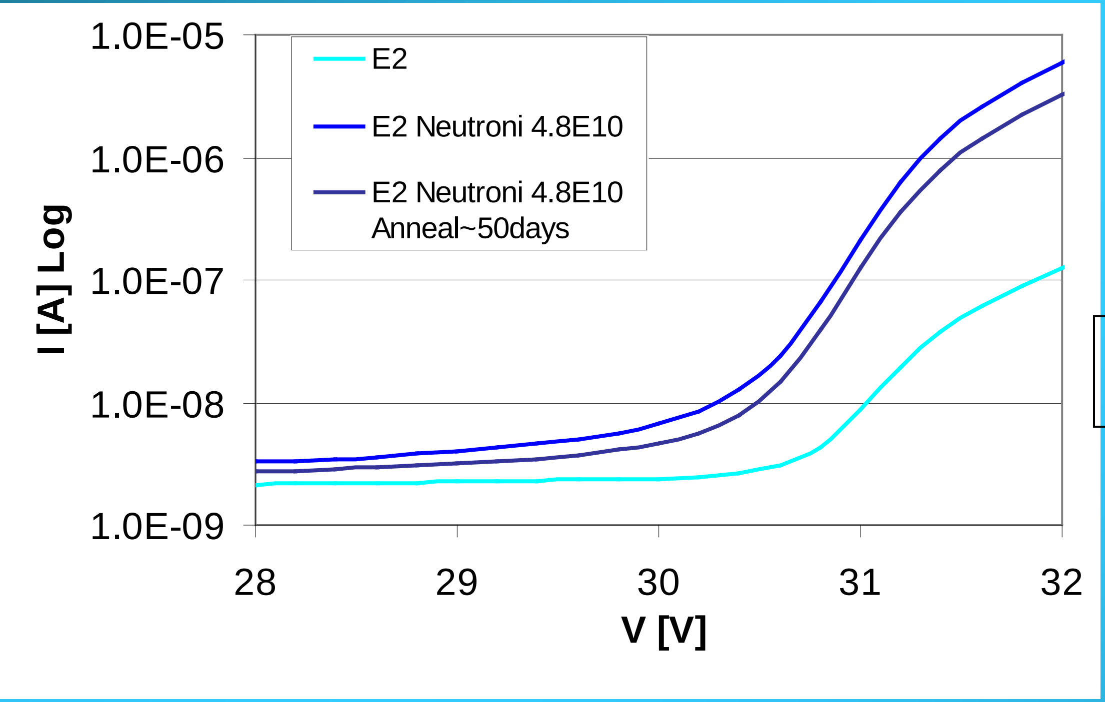
nal Laboratories of Legnaro (LNL), X-ray tube (W target), rate measured with calibrated Si p-i-n diodes

- Neutrons

eactor of the Institute Josef Stefan of Ljubljana (Slo), max power ~ n fluence achievable

I-V characterization, dark count and gain before and er irradiations, annealing studies

Irradiation tests of SiPMs - 2



FBK-irs circular SiPM
1.2 mm diam, 688 pixels

24 devices from FBK-irst, Photonique (CPTA) and Hamamatsu irradiated so far

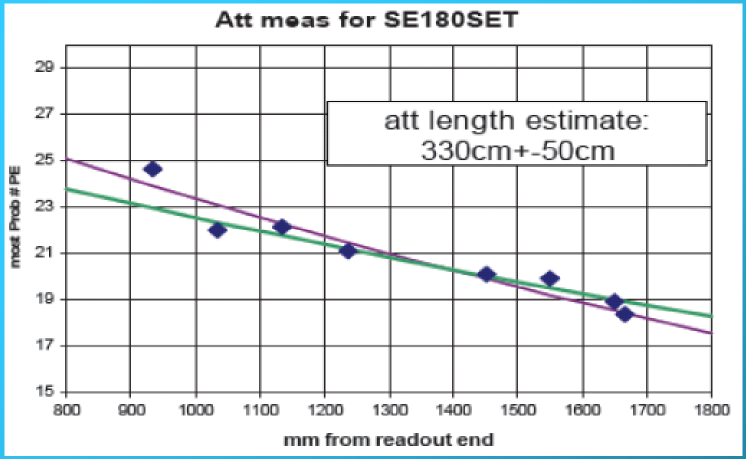
- **X-rays: 50, 100, 150, 300 and 500 krad**
- **neutrons: $4.8 \cdot 10^{10}$ and 10^{11} n cm^{-2}**

Data analysis and study of the annealing effects are currently going on

Further irradiations are foreseen in the next months on single microcells

Application of SiPMs to extruded scintillators for tail catchers - 2

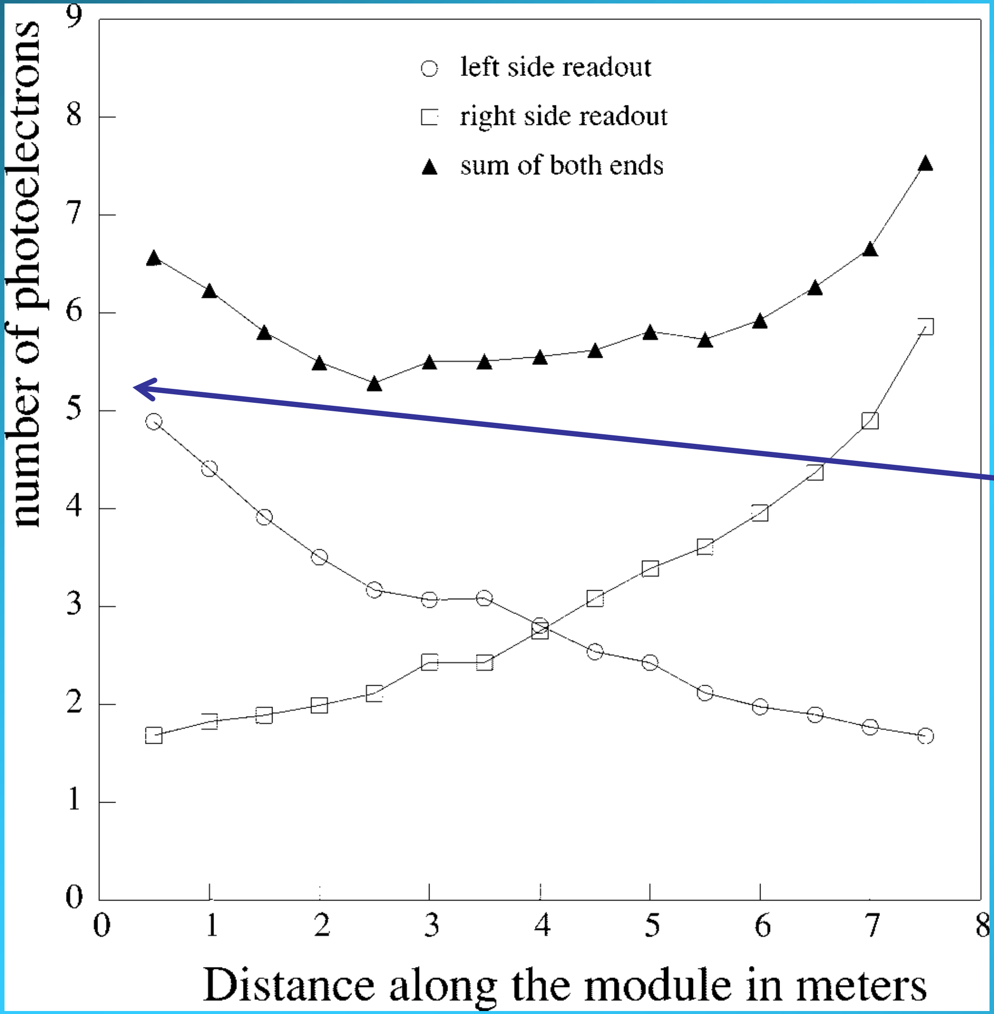
Preparazione di barre di scintillatori estrusi di diversa lunghezza da 1 a 3 m) per i test su fascio di pioni (120 GeV/c) al FNAL.



Misura della lunghezza di attenuazione delle barre di scintillatori estrusi equipaggiati con fibre WLS e SiPM.

Prototipo a 4 canali di scheda di amplificazione/acquisizione usata nei test su fascio a FNAL. Ogni canale (accoppiato in A/C con il SiPM) contiene amplificatore, ADC a 12 bit con un campionamento di 210 MSPS, memoria per 8K punti e uscita USB. Dotata anche di generatore di tensione di bias fino a 100 V con controllo dell'offset e monitor di corrente per ogni canale.

Application 1: read-out of large extruded scintillators for muon detectors tail-catchers - 2

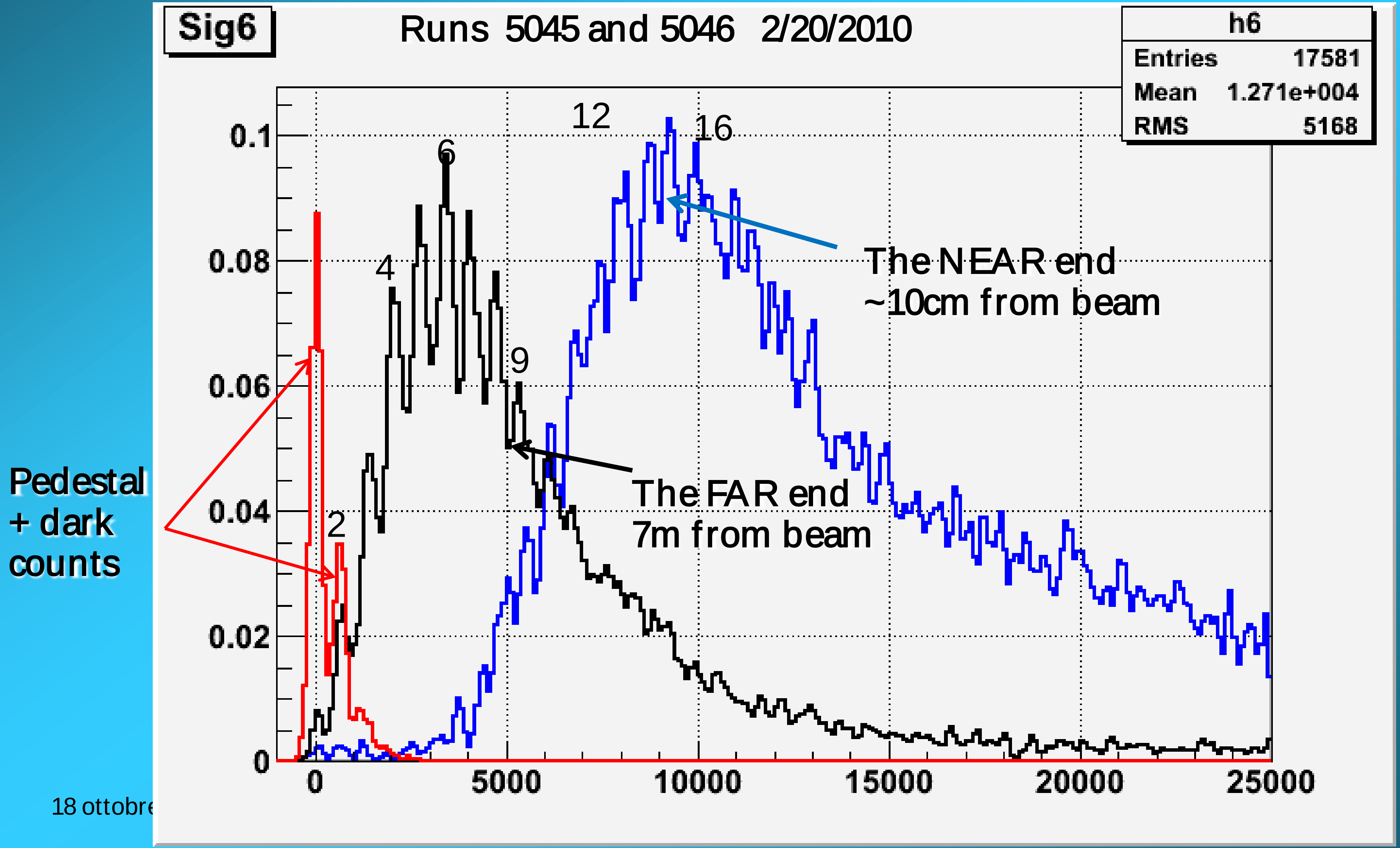


Old measurements with same type of scintillators and wls fibers with PMTs IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 49, NO. 3, JUNE 2002

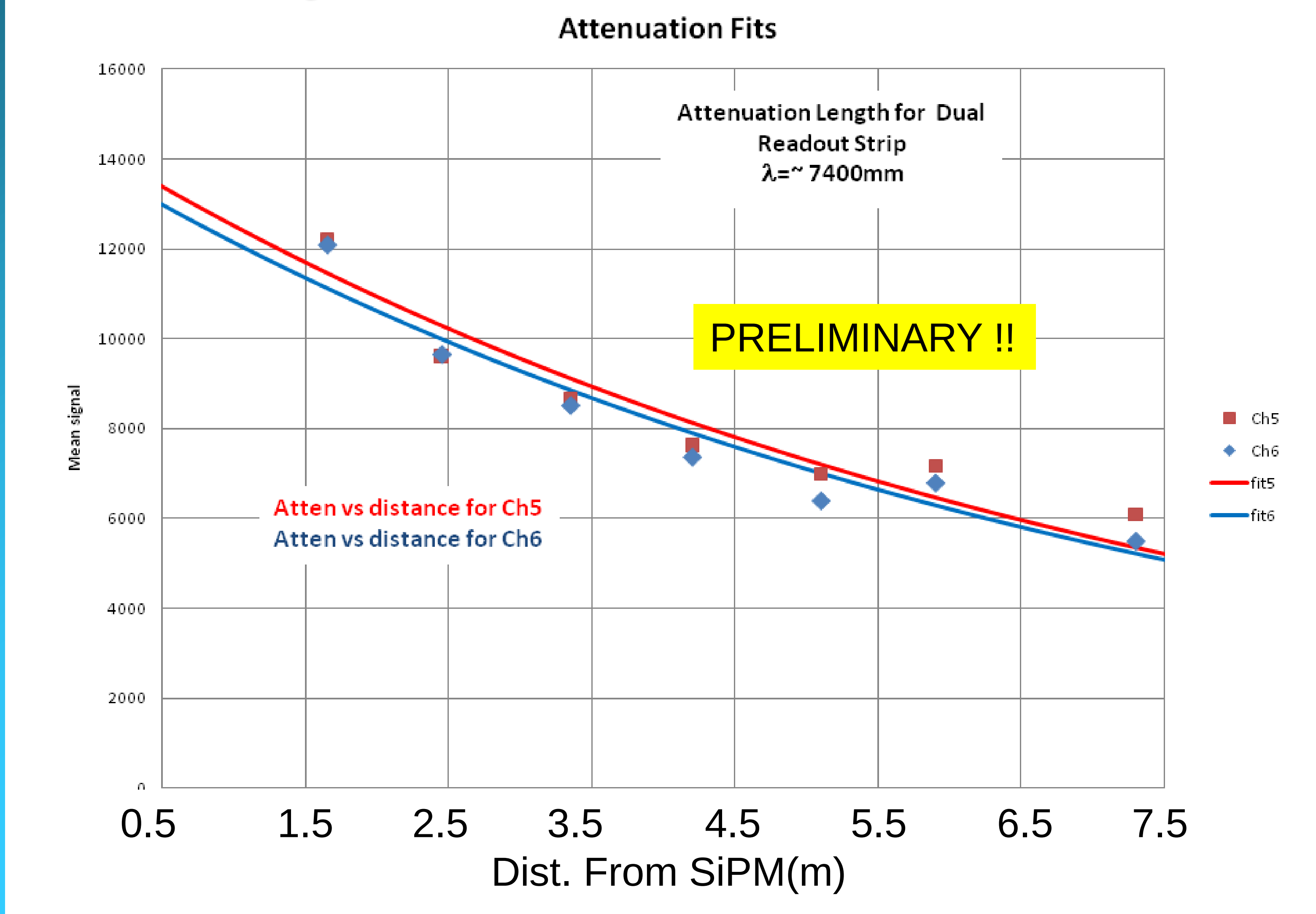
Please note the scale here

This was done with cosmic ray muons.

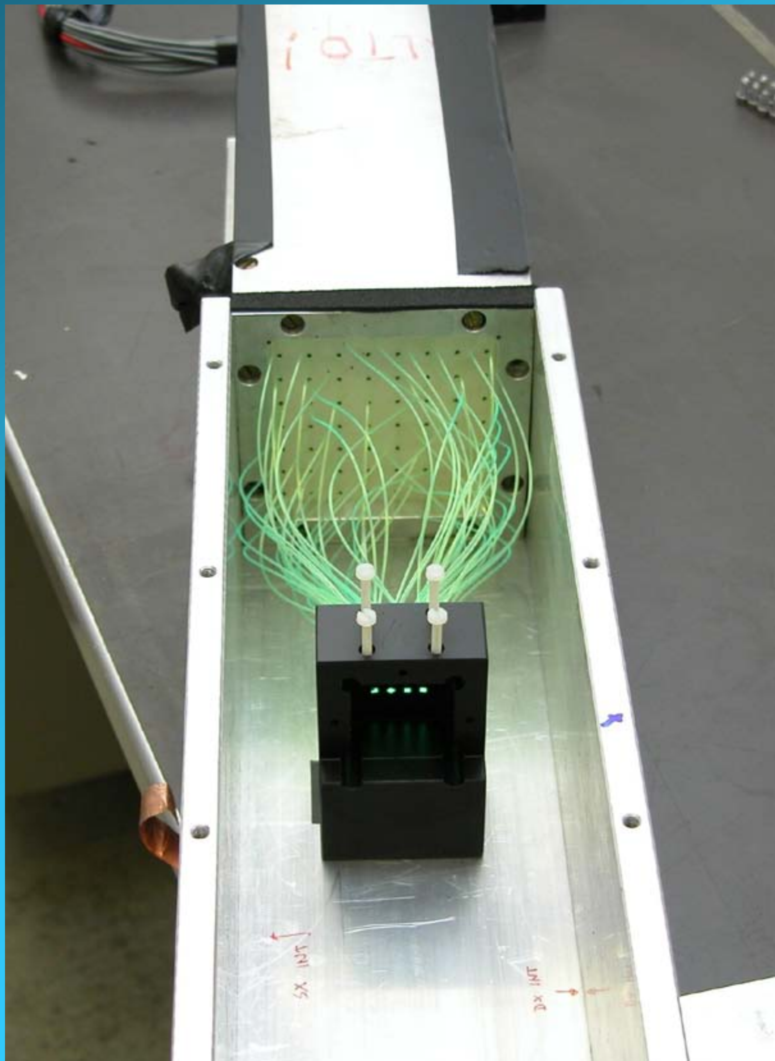
Application 1: read-out of large extruded scintillators for muon detectors tail-catchers - 3



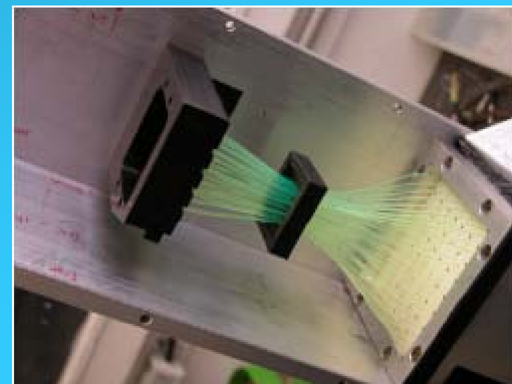
Application 1: read-out of large extruded scintillators for muon detectors tail-catchers - 4



Application 2: read-out of prototype “Shashlik” calorimeters - 1



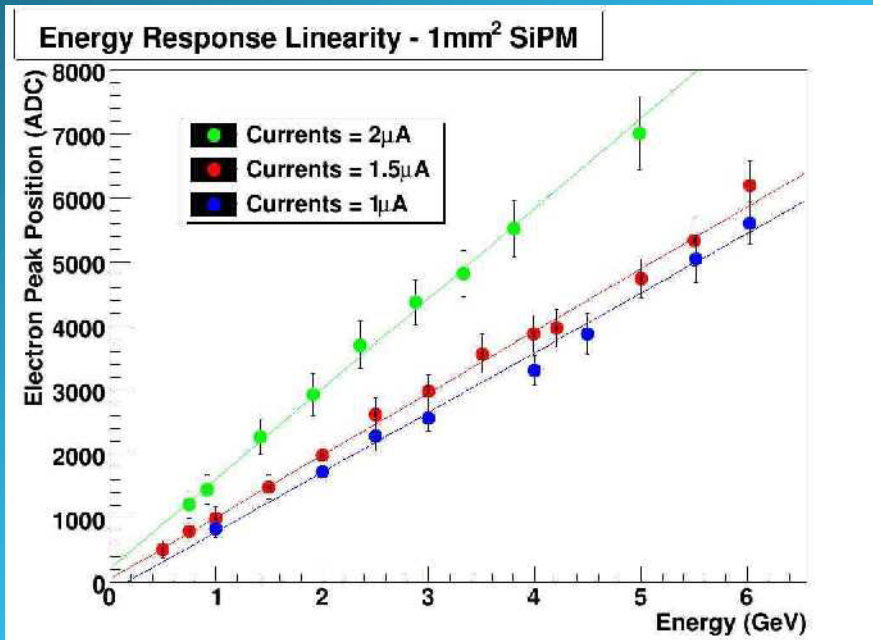
The “prototype 0” Shashlik calorimeter



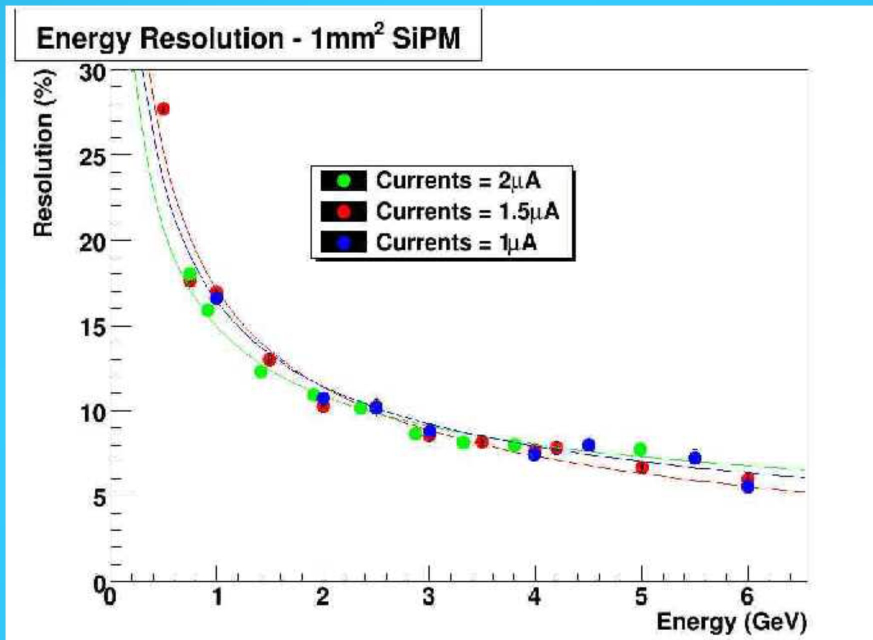
- Manufactured at INFN - Trieste
- 41 tiles of scintillator 8x8 cm^2 and 40 tiles of lead (both 3.27 mm thick) for a total of 24 X_0
- 64 0.8mm WLS fibers (Kuraray Y-11) for the readout grouped in bundles of 4
- Circular (Ø 1.2 mm) SiPMs by FBK-irst
- Tested at the CERN PS T10 and SPS H4 beamlines
- **No front-end/amplifying electronics used for the SiPMs!!!**

Application 2: read-out of prototype "Shashlik" calorimeters - 2

Low energy results: CERN PS T10 beamline, negative particles 0.5 – 6 GeV/c



Linearity obtained with the SiPMs biased with 1, 1.5 and 2 μA

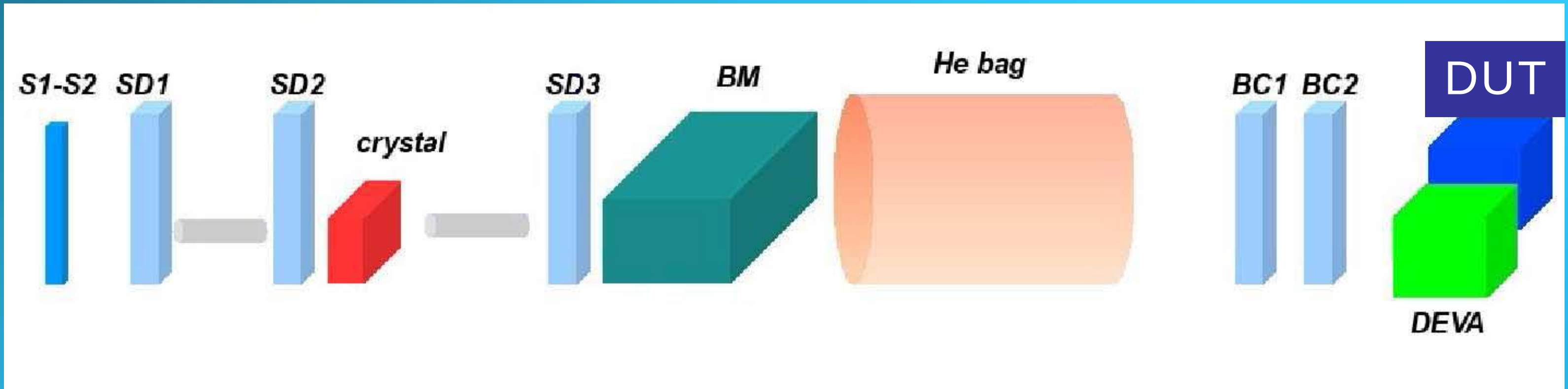


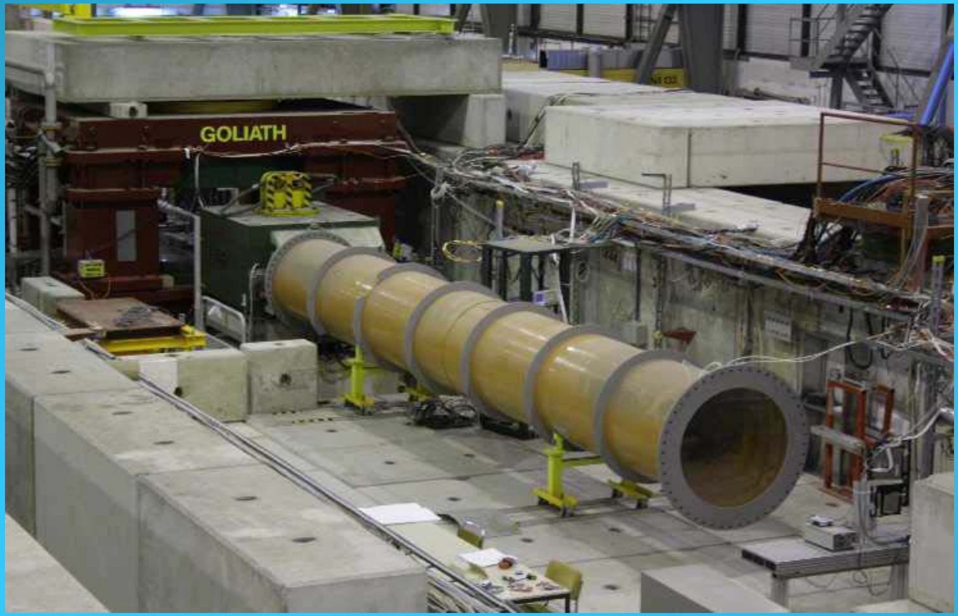
Energy resolution obtained with the SiPMs biased with 1, 1.5 and 2 μA

	SIMULATION	SiPM (1 μA)	SiPM (1.5 μA)	SiPM (2 μA)
Stochastic	12%	16.4%	15.6%	14.6%
Constant	~ 10^{-5} %	~ 10^{-6} %	~ 10^{-6} %	3.6%

Application 2: read-out of prototype "Shashlik" calorimeters - 3

High energy results: CERN SPS H4 beamline, photons up to 120 GeV

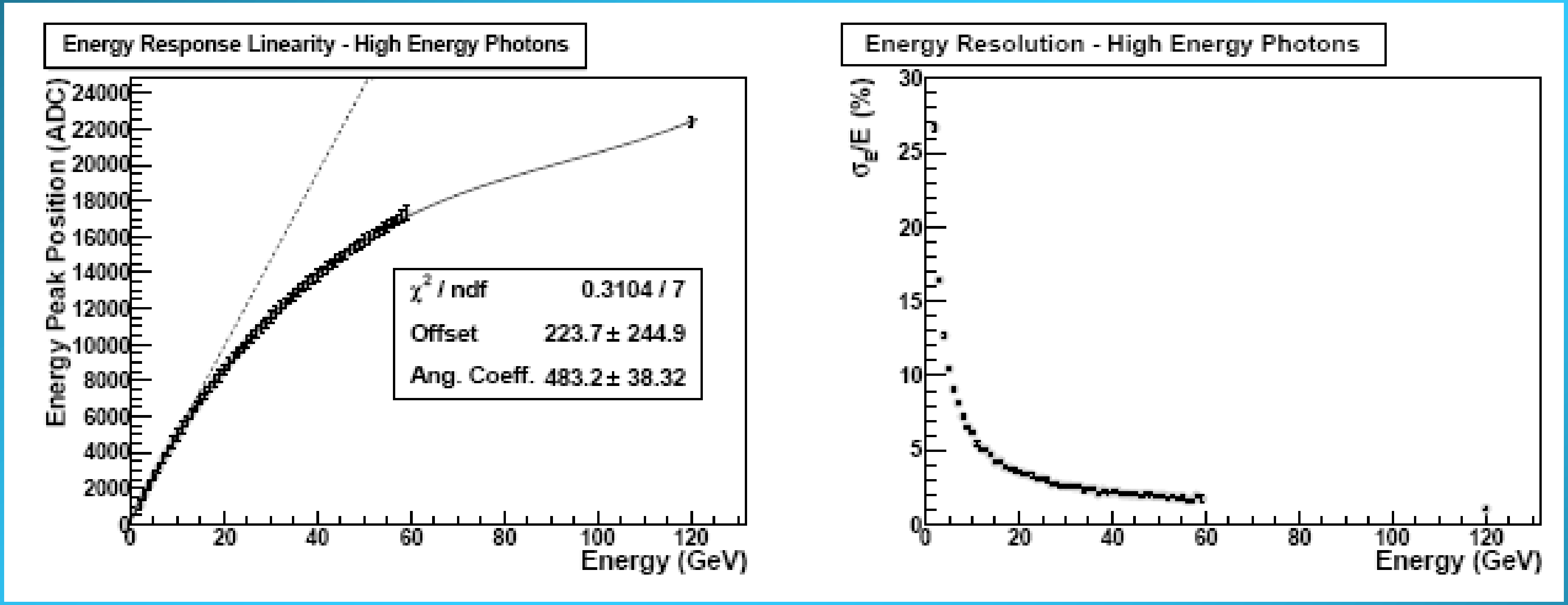




- Production of high energy photons radiated by electrons and positrons channeled in bent crystals
- S1 –S2 plastic scintillators for trigger
- SD1-SD3: SSD telescope
- BM: 3.59 T/m separation magnet
- He bag: for multiple scattering red.
- BC1-BC2: silicon beam chambers
- Two calorimeters: the Shashlik under test to detect the photons, the second to be used in the trigger to identify positrons

Application 2: read-out of prototype "Shashlik" calorimeters - 4

High energy results: CERN SPS H4 beamline, photons up to 120 GeV

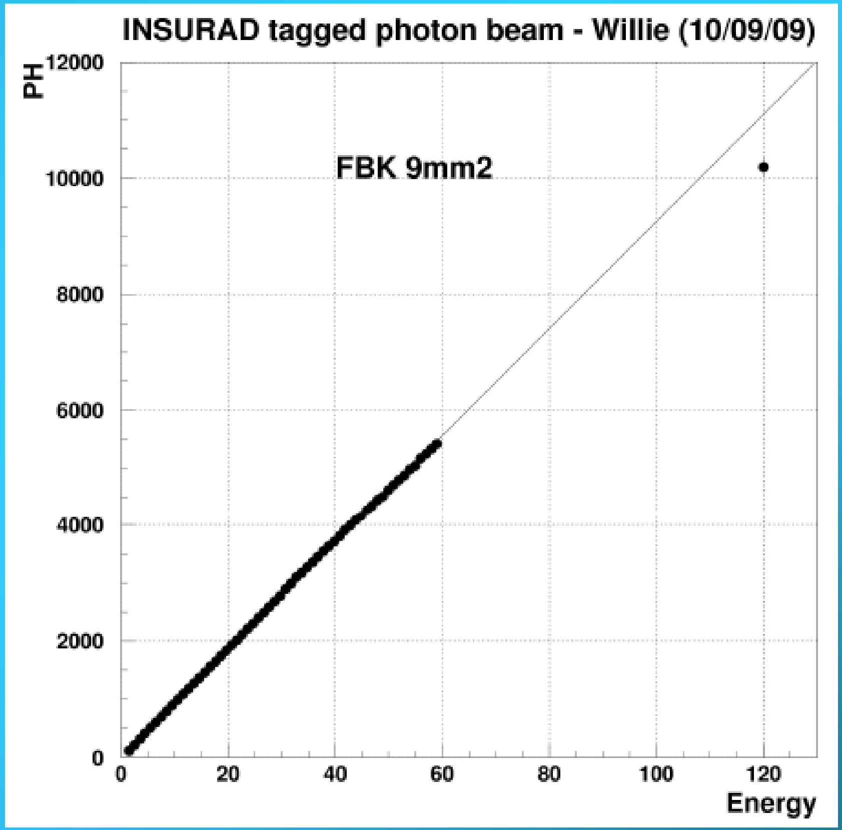


- Linearity good up to ~ 10 GeV, clear effect of saturation at higher energies
- Expected given the low (688) number of microcells in the small SiPMs used

Application 2: read-out of prototype "Shashlik" calorimeters - 5

High energy results: CERN SPS H4 beamline, photons up to 120 GeV

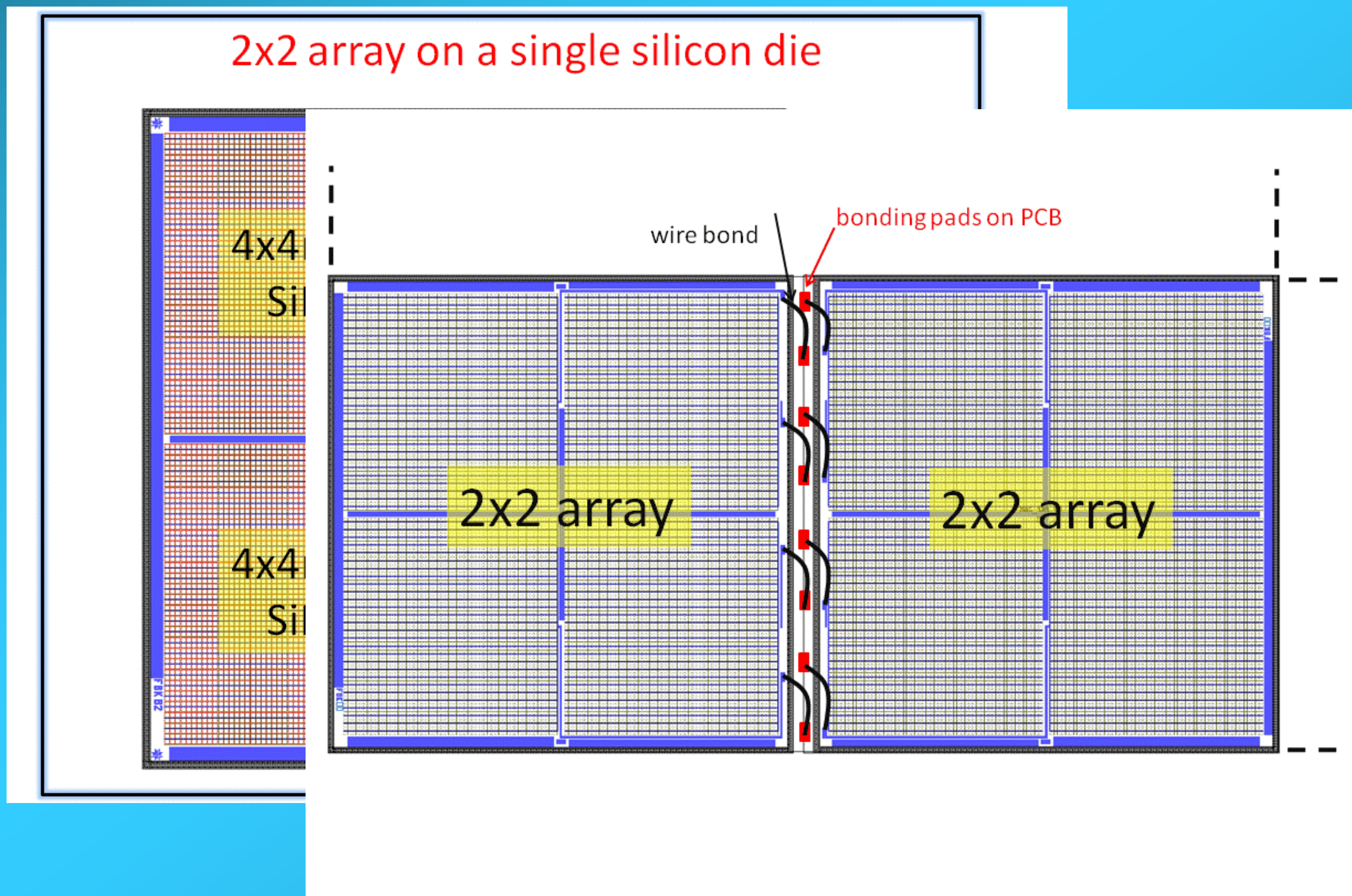
Shashlik calo (prototype 0) read-out
By 3 mm x 3 mm SiPMs (3600 pixels)



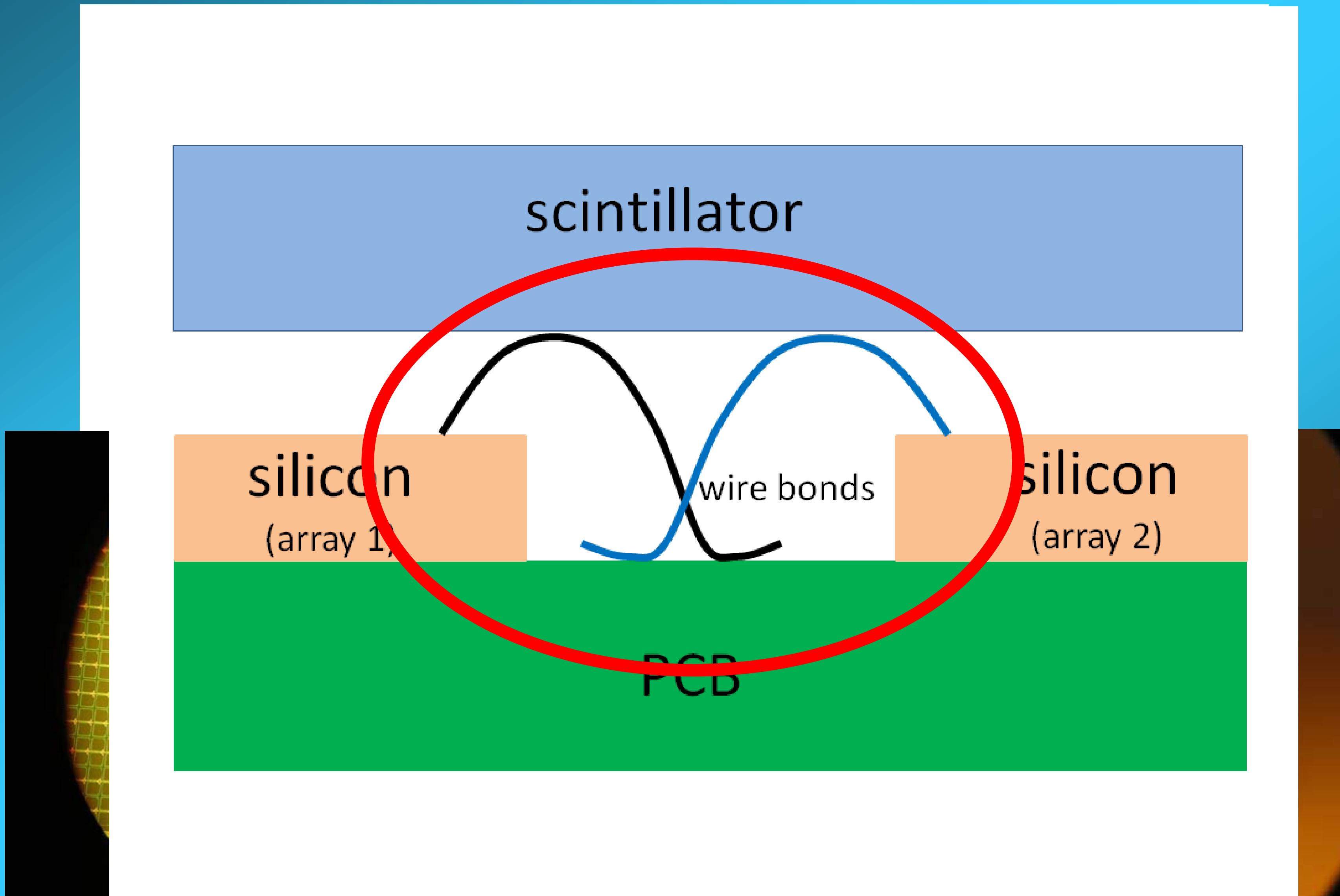
- $3x3\ mm^2$ mounted on simple PCBs
- Number of pixels: 3600
- Pixel area: $50x50\ \mu m^2$

- Very good linearity up to 60 GeV
- Some saturation at 120 GeV
- **Work still in progress**

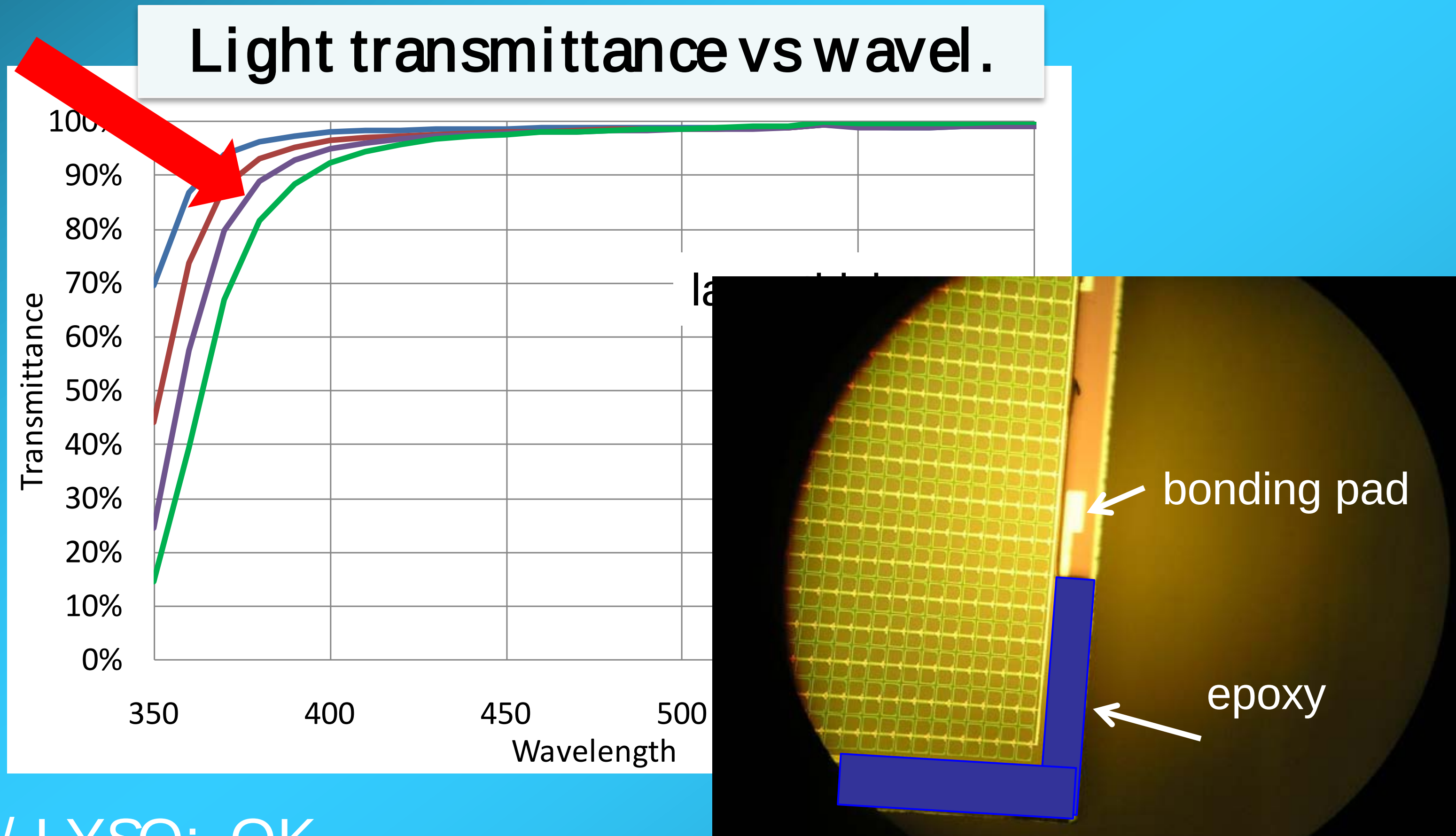
HYPERimage SiPM geometry



Solution for Scintillator/Crystal coupling

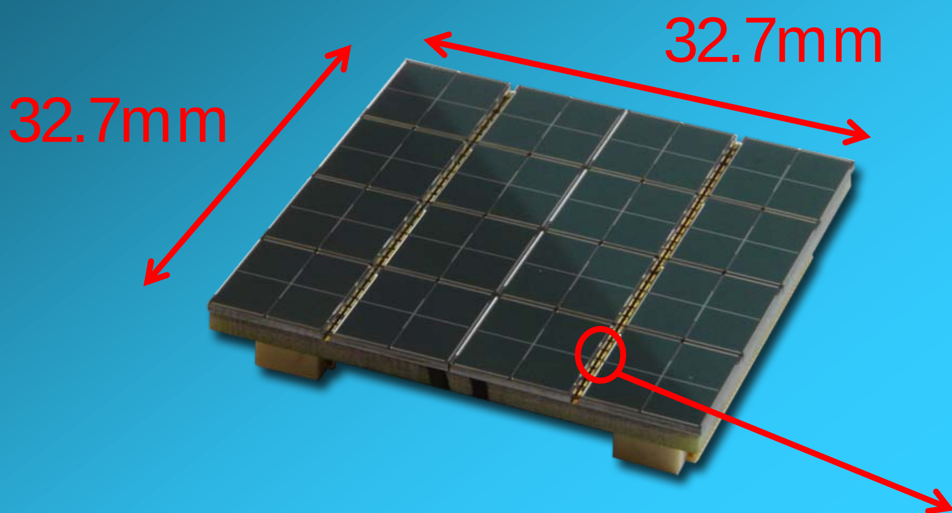


Epoxy layer properties

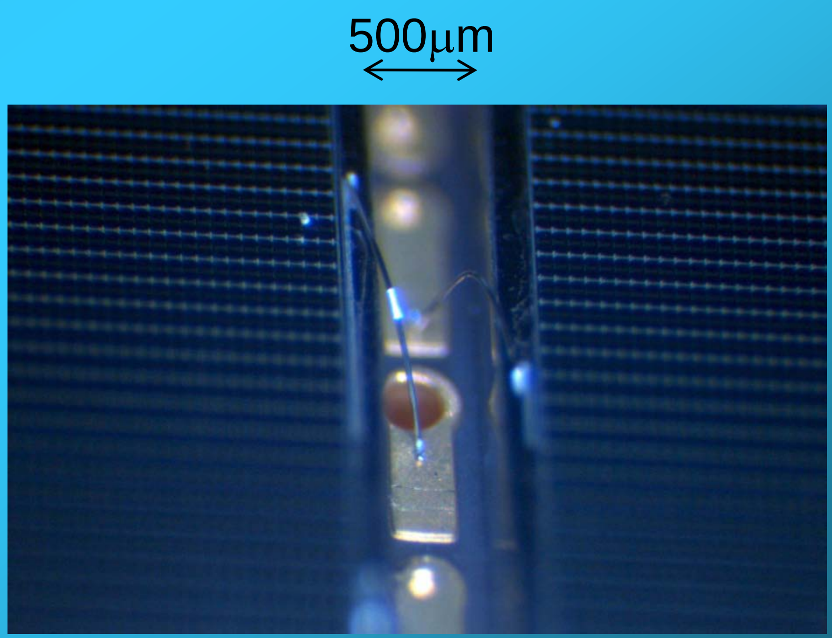


- LSO/ LYSO: OK
- LaBr: epoxy can be removed from active area leaving only a support frame around the device

The large-area SiPM tile



- **Fill factor ~ 84%**
  (not including SiPM FF)
- **Flat surface for crystal mounting**



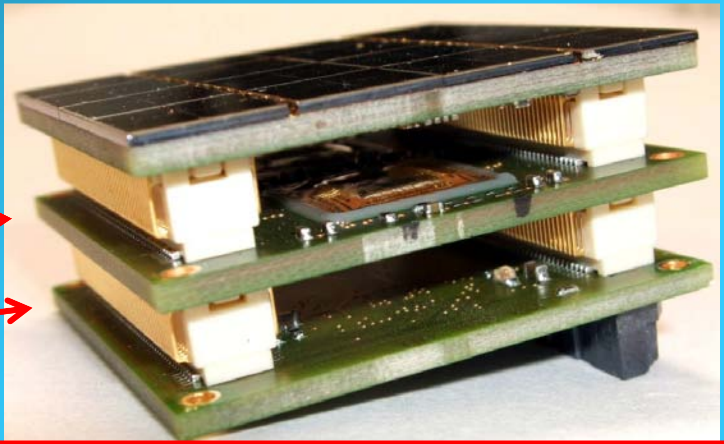
Technology developed by FBK-irst

The stack

SiPM tile

ASIC tile

Interface tile



Mounting and measurements at Uni. Heidelberg and Philips

The stack works.
Intrinsic performance is much better than values below:

- Energy resolution ~16%
- Coincidence res. time ~670ps

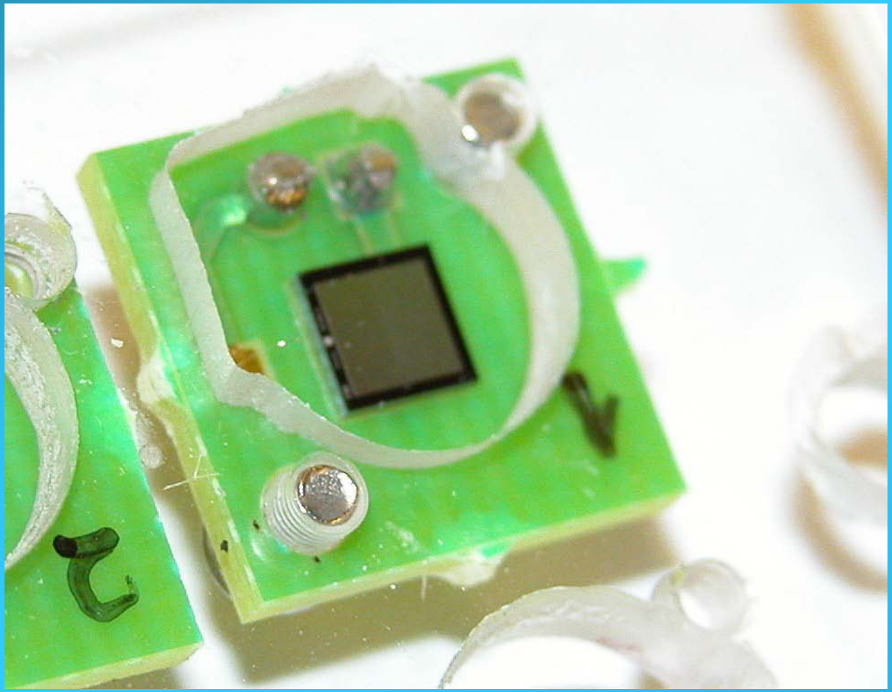
SiPMs used in the test beams

- Circular Ø 1.2 mm mounted on TO18
- Breakdown voltage: ~ 31V
- Overvoltage range: ~ 5V
- Number of pixels: 688
- Pixel area: 40x40 μm^2
- Gain: ~ 10^6

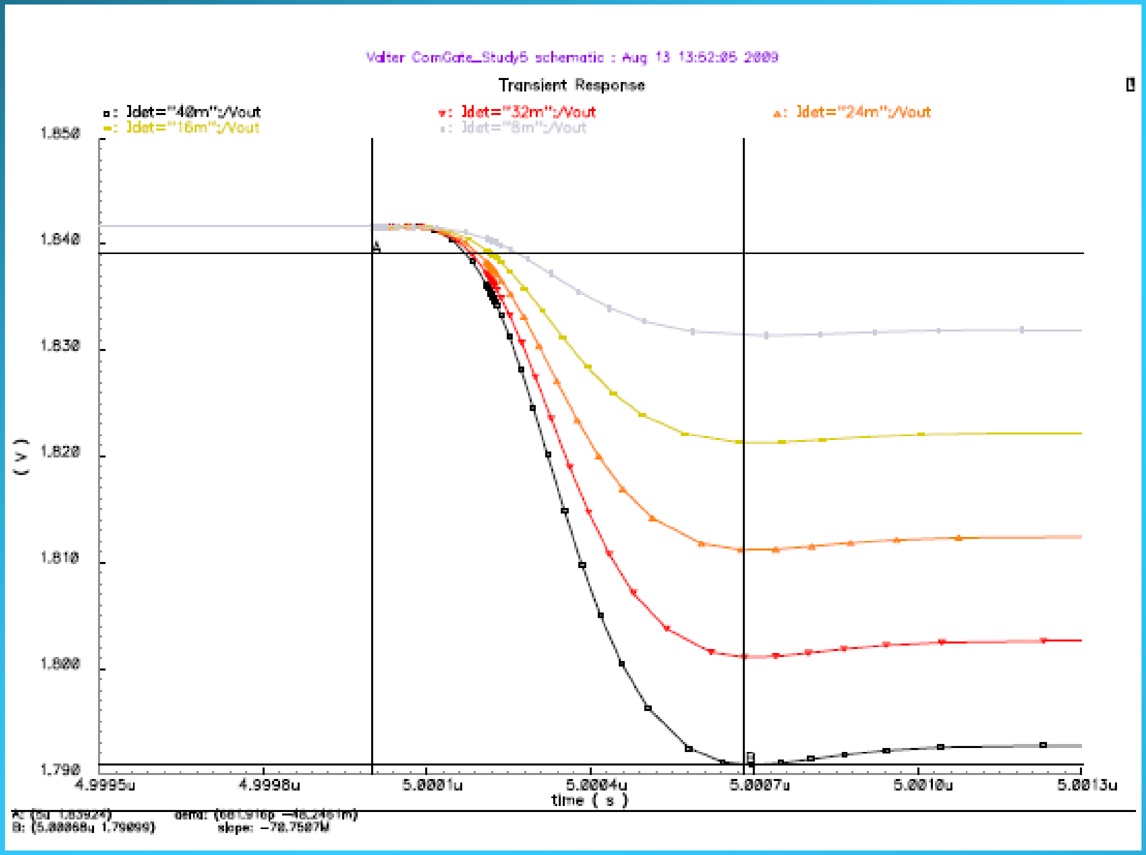
- 3x3 mm^2 mounted on simple PCBs
- Breakdown voltage: ~ 31V
- Overvoltage range: ~ 5V
- Number of pixels: 3600
- Pixel area: 50x50 μm^2
- Gain: ~ 10^6

Experimental results at CERN PS T10: 9 mm² SiPMs (1)

- 3x3 mm2 SiPMs and scintillator bars
- Number of cells of SiPM: 3600
- Detector: 1 scintillating bar (1.5x1.9x22 cm3)
- Readout by 3 1.2 mm WLS fibers by Bicron
- **No front-end/driving electronics used!!!**



Simulations of a VLSI CMOS ultra-fast amplifier for a SiPM-TOF in space



- Ultra-low input impedance design
- Common-gate input amplifier in 0.35 μm AMS CMOS;
- SiPM model of a 4x4 mm^2 large area FBK device (C_{det} > 200 pF);
- Signals correspond to 10, 20, 30, 40 and 50 microcells hit;
- Rise time (10-90%) is **300 ps** and bandwith (-3 dB) is **1.15 GHz with input load > 200 pF!**