SIPMs: Italy Team Report

SiPMs development at FBK-irst started in 2005 as collaboration with INFN(*) for:

- tracking with sci-fi;
- PET;
- TOF;
- calorimetry;
- muon counters.

(*) Pisa, Bari, Bologna, Messina, Perugia, Roma, Trento, Trieste, Udine

Aldo Penzo, INFN-Trieste
HCAL Working group, CMS Upgrade Workshop
FNAL, 19 Nov 2008

Summary of multiple contributions

- http://www.ts.infn.it/eventi/TPDPPC_2008/

- Valter Bonvicini - The INFN R&D FACTOR
- Claudio Piemonte - Development of SiPMs at FBK-irst
- Arjan Heering - Requirements of SiPMs for CMS HCAL upgrades
- Adam Para - Photodectors for dual readout calorimetry: characterization and testing of SiPMT's
- Aldo Penzo - Calorimetry R&D in FACTOR
- Dalla Torre - Single photon detectors for Cherenkov Imaging
- Valter Bonvicini - Preliminary results on SiPM irradiation tests
- Giovanni Pauletta - SiPM characterization and applications; past and future test activities at FNAL

FACTOR Project

[Walter Bonvicini *et al.*: Messina, Roma, Trieste, Udine + FBK/irst]

- Within FBK/irst - INFN agreement, a (3-year) project (FACTOR) aims at establishing SiPMs as choice devices for (dual) readout of (compensating) hadron calorimeters.

- FBK-IRST has long-standing collaboration with INFN in the fields of:
  - Radiation-hard Si detectors (for SLHC)
  - use of oxigen-rich substrates:
    - DOFZ substrates
    - Cz/MCz substrates (Magnetic Czochralski)
    - Epitaxial substrates
  - use of p-type substrates
  - Integration of Si detectors and (front-end) circuits on the same substrate
  - 3D detectors

ITC-IRST (Trento)

ITC (Now Fondazione Bruno Kessler) – IRST is a public research and technology Institute, working since 1994 on the development and on the production od semiconductor devices for research and applications. It has a fully equipped Microfabrication Laboratory in which silicon devices are built.

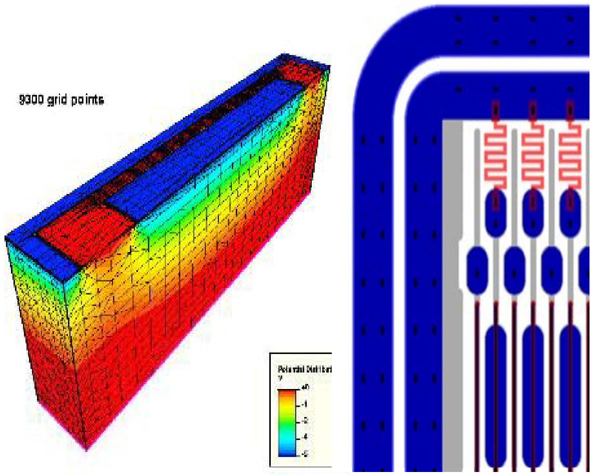
- Ion Implanter
- Furnaces
- Litho (Mask Aligner)
- Dry&Wet Etching
- Sputtering &Evaporator
- On line inspection
- Dicing

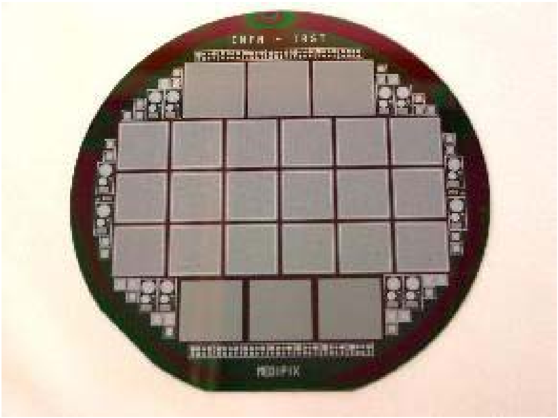
Activity of SRD group

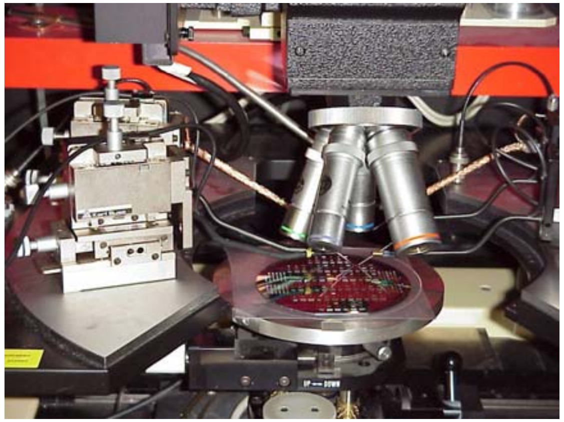
Development and production of Si radiation detectors.

Expertise covers the main aspects of the development:

TCAD simulation
CAD design → Fabrication → Device testing



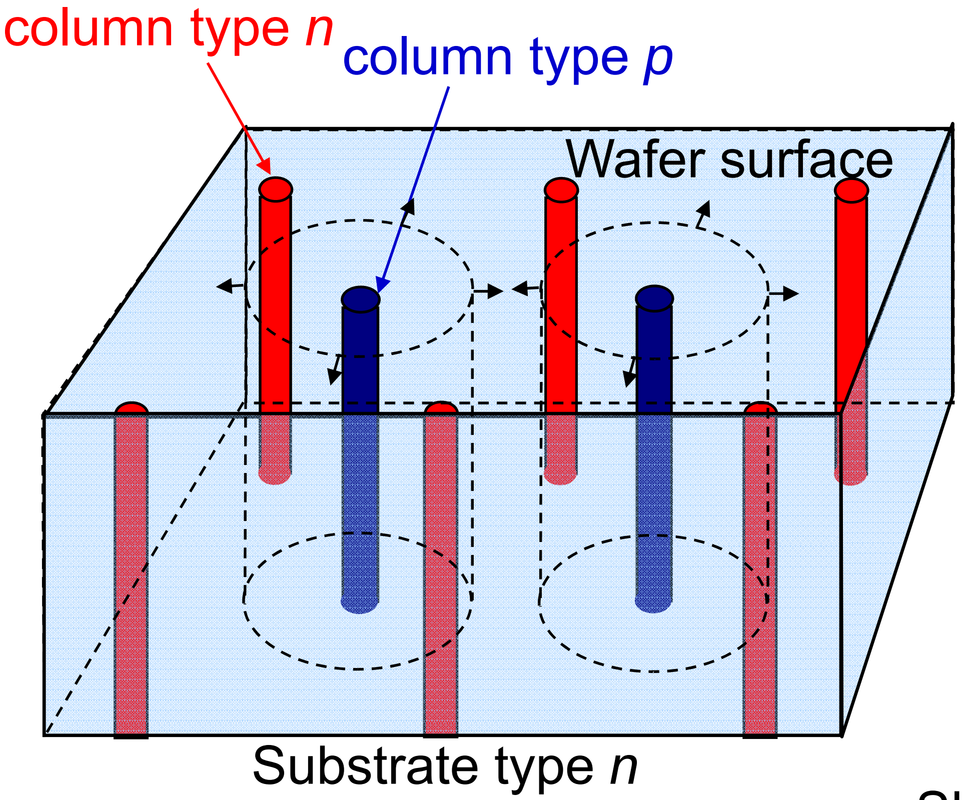


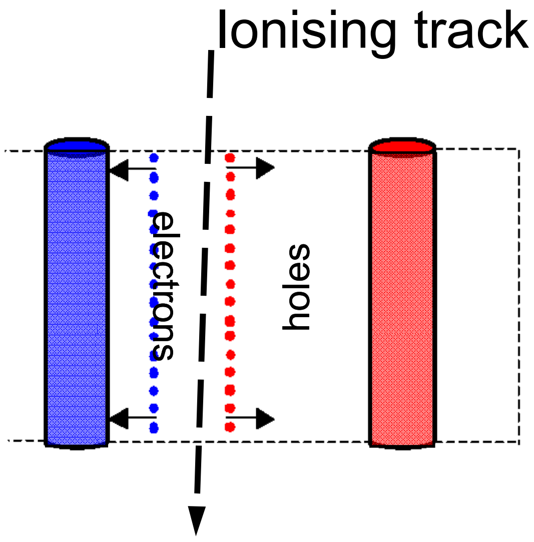


Previous/current products

- Double-sided strip detectors:
  - Area:7.5x4.2cm2
  - Orthogonal or inclined strips on 2 sides
  - DC- or AC-coupled
  - 700 + 800 “in spec” devices fabricated for AMS and ALICE (2002-2005)
- Pixel detectors:
  - MEDIPIX (thick 1.5mm), 170x170/55x55 μm^2
  - ALICE (200μm) 400x50 μm^2

3D Si Detectors





(carriers generated along the track are collected almost simoultaneously)

Electrodes are columns penetrating into the bulk

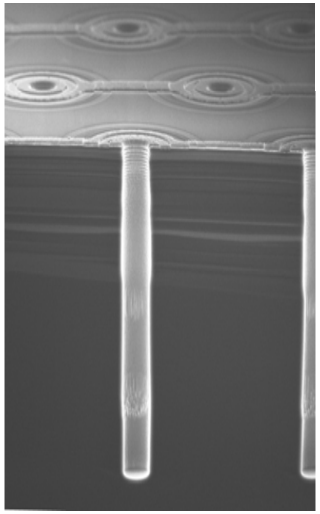
Short distance electrodes *n* e *p*:
⇒ low depletion voltage
⇒ short charge collection distance

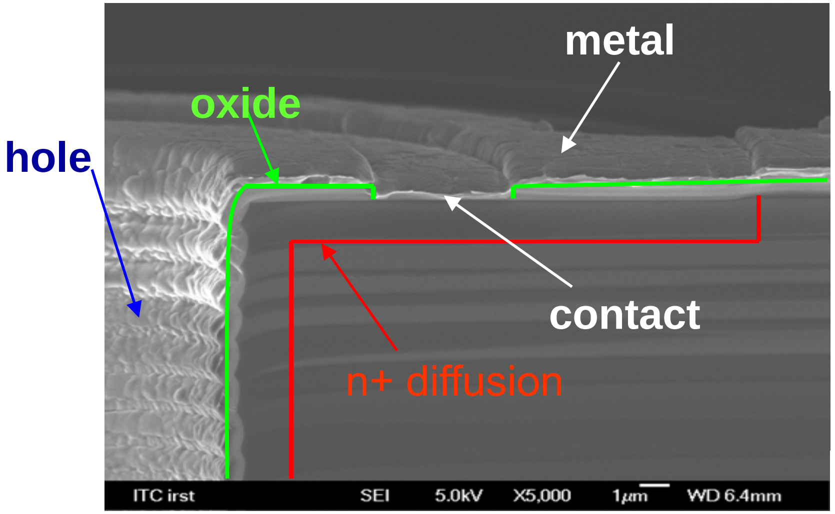
⇨ extremely **fast** and **radiation resistant**

See S. Parker et al., NIM A395 (1997)

3D Si Detector Project

FBK-irst and INFN-Trieste (L. Bosisio *et al*.)





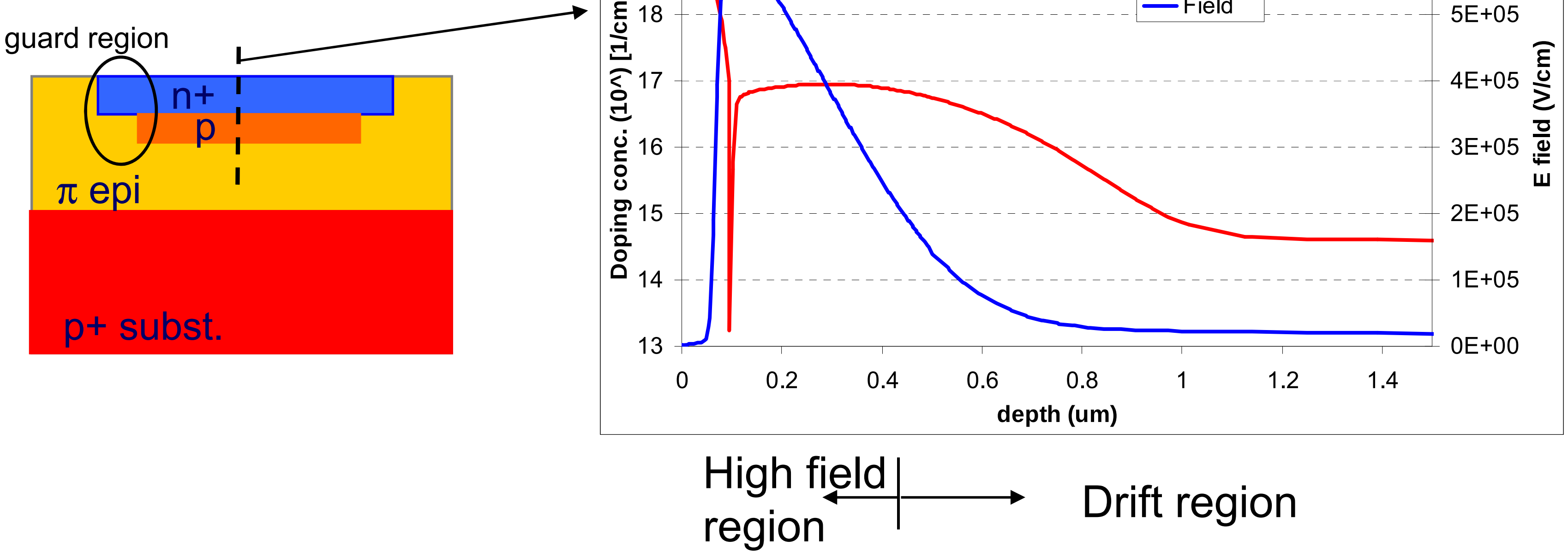
SEM pictures of 3D devices

Col. depth 180μm
Col. width 10μm

- Collaboration for tests:
  - Ljubljana
  - UC Santa Cruz
  - INFN-Genova (ATLAS Pixel)
  - CERN (ALICE Pixel)
- ***Applications of this technology in other devices:***
  - ‘throughout holes” transfer signals to back face (ex.SiPM)
  - planar detectors with “active edge’ (ex. imaging X-rays)

SiPM IRST technology

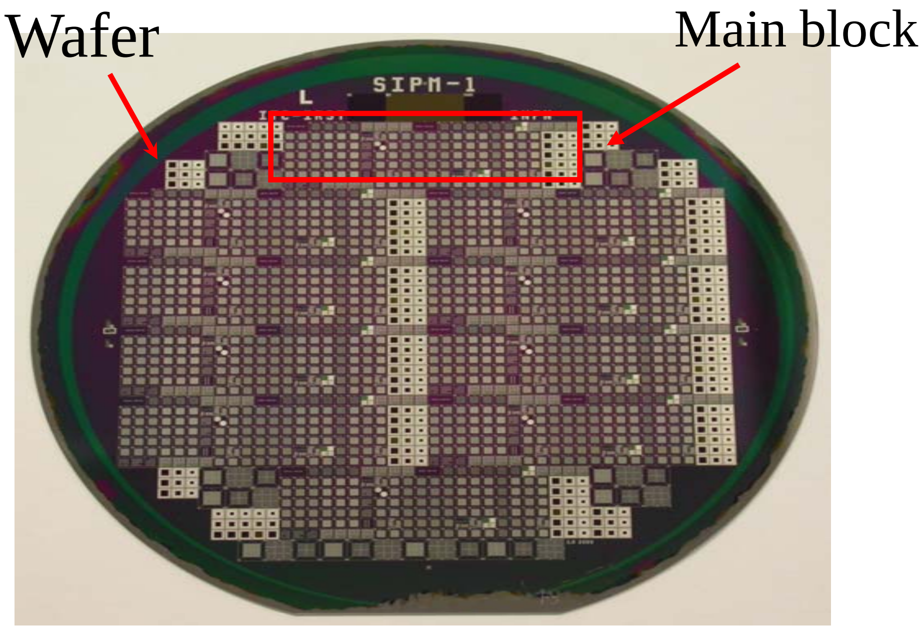
Shallow-Junction SiPM



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

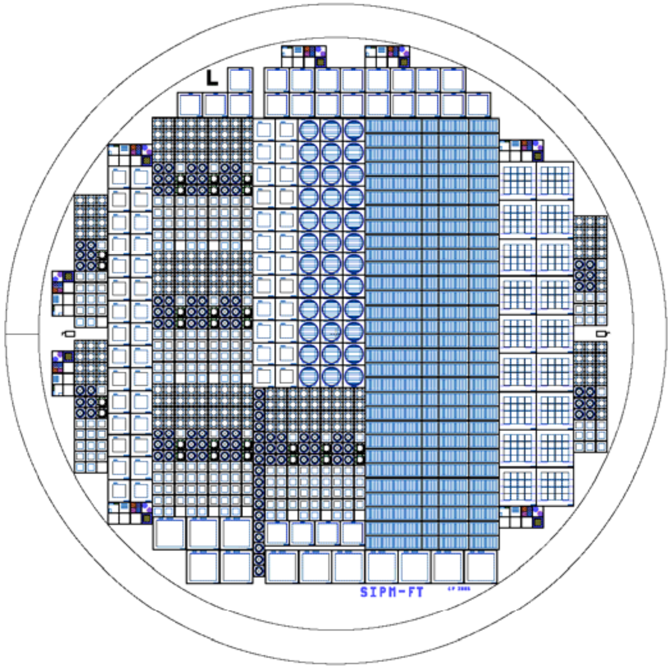
**[C. Piemonte:
"A new Silicon Photomultiplier structure for blue light detection"
NIMA 568 (2006) 224-232]**

Configuration on Si wafer



First production run (2005)

Second production run

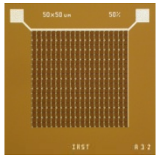


- square SiPMs with area:
  - 1x1mm^2,2x2mm^2
  - 3x3mm^2, 4x4mm^2
- circular SiPMs
- linear arrays of SiPMs:
  - 1x8, 1x16, 1x32
- 4x4 matrix of SiPMs

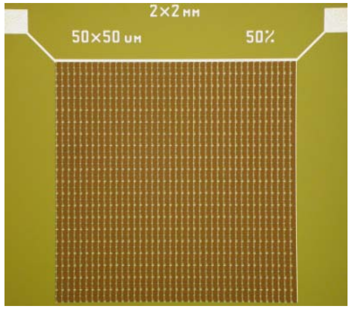
Characteristics of FBK-irst SiPMs

Geometries:

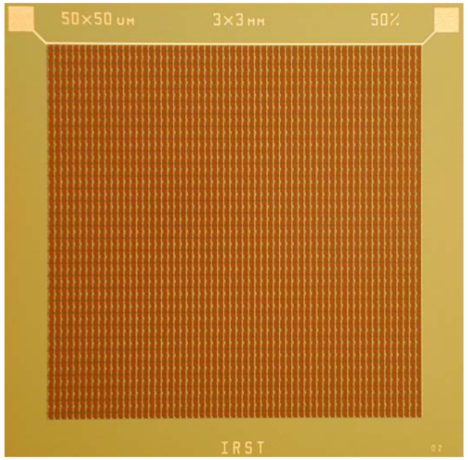
1x1mm^2



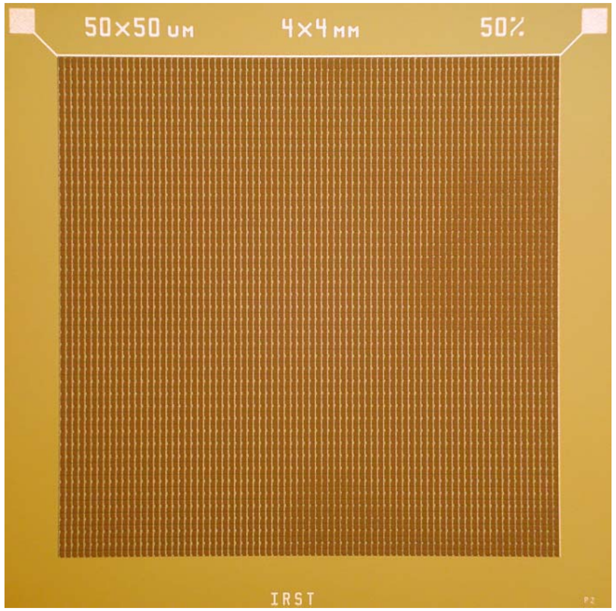
2x2mm^2

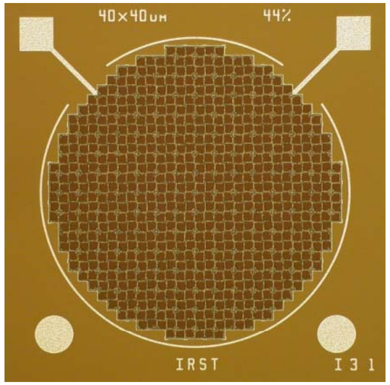


3x3mm^2 (3600 cells)



4x4mm^2 (6400 cells)





Circular: diameter 1.2mm
diameter 2.8mm

Fill factor: 40x40μm^2 => ~ 40%
50x50μm^2 => ~ 50%
100x100μm^2 => ~ 76%

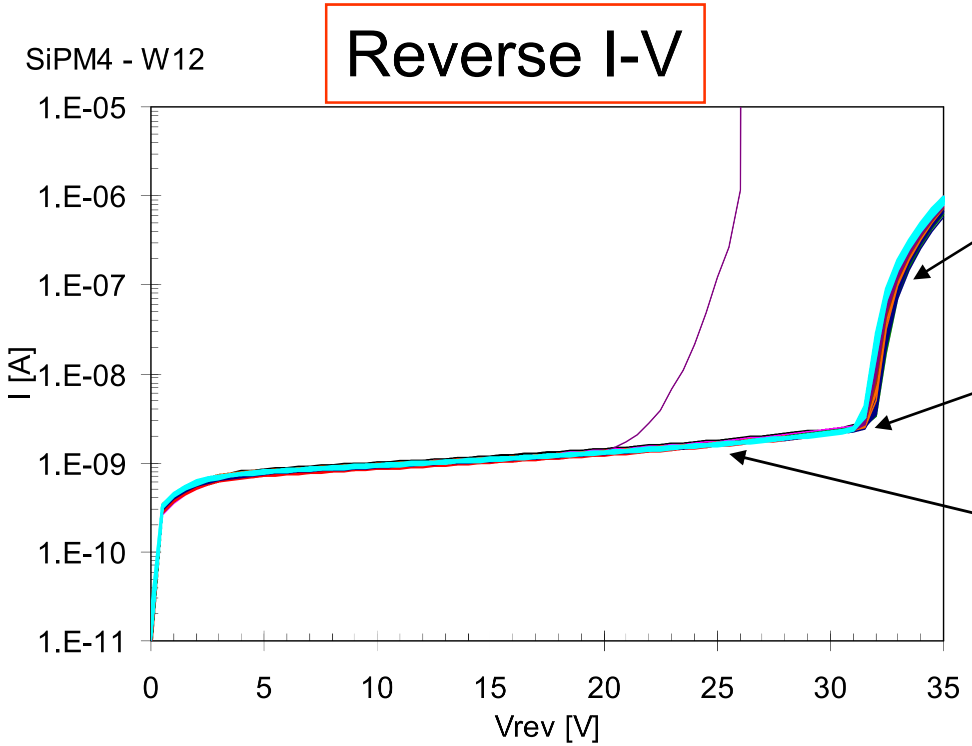
Tests performed at FBK

- ***I-V 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 (I-V)



Reverse I-V

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:

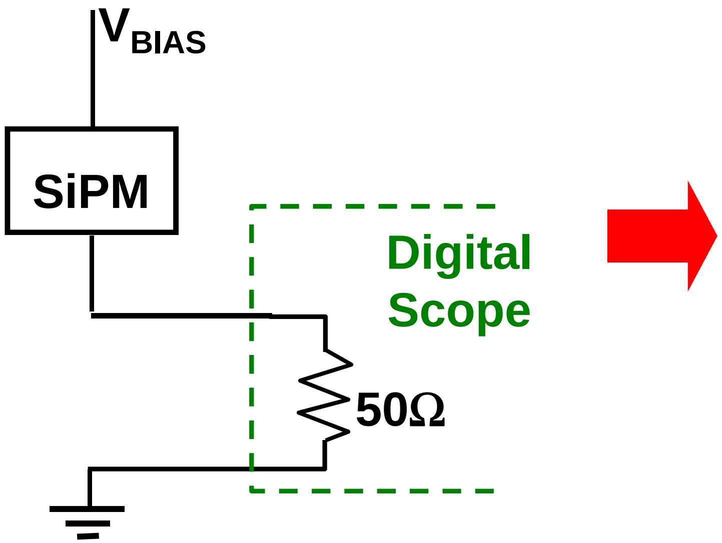
- Device functionality
- Breakdown voltage
- (Dark rate)x(Gain) uniformity
- Quenching resistance (from forward I-V)

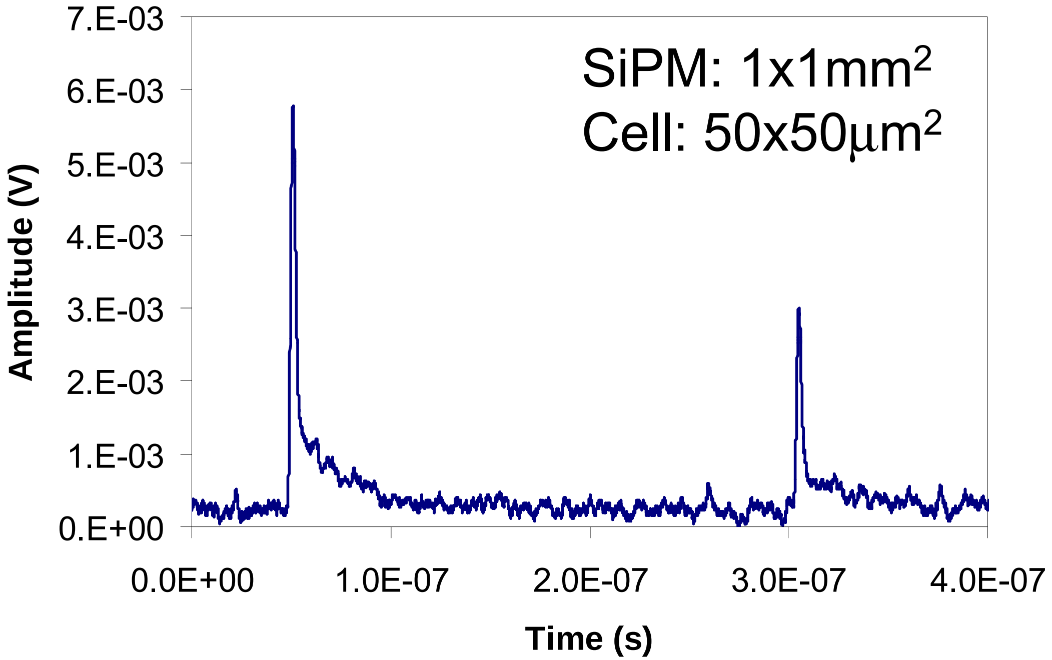
Performed on several thousands of devices at wafer level

Signal properties – NO amplifier

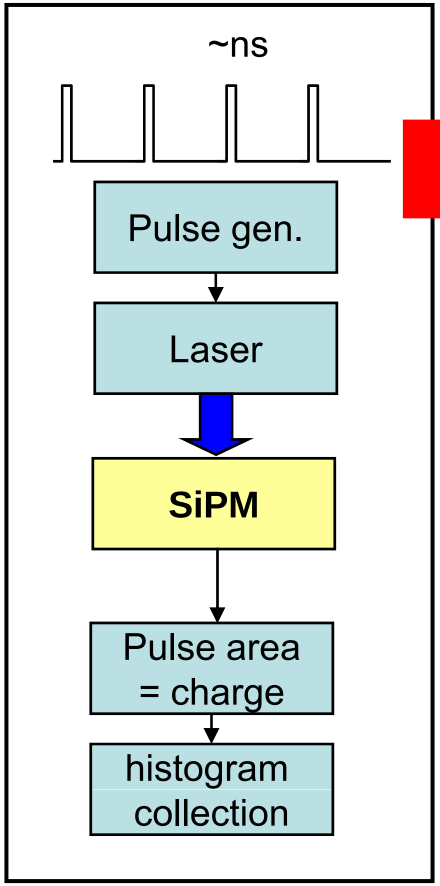
Dark signals are exactly equal to photo-generated signals
⇨ functional measurements in dark give a complete picture of the SiPM functioning

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





Signal properties – NO amplifier



~ns

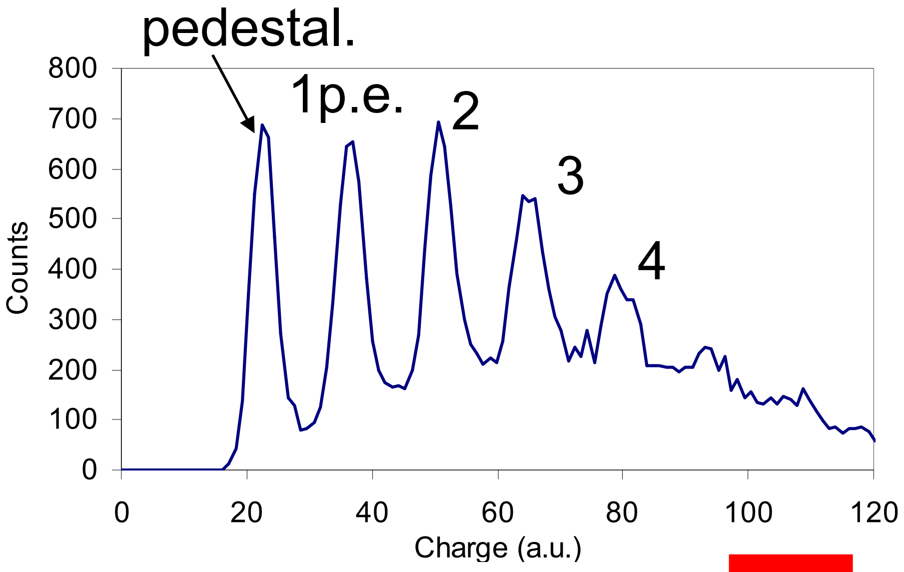
Pulse gen.

Laser

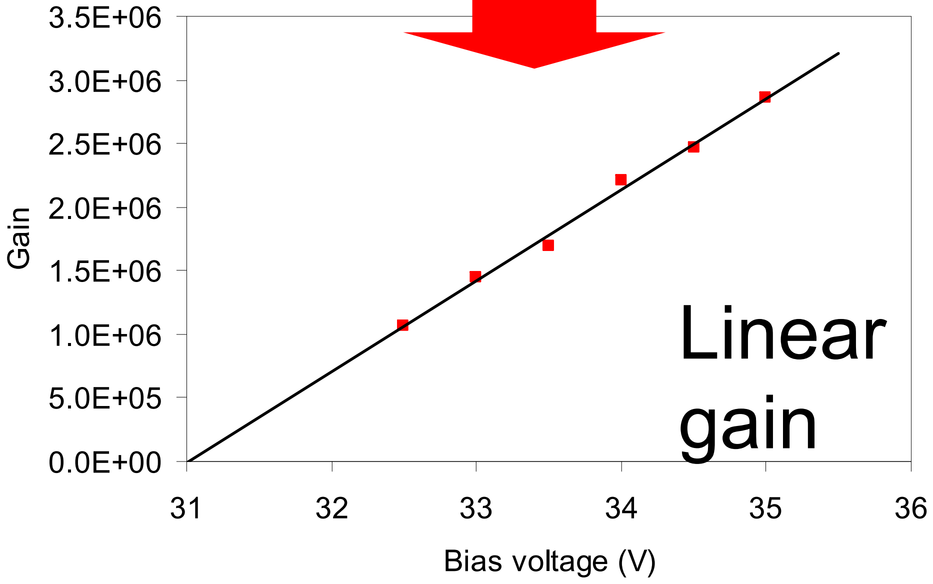
SiPM

Pulse area = charge

histogram collection



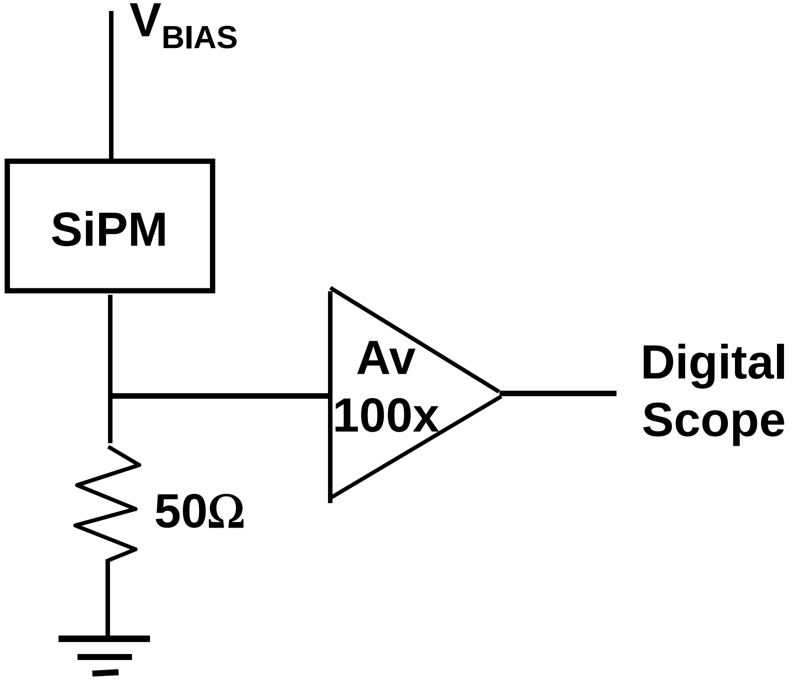
Excellent cell uniformity



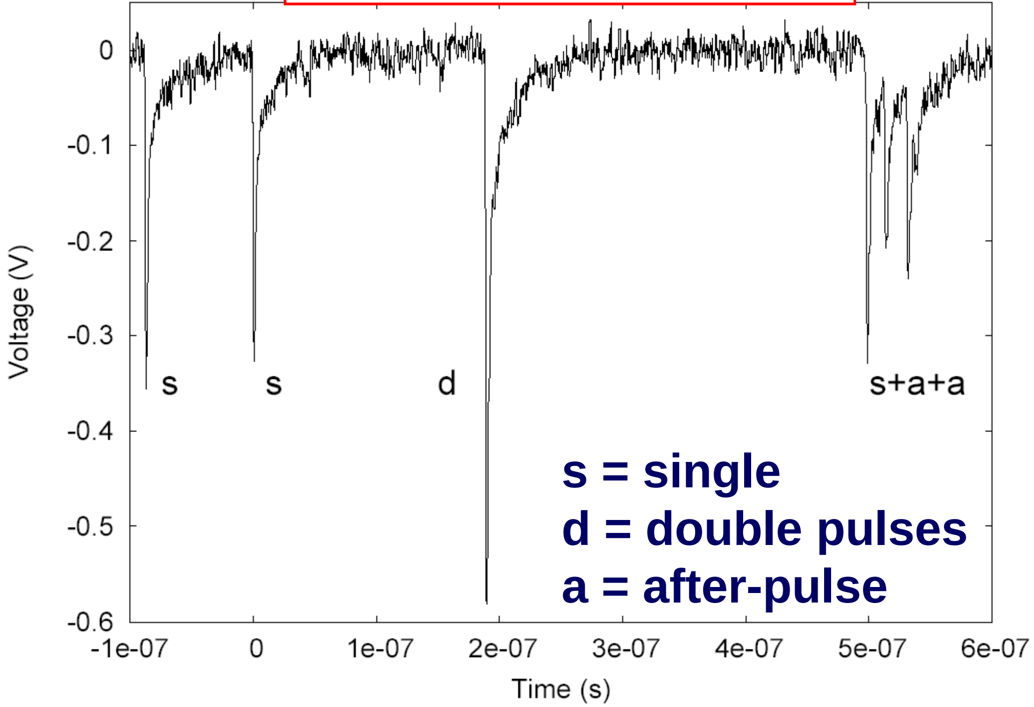
Linear gain

Signal properties – with amplifier

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



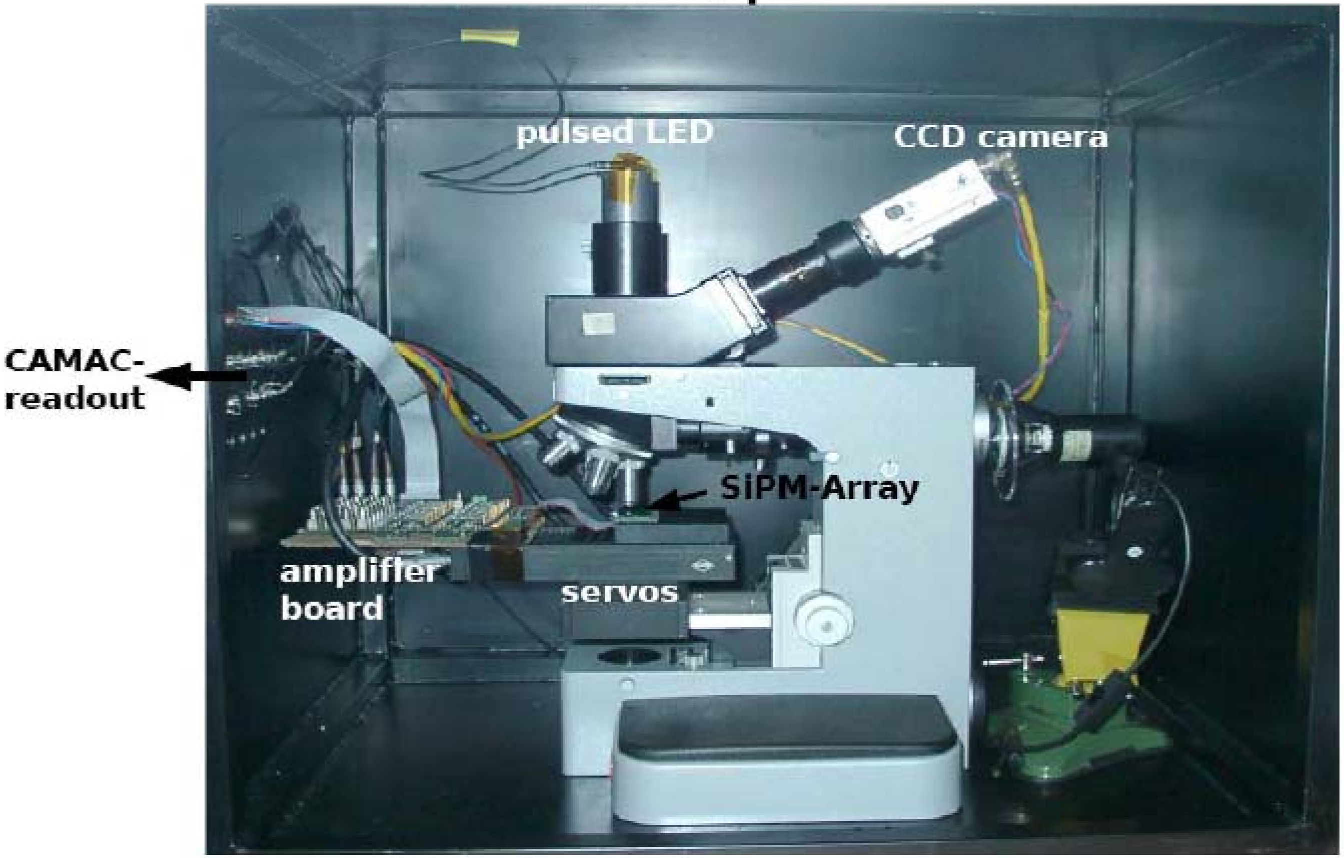
Pulses at the scope.



s = single
d = double pulses
a = after-pulse

Microcell functionality measurements

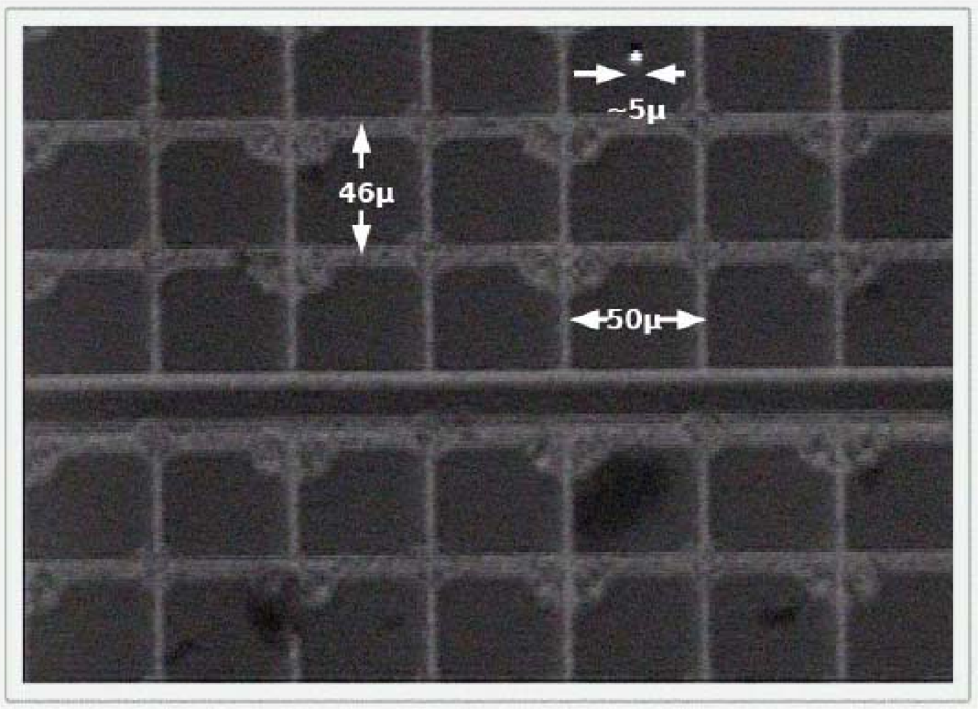
setup



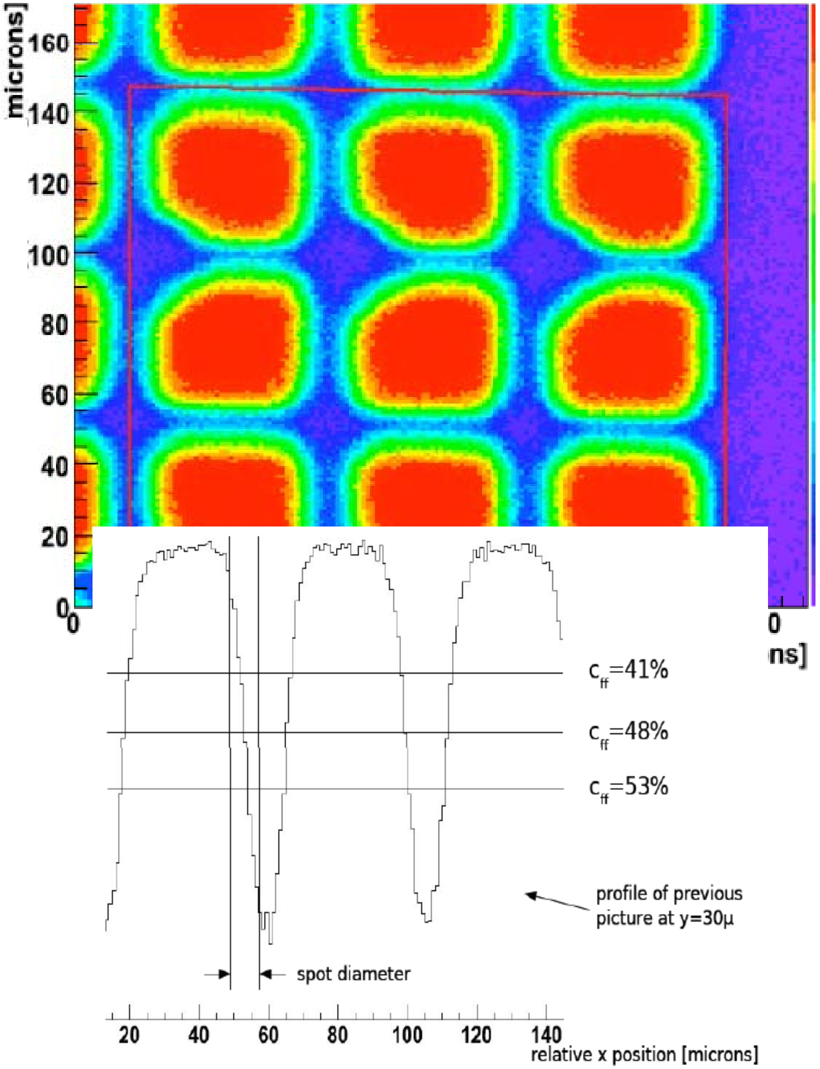
measurements with RWTH, Aachen and Josef Stefan , Ljublijana

Pencil LED scan

Measurement of the microcells with 5µm LED spot diameter

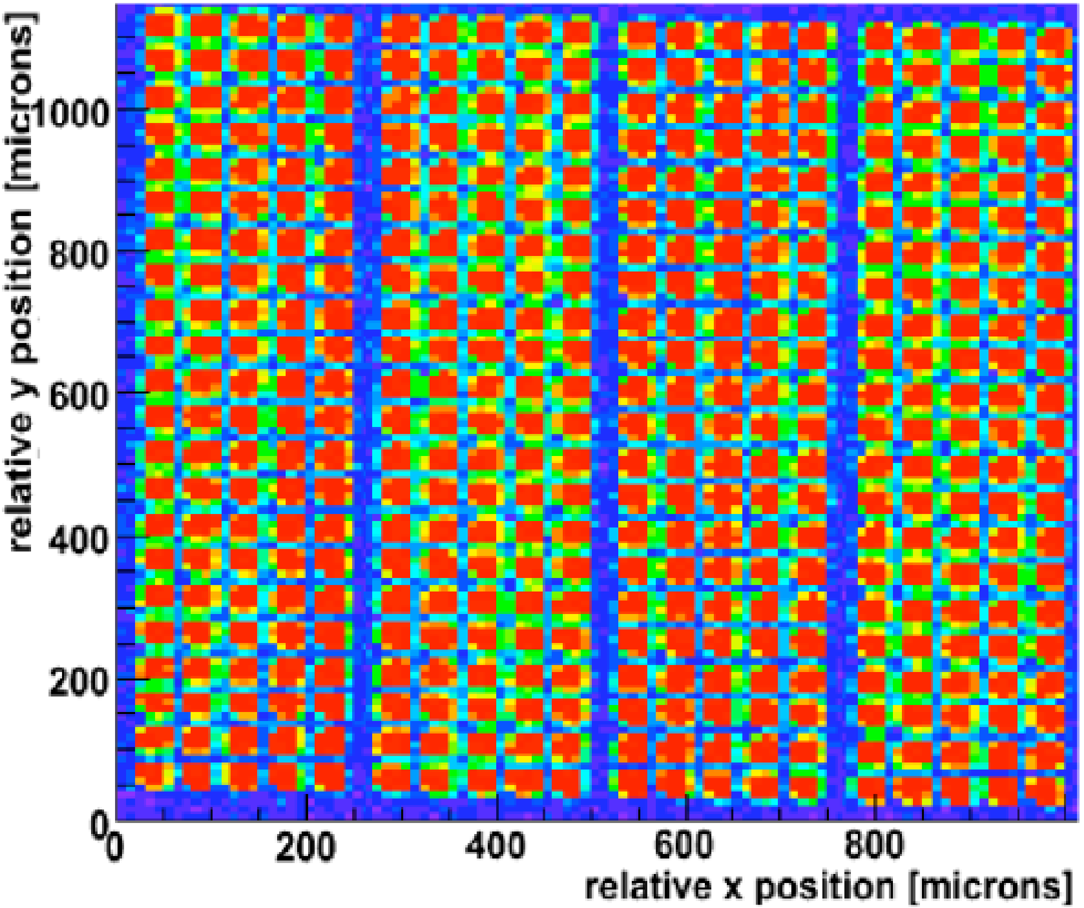


fillfactor



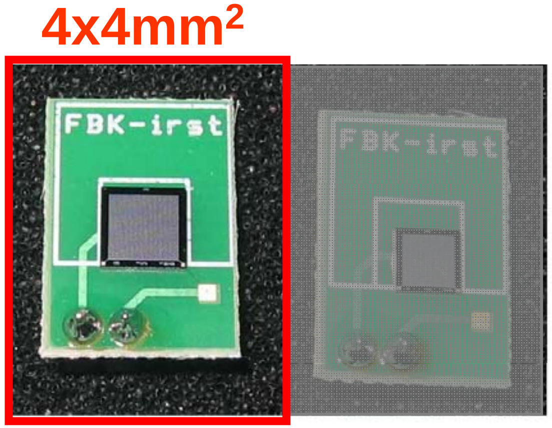
Uniformity map

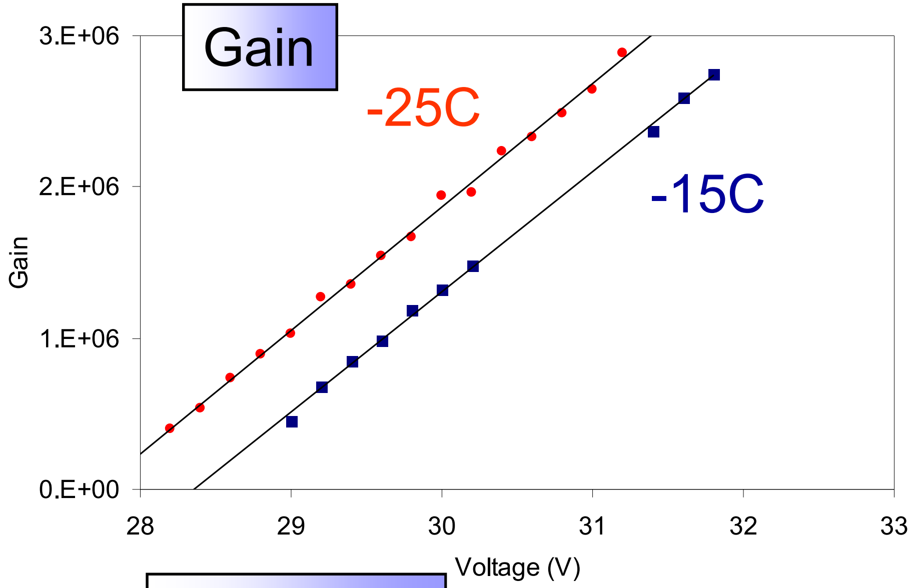
pixel quality check

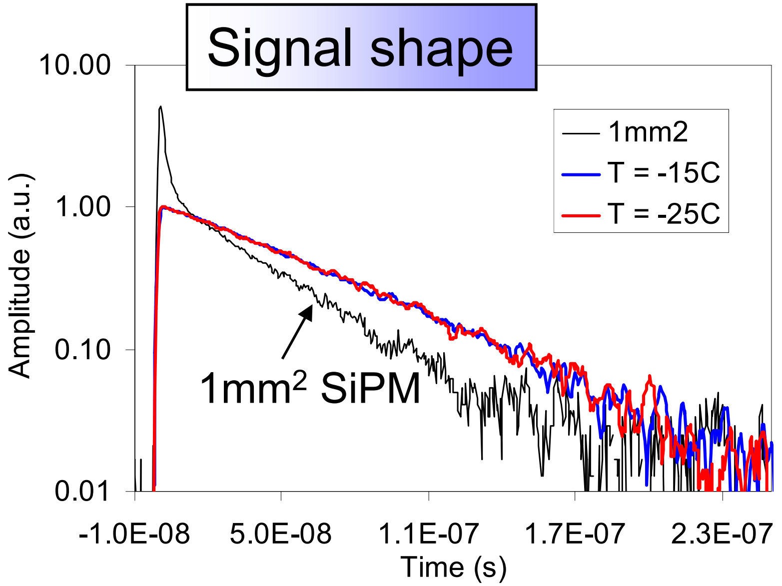


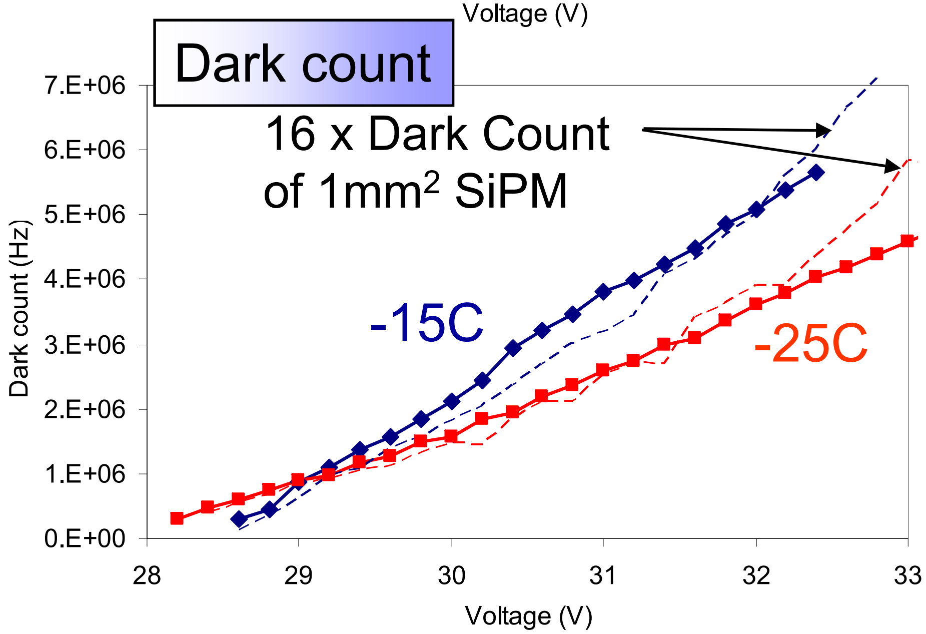
step size 10µ, spot diameter ~10µ → all pixels on C15 work fine

4x4mm^2 SiPM - 50x50μm^2 cell



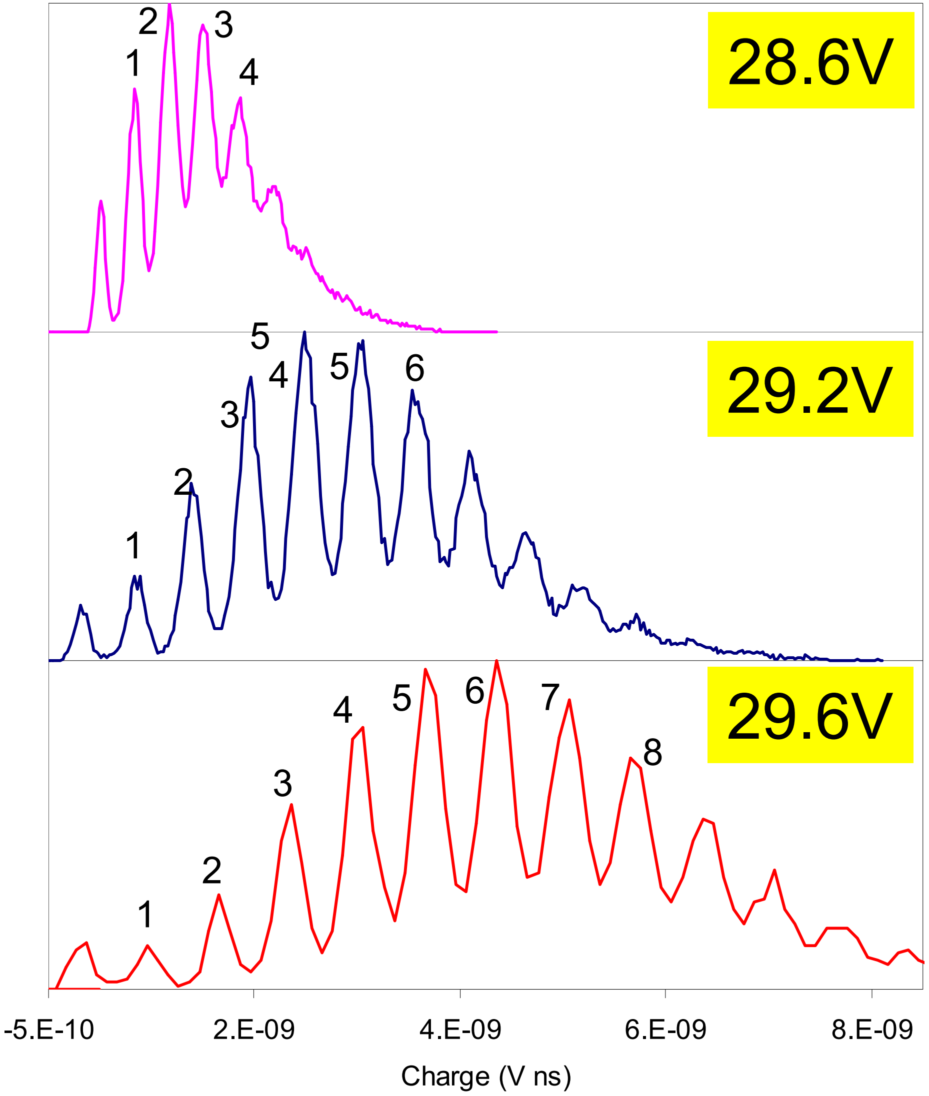






4x4mm^2 SiPM - 50x50μm^2 cell

T=-25C Vbd=27.6V



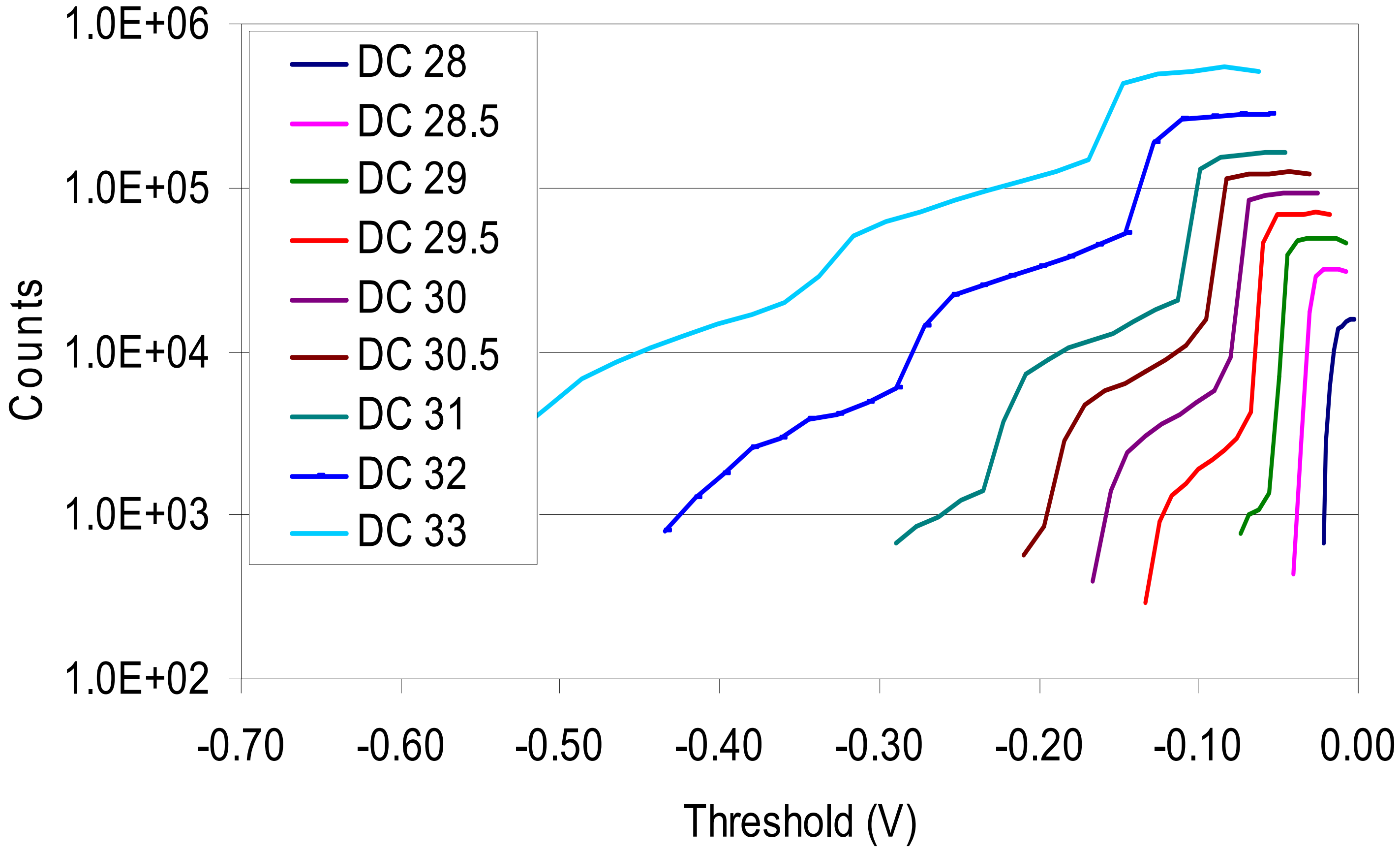
Charge spectra when illuminating the device with short light pulses

Same conclusions as for the previous device:

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

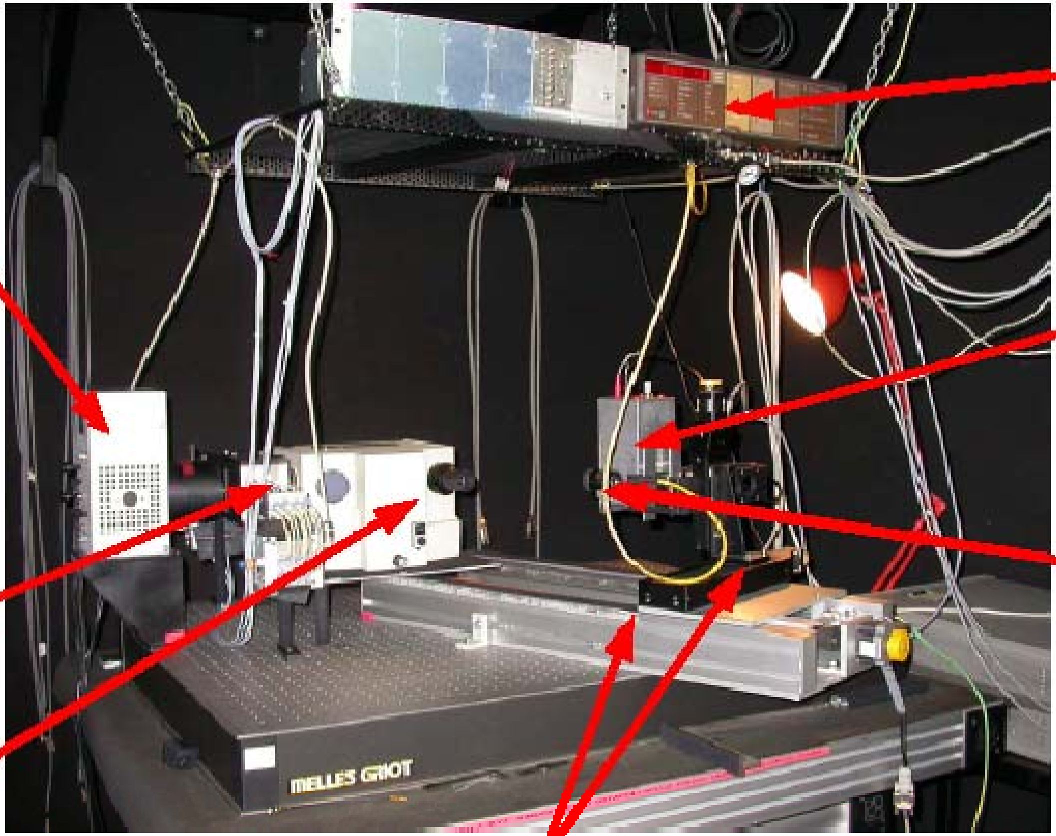
Width of peaks dominated by electronic noise

Dark counts vs discrim. threshold



- Each of the above curves represents the dark count rate as a function of the counting discriminator threshold.
- Different curves correspond to different bias voltages. Dark counts were also measured as a function of temperature.

Photo-detection efficiency



Optometer

Halogen
white lamp

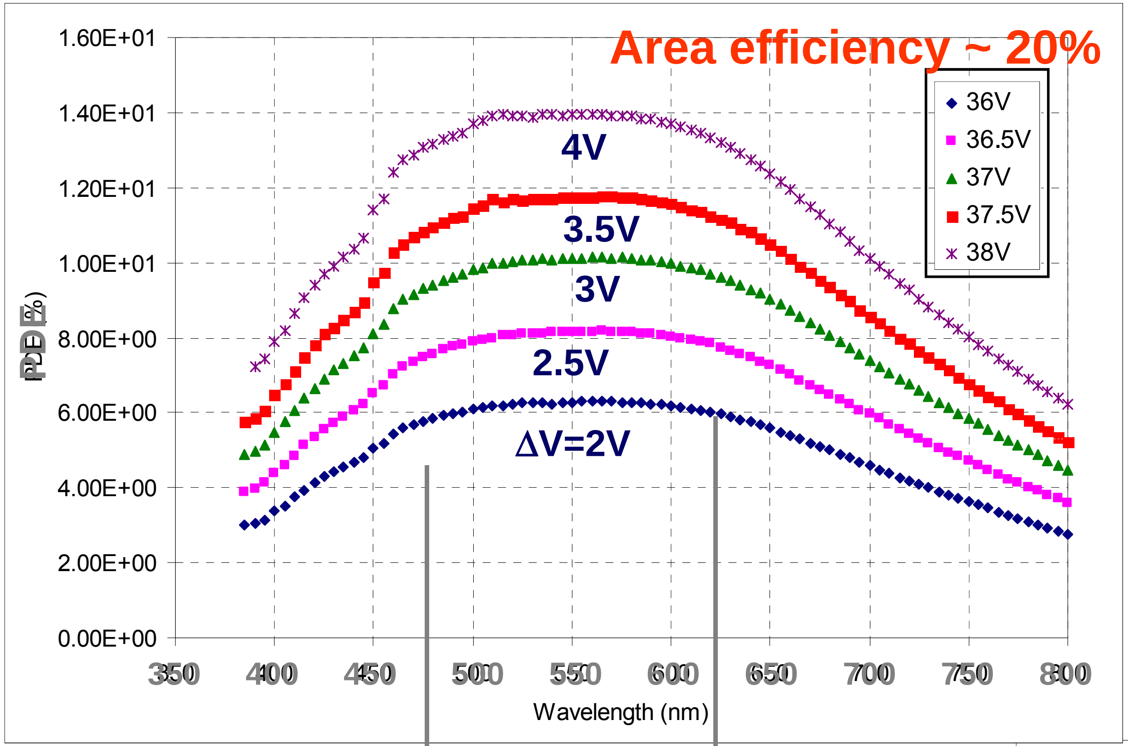
SiPM+
preamplifier

Neutral filters
(transmittance
10%)

Photodiode
UDT221

Monocromator

Stage with 3D micrometers movement (50um precision)



PDE=QE*Pt*Ae

QE=quantum eff.

P_t=avalanche prob.

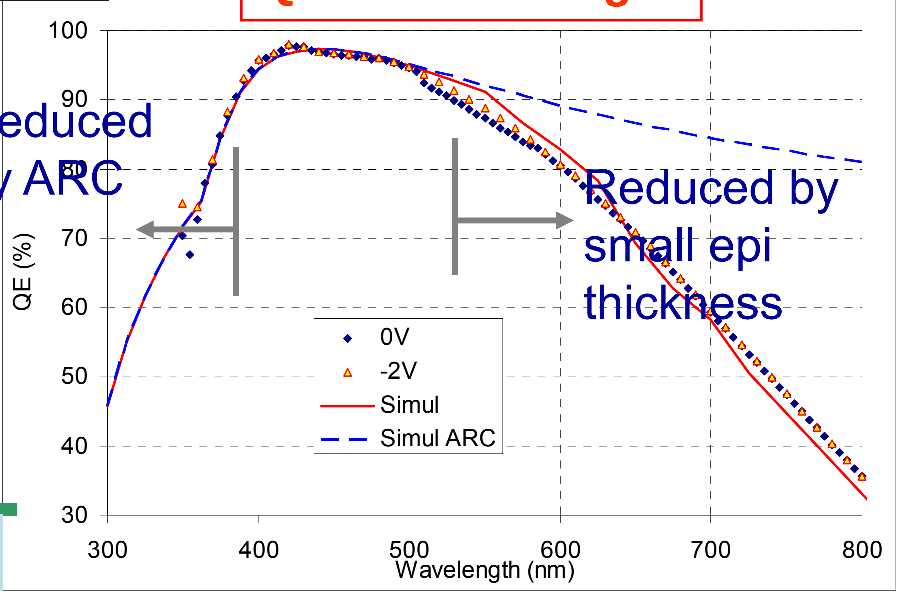
A_e=area eff.

short λ:
low PDE
because
avalanche
triggered by
holes

long λ:
low PDE
because
low QE

Measured on a diode

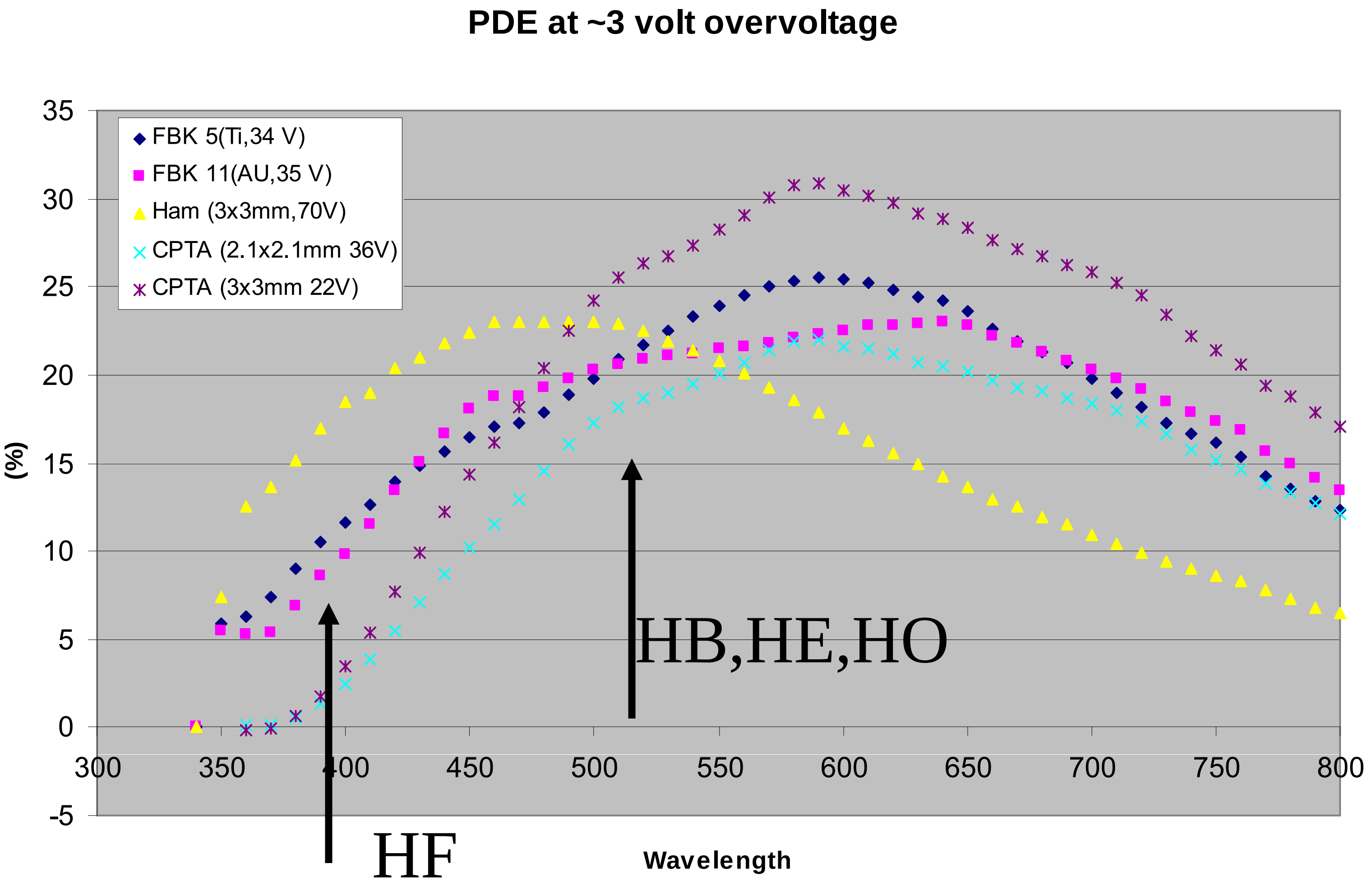
QE *vs* Wavelength



Reduced
by ARC

Reduced by
small epi
thickness

Comparison of PDE



- From Arjan in Trieste, 3 June 2008

Activities at Trieste-Udine

- The FACTOR collaboration is interested in the development of the device and in its optimization for application to:

- **Present application interests:**
  - Calorimetry with fiber-based optical readout
  - Large – area scintillator – based muon counters
  - Scintillating fiber – based tracking
  - future space experiments for detection of UHECR
  - FEL studies and instrumentation
  - future large – area, ground – based x-ray telescopes

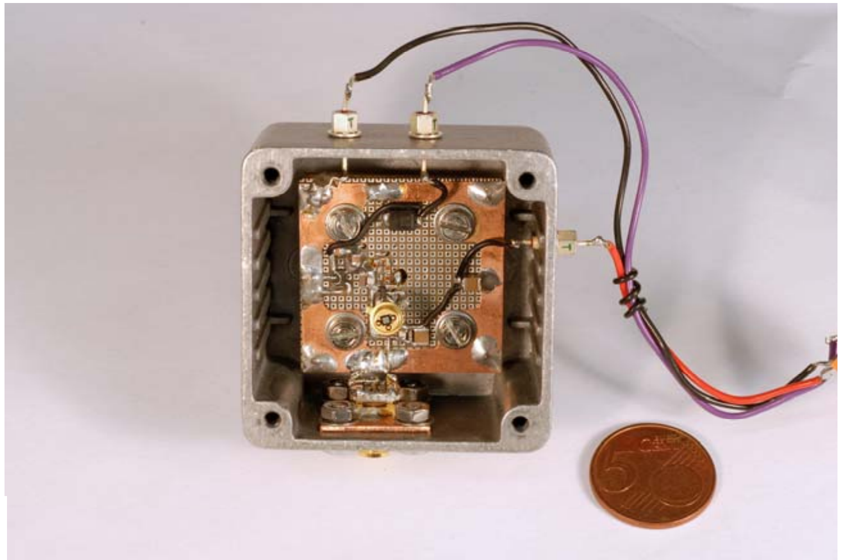
- **Action Plan:**
  - comparative studies for detailed understanding of device characteristics
  - Application tests
  - Optimization of properties as a function of application

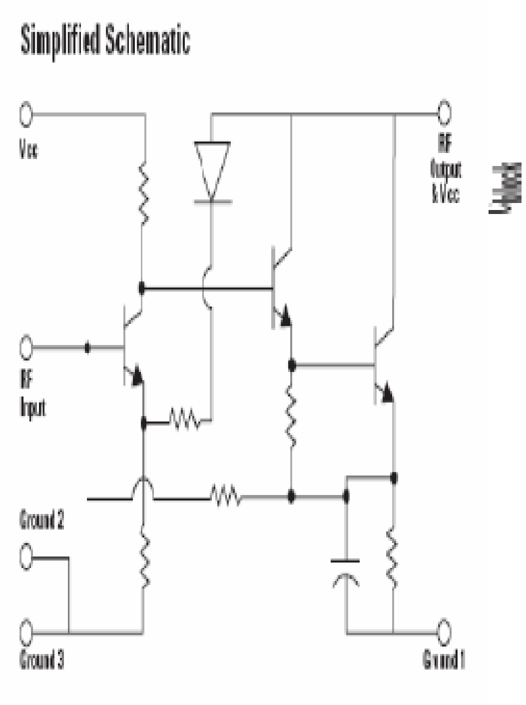
First year FACTOR

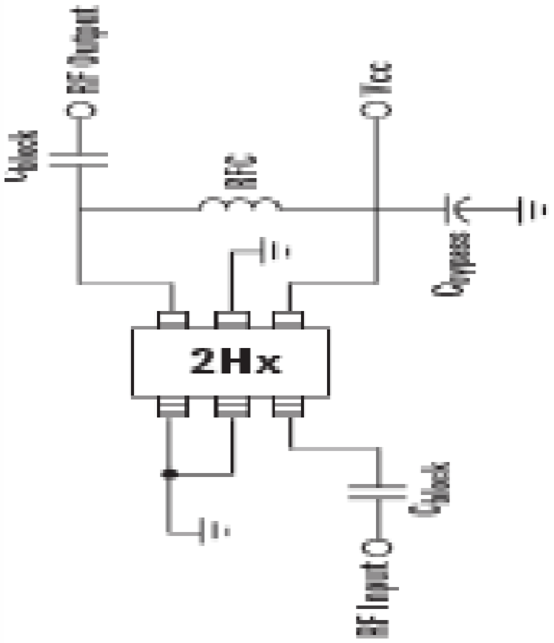
- Comparison of SiPM characteristics produced by different manufacturers;
- Measurements of SiPM characteristics as a function of T;
- Irradiation of the devices and study of radiation damage effects;
- Tests with SiPMs coupled to wls fibers for scintillator read-out.
- Energy and time resolution measurements;
- Study of optimal packaging, electronics placement, etc.
- At the moment, we are performing tests on SiPMs from 3 different
- sources:
- Forimtech (MRS):
  - 1 mm2 in TO18 - λP ≈ 560 nm - 556 μcells ~ 43x43 μm2
- Photonique (MRS):
  - "GR sensitive" - 1 mm2 in TO18 - 556 μcells ~ 43x43 μm2
  - "Blue sensitive" - 1 mm2 in TO18 - 556 μcells ~ 43x43 μm2
  - "Blue sensitive" - 4.4 mm2 on PCB - 1748 μcells ~ 50x50 μm2
  - "Blue enhanced" – 9 mm2 in TO5 – 8100 μcells ~ 33x33 μm2
- IRST (polysilicon), 1 mm2 - λP ≈ 420 nm (devices from 2nd and 3rd batch)
  - 625 μcells, 40x40 μm2

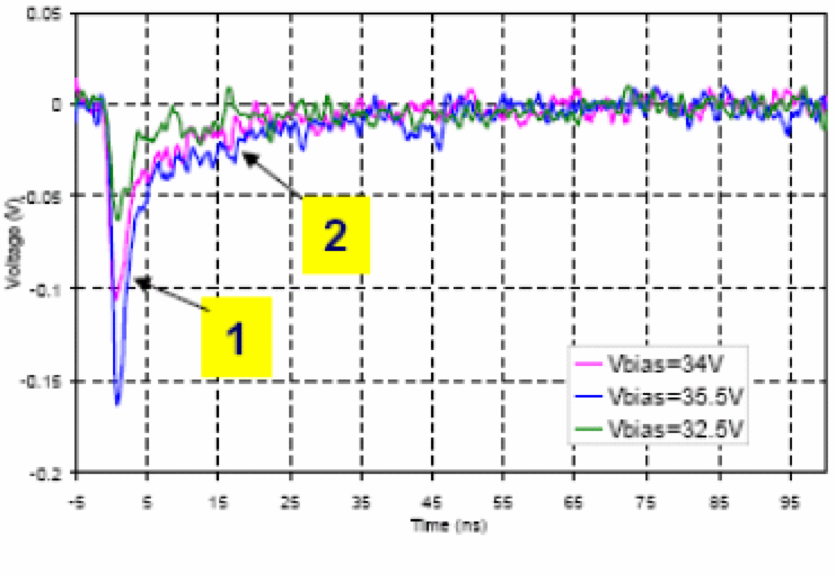
Fast Amplifier

- Amplifier used for fast characterization of SiPMs:
- Agilent ABA-52563 3.5 GHz RFIC Amplifier
- (economic, compact, internally 50-Ω matched, gain ~ 20 dB)





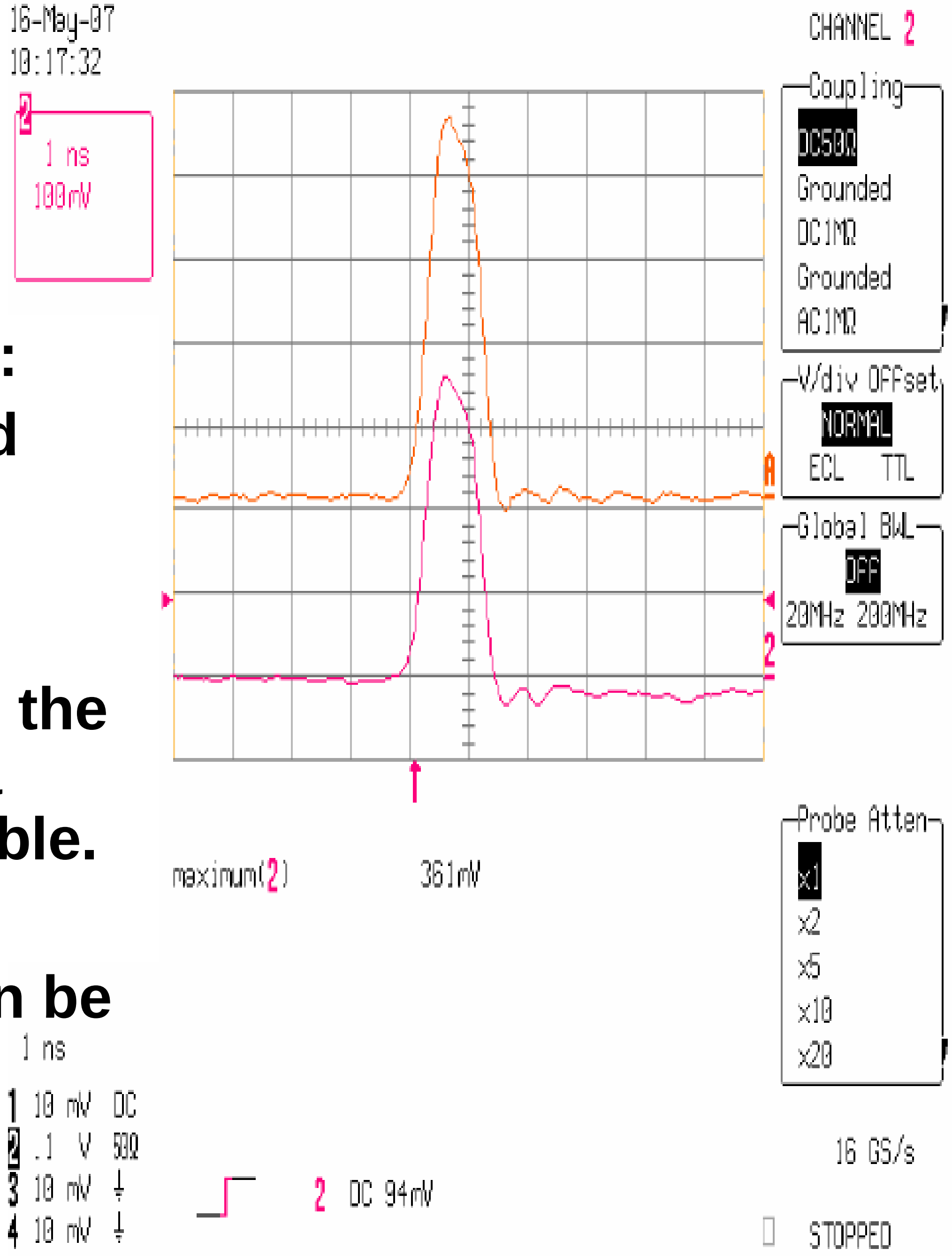




Amplifier Characterization

- **Temperature dependence:**
- **Measurements performed with the DUT in a climatic chamber (with humidity control)**
- **The amplifier was outside the chamber, connected via a special 18 GHz ft 50 Ω cable.**

- **Timing characteristics can be studied**



16-May-07
10:17:32

1 ns
100 mV

CHANNEL 2

Coupling
DC50Ω
Grounded
DC1MΩ
Grounded
AC1MΩ

V/div Offset
NORMAL
ECL TTL

Global BWL
OFF
20MHz 200MHz

maximum(2) 361mV

Probe Atten
x1
x2
x5
x10
x20

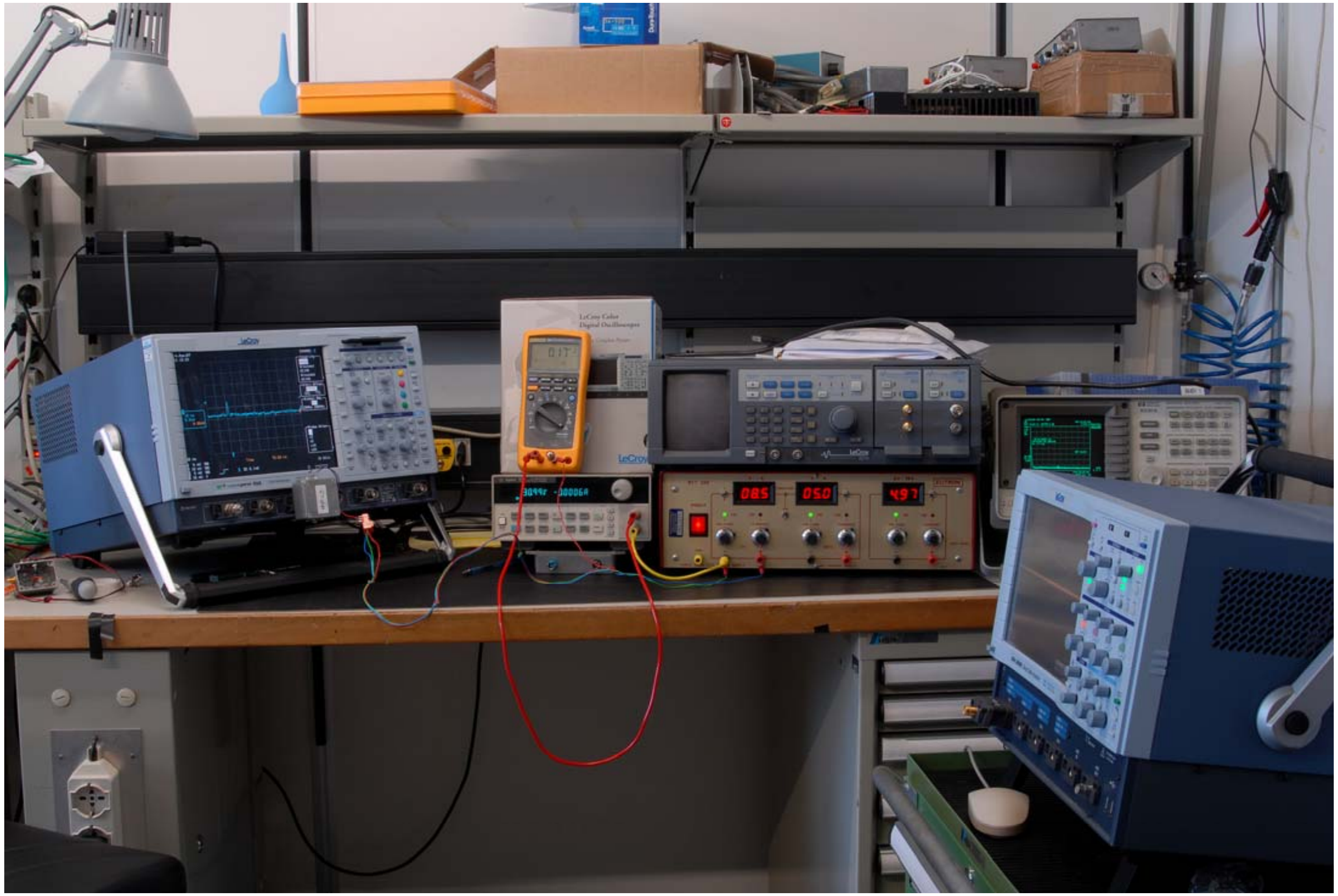
1 ns
1 10 mV DC
2 .1 V 50Ω
3 10 mV ⏚
4 10 mV ⏚

2 DC 94mV

16 GS/s

STOPPED

Test Setup at INFN Lab

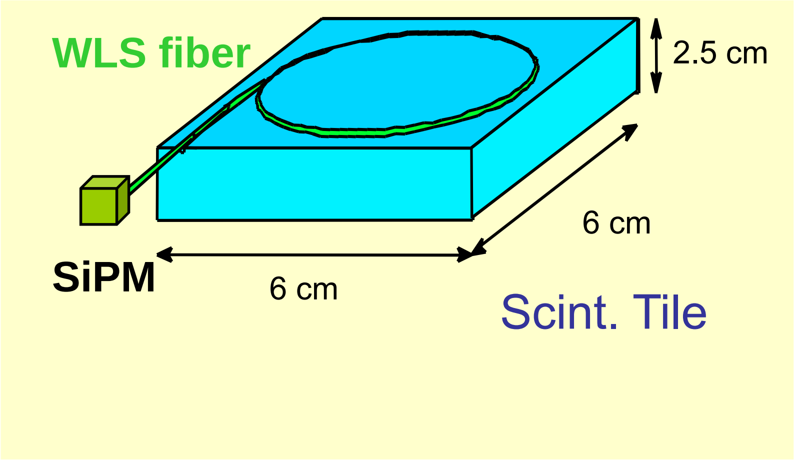


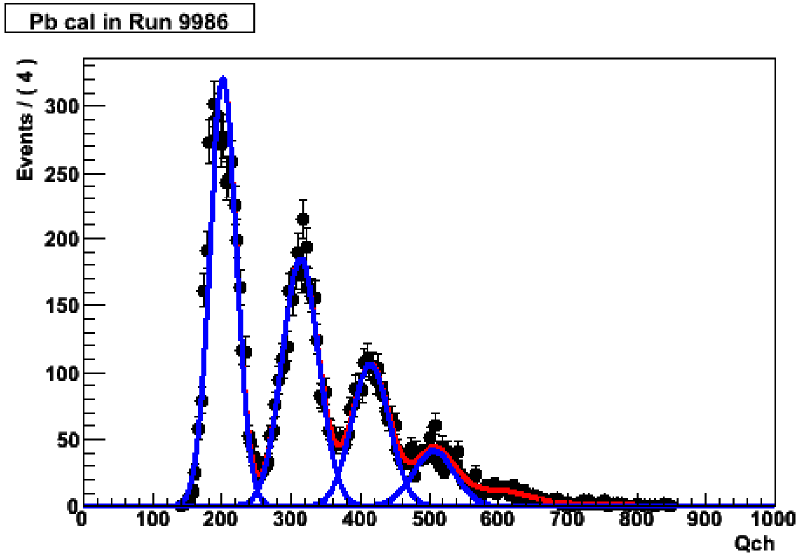
Present Tasks

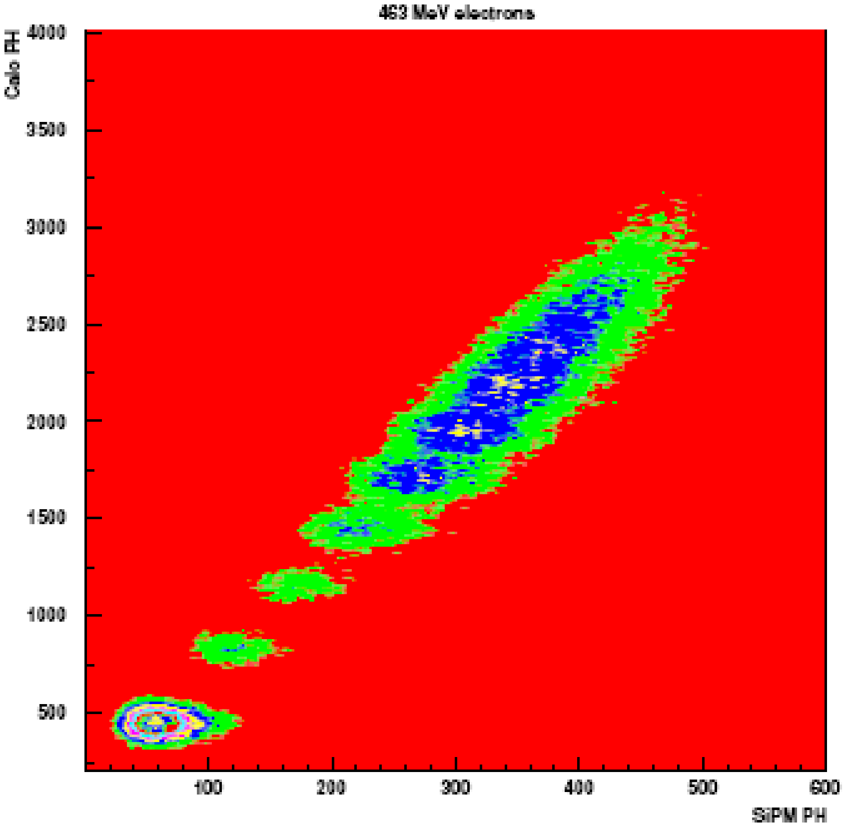
- **SiPM Development**
  - Comparative device characterization (ISRT, Hamamatsu, Formitech)
  - Development (in collaboration with IRST)
  - Optimization of packaging & (fast!) preamplification
- **Irradiation studies** (so far on 24 SiPM's)
  - FBK-irst, Hamamatsu Photonique, Formitech
  - X-rays @ INFN Legnaro Labs (50 – 500 krad)
  - neutrons @ IJS reactor, Ljubljana (~4.8 x 101 0 n/cm 2)
- **Application Studies**
  - Large area muon counters (FNAL)
  - Calorimetry with optical readout (FNAL/CERN/Frascati)
  - Scintillator-based fine-grained hodoscopes (CERN)

- Preliminary study of Scint. Strips viewed by IRST SiPM at the FNAL test beam (prototype of muon detector/tail catcher for ILC)

Test at Frascati





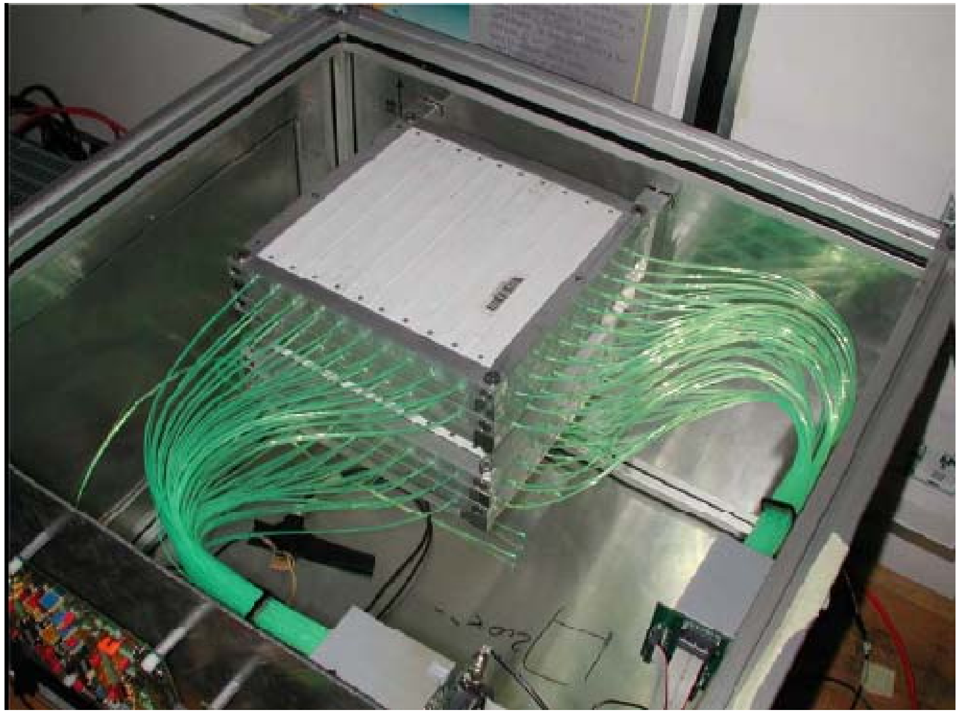


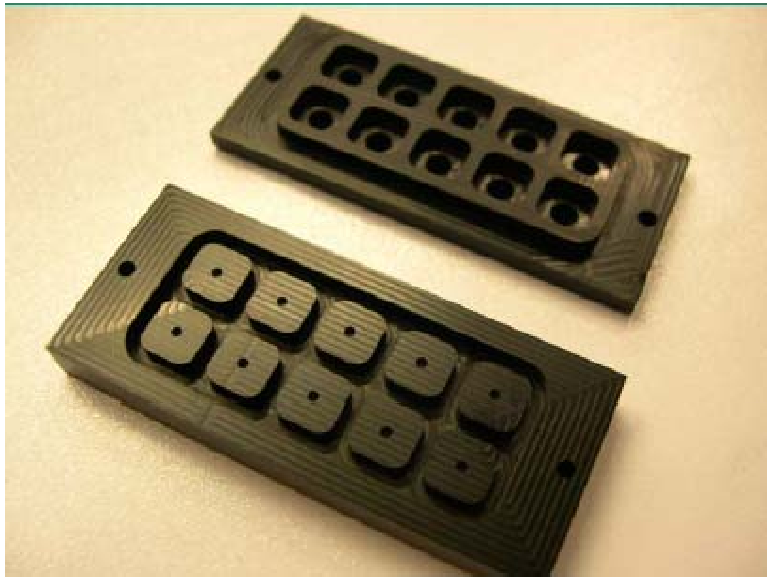
Electron beam with a Cherenkov calorimeter counting multiplicity

Test beam at CERN

- Test beam at CERN (May/June 2008) with the MICE experiment: 8 extruded scintillator bars (1.5x1.9x19 cm3) with wls fibers, read out by SiPMs (IRST and Hamamatsu), all other bars of the MICE calorimeter read out by MAPMT.
- An ad hoc mechanical receptacle was realized to couple and align the fibers with the SiPMs and test them in a 2 GeV positron beam
- Frontend electronics: VA64TAP3.1 +LS64 by Gamma Medica-IDEAS; trigger signals sampled by an Altera with a 320 MHz clock

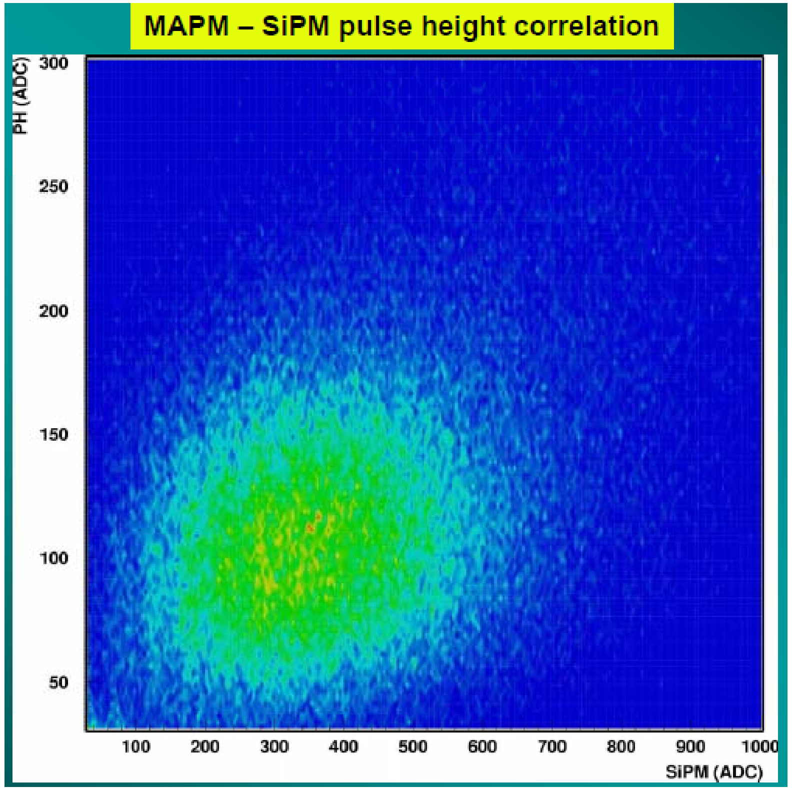
Mice detector



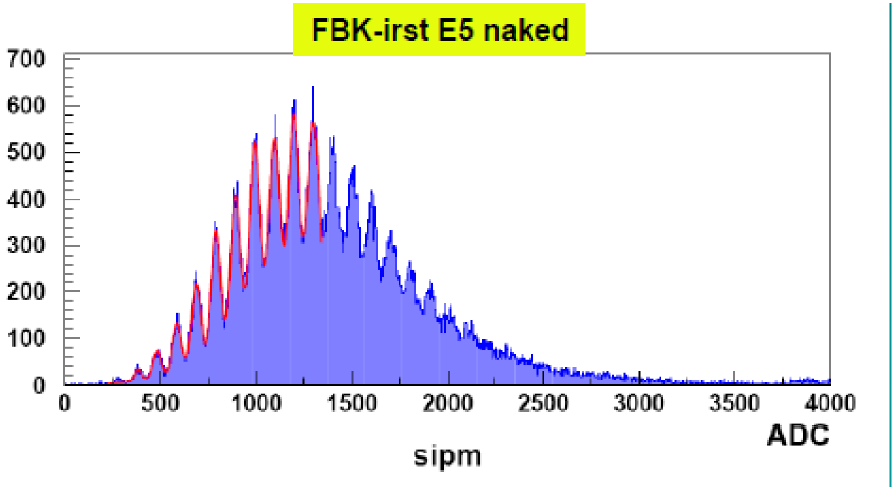


- A small fraction of the prototype fibers are readout with SiPM. The SiPM receptacle is visible to the right

The SiPM response



Pulse-height plot of the SiPM obtained selecting good events on the MAPM side



- Correlation MAPMT vs SiPM amplitude

Radiation studies

- Systematic campaign this year: study resistance to radiation effects of SiPMs produced by different manufacturers
  - Objective: study both surface and bulk damage in the devices
  - Types of radiation used: X-rays (up to 50 keV) and neutrons
  - Measurement strategy: I-V characterization, dark count and gain before and after irradiations, annealing studies
  - 24 devices from FBK-irst, Photonique (CPTA) and Hamamatsu irradiated so far; **further irradiations are foreseen in the next weeks**

- **X-rays: INFN National Laboratories of Legnaro (LNL), X-ray tube (W target), Vmax = 50 kV, dose rate measured with calibrated Si p-i-n diodes**
- **Neutrons: Nuclear Reactor of the Institute Josef Stefan of Ljubljana (Slo), max power ~ 250 kW, very high fluence achievable**

X-rays @ INFN Legnaro Labs (50, 100 and 150 krad);
X-rays @ INFN Legnaro Labs (300 and 500 krad);
neutrons @ IJS reactor, Ljubljana (fluence ~ 4.8 x 10^{10} n/cm^{-2});

Irradiation studies (so far on 24 SiPM's)

- X-rays @ INFN Legnaro Labs (50 – 500 krad)
- neutrons @ IJS reactor, Ljubljana (~4.8×10^{10} n/cm^2)
- (spectrum ?)
- Very preliminarly:

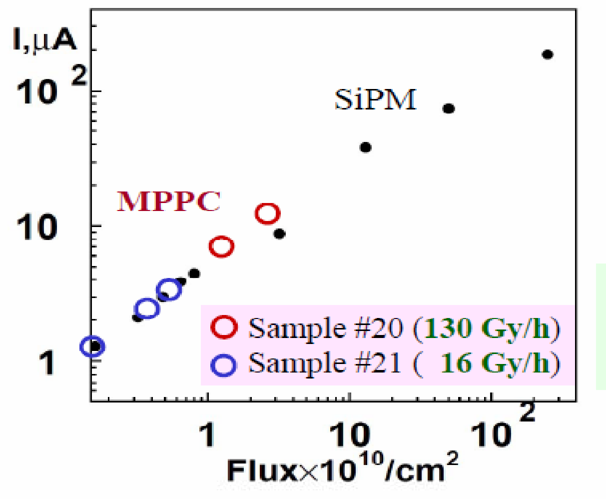
- With 300 krad X-rays, HPK DC increase by 20 – 25
- FBK by 4 - 5
- With 500 krad, HPK by 36-40, FBK by 6 - 8

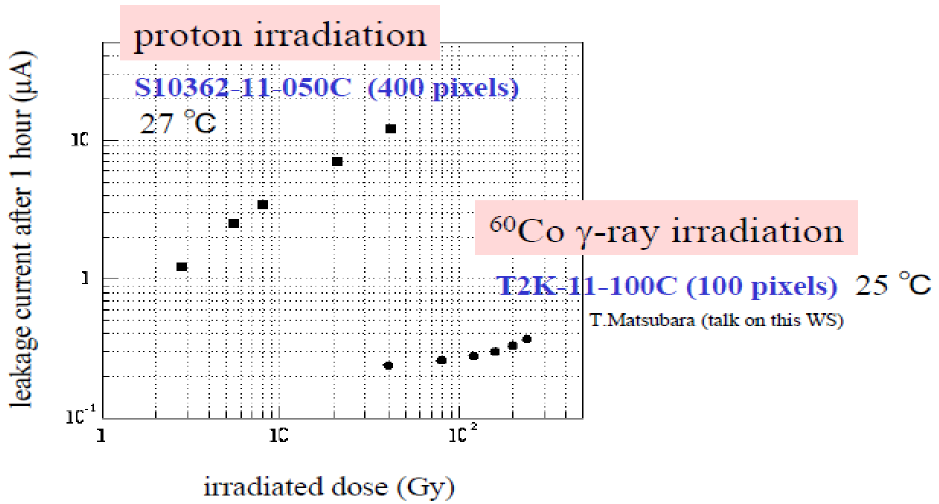
- With 4.8×10^{10} n/cm^2, HPK DC increase by 45-60, FBK by 15 - 20 .

(See next page)

Other measurements and estimates

M.Danilov arXiv:0704.3514v1



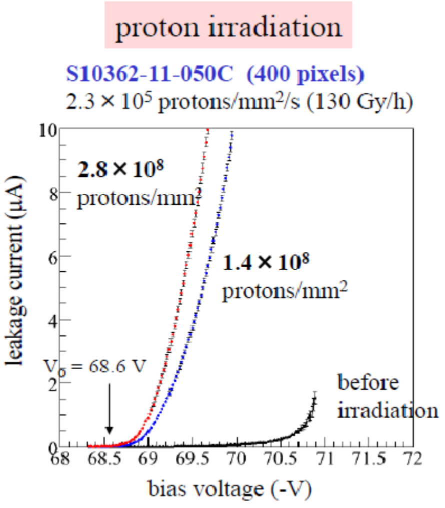

proton irradiation

S10362-11-050C (400 pixels) 27 °C

^{60}Co γ-ray irradiation

T2K-11-100C (100 pixels) 25 °C

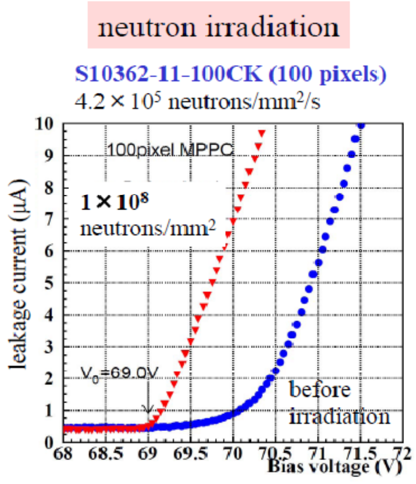
T.Matsubara (talk on this WS)


proton irradiation

S10362-11-050C (400 pixels)

2.3 × 10^5 protons/mm^2/s (130 Gy/h)

I_{leak} @ (V_{op}, 1.4x10^8 p/mm^2) = 6.7 μA


neutron irradiation

S10362-11-100CK (100 pixels)

4.2 × 10^5 neutrons/mm^2/s

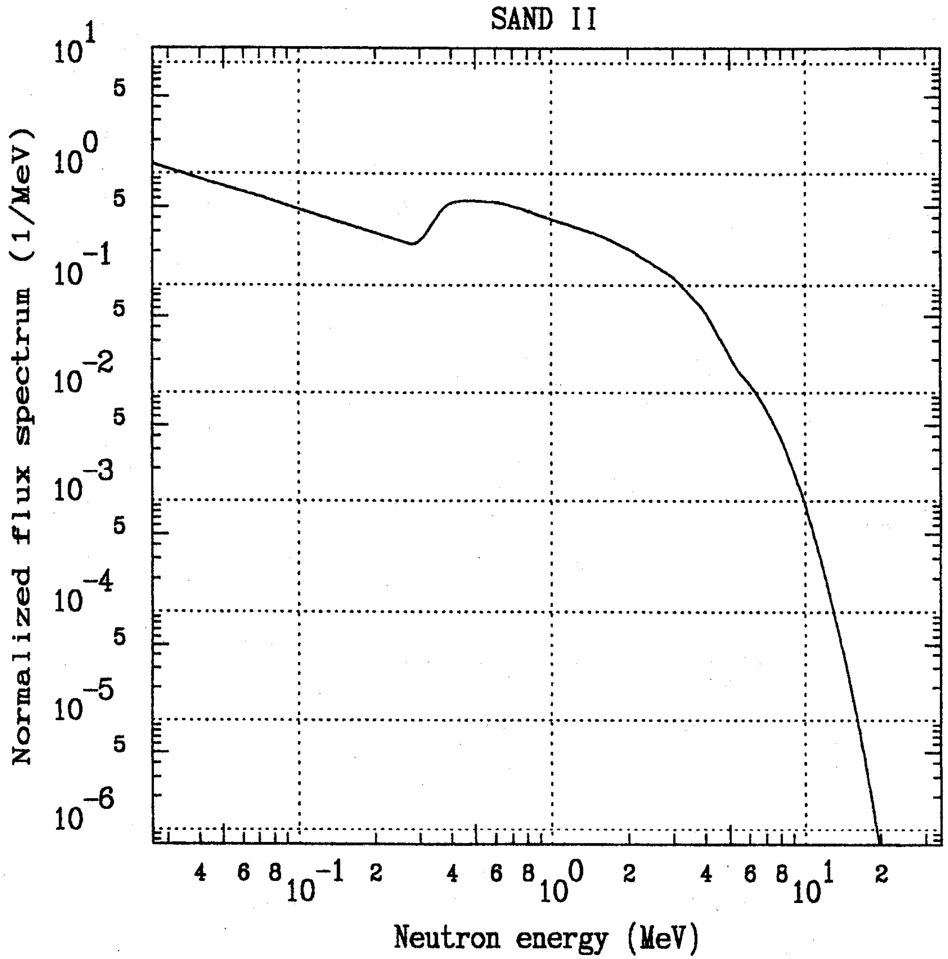
I_{leak} @ (V_{op}, 1.0x10^8 n/mm^2) = 8.5 μA

See:
T. Matsumura (June 29, 2007)
International Workshop on new photon-detectors (PD07)
(Kobe University)

Neutron ≈ Proton

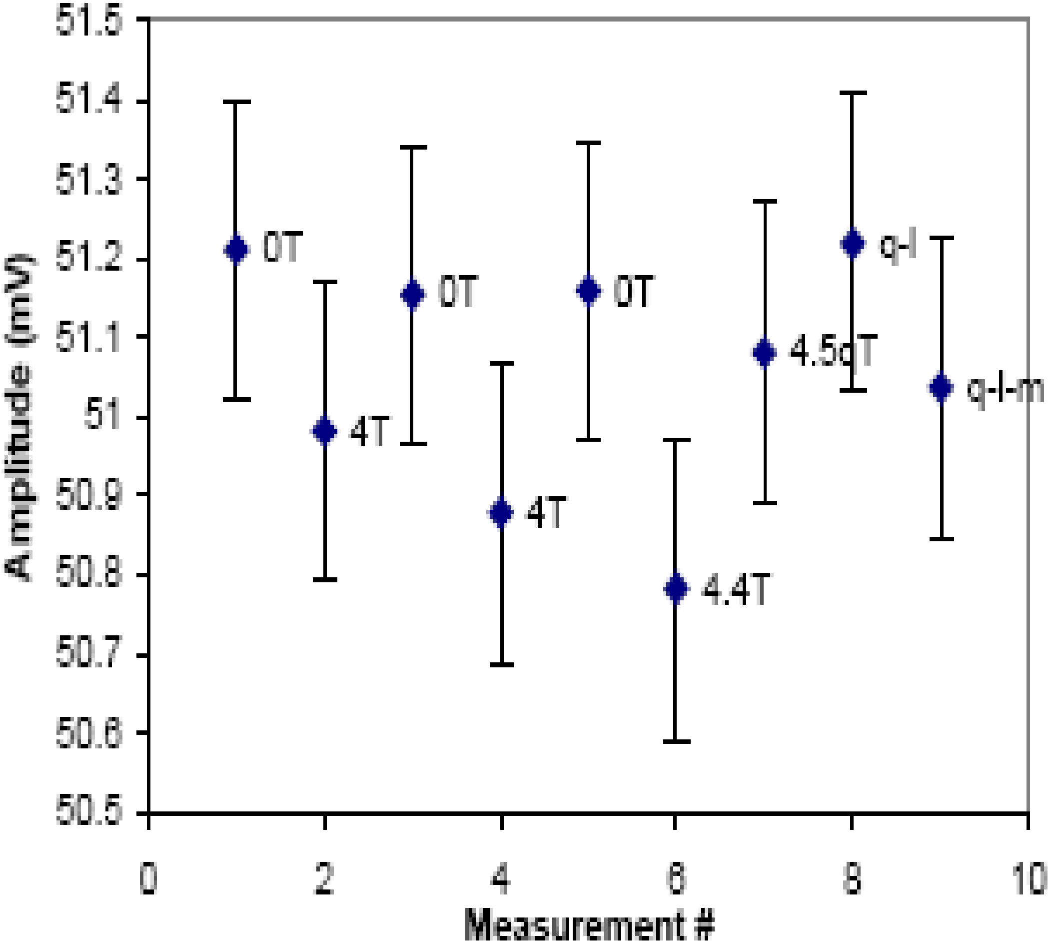
Proton ≈ 100 x X-ray

Triga 3 reactor JSL



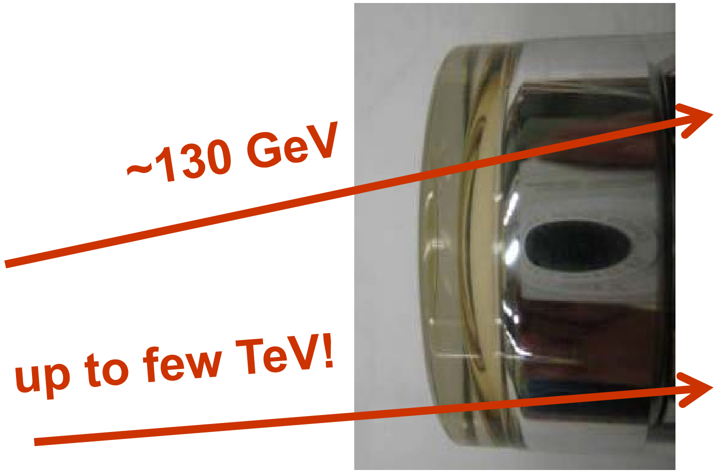
Magnetic field resistance

- “Investigation of a Solid-state Photodetector”, NIM A 545:727-737 (2005).
- “Effects of a strong magnetic field on LED, extruded scintillator and MRS photodiode”, NIM A553: 438-447 (2005)
- (Vishnu V. Zutshi)



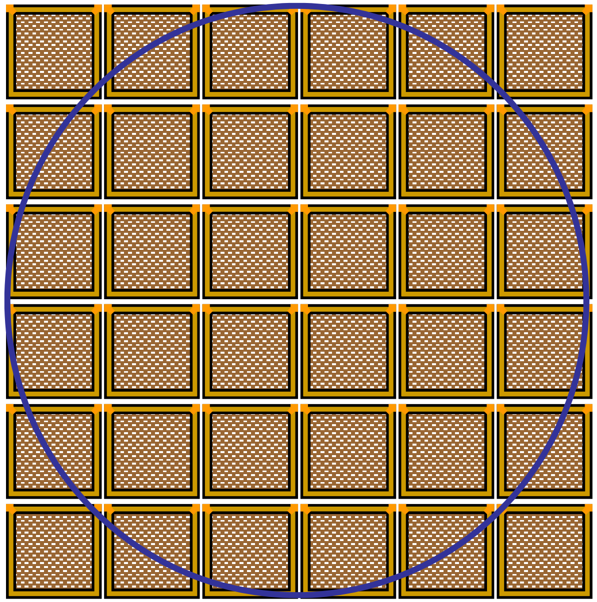
SiPM for HF?

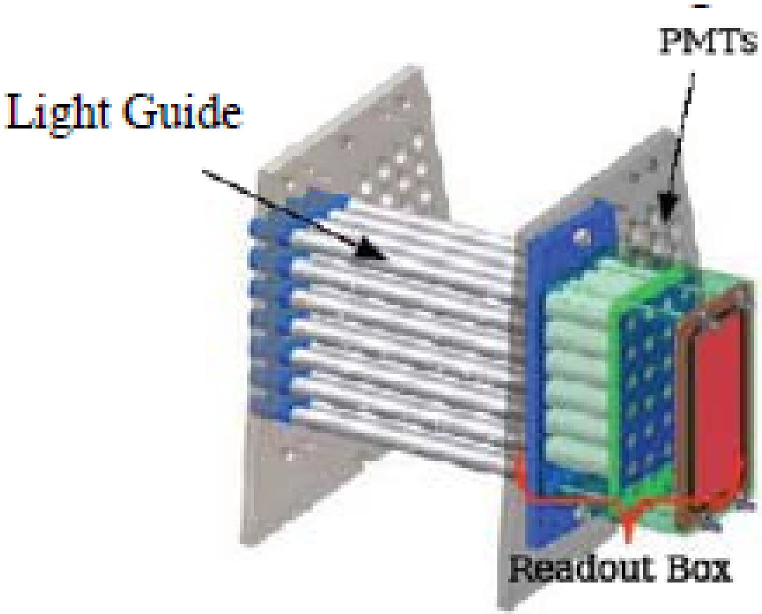
- PMT fake signals in HF: show-stopper?
- SiPM useful but:
- Radiation hard?
- Small dimensions?
- Dinamic range?



- Consider matrix of 4x4 mm^2 FBK SiPM
  - To cover 2.4 cm diameter PMT window

SiPM matrix…





…if 1 SiPM costs ≤10$ …

… not out of question?