SiPM: Development and Applications

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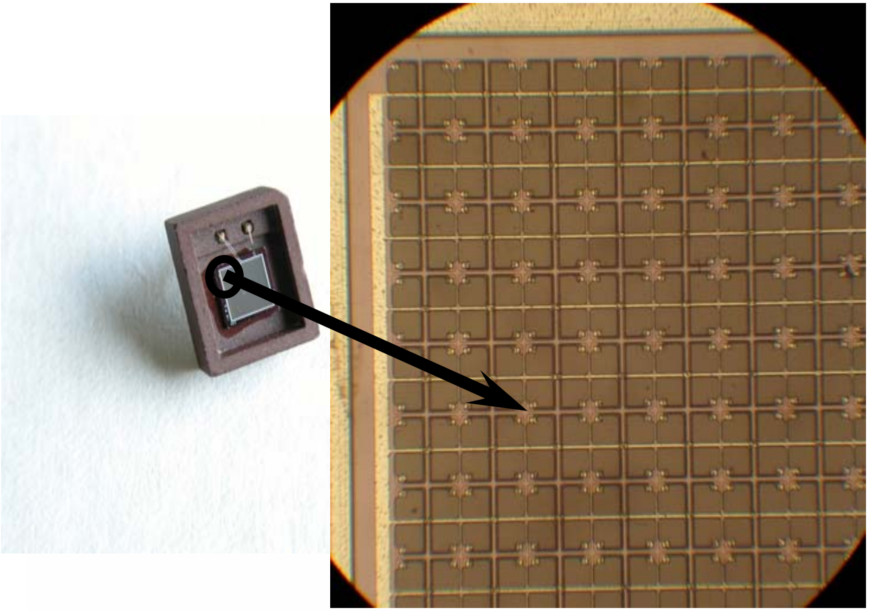
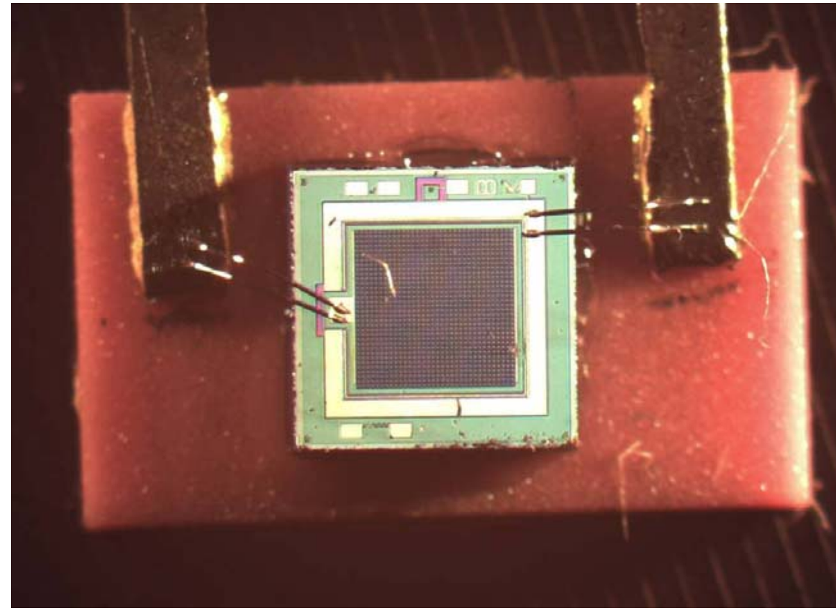
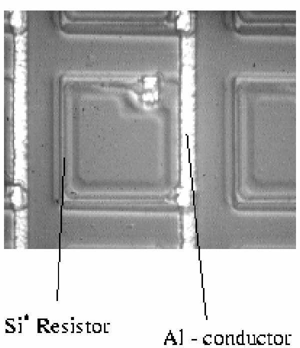
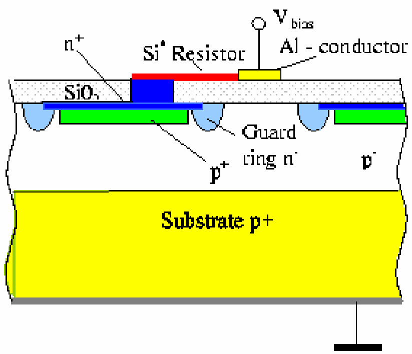


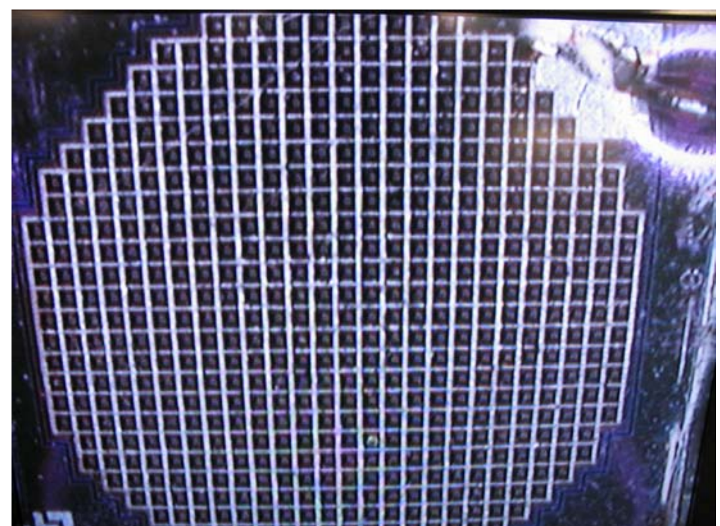



Si+ Resistor
Al - conductor

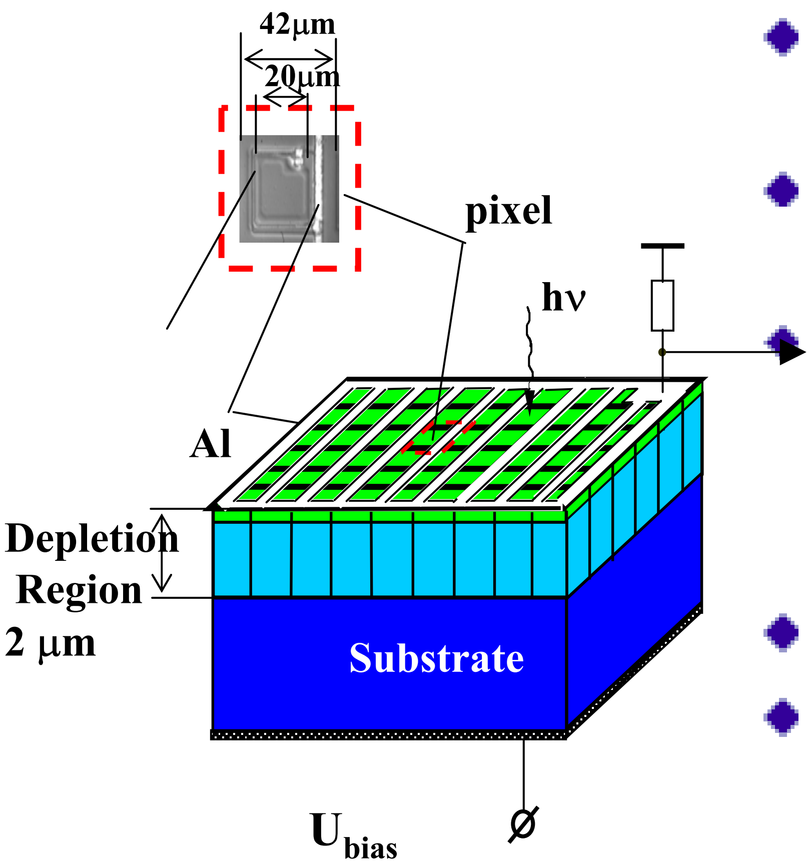
a


V bias
n+
Si+ Resistor
Al - conductor
SiO2
Guard
ring n-
p+
p-
Substrate p+

b

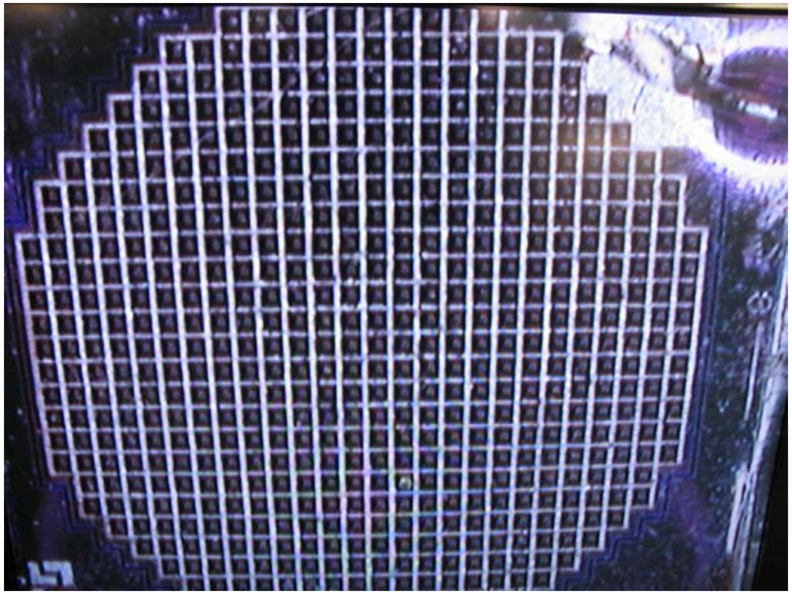


SiPM characteristics: general



- Matrix of independent pixels arranged on a common subtrate
- Each pixel operates in a self-quenching Geiger mode
- Each pixel produces a standard response independent on number of incident photons (arrived within quenching time)
- One pixel – logical signal: 0 or 1
- SiPM at whole integrates over all pixels: SiPM response = number of fired pixels
- Dynamic range ~ number of pixels

Geometry

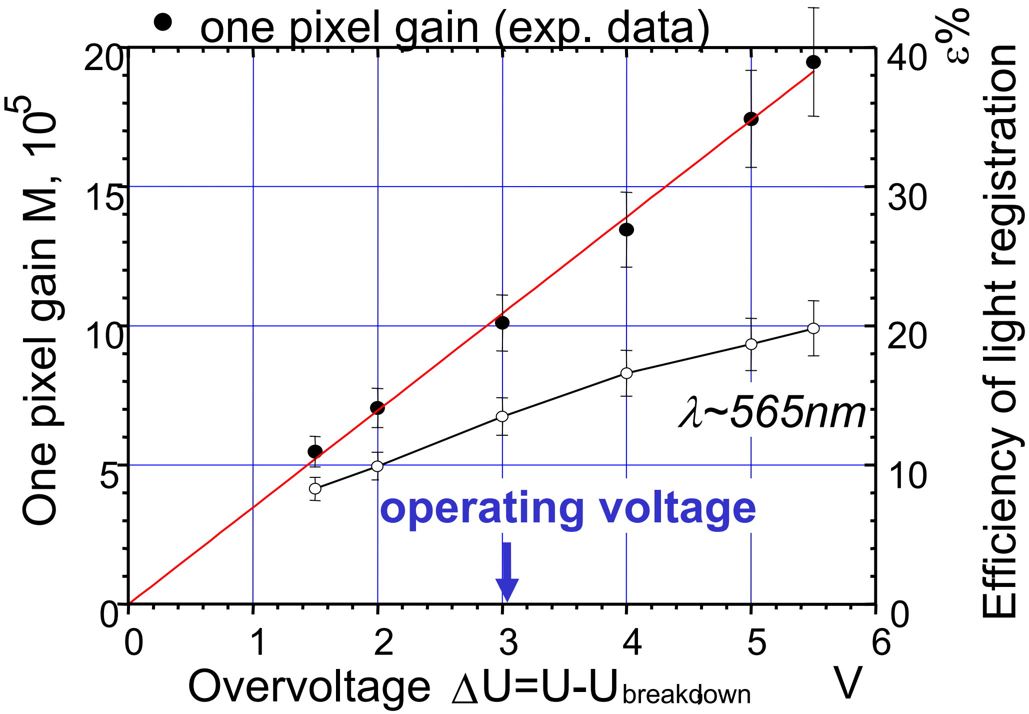


- Each pixel has a size 20-30μ
- 500-4000 pixels/mm^2
- Macroscopic unit ~ 1-3 mm

(0.5mm and 5mm units have been also produced recently)

- Pixels can be arranged in any shape to fit the shape of fiber

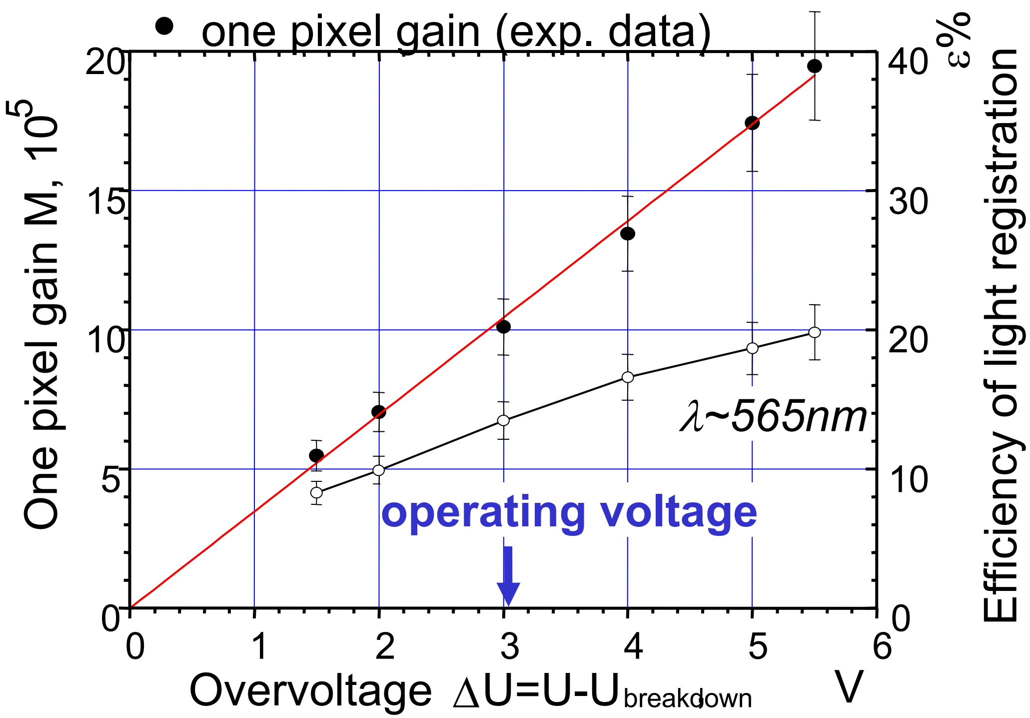
HV and gain



- Working point $V_{bias}=V_{breakdown}$ + ΔV; V ≈ 50-60 V (experimental series with 20-120V) ; ΔV ≈ 3V above breakdown voltage

Each pixel works as a Geiger counter with charge Q=ΔVC, C~ 50fmF; Q~ 3×50 fmC =150fmC = 10^6 e – comparable to vacuum phototubes; much higher than avalanche photo-diods.

HV and gain



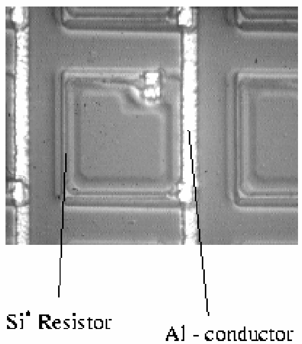
- One pixel signal on 50 Ohm corresponds to pulse amplitude ~1mV

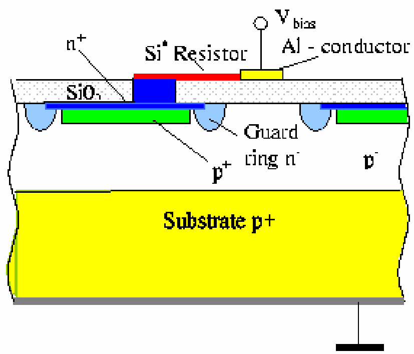
Gain increases linearly with overvoltage!

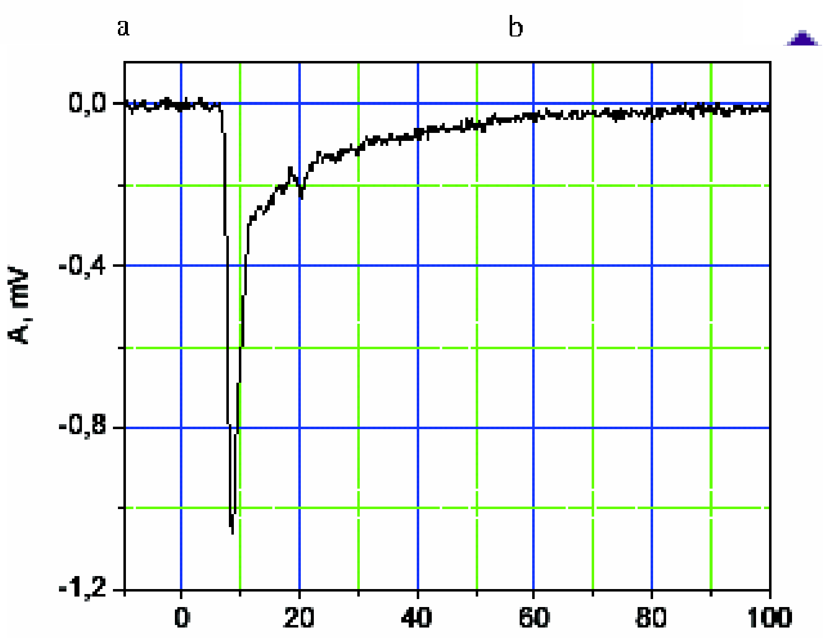
(APD has exponentional behaviour)

Optimal overvoltage is compromise with increased cross-talk (resulting in increased noise rate)

Timing characteristics

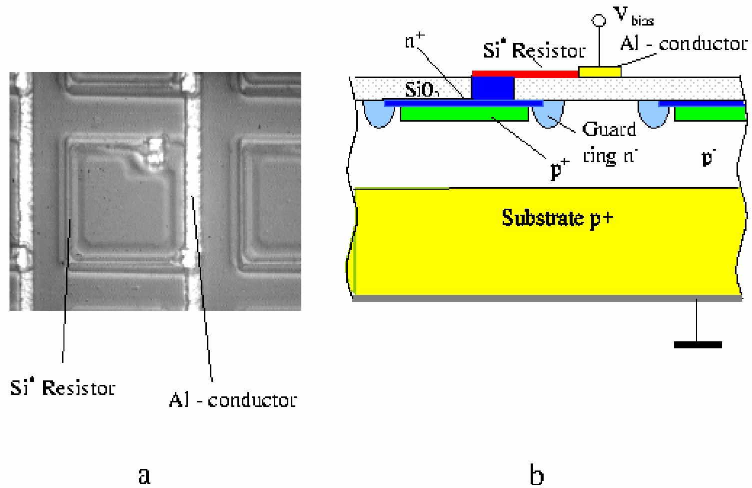






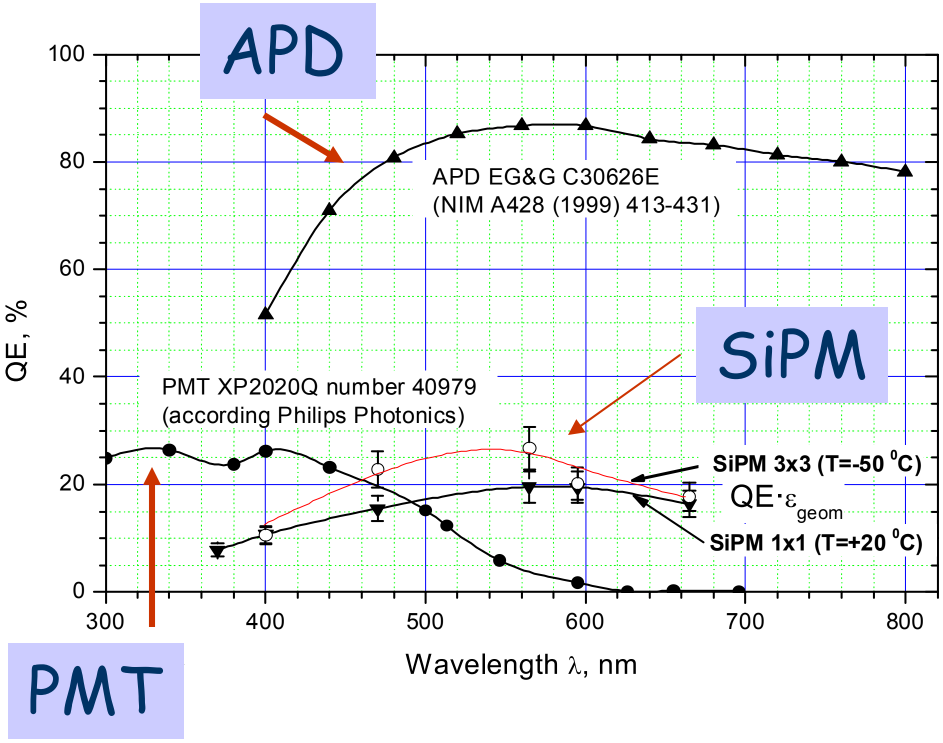
- Short Geiger discharge development < 500 ps
- Discharge is quenched by current limiting with polysilicon resistor in each pixel $I<10\mu A$
- Pixel recovery time ~ $C_{pixel}R_{pixel}$=100-500ns

Photon Detection Efficiency (PDE)



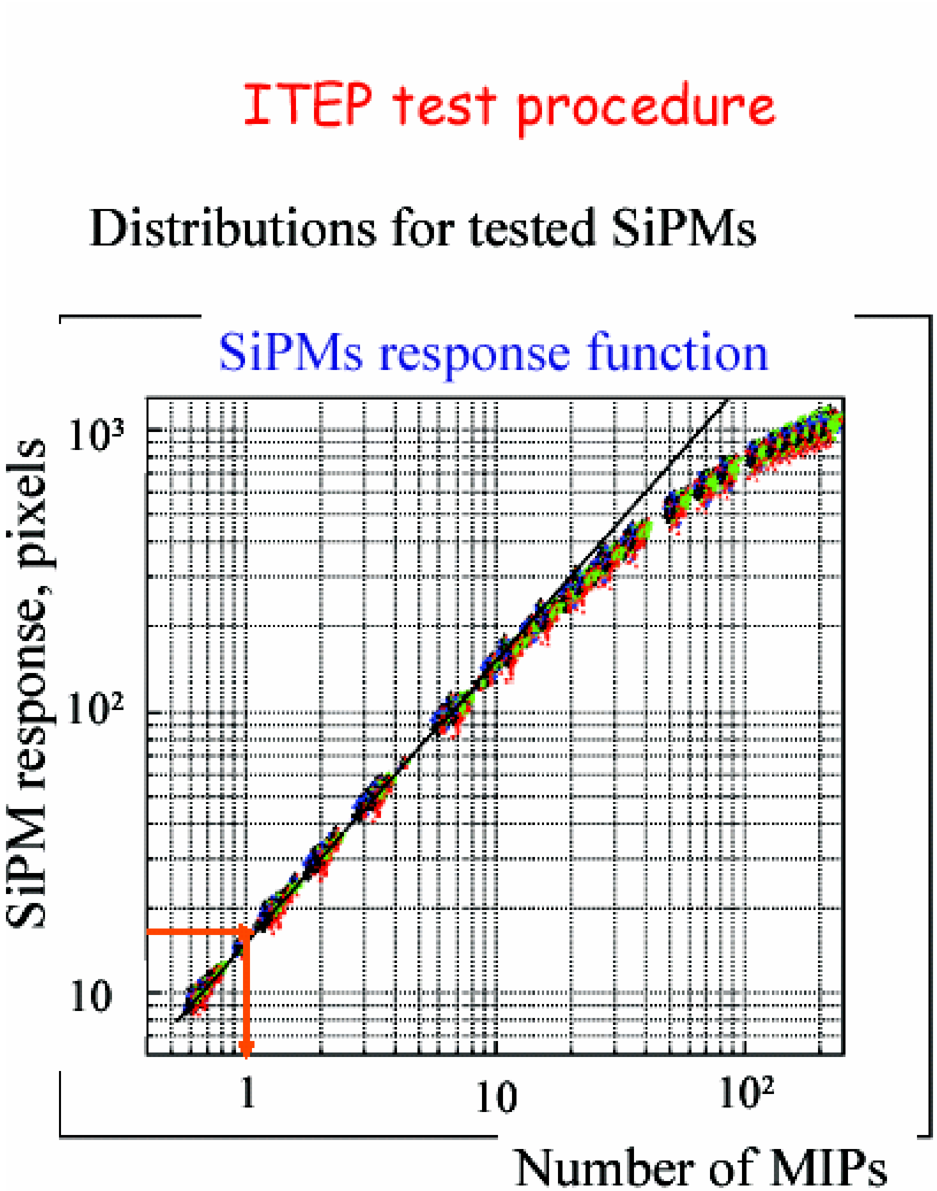
- Quantum efficiency is high ~ >80% for optical photons like other Si photodetectors
- Geometrical unefficiency is due to restricted sensitive area: eff ~30-50% depending on sensitive are/total area
- Probability to initiate Geiger discharge ~ 60%
- Finite recovery time for pixels ⇒ dead time depends on internal noise rate and photon occupancies

Spectral behaviour



- Photon absorbtion length in Si (~1μ) depends on wavelength
- The maximum efficiency can be tuned according to the task changing the width of depletion region (from green to red)

Dynamic range



- Check the linearity of the SiPM response
- Use light collected from scintillator and study SiPM response vs number of incident MIPs
- Non-linearity at large N because of saturation due to finite number of pixels

Single pixel dark rate

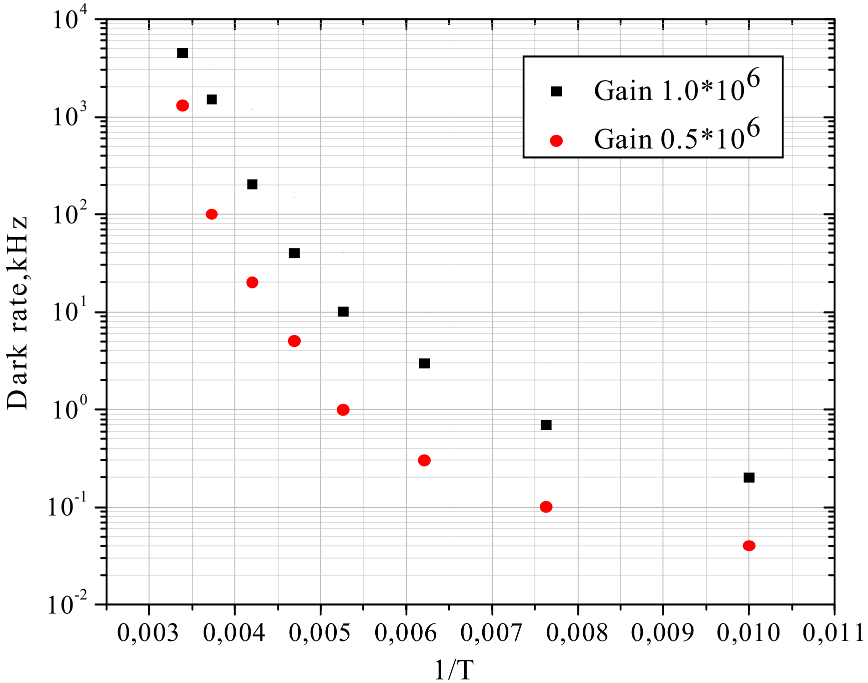


Fig. 3

- Electronic noise is small <10% of a single pixel standard signal -> results only on smearing of the standard signal
- Thermal creation of carriers in the sensitive volume results in standard pulses

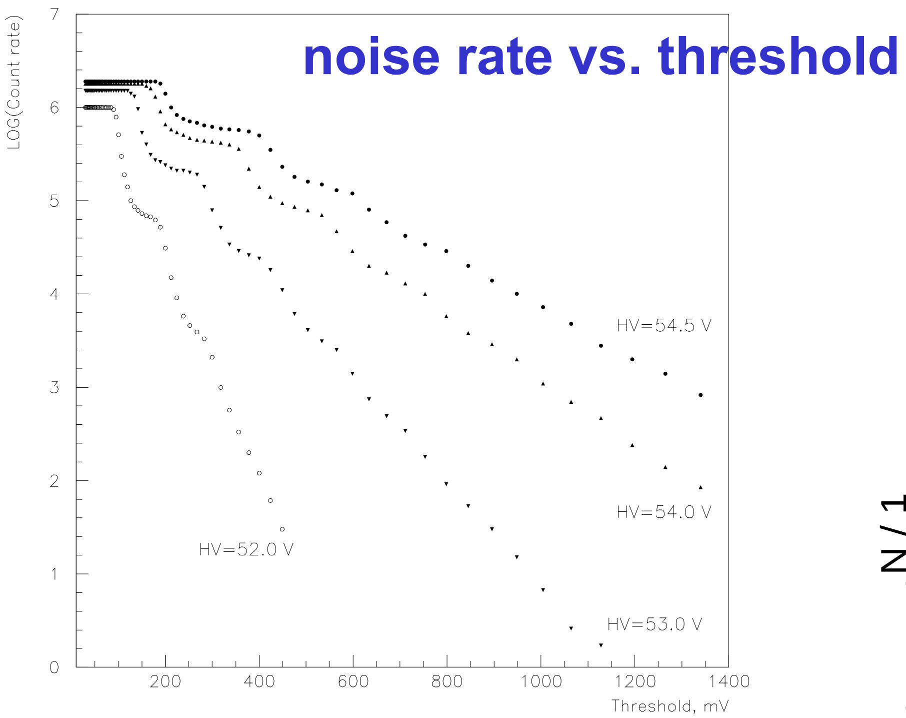
Typical one pixel dark rate ~ 1-2 MHz/mm^2 at room temperature

200 Hz/mm^2 at T=100K

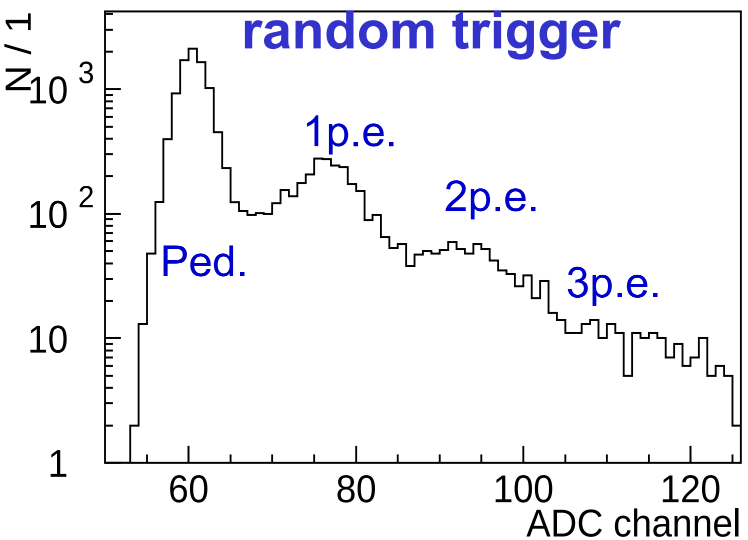
Internal cross-talk

- Single pixel noise rate is huge ⇒ restrict the SiPM application for small light yields (at least at room temperature)
- The probability of N pixel RANDOM noise coincidence within integration time (typically 100 ns) is ~$(100)^N$ times smaller
- BUT! Cross-talk violates the pixel independence:
  - Optical cross-talk: photons created in Geiger discharge (10^{-5}/e) can propagate to neighboring pixel
  - Electrical pixel-to-pixel decoupling (boundary between pixels and independent quenching resistors) seems to provide electrical pixels independence.
- Cross-talk increases the multypixel firing probabilities

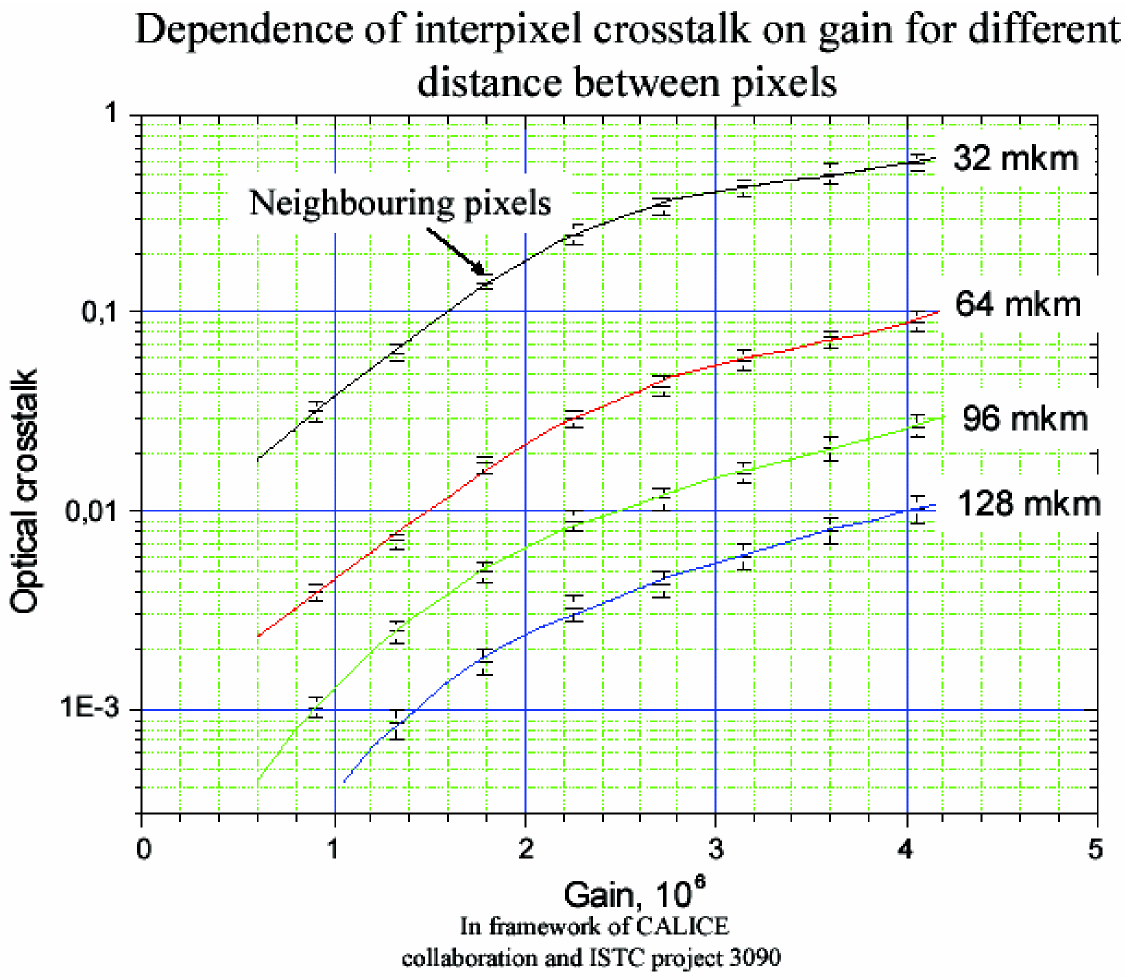
Internal cross-talk



1p.e. noise rate ~2MHz.
threshold 3.5p.e. ~10kHz
threshold 6p.e. ~1kHz

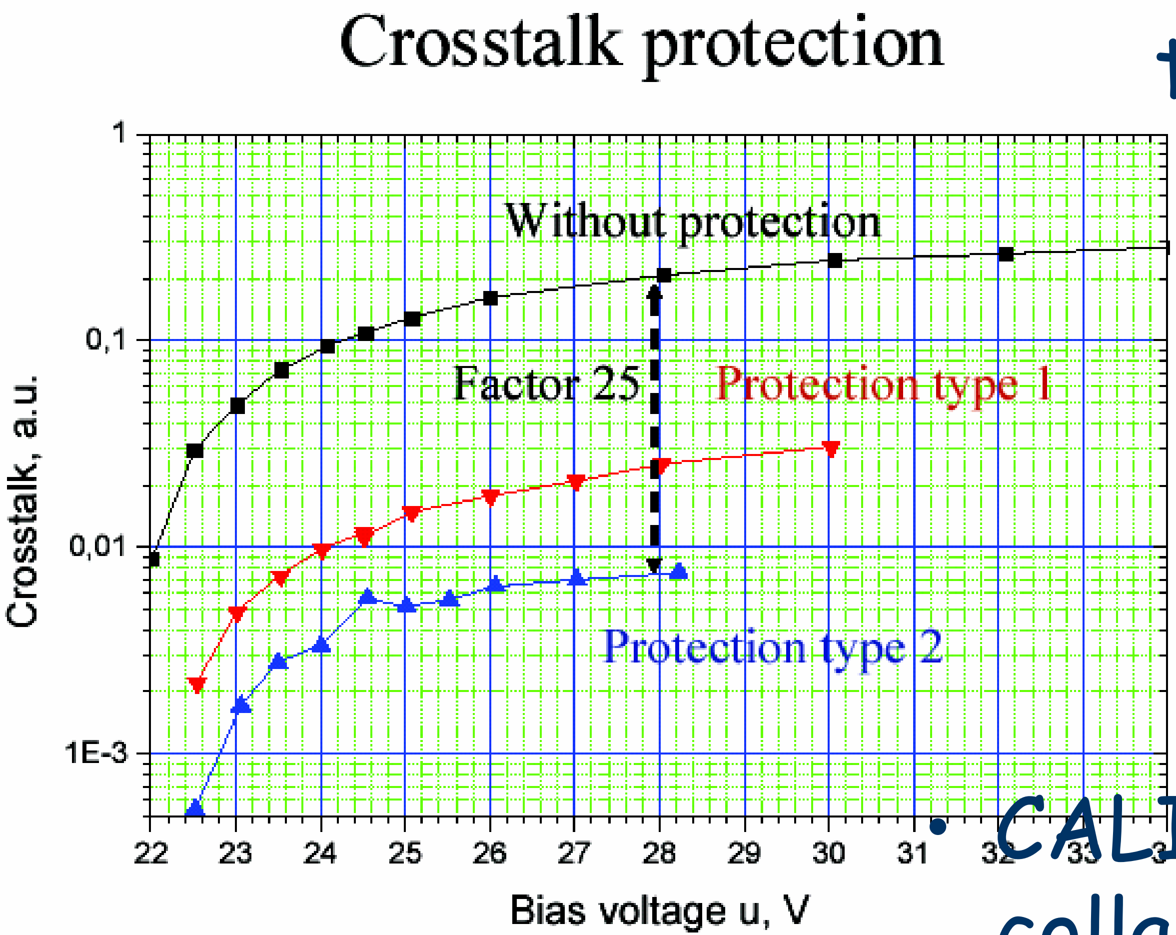


Internal cross-talk



The larger distance between pixel - the smaller cross-talk, but also smaller PDE

Cross-talk protection

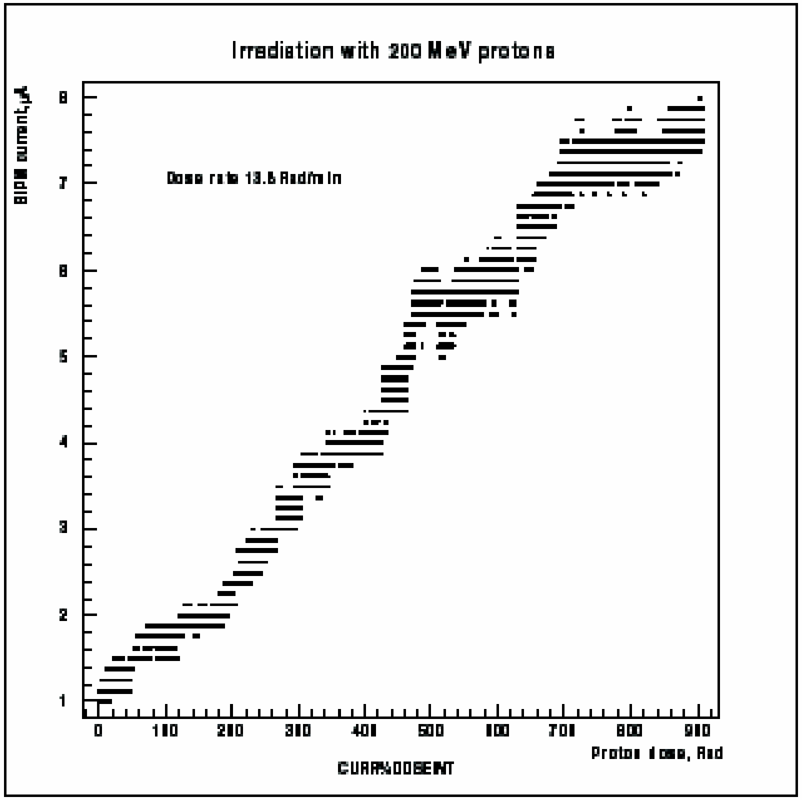


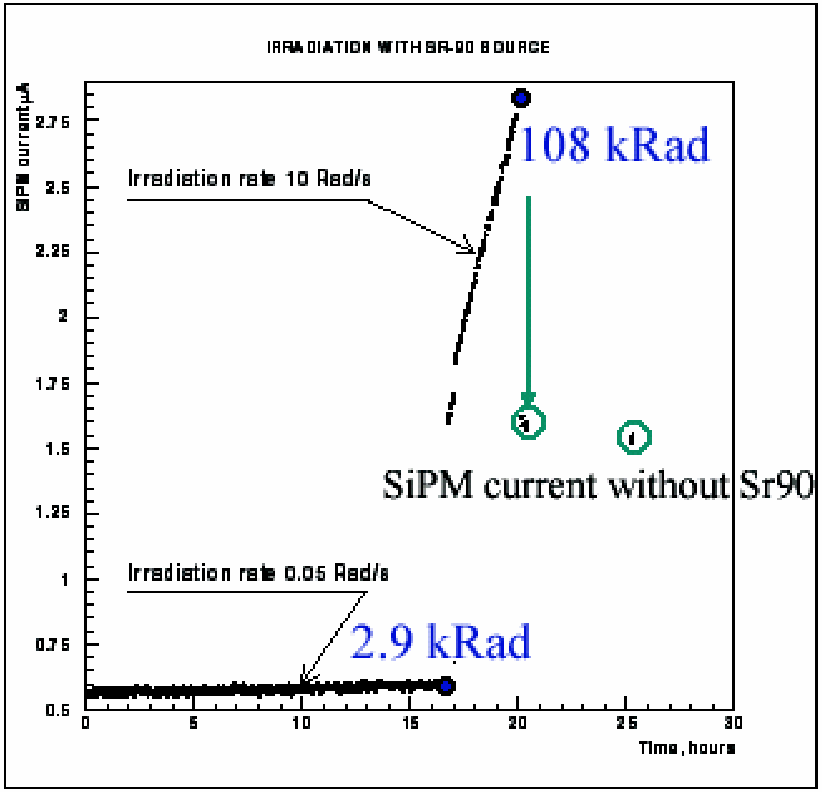
- Use special topology
- CALICE collaboration preliminary

Radiation hardness

Under investigation at ITEP now:

protons electrons neutrons gammas



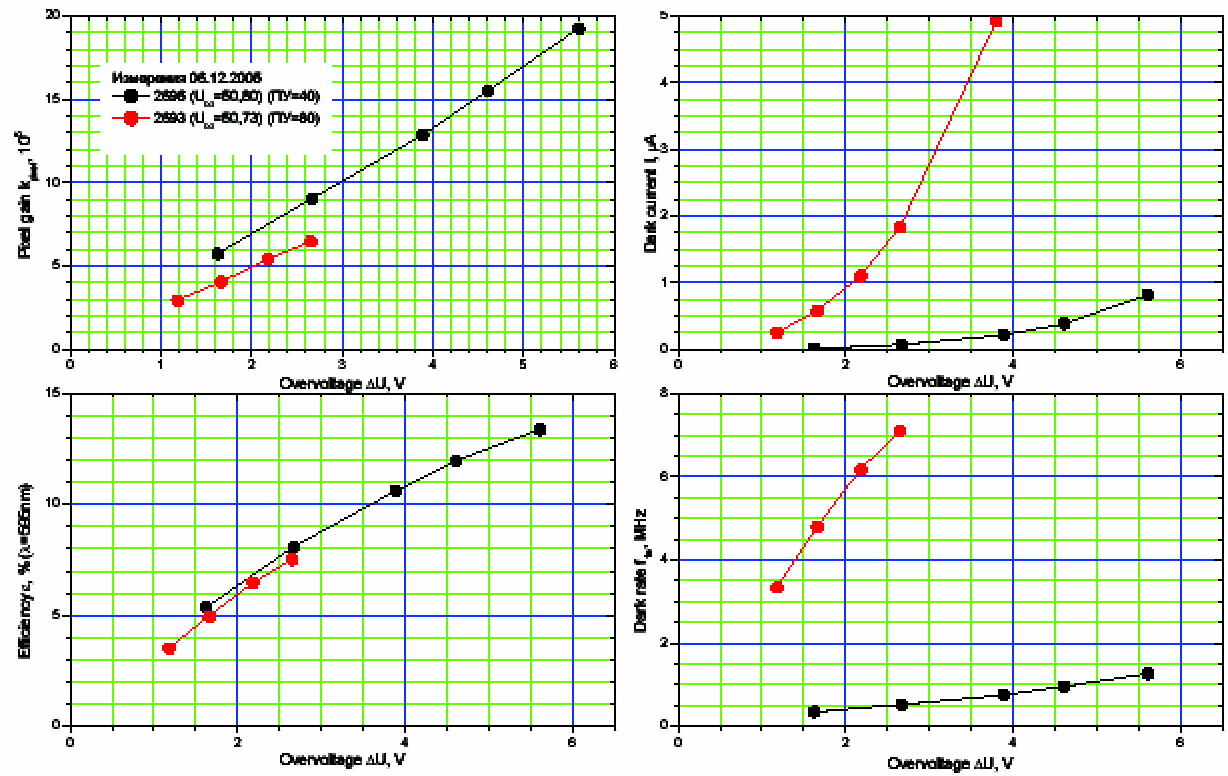


- Very preliminary

Radiation hardness

SiPM's characteristics **without irradiation** and

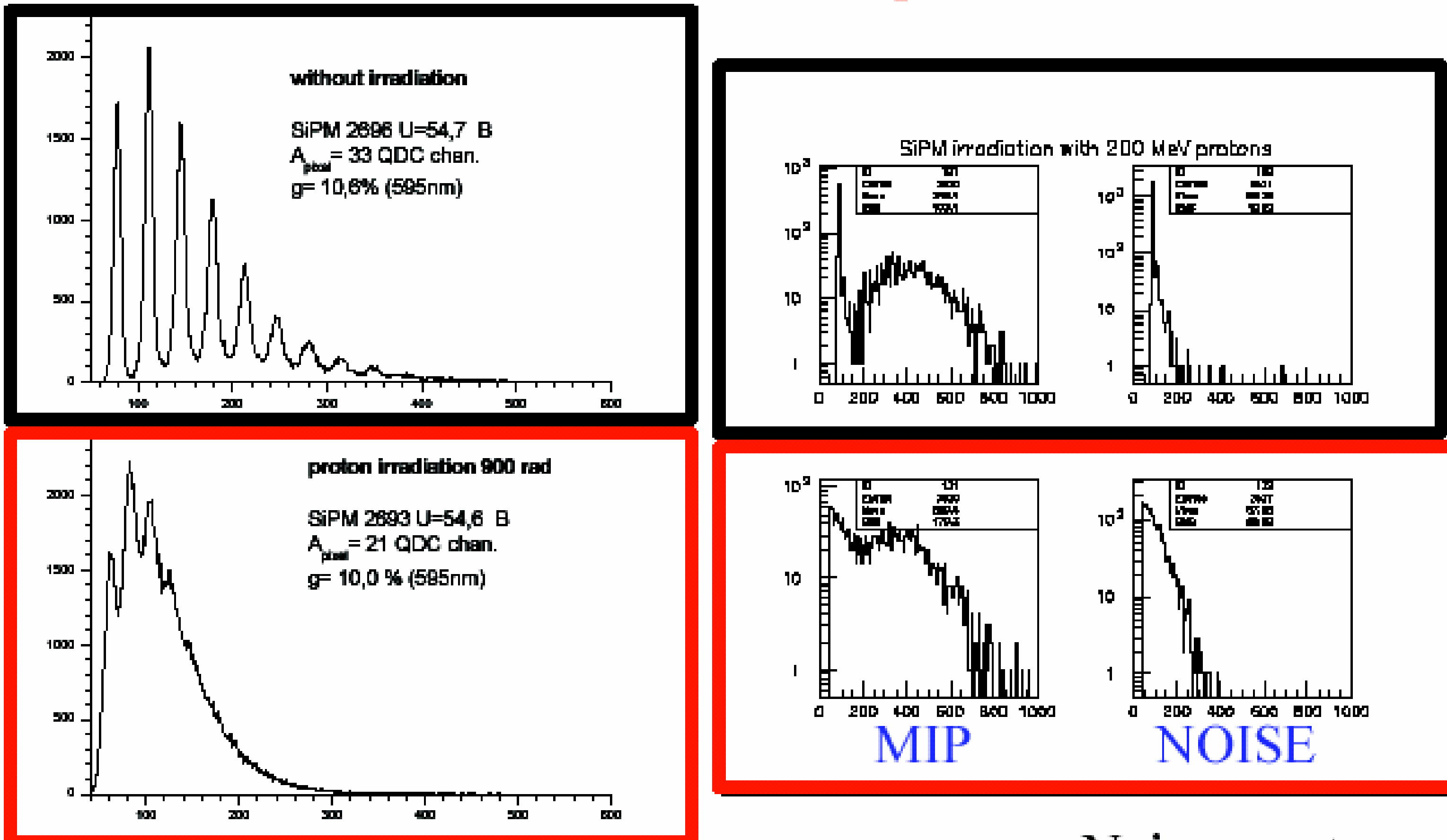
after 900 rad proton 200 MeV



- Very preliminary

Radiation hardness

SiPM single pixel spectra and MIP registration **without irradiation** and **after 900 rad proton 200 MeV**



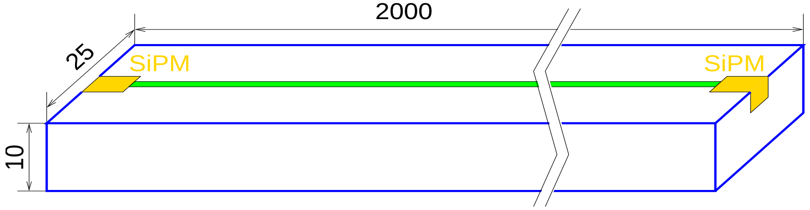
Noise events

Radiation hardness

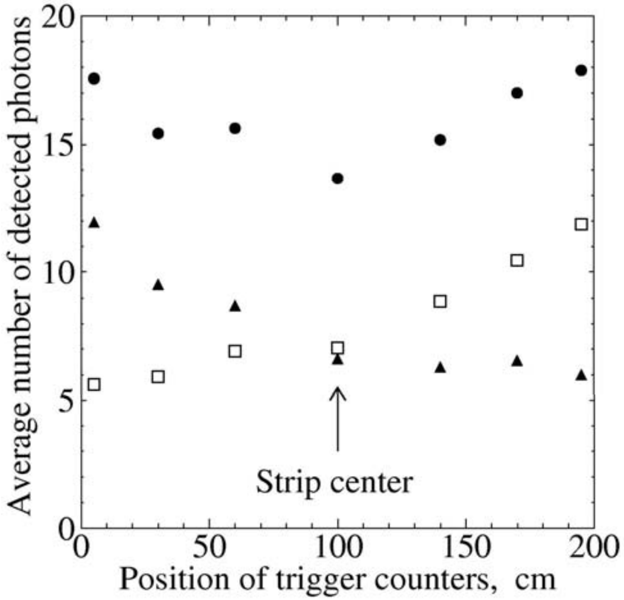
- Radiation increases a number of defects around the sensitive area ⇒ The noise rate increases; efficiency becomes smaller due to larger dead time; electronic noise also increased and smear the single pixel signal
- All previous tests on radiation hardness were done with electron or gamma beams.
- Very preliminary conclusion:
  - ~1kRad dose (proton or neutrons) results in ~10 times higher dark current and single pixel noise rate ; PED affected just slightly
  - Equivalent electron dose is much higher
- Please note that we worked with fast irradiation! Slow irradiation should be more safe for SiPM

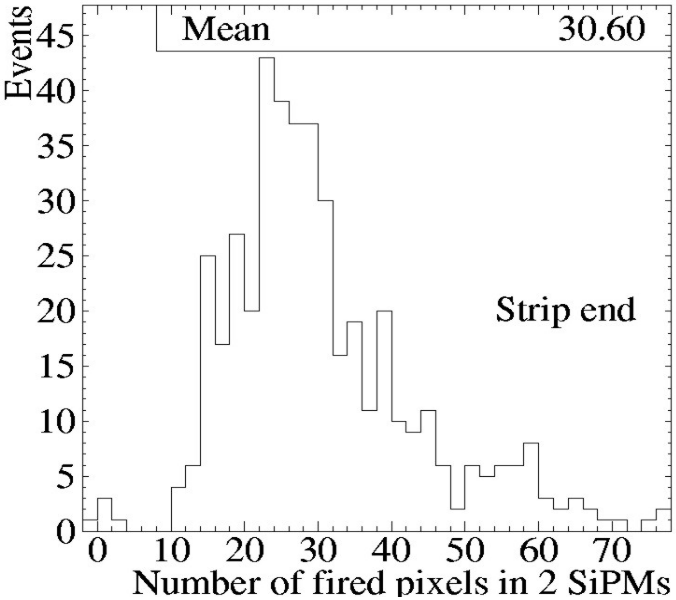
Applications

- Scintillator + Wavelength shifter + SiPM



Scintillator based muon systems





More than 13 detected photons per MIP
ε>99%at rate >1kHz/cm²

MIP Landau distribution starts above 10 fired pixels!
(WLS fiber is not glued to strip)

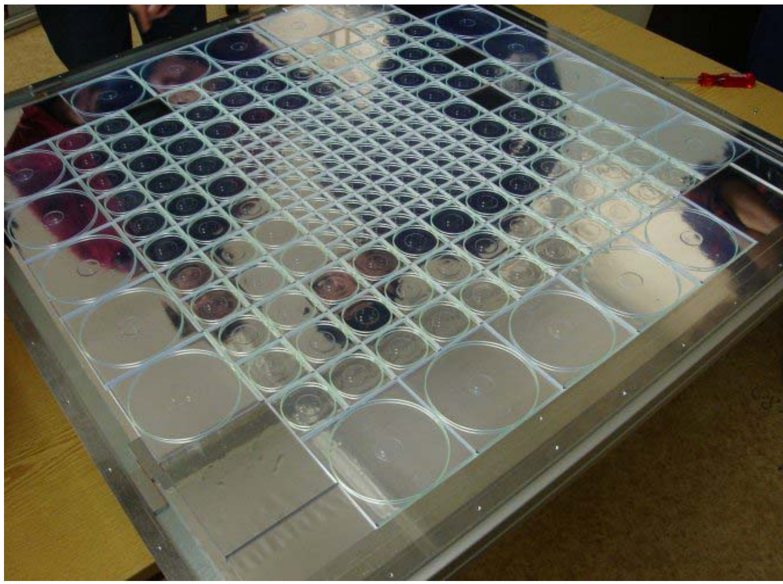
Applications

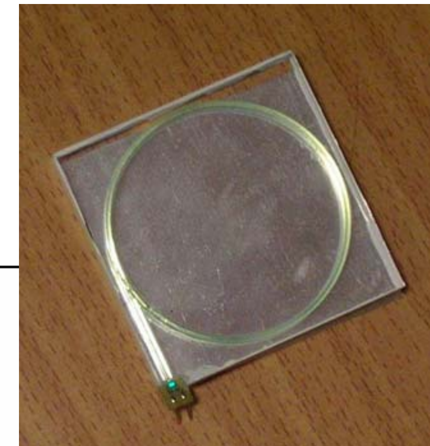
$8m^2$ ALICE TOF Cosmic Test System is being built at ITEP

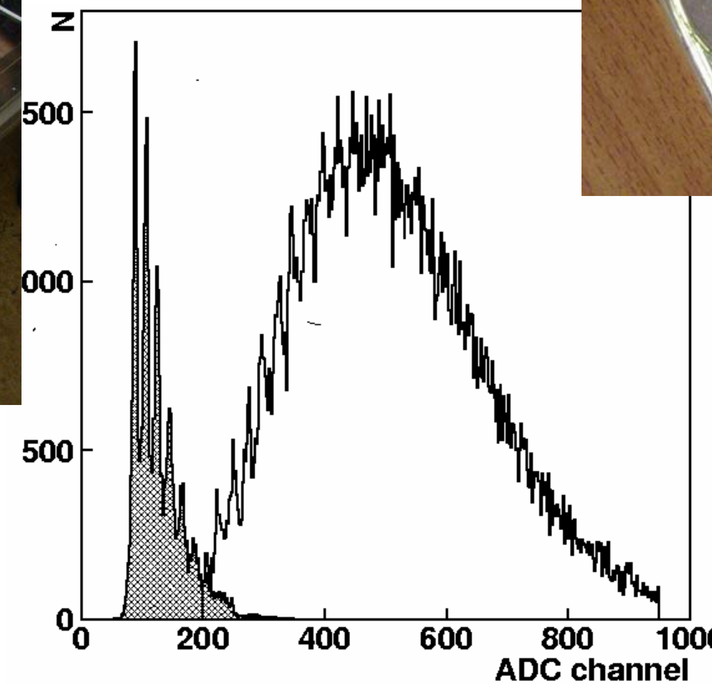
- dense packing ensures the absence of 'dead' zones
- intrinsic noise of a single cell ~ 0.01 Hz
- rate capability up to ~ $10 KHz/cm^2$
- time resolution ~ 1.2 ns

Applications

CALICE Collaboration: **Scintillator tile analog or semi-digital HCAL**





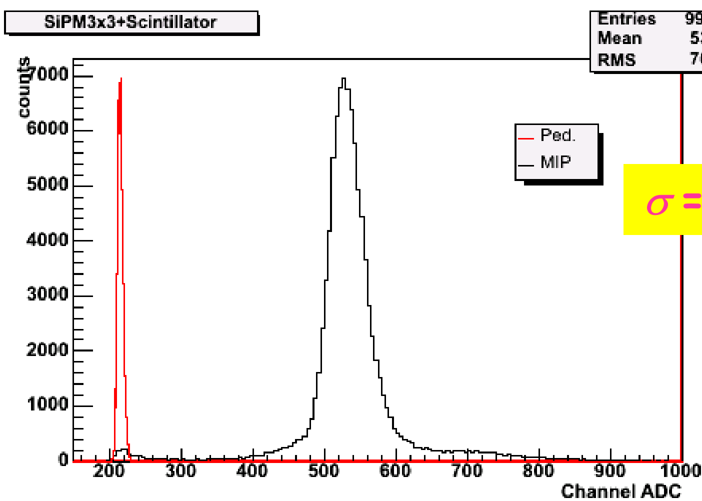


Applications

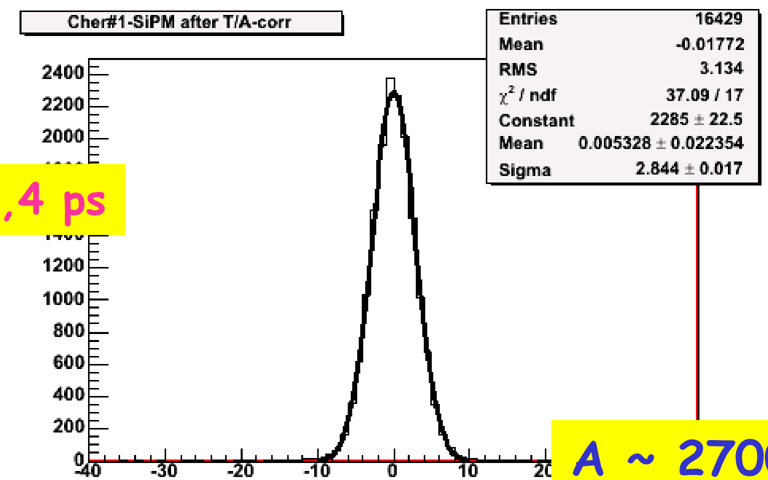
TOF with SiPM (MEPhI)

SiPM 3x3 mm^2 attached directly to BICRON - 418 scintillator 3x3x40 mm^3

Signal is readout directly from SiPM w/o preamp and shaper !



σ = 48,4 ps



A ~ 2700 pix
Threshold~100pix
σ = 48,4 ps
σ_{elect} = 33 ps
(not subtracted)

Producers

- In Russia SiPM are produced by three independent (and competing) groups: MEPhI (B.Dolgoshein), CPTA Moscow (V.Golovin) and Dubna (Z.Sadygov)
- Similar performance has been reached.
- No real mass production yet, each of the producers is has built ~10000 pieces so far
- Many R&D for future detectors including LHC and ILC use SiPM from all three producers.
- Now developed at Hamamatsu

Summary

- Many real advantages of SiPM (in addition to discussed above):
  - Compactness
  - Insensitivity to Magnetic fields
  - Low operating voltage, low power consumption
  - Low charge particle sensitivity
  - Long term stability (but further study required)
- But there are some critical points:
  - Radiation hardness is low
  - Large noise restricts the application with low light yield
  - No real detector based on SiPM built sofar