Experimental results and applications of FBK-irst SiPM pixels and matrices by the DASIPM collaboration

Gabriela Llosá

University of Pisa. Department of Physics. Pisa, Italy

On behalf of the DASIPM collaboration

Universities/INFN sections of Pisa, Bari, Bologna, Perugia, Trento and FBK-irst

http://sipm.itc.it/

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Outline

- SiPMs by FBK-irst (previously ITC-irst)
- Results:
  - Characterization
  - Evaluation for PET applications
- Application to medical imaging: small animal PET and PET/MR.

DASIPM collaboration

- SiPMs development at FBK-irst (Center for Scientific and Technological Research, Trento, Italy) within the DASIPM collaboration.
- DASIPM: Development and Application of Silicon Photomultipliers. Universities/INFN sections of Bari, Bologna, Perugia, Pisa, Trento + FBK-irst.
  - SiPM development
  - Electronics development (Dedicated ASIC + readout system)
  - Application to:
    - Space physics (AMS TOF)
    - Fiber tracking
    - **Medical imaging: Small animal PET.**

Gabriela.Llosa@pi.infn.it

SiPM development at FBK-irst

- Development process since beginning of 2005.
- Aimed at:
    - Fabrication and optimization of blue sensitive devices.
    - Fabrication of SiPM matrices in common substrate.
- Perfect understanding of the devices and expected results.
- Development process in several steps:
    - Simulation
    - Test functionality
    - Test reproducibility
    - Reduction of optical cross-talk
    - Reduction of dark noise with gettering techniques.
    - Optimization of the fill factor → New SiPMs to be tested.

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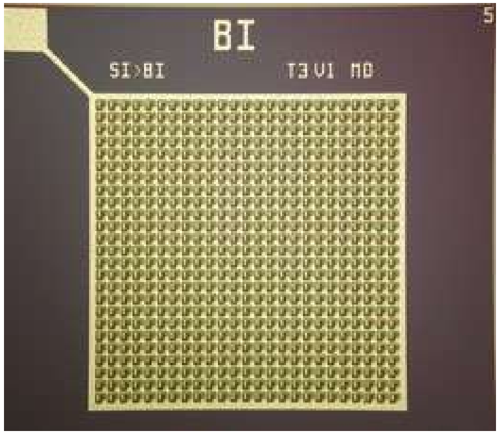
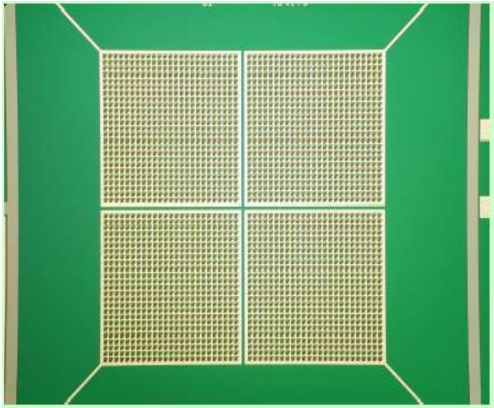
SiPMs produced

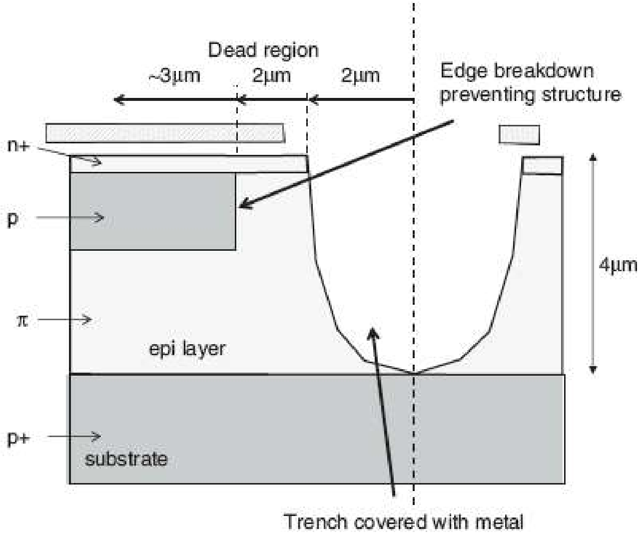


Single SiPMs: 1 mm x 1 mm
area in 1.5 mm x 1.5 mm pitch.

Test matrices 2x2 elements
in common substrate .
same characteristics



- Structure: n^+-p-π-p^+ optimized for blue light: Shallow n^+ layer + specific antireflective coating.
- 625 (25 x 25) microcells.
- Size: 40 µm x 40 µm.
- Polysilicon quenching resistance.
- Fill factor (GF) up to 30%.
- optical trenches to avoid cross-talk.

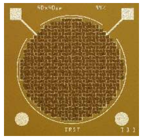


SiPMs from development runs tested

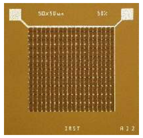
New detectors recently produced

- Different geometry, size, microcell size and GF.

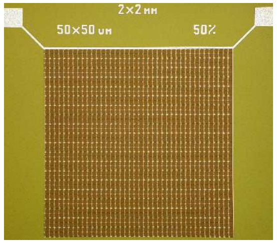
40x40µm => GF 44%
50x50µm => GF 50%
100x100µm => GF 76%



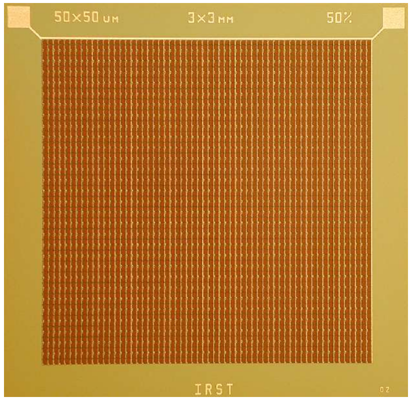
circular (1mm diam)



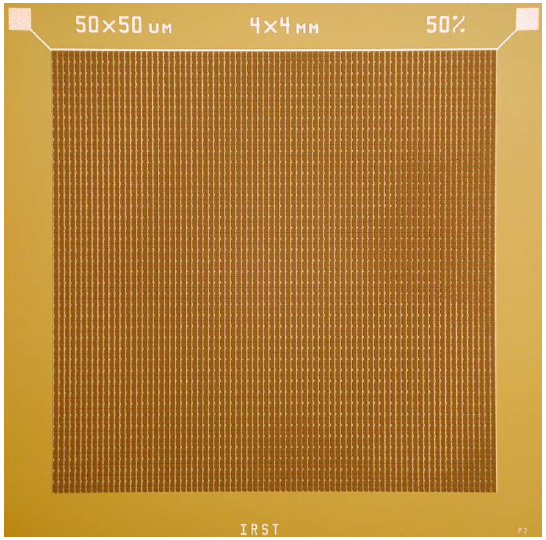
1x1mm



2x2 mm

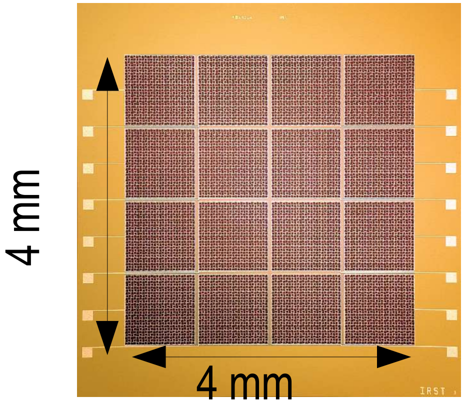


3x3 mm (3600 cells)

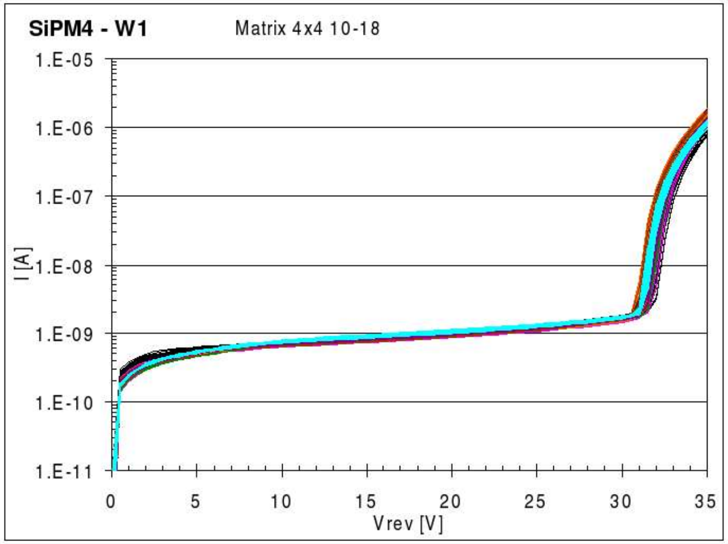


4x4 mm (6400 cells)

- Matrices 16 elements (4x4)



IV CURVES OF 9 MATRICES.
VERY UNIFORM
BREAKDOWN POINT



Evaluation of FBK- irst SiPMs for PET and PET/MR

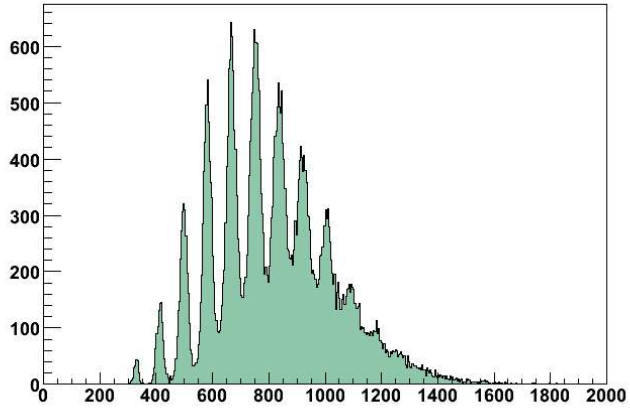
- Characterization
  - Electro-optical characterization
  - Intrinsic timing
  - Photon detection efficiency
  - Variation with temperature
- Evaluation for PET and PET/MR.
  - Energy resolution
  - Coincidence timing resolution.
  - Results in an MR system
  - First results with SiPM matrices

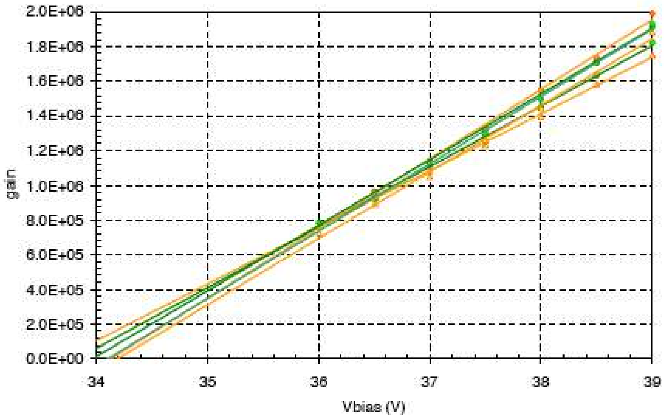
Gabriela.Llosa@pi.infn.it

Results: characterization

- Breakdown voltage V_B ~ 30V, very good uniformity (0.4 V sigma).
- Operation 2-5 V overvoltage.
- Single photoelectron spectrum: well resolved peaks from at room temperature.
- Gain: ~10^6
  - Linear for a few volts over V_{BD}.
  - Related to the recharge of the diode capacitance C_D from V_{BD} to V_{BIAS} during the avalanche quenching. $G=(V_{BIAS}-V_B) \times C_D/q$

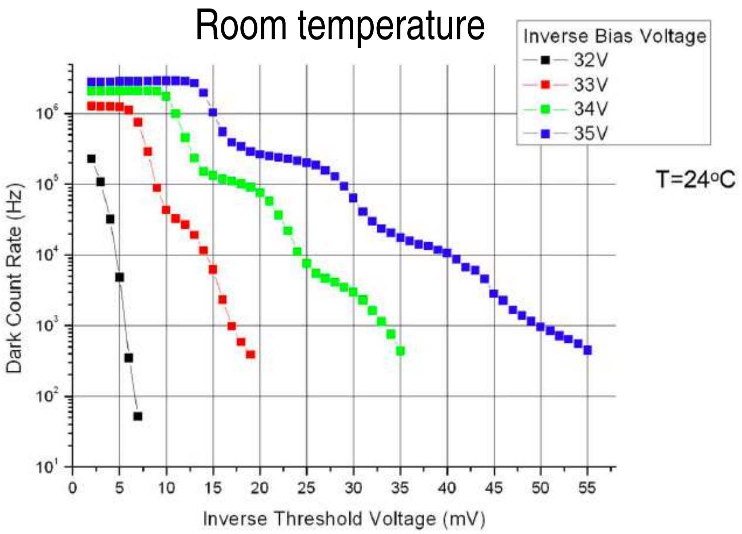
Room temperature



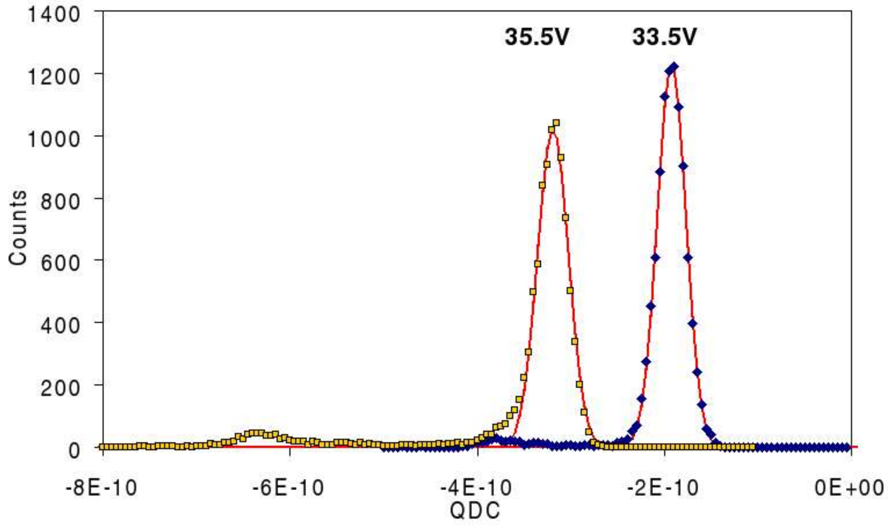


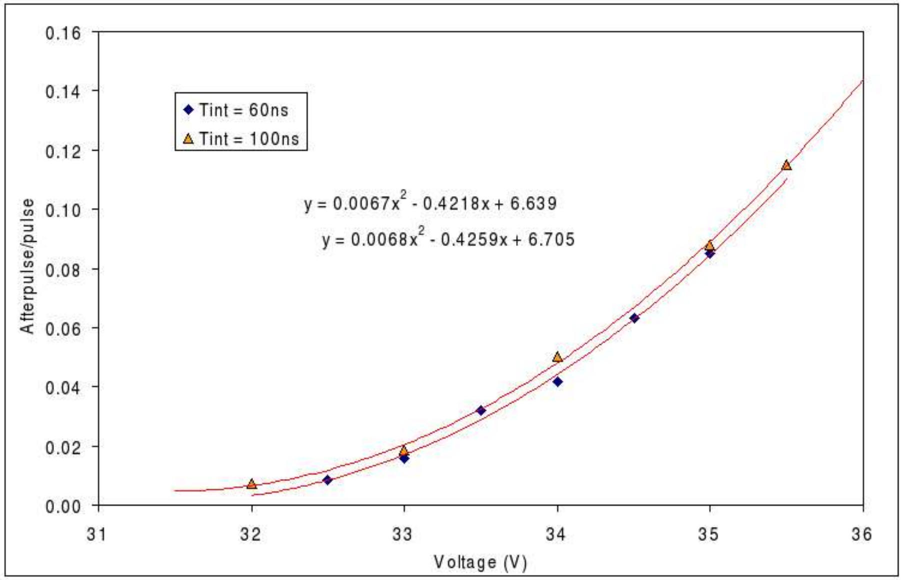
Results: Noise

- Dark rate:
  - 1-3 MHz at 1-2 photoelectron (p.e.) level, ~KHz at 3-4 p.e (room temperature).
  - Not a concern for PET applications.
  - Reduced in the new detectors



- Cross talk below 5% at 4V overvoltage.
- Afterpulse





Photon detection efficiency

$$PDE = QE \times Pt \times GF$$

Quantum efficiency

- -Intrinsic quantum efficiency
- -Transmission factor of the coating T=(1-R)

Avalanche triggering probability

Pt=Pe+Ph-PePh

-Electrons have higher probability because of the higher ionization rate (Pe>Ph).

-In any case, the higher the Vbias, the higher Pt.

- For a given SiPM structure, it depends on the interaction position, i.e, on the wavelength.

Geometrical efficiency:

Active area / Total area of microcell

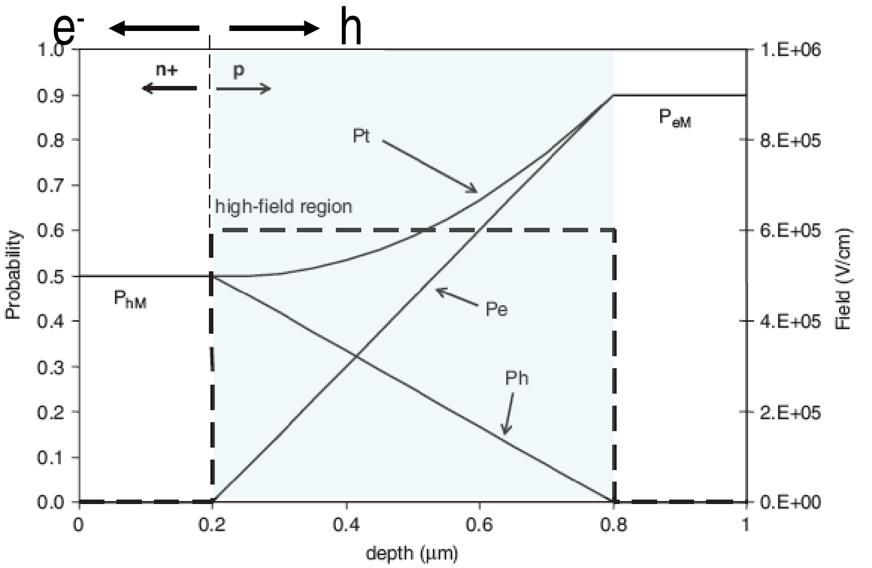
$$QE = (1-e^{(-\eta x)})(1-R)$$

Probability of photoabsorption once the photons have traversed the coating.

$\eta=\eta(\lambda)$ linear absorption coeficient.

QE optimization

- n+p structure: Pt higher for photons interacting deeper => very shallow epi layer.
- Anti-reflective coating optimized for 420 nm

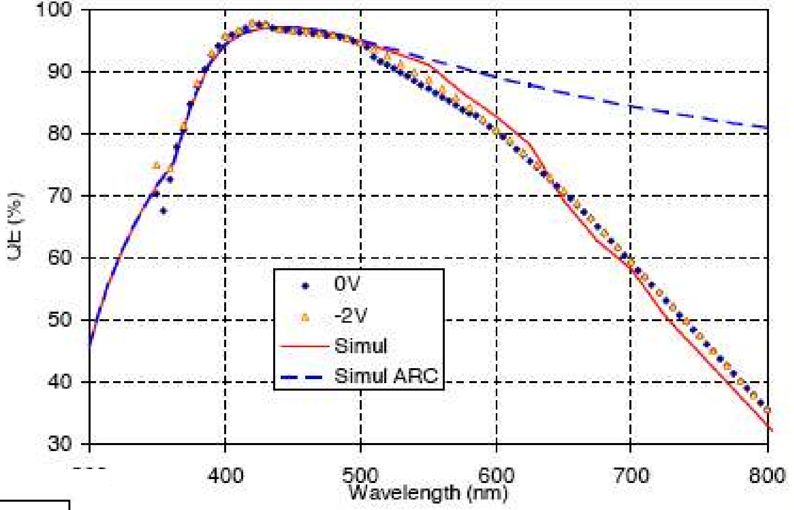


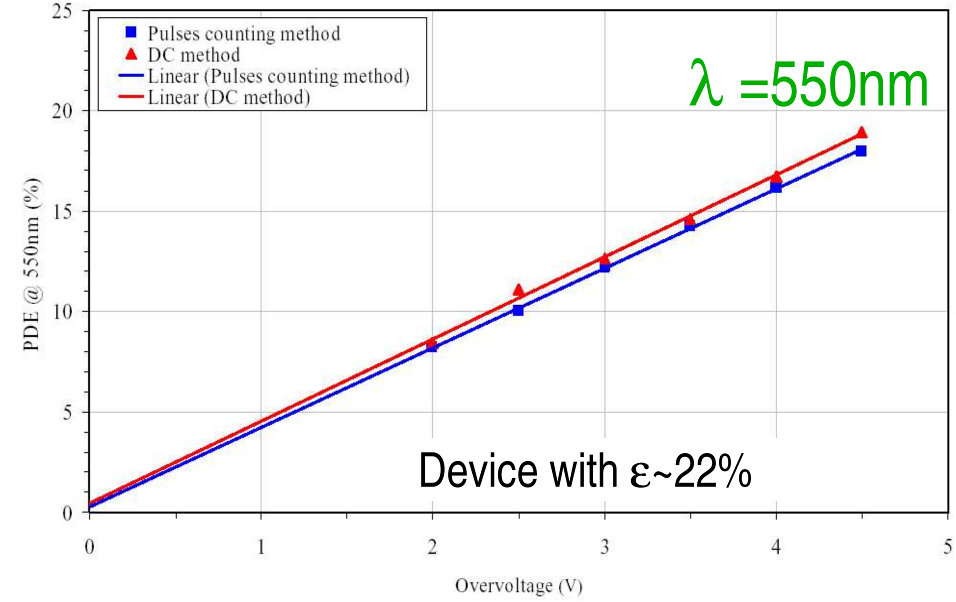
Results: PDE

PDE = QE x Pt x GF

- QE above 95% for 420 nm light wavelengh (LSO emission).
- 10% PDE measured at the same wavelength for a device with 20% GF.

QE > 95% @ 420 nm



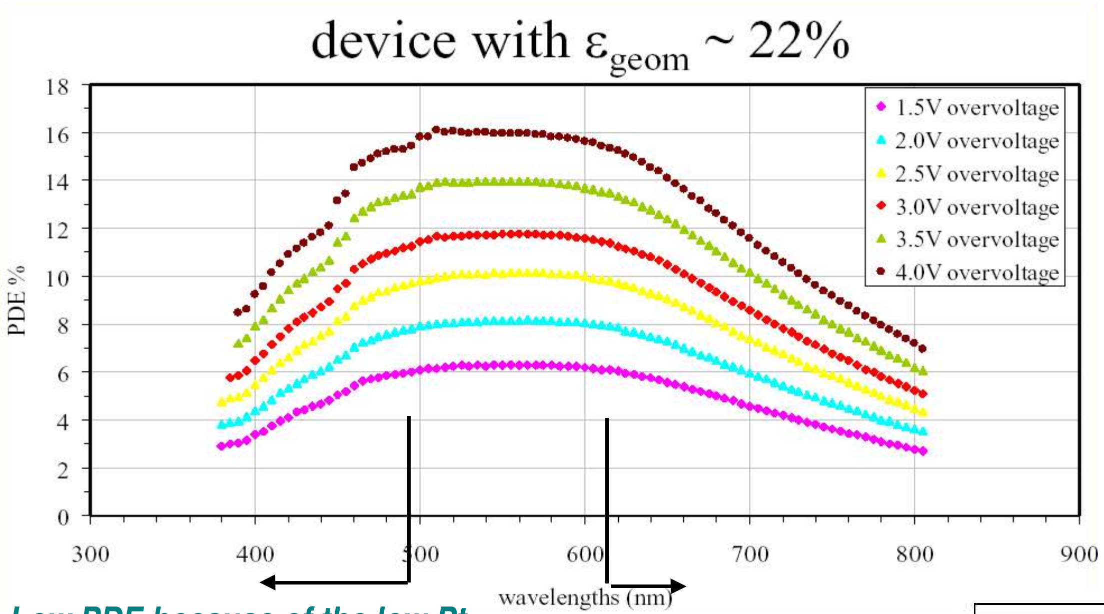


λ =550nm

Device with ε~22%

Results: PDE II

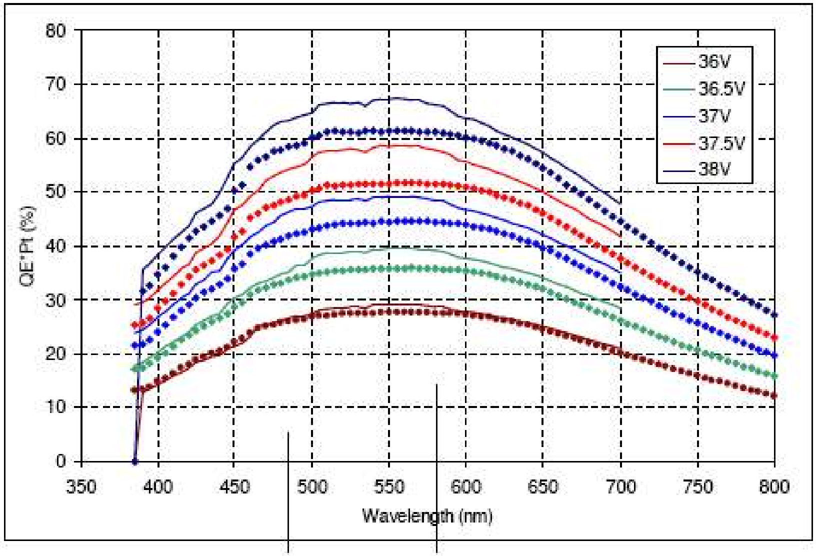
PDE = QE x Pt x GF



Low PDE because of the low Pt (holes trigger the avalanche)

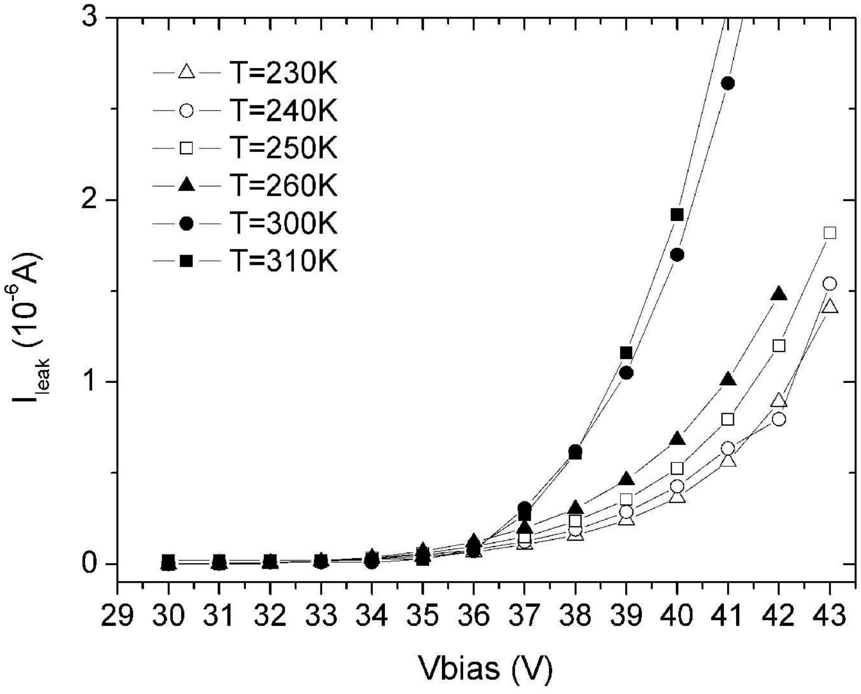
Low PDE because of the low QE

- PDE/GF = QE x Pt is 40% for 420 nm
- Higher PDE expected for optimized GF



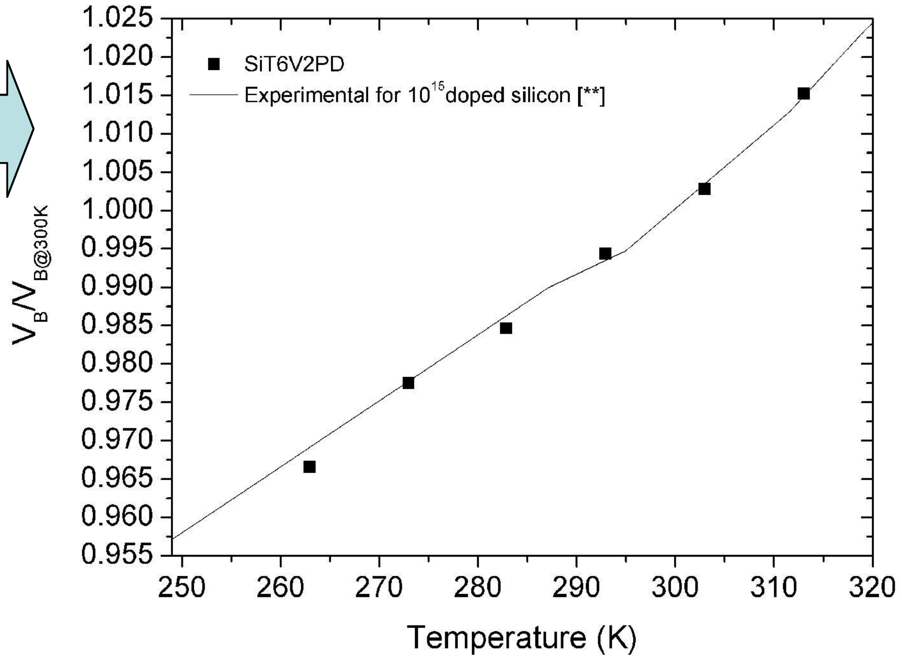
Temperature dependence

- IV curves at different temperature



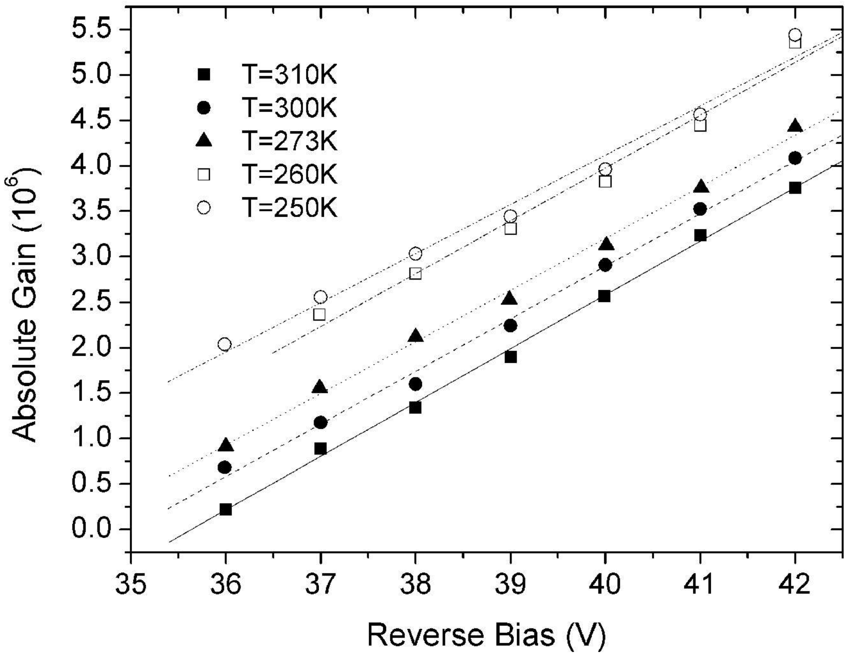
M. Petasecca et al., Perugia(2007)

- Variation of Vbreak with temperature due to variation of Pt



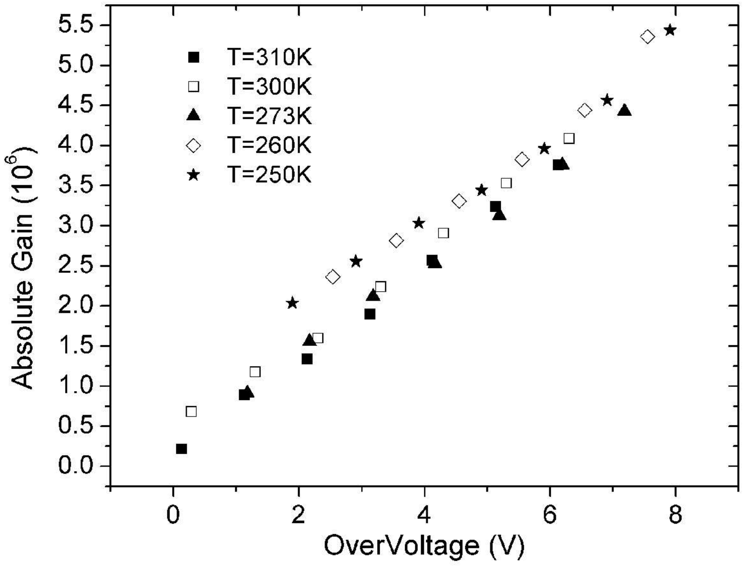
Temperature dependence II

- Gain vs Bias vs Temperature



The residual Gain dependence is due to the variation of Vbreak.

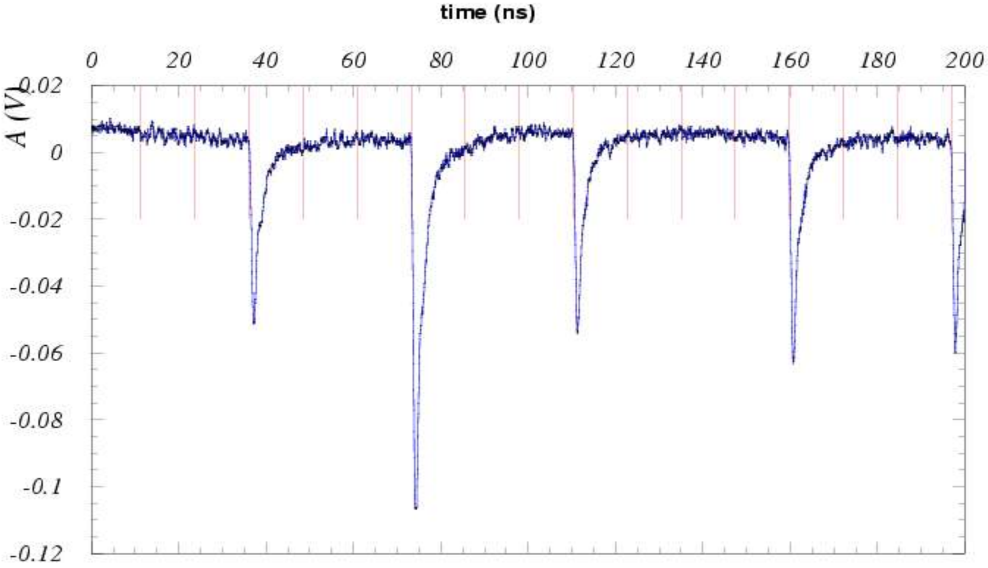
correcting for the variation of Vbreak...

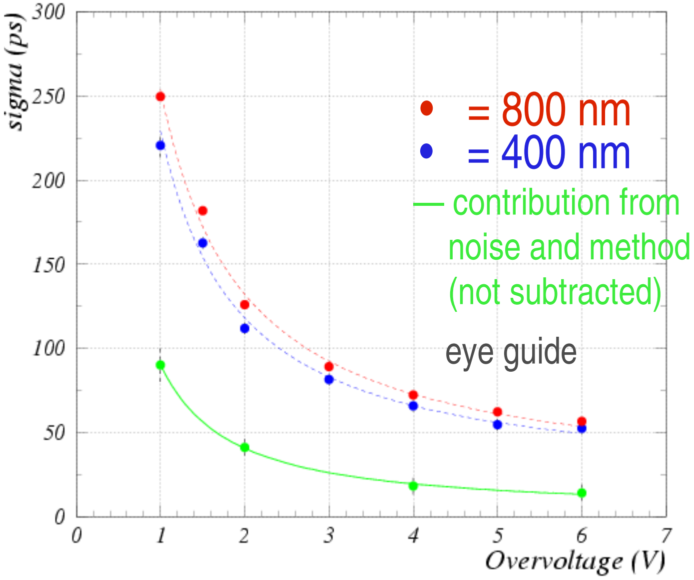


M. Petasecca et al., Perugia(2007)

Results: intrinsic timing

- Intrinsic timing measured at the s.p.e level: 60 ps sigma for blue light.
- SiPM illuminated with a pulsed laser with 60 fs pulse width and 12.34 ns period, with less than 100 fs jitter.
- Two wavelengths measured: λ = 400 ±7 nm and λ = 800 ±15 nm.
- Time difference between contiguous pulses is determined.



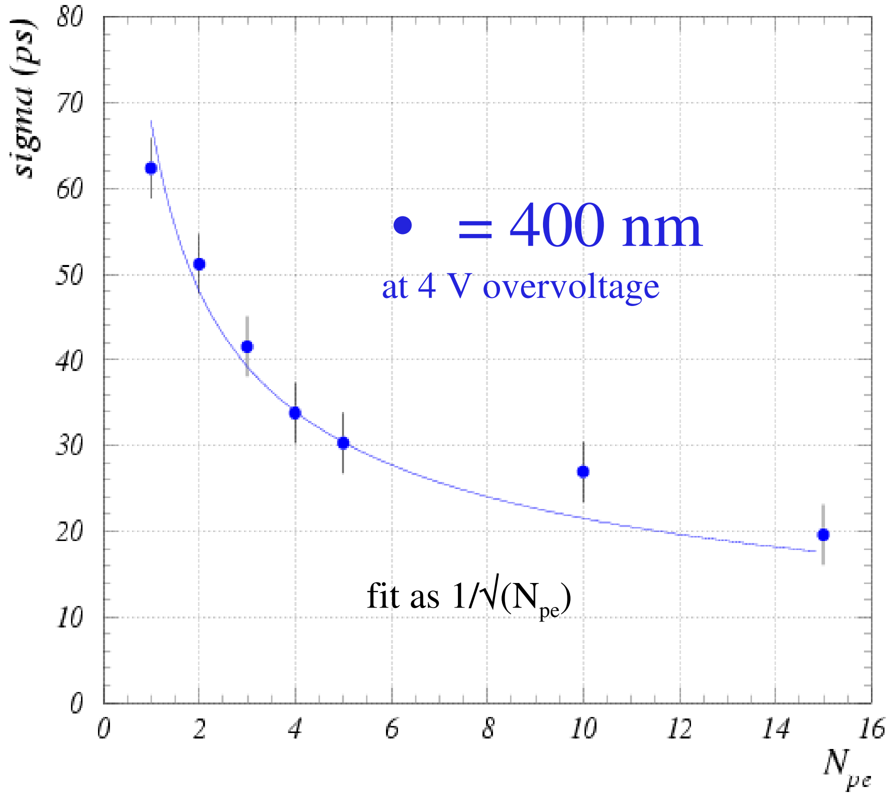


G. Collazuol at VCI 2007, to be published in NIM A.

Results: intrinsic timing II

- The timing decreases with the number of photoelectrons as 1/√Npe.

20 ps at 15 photoelectrons.



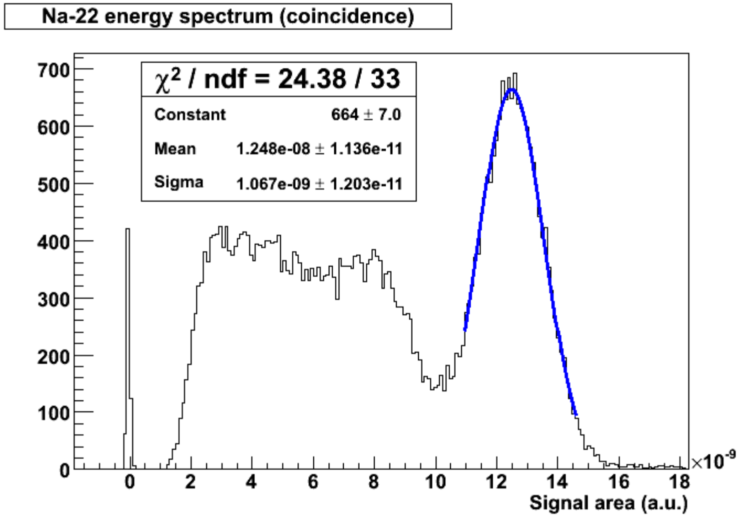
G. Collazuol at VCI 2007, to be published in NIM A.

Results: energy resolution

Energy resolution: 20% FWHM.

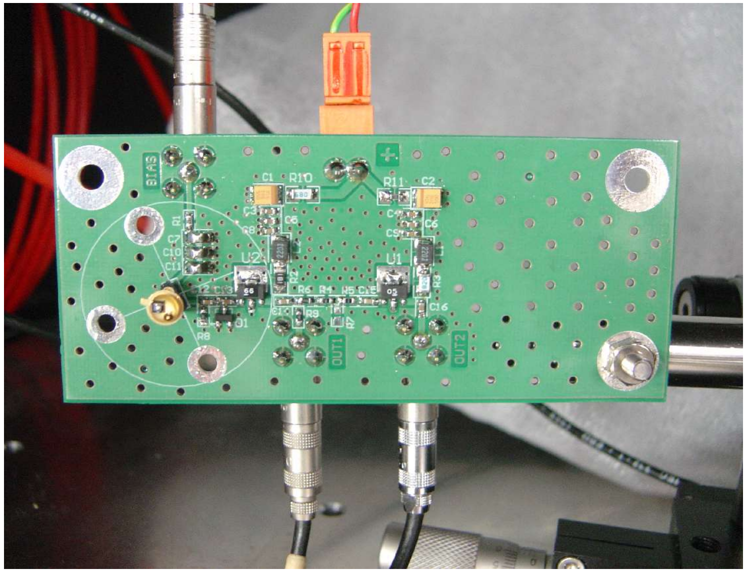
(best result: 17.5 %)

Improvement expected with new SiPMs with higher PDE, better coupling and noise reduction.



Setup:

- 2 LSO 1mm x 1mm x 10mm crystals coupled to 2 SiPMs.
- Home made amplifier board.
- Time coincidence of signals.
- VME QDC for DAQ.
- ^{22}Na source.



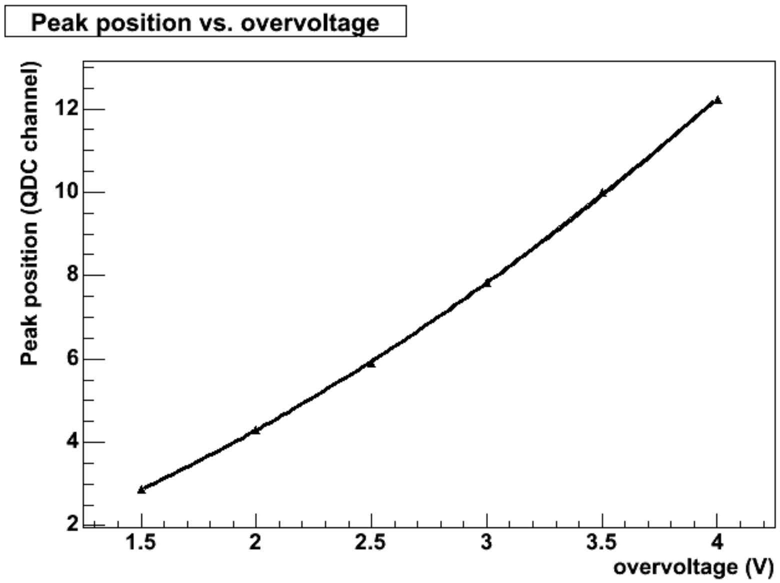
Results: Peak position and energy resolution vs bias

- Peak position $P \sim N_{ph} \times PDE \times G \Rightarrow$ Parabolic with ΔV.

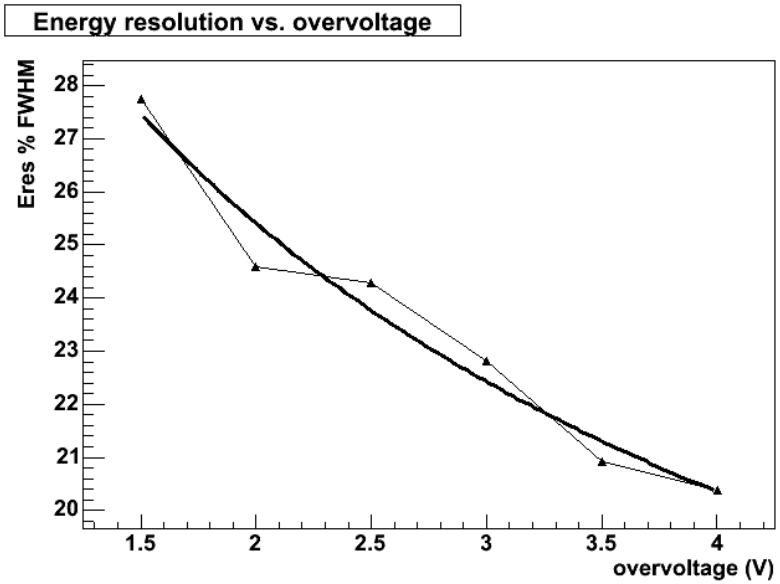
  $PDE \propto \Delta V$

  $G = \Delta V \times C_D / q_e$

- Energy resolution $R \sim 1/\sqrt{P}$



Fit parabola: $p_2 \Delta V^2 + p_1 \Delta V + p_0$



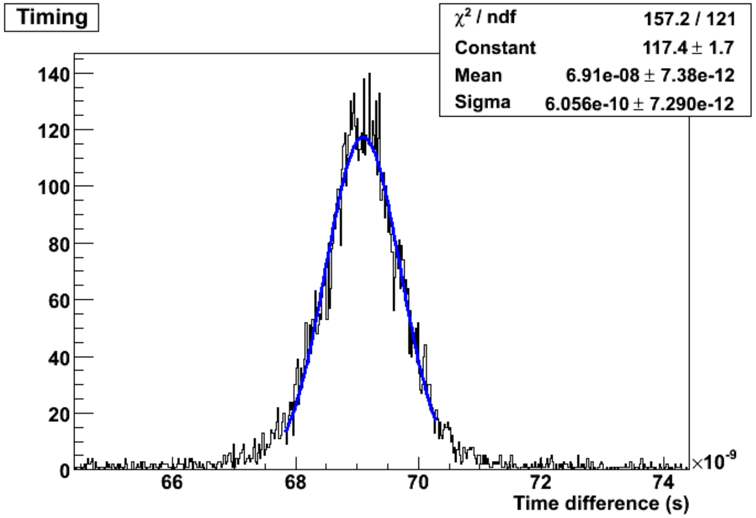
Fit : $p_3/\sqrt{(p_2 \Delta V^2 + p_1 \Delta V + p_0)}$

Results: coincidence timing

- Coincidence measurement with two LSO crystals and two SiPMs

  Measured σt ~ 600 ps sigma.

- Theory for two scintillators in coincidence: $\sigma t = \sqrt{2}\sigma \sim 567$ ps .



Where

$$\sigma \sim \frac{\sqrt{Q}\,\tau}{< N >}$$

Post, Schiff. Phys. Rev. 80 p. 1113 (1950).

<N> = average number of photons: ~ 100 photons at the photopeak.
Q = Trigger level: ~1 photoelectron.
τ = Decay time of the scintillator ~ 40 ns

Measurements in agreement with what we expect.

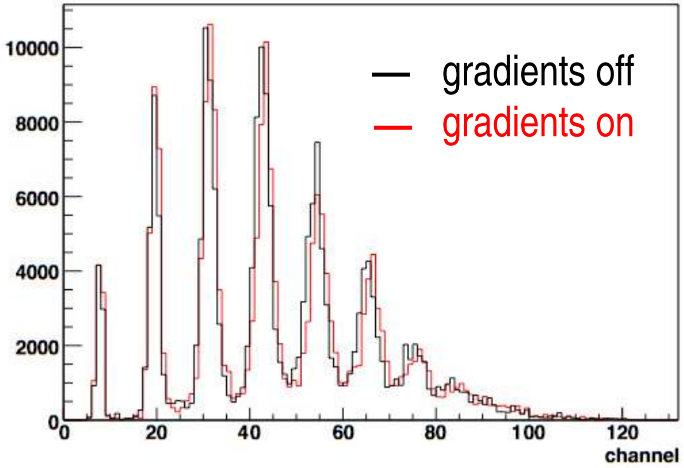
Results: tests in MR system

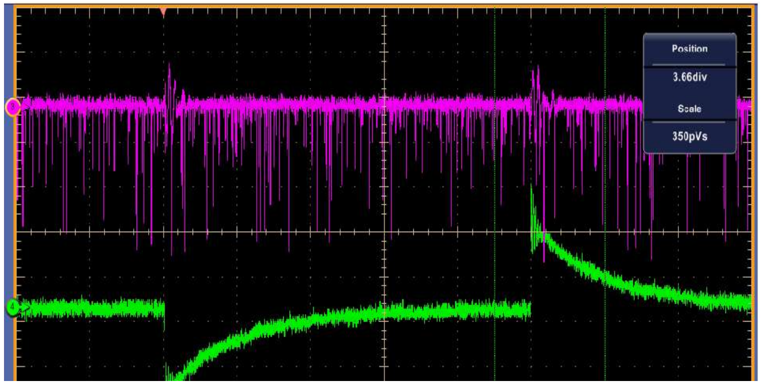
- S.p.e and ^{22}Na energy spectra acquired with gradients off (black line) and on (red line).

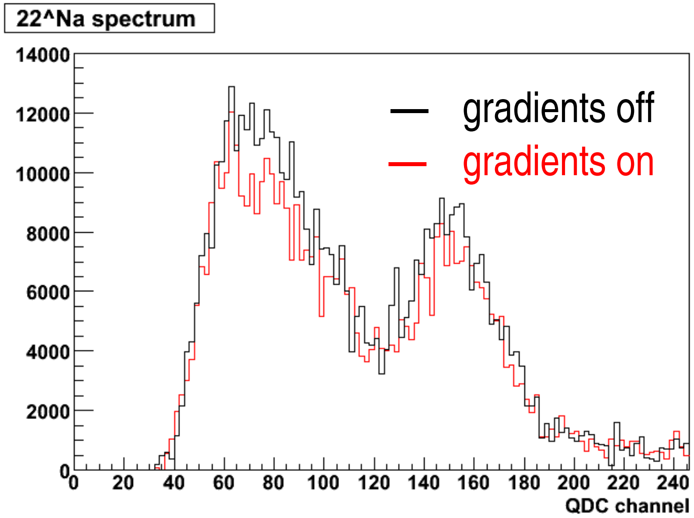
  No difference is appreciated in the data.

- Differences in peak position due to temp changes in the magnet (change in gain due to variation in breakdown voltage). No variation for short acquisition time.

- Pickup in baseline when switching on and off.



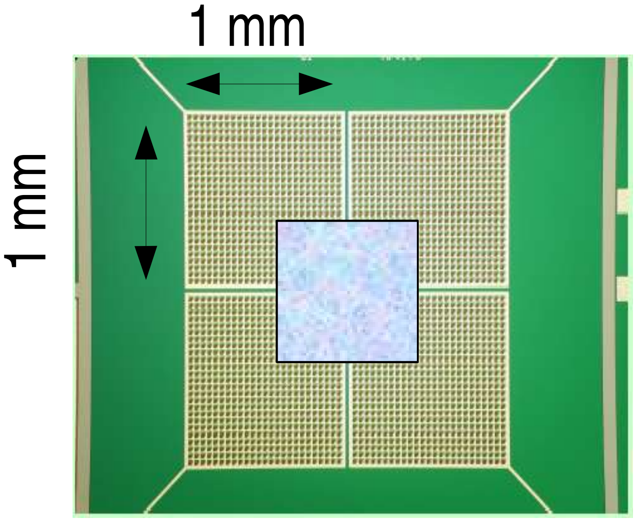


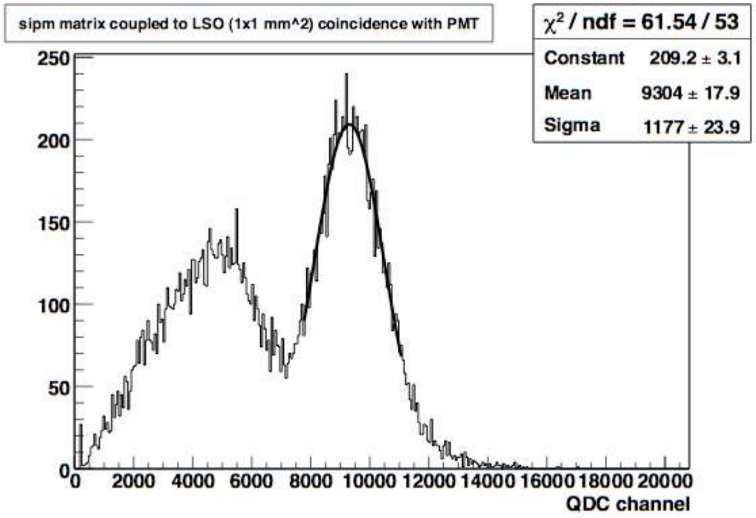

22^Na spectrum

Results: matrices

- Test matrices of 4 SiPM pixels in the same substrate tested.
- Home made 4 amplifier board.
- Coincidence with scintillator+PMT.
- Signals from the 4 SiPMs acquired independently and summed up.
- Energy resolution 30% FWHM.
  - Same as taking the data with one of the SiPMs in the matrix.
  - Same as single SiPM with similar GF.

NO degradation wrt single SiPMs.





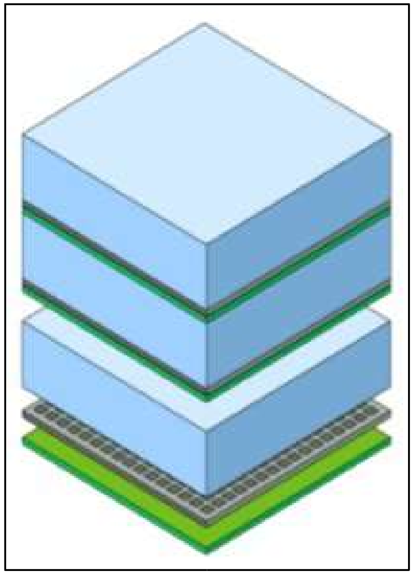
Application to medical imaging: high resolution PET

The use of SiPM matrices allows significant improvements in the design of a detector head for a small animal PET tomograph:

- High photodetection efficiency: SiPM matrices leave low dead area wrt arrays of single SiPMs.
- Stack of several detector layers thanks to compactness:
  - Scintillator thickness can be increased => High efficiency
  - DOI information that reduces parallax error => high spatial resolution.

Use of continuous scintillator slabs + finely pixellated SiPM matrix instead of segmented scintillator blocks + PSPMT:

- Very good spatial resolution maintaining high efficiency.
- low cost.



MR compatibility: SiPMs are compact (detectors fit in magnet bore) and insensitive to magnetic fields.

Detector head performance

- Geometry optimization and performance estimated with GEANT4 simulations.
- Head geometry: stack of three detector layers (4 cm x 4 cm).
  - Scintillator: continuous slab of LSO or LYSO, 5 mm thick.
  - SiPM matrix with 1.5 mm pitch elements as photodetector.
- Head performance:
  - About **70% efficiency** for 511 keV photons.
  - **Intrinsic spatial resolution – 0.3 mm FWHM** in the center of the crystal < 1mm in the edges.
    - Center-of-gravity position determination algorithms worsen resolution and displacement errors towards the edges.
    - ML methods (skeweness and barycenter based) reduce error towards the edges.
  - backscattering within a detector head < 5%.
- Maximum parallax error for two detector heads at 10 cm: 1 mm.

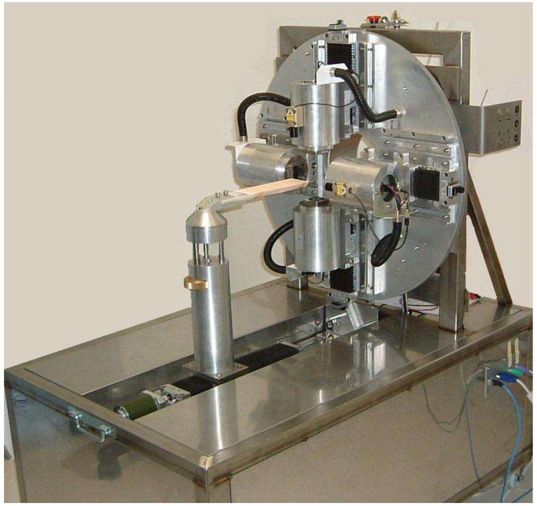
S. Moehrs et al. ***A detector head design for small-animal PET with silicon photomultipliers (SiPM).***
Phys. Med. Biol. 51 (2006) 1113-1127.

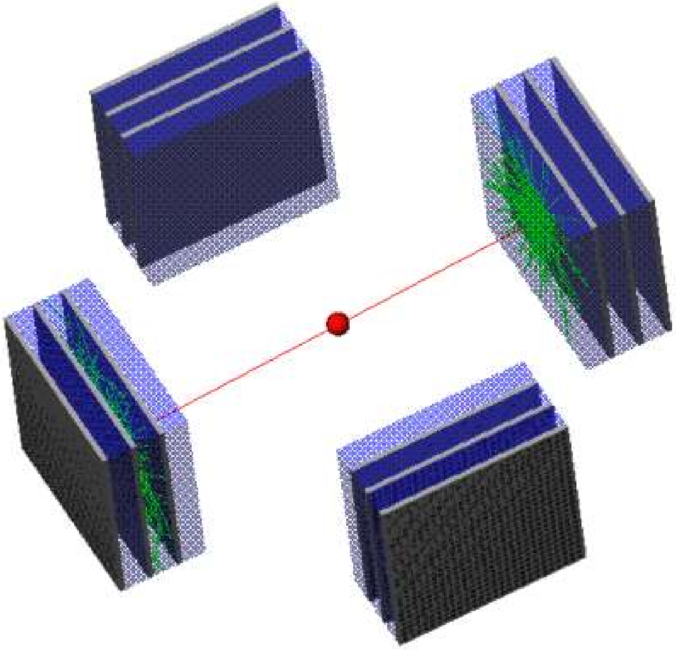
Gabriela.Llosa@pi.infn.it

PET applications: VHR PET

4-head tomograph (same concept as YAP(S)-PET):

- 2(4) rotating detector heads at 10-15 cm distance.
- FOV 4 cm axial, 4 cm transaxial.
- efficiency around 4%.
- Spatial resolution well below 1 mm^3 for a point source in the CFOV.
- low cost.

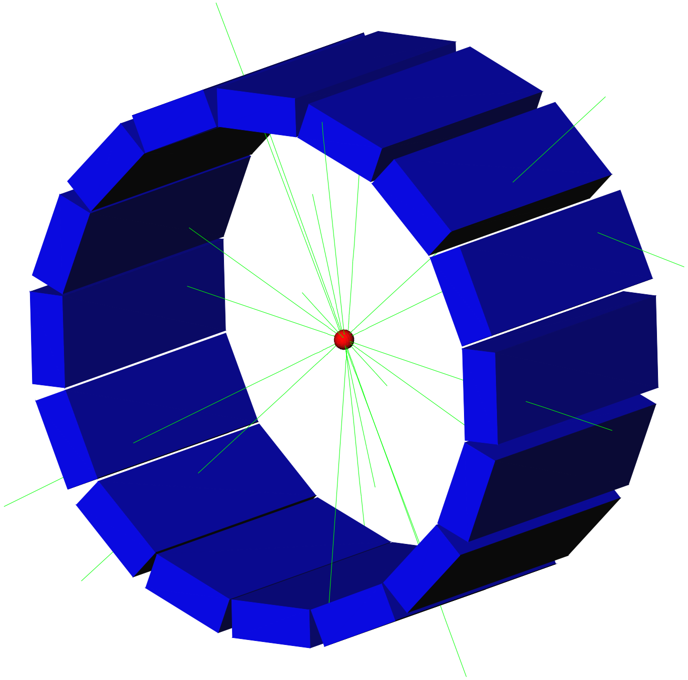




PET applications: MR compatible ring tomograph

PET insert for simultaneous PET/MR.

- 16 detector heads, 7 cm x 2.4 cm;
- FOV axial 7 cm, transaxial FOV ~6 cm.
- Spatial resolution: 0.76 mm for a ^{18}F point source in the CFOV with FBP.
- efficiency around 11% for 250 keV energy threshold.
- To be inserted in magnet bore.



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Conclusions

- SiPMs are a novel type of solid state photodetectors, with important advantages over the existing ones and potential for improvement.

- FBK-irst is developing SiPMs and SiPM matrices. The first results obtained are extremely encouraging. New devices with improved characteristics have been produced and are being tested.

- SiPMs from FBK-irst have been evaluated for their use in the PET tomograph construction. The results obtained are very good: energy resolution 20% FWHM for 511 keV photons, intrinsic timing resolution of 60 ps sigma, and 600 ps coincidence timing resolution. The possibility of employing SiPMs in an MR system has been assessed.

- A very high resolution PET tomograph for small animals and a MR compatible PET insert employing SiPMs, are under development at the University of Pisa. A spatial resolution of 0.76 mm FWHM is expected for a ^{18}F point source in water in the centre of the FOV, with FBP, according to GEANT4 simulations.

Gabriela.Llosa@pi.infn.it

- Several presentations accepted at IEEE NSS-MIC 2007
  - N41-2: C. Piemonte. *Recent Progress in the Performance of Silicon Photomultipliers produced at FBK-irst.*
  - M14-4: G. Llosa et al. *Silicon Photomultipliers and SiPM matrices as photodetectors for Scintillator readout in Nuclear Medicine.*
  - M18-11: R. Hawkes et al. *Silicon Photomultiplier performance tests in Magnetic Resonance Pulsed Fields.*
  - N15-49: C. Marzocca et al. Preliminary results from a Current-Mode CMOS Front-end circuit for Silicon Photomultiplier detectors.

See you in Hawaii !!