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University and INFN Pisa

UPDATE OF THE INFN PISA GROUP ACTIVITIES

Outlook

- Characterization of LSO:Ce, Ca crystals coupled to SiPMs: model and measurements
- SiPM matrices Read-out electronics: performance assessment

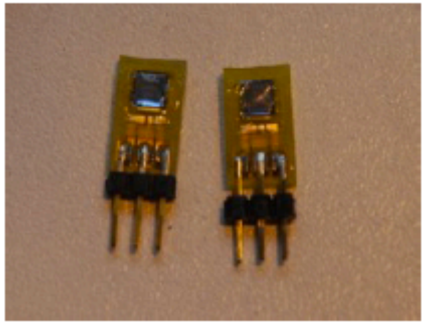
Motivation

- LSO:Ce, Ca
  - University of Tennessee (C.Melcher and coll.)
  - Ca++ co-doping decreases the decay time and increases the light yield and the energy resolution
- SiPM
  - lower bias voltage, smaller dimensions than PMT, fast, magnetic field insensitive, integration and compactness

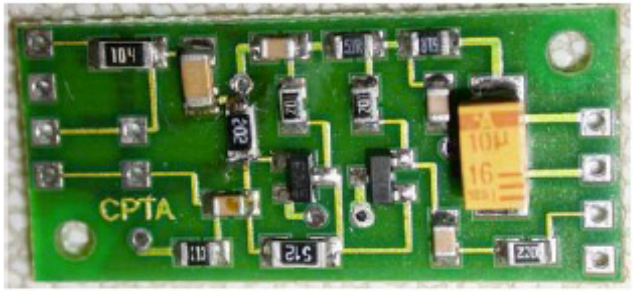
MERGE THE TWO TECHNOLOGIES TO BUILD A NEW DETECTOR WITH HIGH PERFORMANCES

Materials and Methods

•SiPM: fbk-IRST, 3600 microcells



•Amplification circuit:



•Crystals: LSO codoped with Ca (0.1, 0.2, 0.3 % Ca)

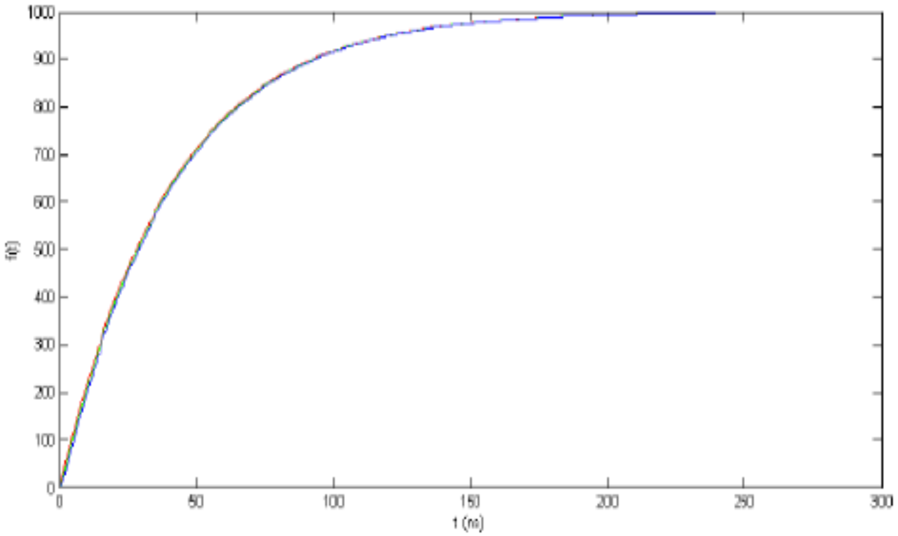
Simulations:
•Orcad Pspice: Simulation of SiPM and amplification circuit;
•Matlab: Simulation of crystal, simulation of the behaviour of N fired microcells, data analysis.

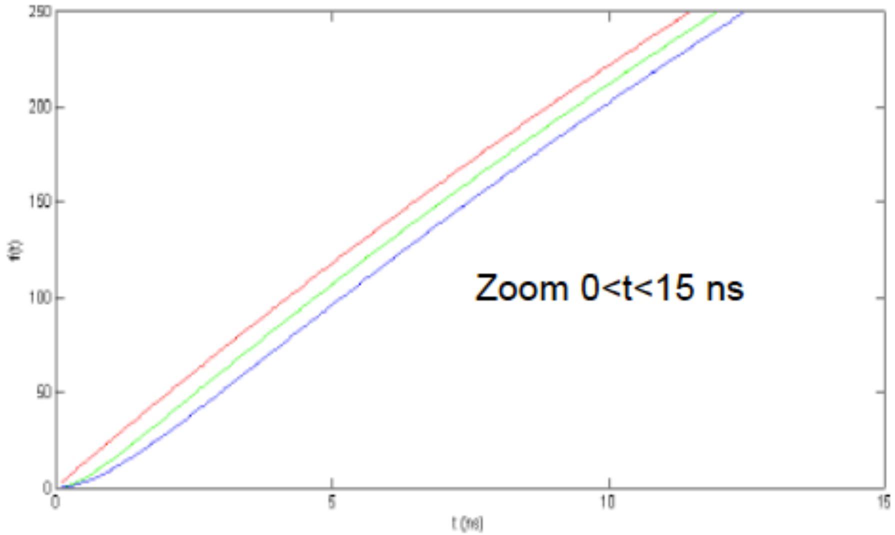
Simulations

Crystal:considering a model with double exponential:

$$f(t) = R\left(1 - \frac{\tau_{rise} + \tau}{\tau} e^{\frac{-t}{\tau}} + \frac{\tau_{rise}}{\tau} e^{-t\left(\frac{1}{\tau} + \frac{1}{\tau_{rise}}\right)}\right)$$

R=total photoelectron yield (1000 in fig.)
decay time (40 ns in fig.)
rise time (0 ns, 0.5 ns , 1 ns in fig.)

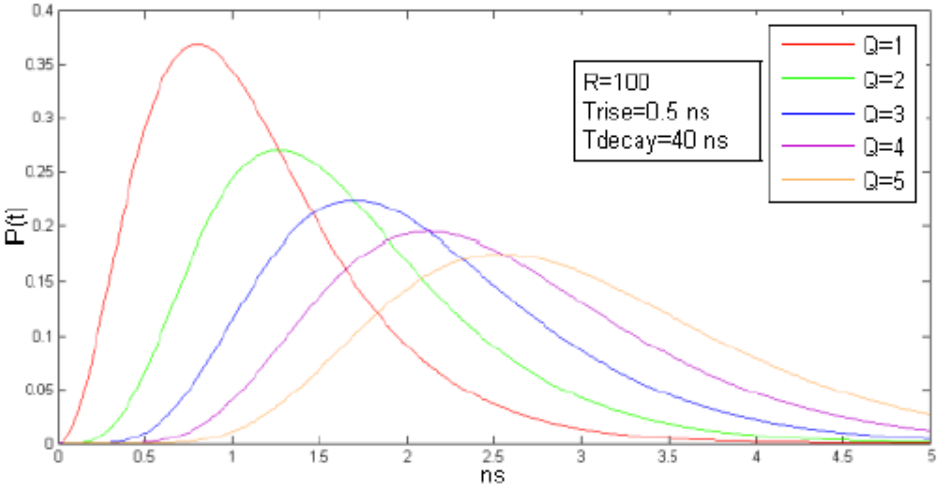




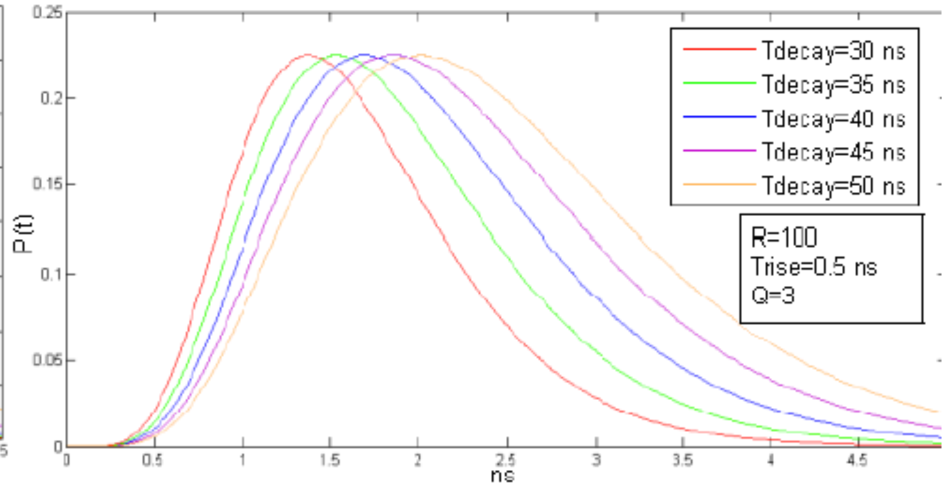
Focusing on t comparable with rise time

The emission probability of the Q-th photoelectron has been described by using the Poisson statistics:

$$P_Q(t) = \frac{f(t)^Q e^{-f(t)}}{Q!}$$



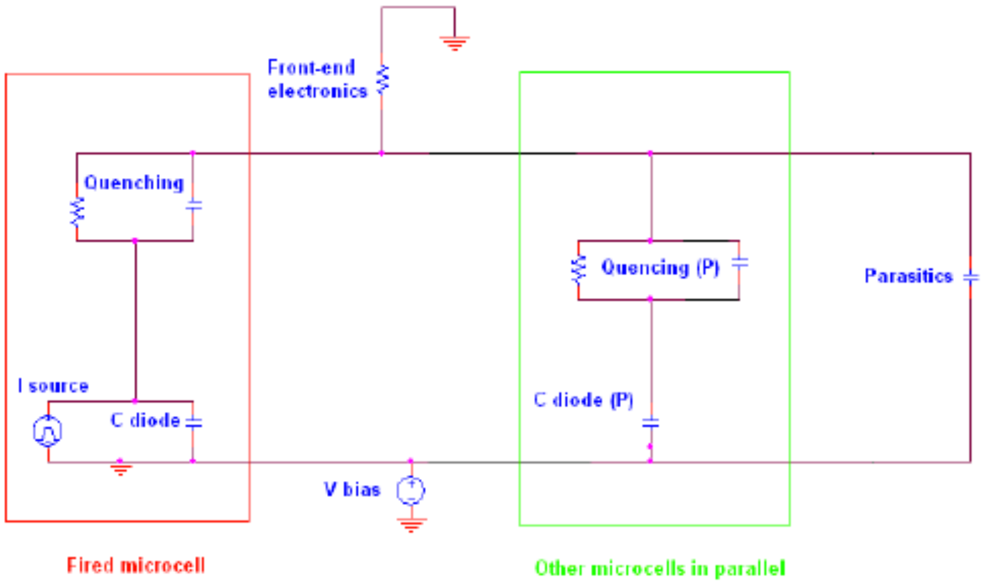
a

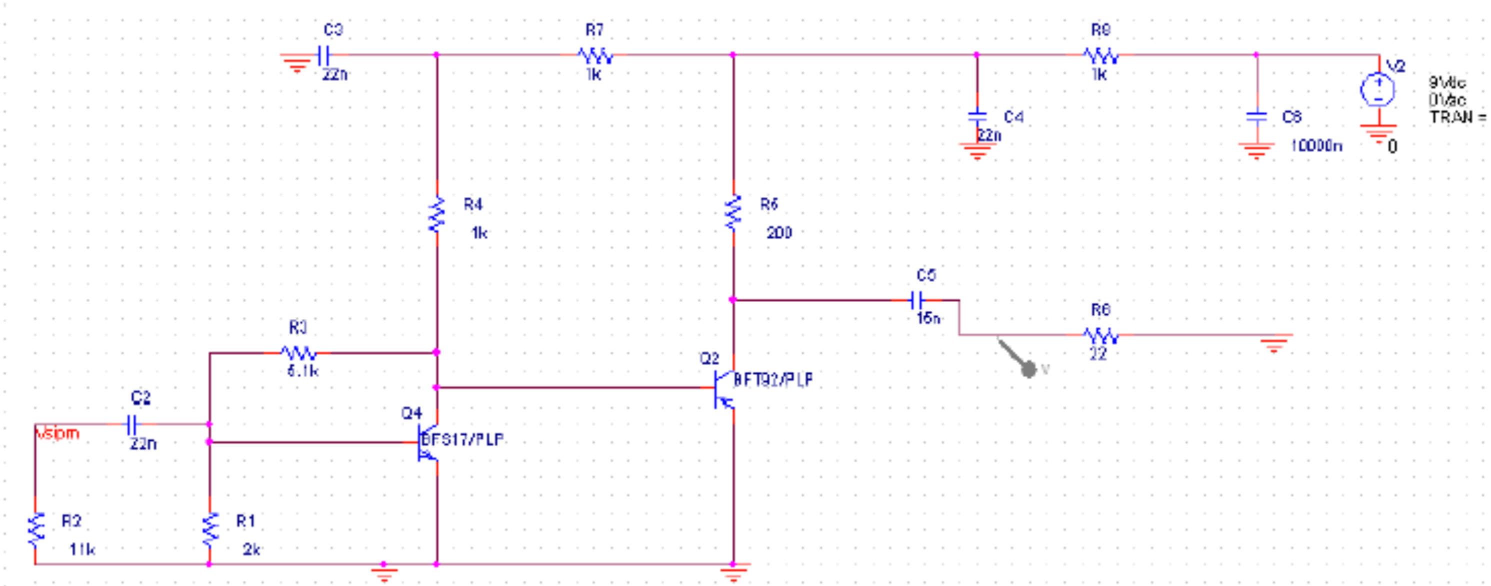


b

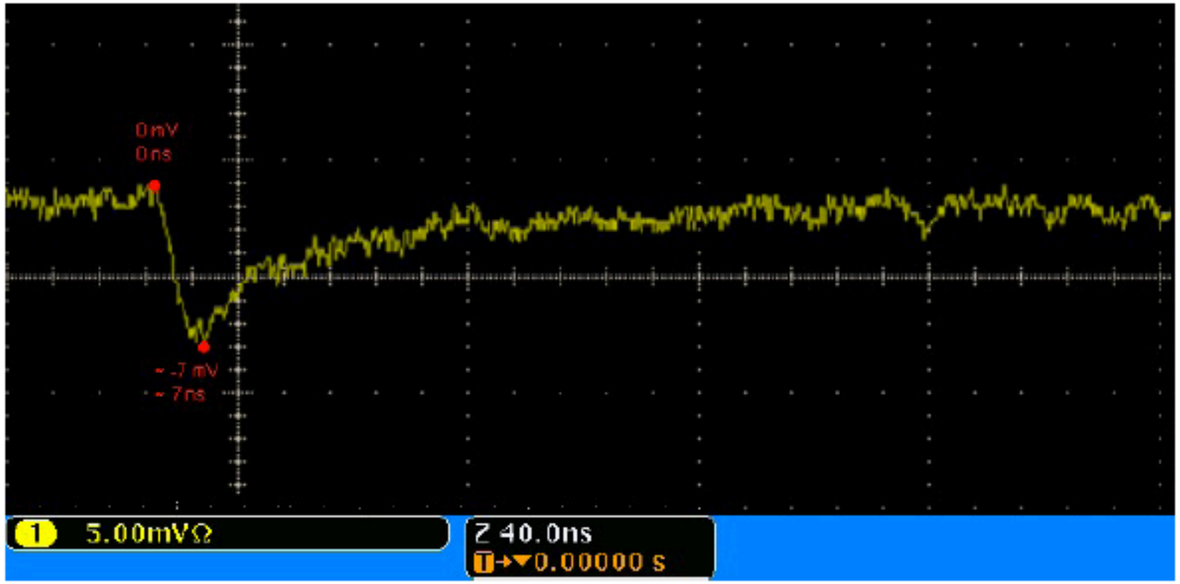
P(t) as a function of time (ns) varying Q from 1 to 5 (fig.a) and decay from 30 ns to 50 ns (fig.b). The probability density suggests that to improve the timing resolution one must put the detection threshold as low as possible and consider the arrival time of the first photons on the photodetector. On the other side, one must observe that the timing resolution improves also by decreasing the decay time of the scintillator.

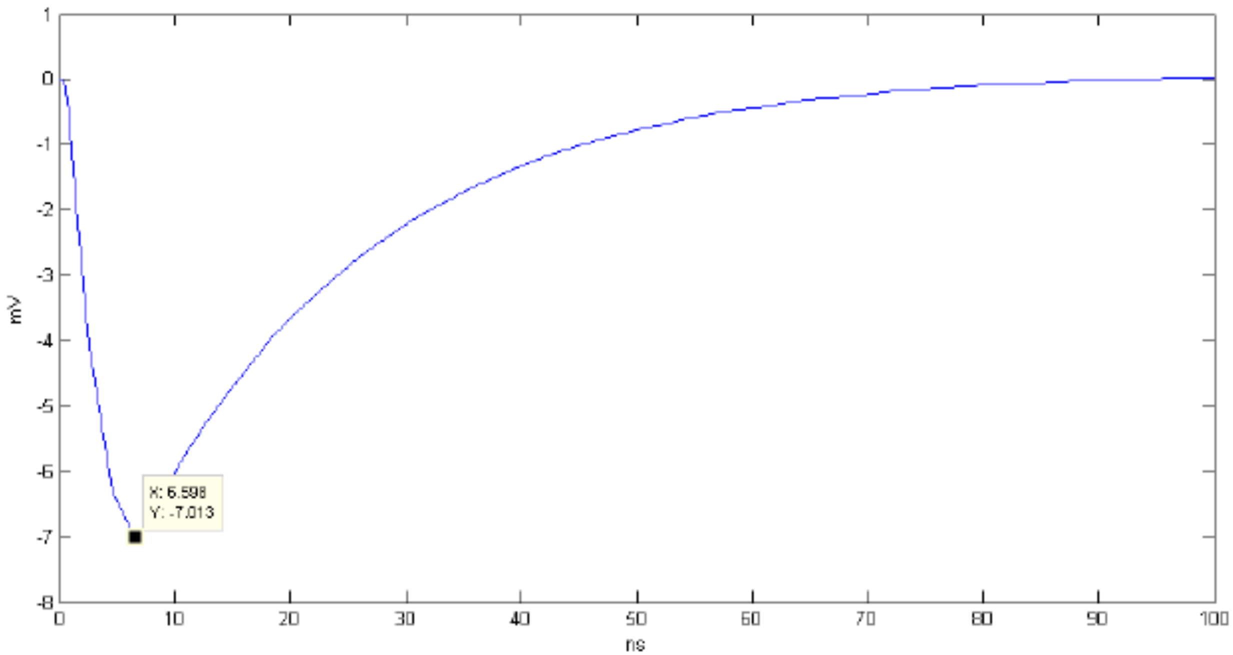
SiPM: model based on the equivalent electrical circuit of a microcell fired by an incident photon and the other microcells not fired in parallel. The output is sent to the amplifier.





Validation of the model:





Good reproduction of:

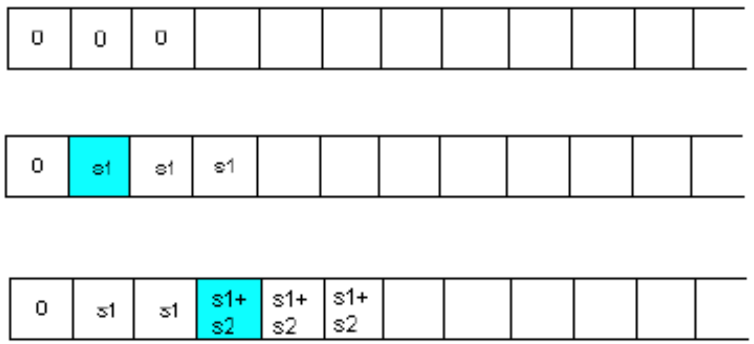
- Typical rise time
- Typical signal minimum voltage
- Typical signal decay behaviour

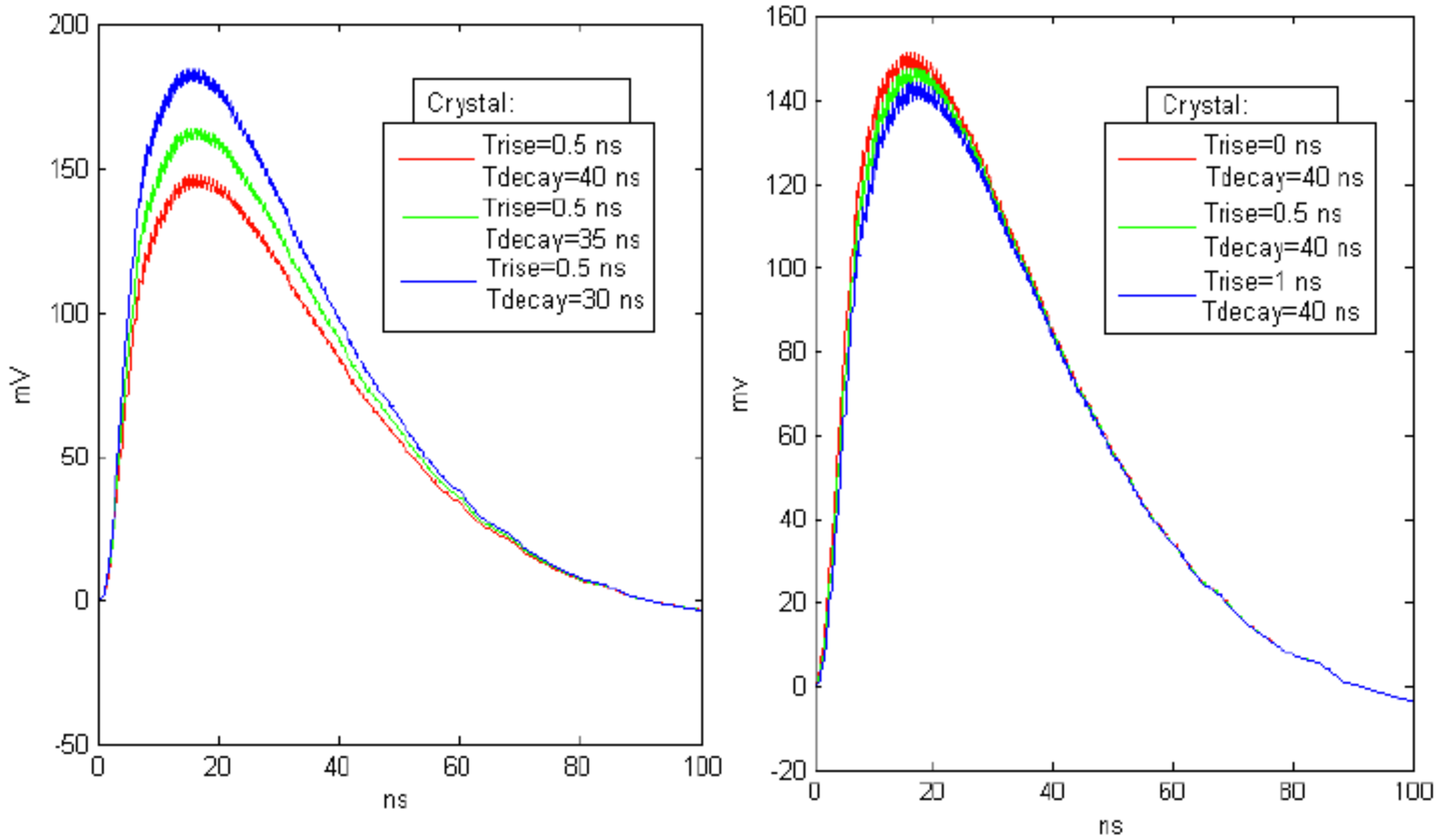
Simulation of N microcells:

SiPM IRST: 3mm x 3mm, 3600 microcells.

tQ is the time when the probability of the Q-th photon emission assumes the maximum value (refers to prev.fig.).

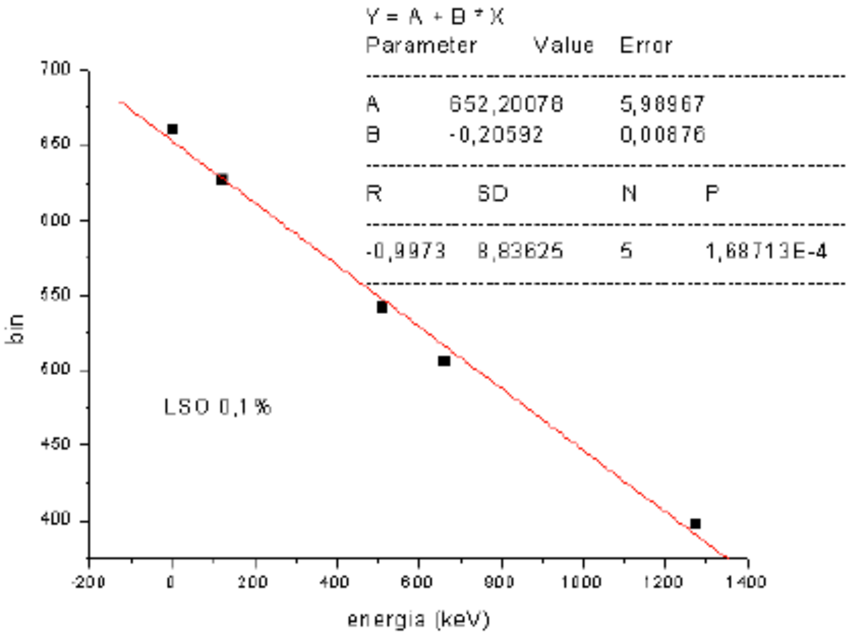
$$Sign_{tot} = \sum_{Q=1}^{N} Sign_{cell}(t - t_Q)$$

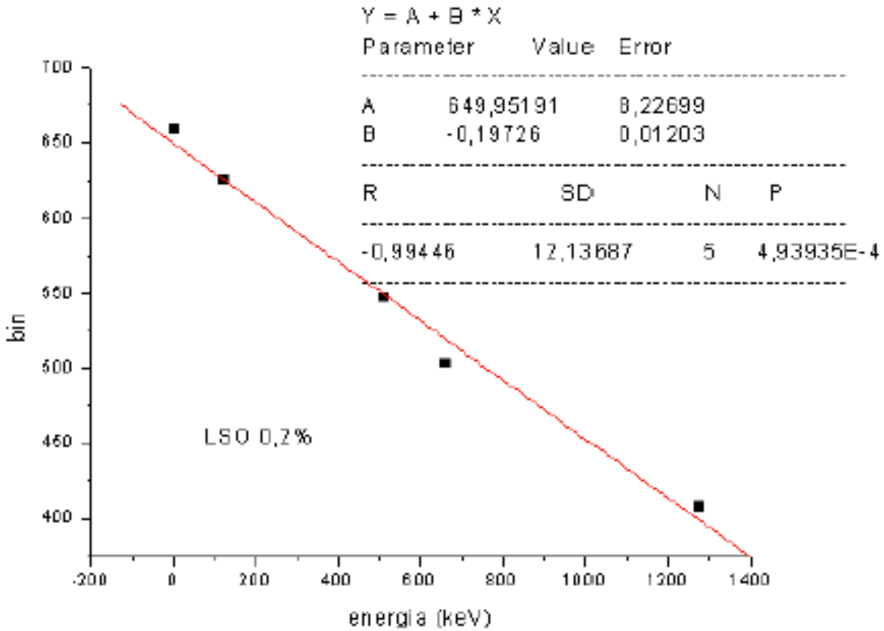


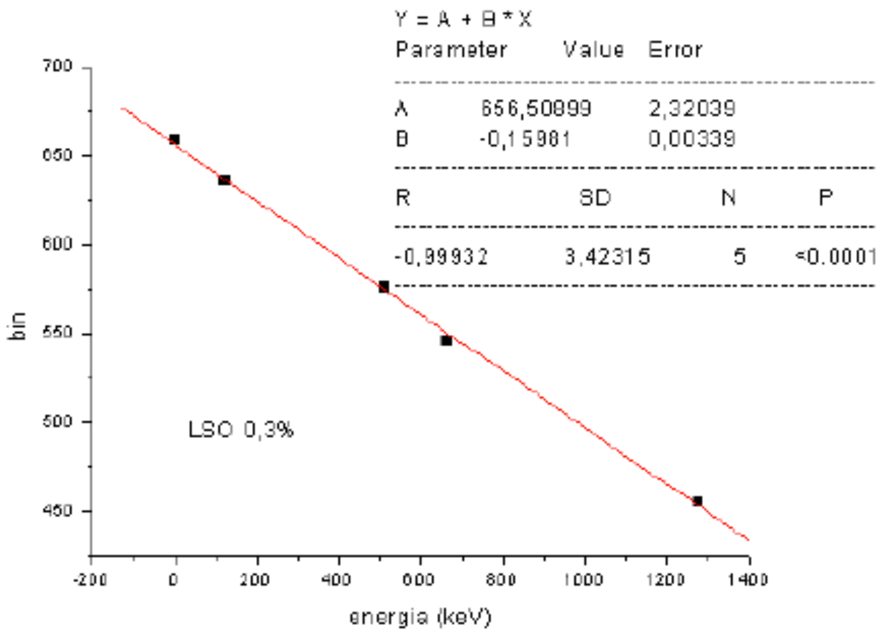


Output of the SiPM+amplifier system varying tau decay and tau rise of the crystal.

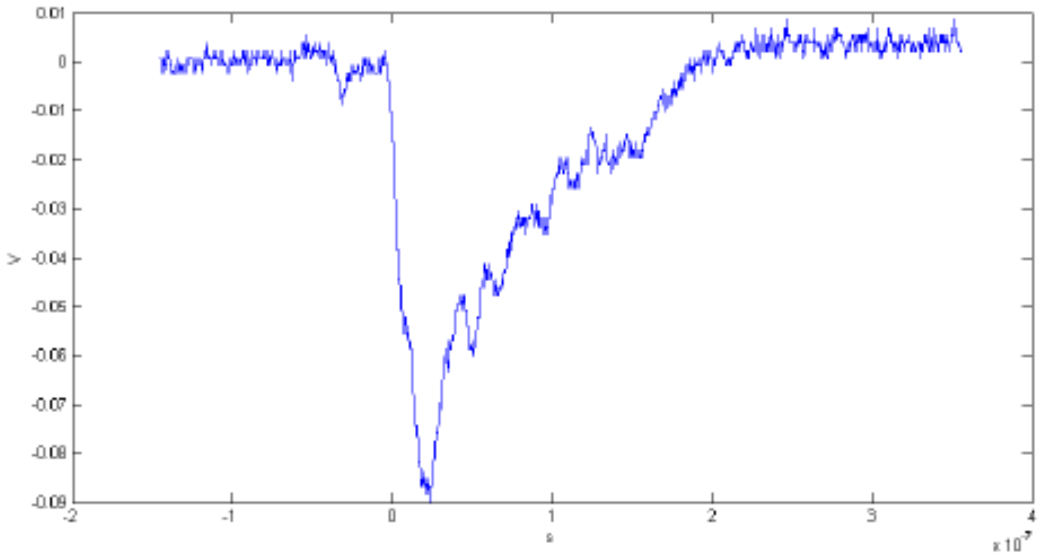
Measurements: linearity of the LSO:Ce,Ca crystals by using SiPM



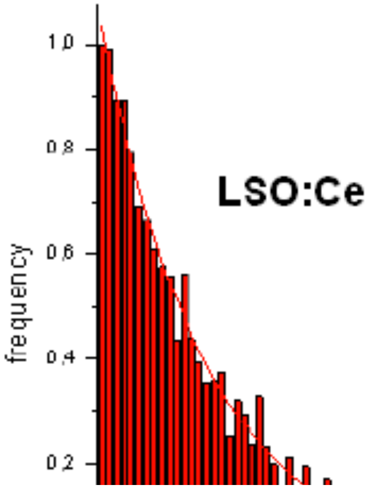


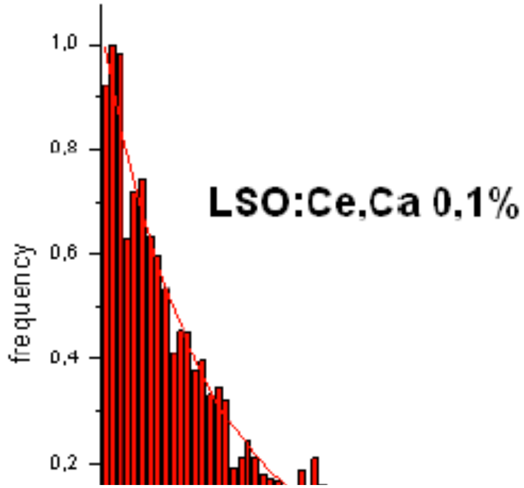


Measurements: decay times of LSO:Ce,Ca crystals by using SiPM



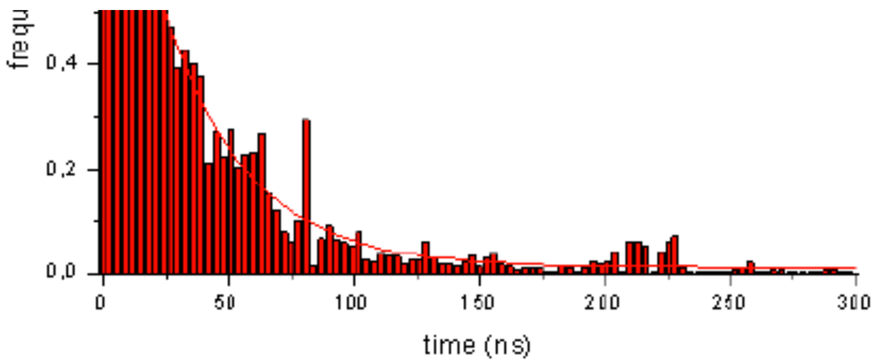
Histogram of the photon shower in output from SiPM

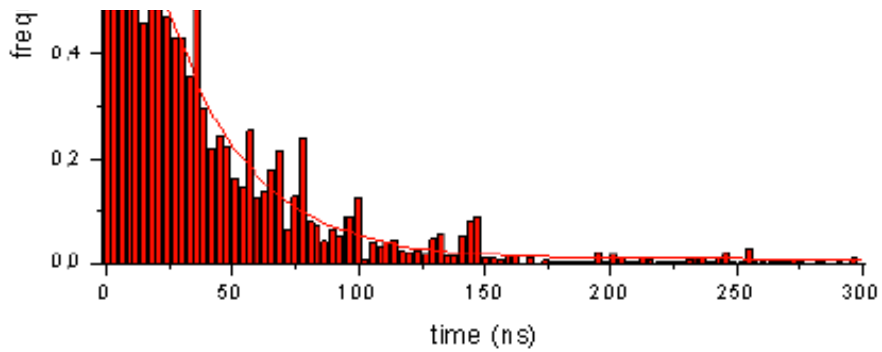




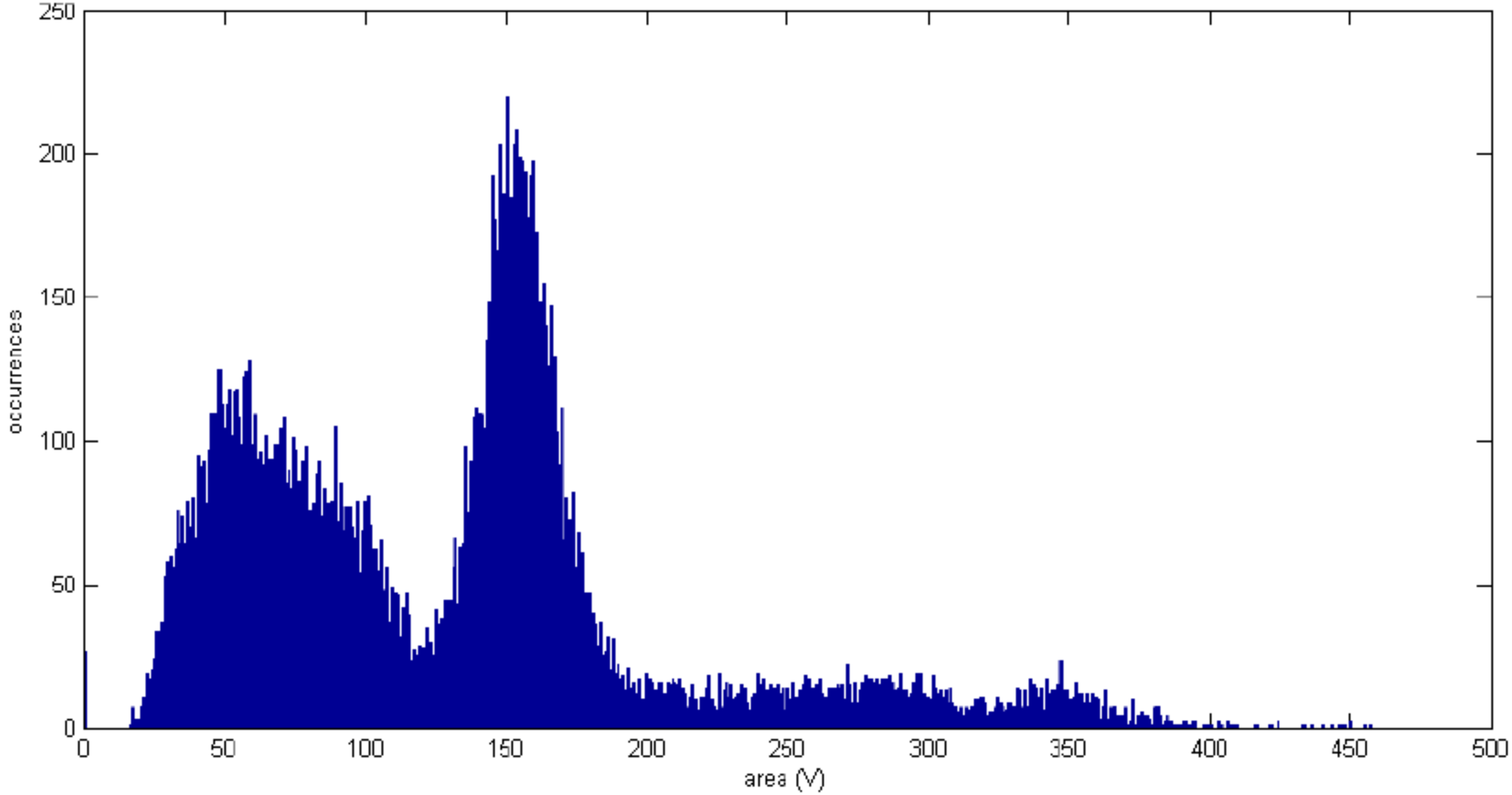
Ca concentration	Decay time τ (ns)	Literature value (ns)
LSO:Ce,Ca (0% Ca)	41,5 ± 1,1	43
LSO:Ce,Ca (0,1% Ca)	38,4 ± 1,2	37
LSO:Ce,Ca (0,2% Ca)	33,4 ± 1,4	34
LSO:Ce,Ca (0,3% Ca)	32,3 ± 1,3	31

→ The decay time decrease by increasing the Ca codoping.



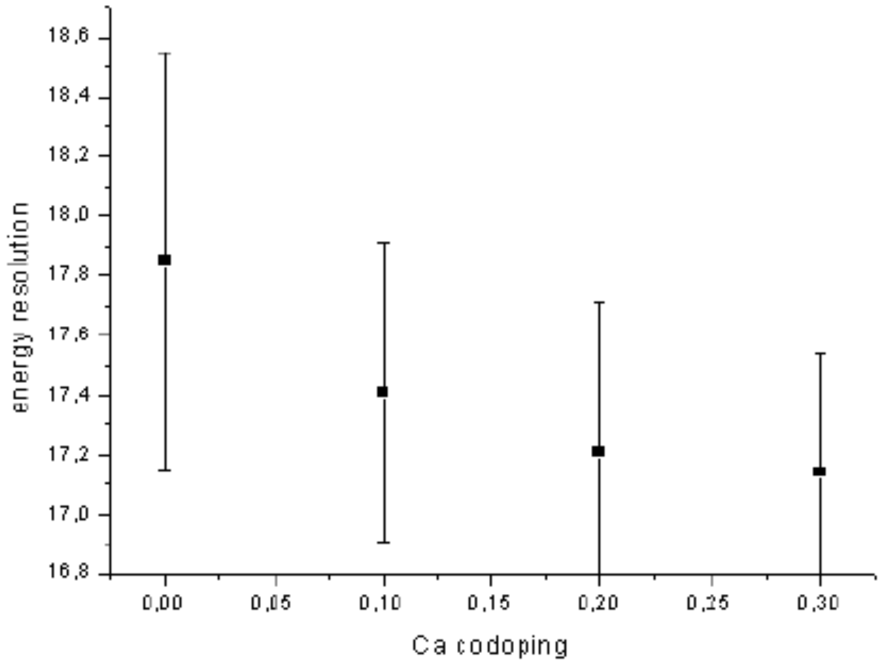


Measurements: energy resolution of the LSO:Ce,Ca crystals by using SiPM



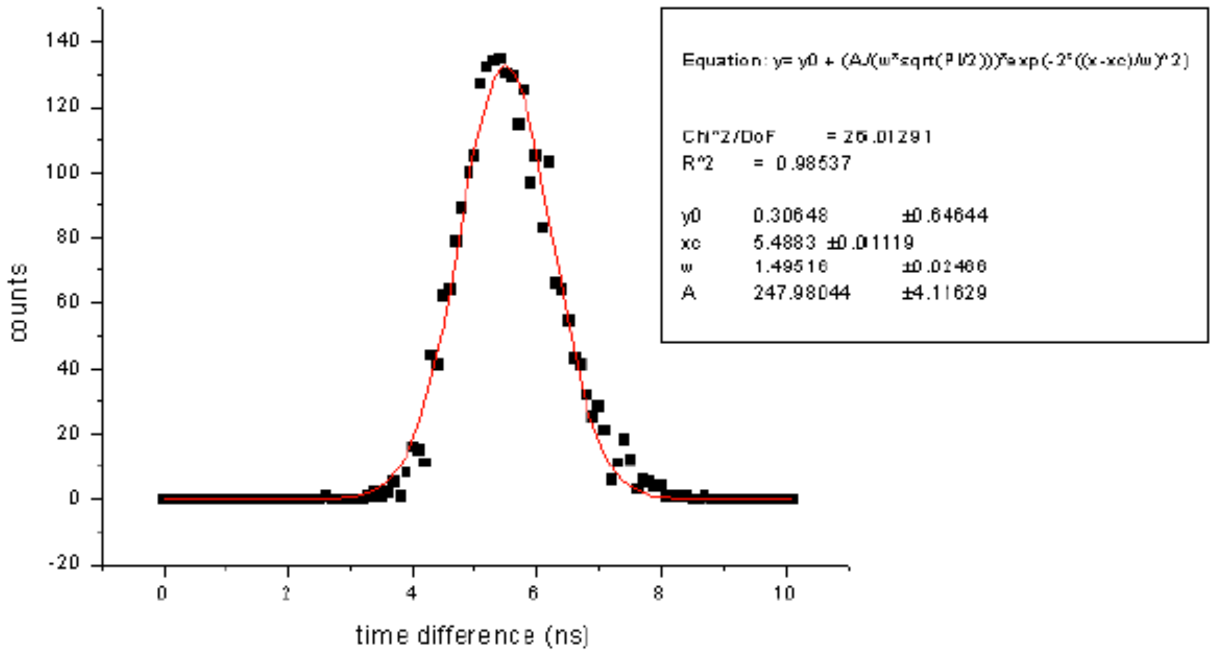
Example of LSO:Ce,Ca 0,2% Na22 spectrum obtained with SiPM.

Measurements: energy resolution of the LSO:Ce,Ca crystals by using SiPM



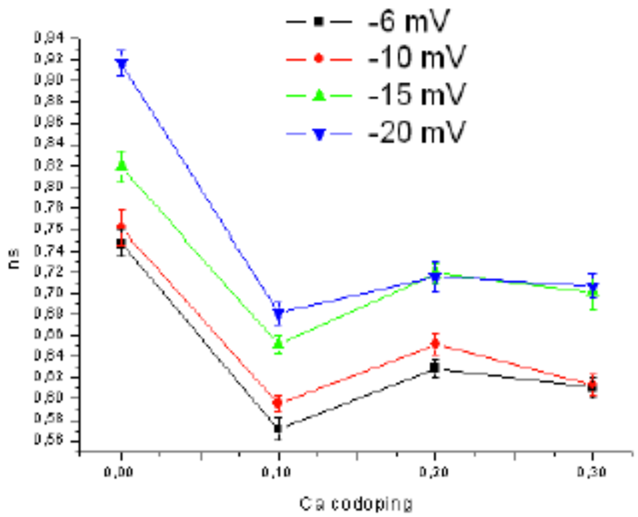
The energy resolution improves by increasing the Ca codoping

Measurements: timing of the LSO:Ce,Ca crystals by using SiPM with offline data processing in order to study timing as a function of the thresholds.

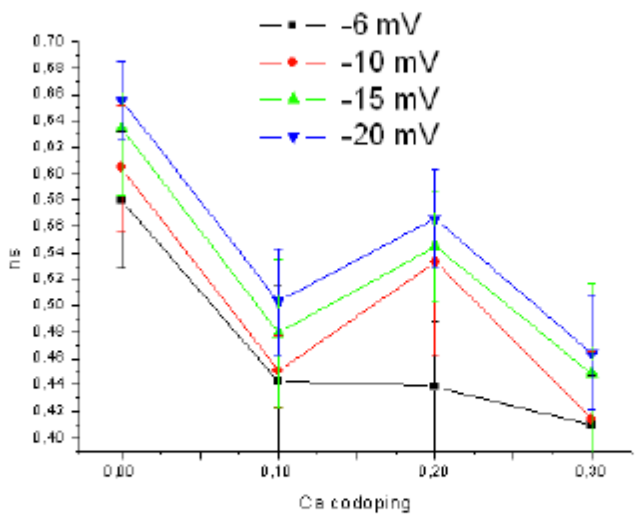


Example of timing events distribution, for LSO:Ce with no Ca codoping, threshold -6 mV, overvoltage 1V.

Measurements: timing of the LSO:Ce,Ca crystals by using SiPM with offline data processing in order to study timing as a function of the thresholds.



Timing resolution of the coincidence by varying the skew threshold, with 1V overvoltage



Timing resolution of the coincidence by varying the skew threshold, with 2V overvoltage

The timing resolution is estimated as the sigma of the gaussian distribution used to fit the timing distributions.

→ The timing resolution increases thanks to the Ca codoping.

Conclusions:

Model:

- study the signal shape of an innovative detector module based on LSO:Ce,Ca and SiPM (jitter, TOT, ...)
- Best timing performances if shorter tau decay
- Best timing performances if trigger on first photoelectrons

Measurement:

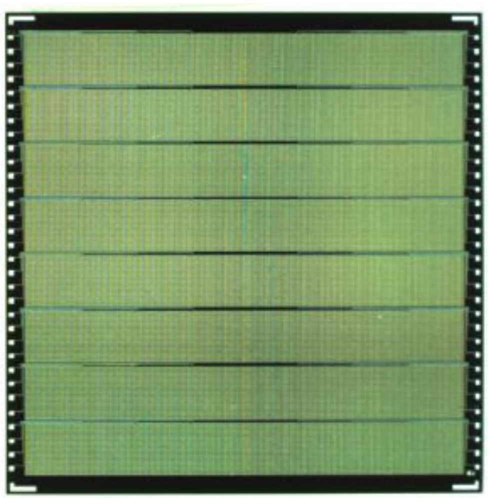
- Verified the linearity and the time constants used in the model
- Confirmation: best timing performances if shorter tau decay and trigger on first photoelectrons
- Ca codoping improves timing performances and energy resolution.

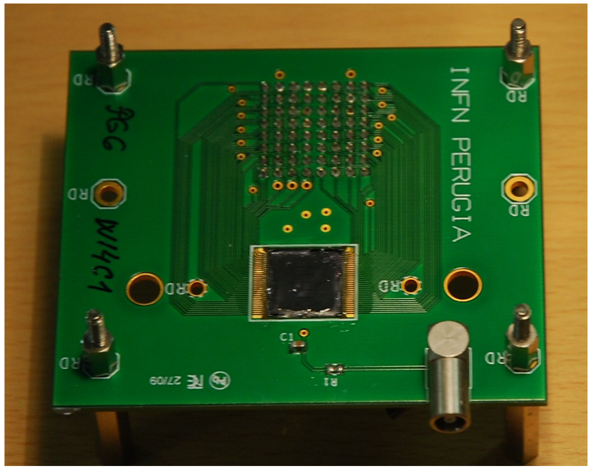
SiPMs MATRIX

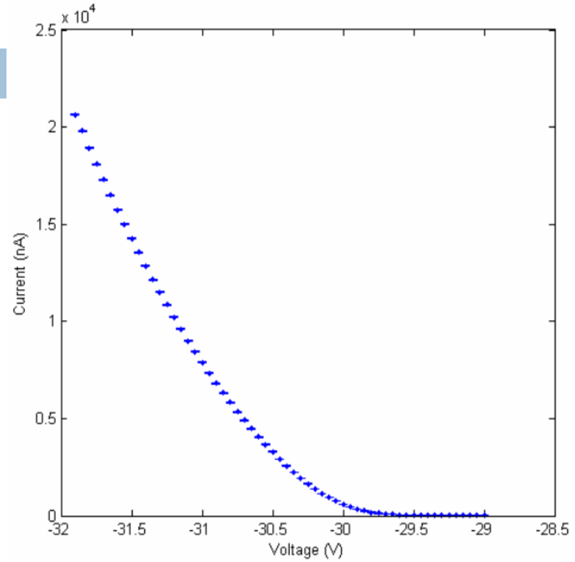
Matrices 8 x 8

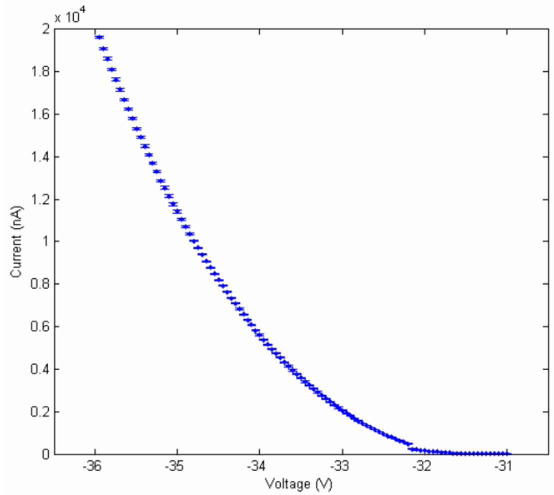
FBK – IRST:

- ✓ 840 microcells per SiPM
- ✓ Pitch of 1,5 mm
- ✓ Dimension of 13,1 x 13,1 mm^2 with 131,7 mm^2 (77%) of active region
- ✓ Common bias Voltage





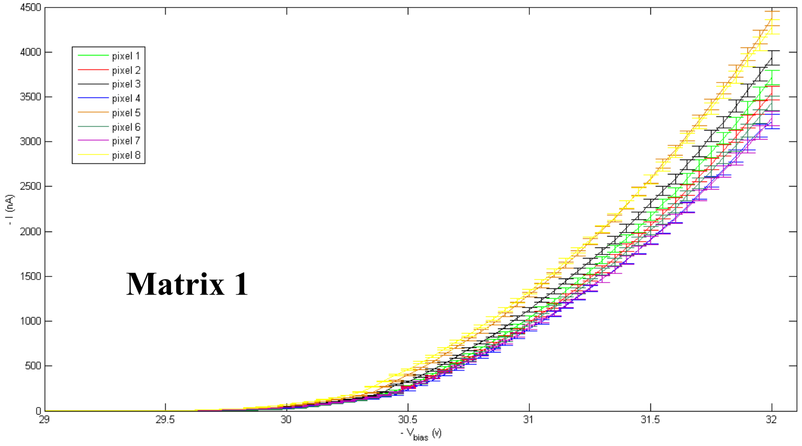


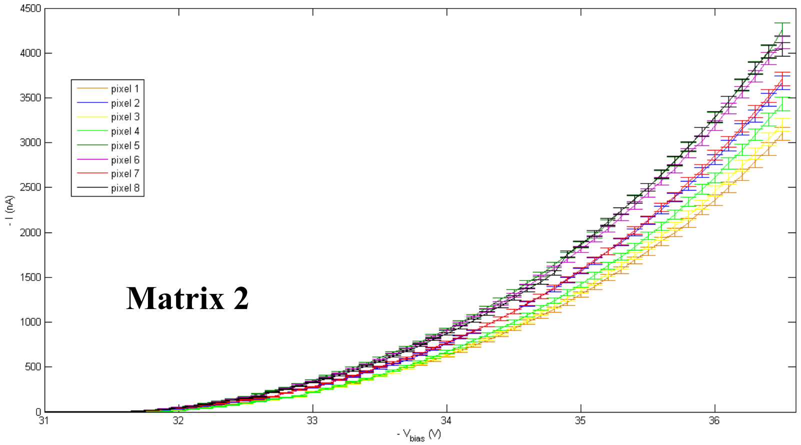


I – V curve of a line for each matrix

I – V CURVE

✓ I – V Curve for each pixel of the used line





PEAK – VOLTAGE POSITION

✓ Position of the photo-peak in function of the bias voltage

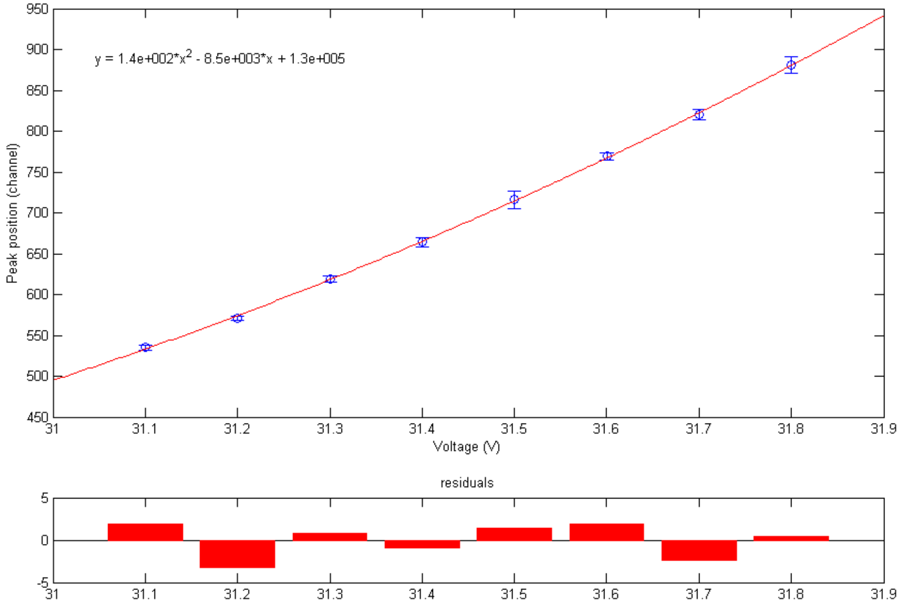
$$E = N \cdot e \cdot G(V)PDE(V)$$

E = Signal amplitude

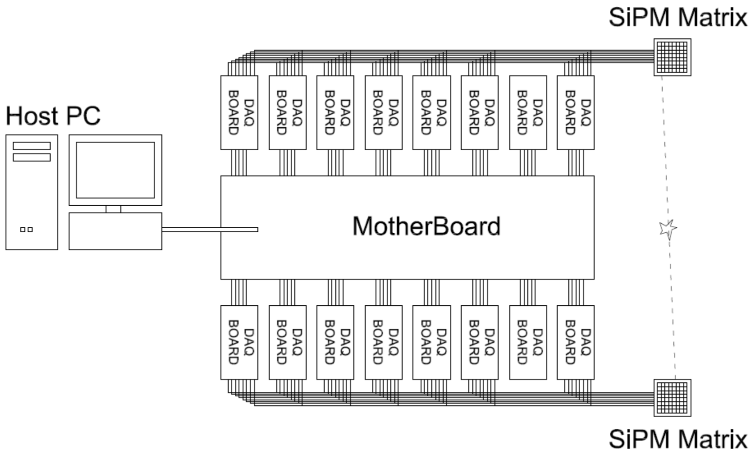
N = number of photo-electron

PDE = Photon Detection Efficiency

G = SiPM gain



THE ACQUISITION SYSTEM



✓ DAQ with 8-channels Front-End electronics (BASIC) *

✓ MotherBoard to host up to 18 DAQ

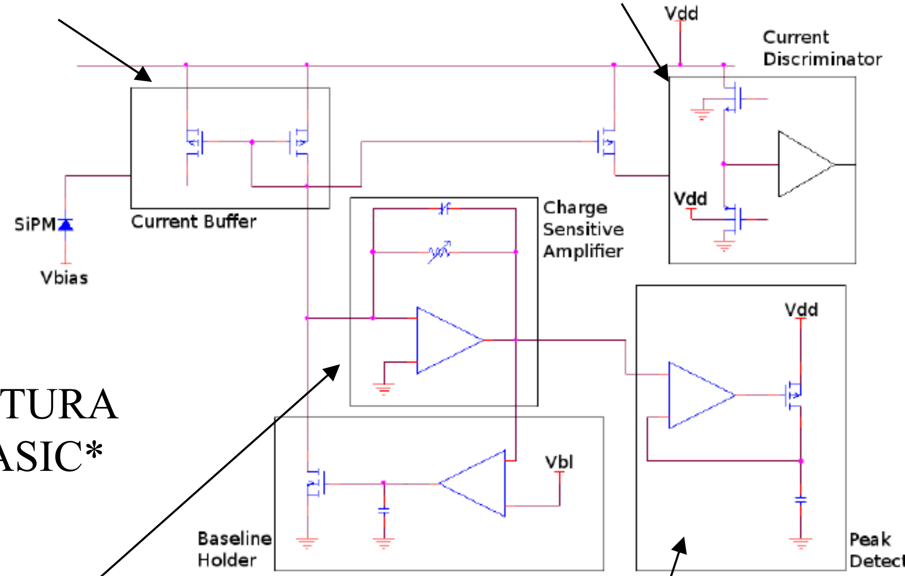
✓ FPGA Altera Stratix III for signals coincidence

✓ USB connection to a Host PC

Current Buffer (band-width of about 250 MHz)

Current Discriminator (Fast Trigger)

STRUTTURA DELL'ASIC*



CSA (signal integration)

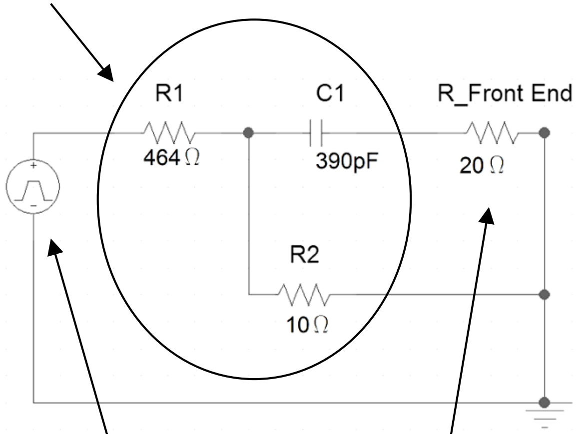
Peak Detector (read-out of the signal)

* *F. Corsi et al., N19-2, BASIC: an 8-channel Front-end ASIC for Silicon Photomultiplier Detectors 2009 IEEE Nuclear Science Symposium Conference Record 2009*

DAQ LINEARITY

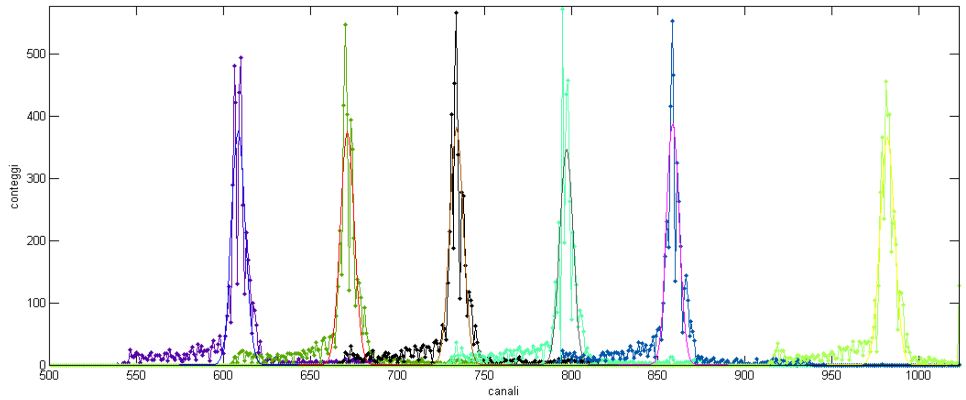
TEST SIGNAL TO VERIFY DAQ LINEARITY

Shaping circuit to simulate charge injection

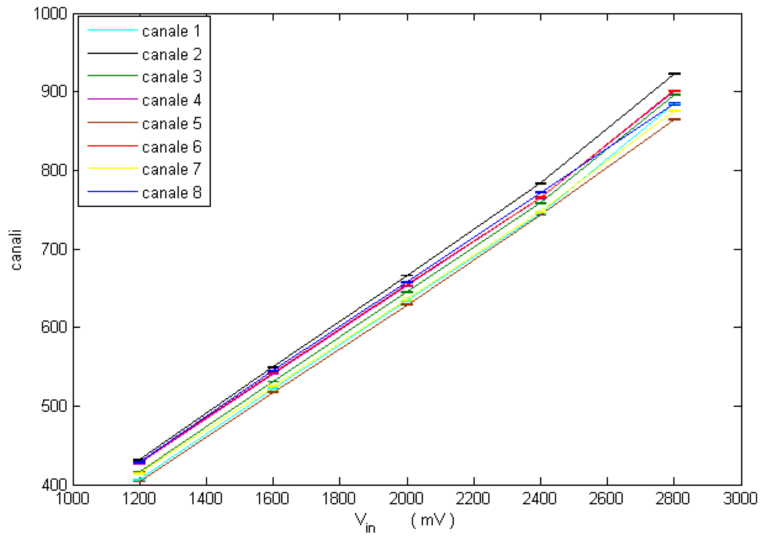


Square wave generator

Front-End impedance lower than 20Ω.



$$Channel = Amplitude * A + Pedestrial$$

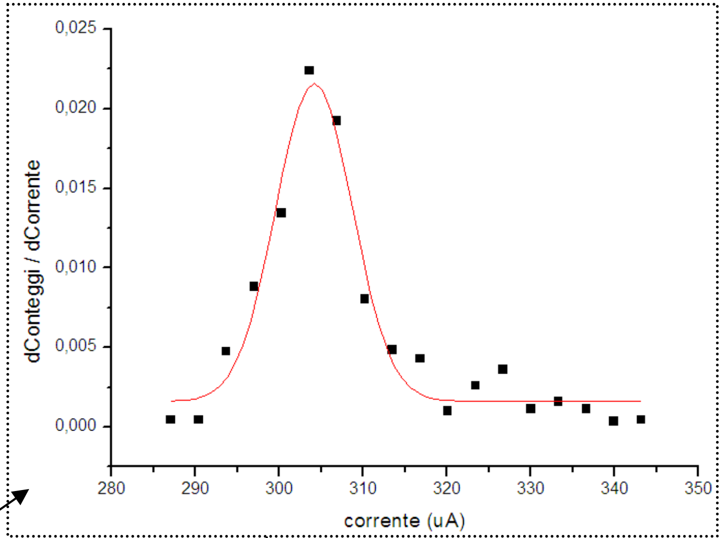


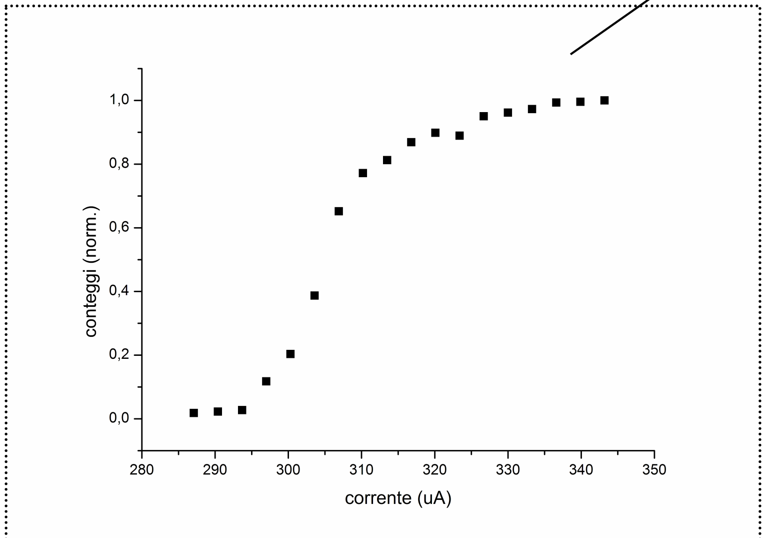
TRIGGER LEVELS

MEASUREMENT OF THRESHOLD LEVELS FOR THE CURRENT DISCRIMINATOR

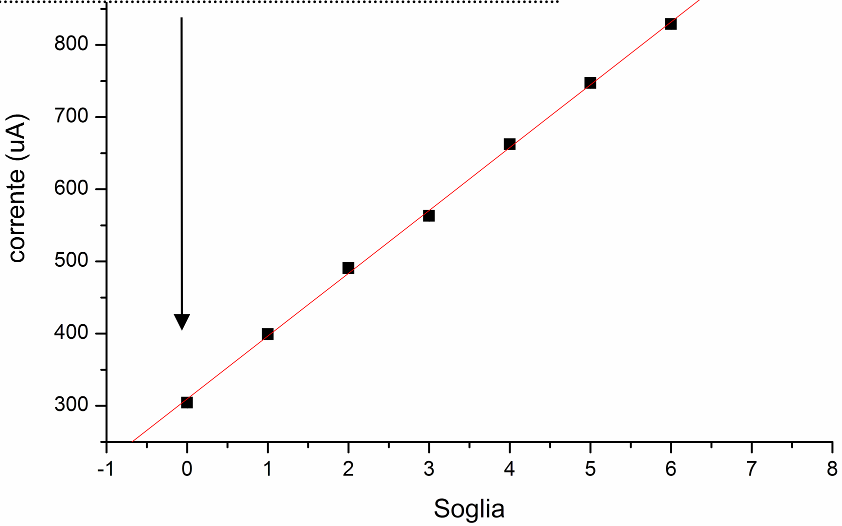
Counts measurements in function of the test signals amplitude:

$$P = \int_{V_{Th}}^{\infty} \frac{1}{\sqrt{2\pi\sigma}} e^{-(V-V_{IN})^2/2\sigma^2} dV$$

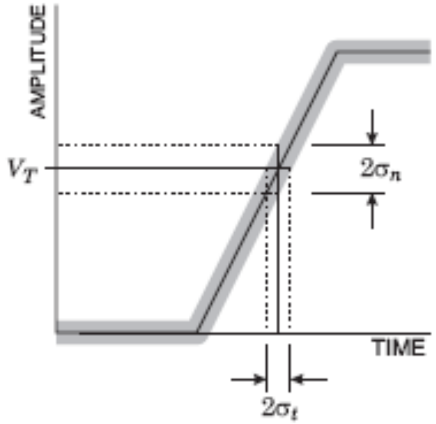




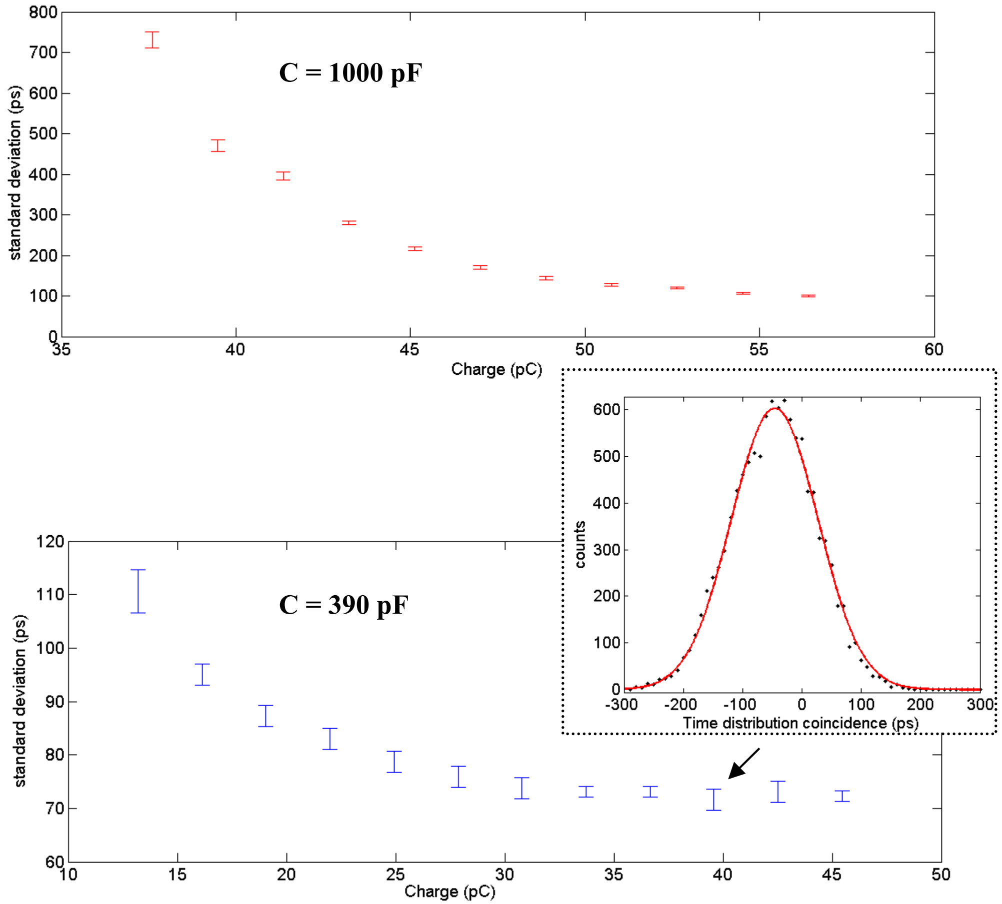
Level	Treshold (μA)
0	304 ± 5
1	399 ± 6
2	491 ± 7
3	563 ± 8
4	622 ± 8
5	747 ± 10
6	829 ± 12
7	918 ± 10



ELECTRONIC JITTER



Measurements with two different values of capacitors in the shaping circuit



$$\sigma_t = \frac{\sigma_n}{\left(dS/dt\right)} \approx \frac{t_r}{S/N}$$

Best result:

σ = 70 ± 3 ps

* *H. Spieler, Fast Timing Methods for Semiconductor Detectors, IEEE Trans. Nucl. Sci. NS-29/3 1142-1158*

TIME RESOLUTION

$$\sigma^2_{tot} \approx \sigma^2_{crystal} + \sigma^2_{detector} + \sigma^2_{elect}$$

$\sigma_{detector}$: detector contribution

✓ Charge drift in the depletion layer

$$\vec{v} = \mu\vec{E}$$

Few tens of pico-seconds*

$\sigma_{crystal}$: crystal contribution

✓ Statistical fluctuation in generation and detection of photons

$$\sigma^2 \approx \frac{Q\tau^2}{R^2}$$

σ_{elect} : electronic contribution

✓ Intrinsic electronic jitter

G. Collazuol et al., Single photon timing resolution and detection efficiency of the IRSTsilicon photo-multipliers, Nuclear Instruments and Methods in Physics Research A 581 (2007) 461–464

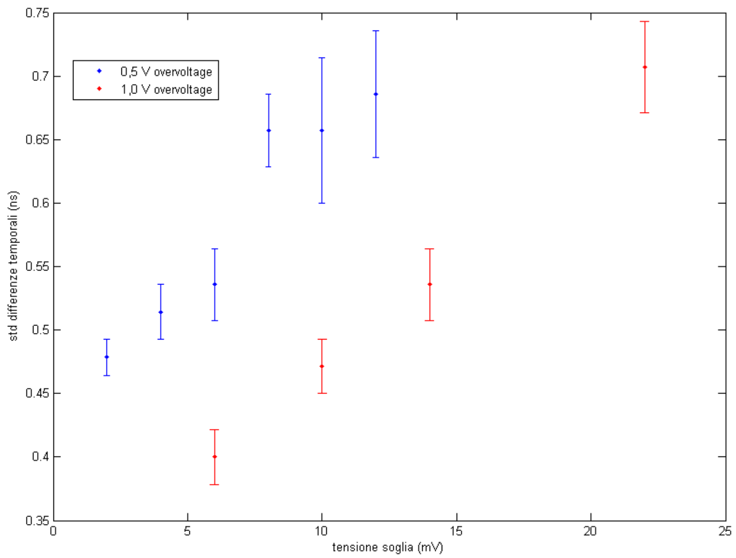
*** Post and Shiff, Statistical Limitation on the Resolving time of a Scintillation Counter, Phys. Rev. 80, pag. 1113, 1950.*

TIME RESOLUTION WITH SiPM AND LSO CRYSTAL

MEASUREMENT OF THE COINCIDENCE TIME DISTRIBUTION

→ SiPM Hamamatsu 3 x 3 mm^2 coupled to LSO 3 x 3 x 10 mm^3 crystal

✓ Signal sent to the scope

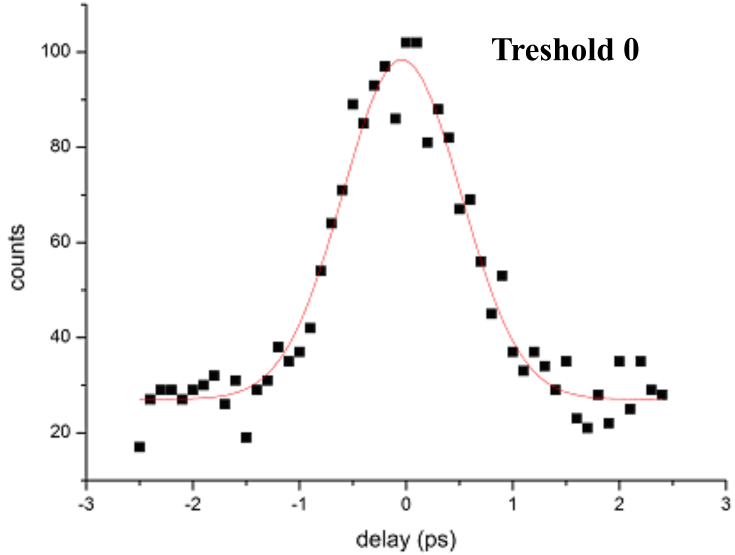


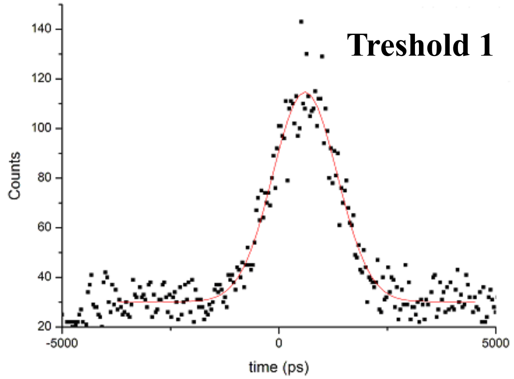
✓ Signal sent to DAQs

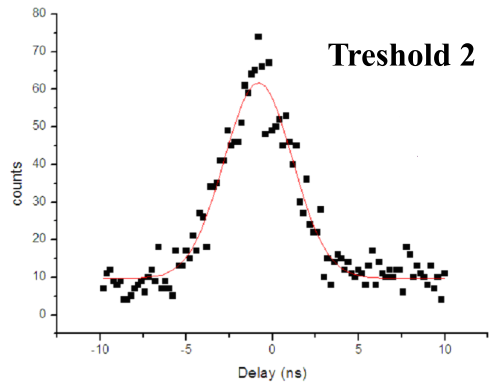
$\sigma_{th0} = 550 \pm 20$ ps

$\sigma_{th1} = 740 \pm 20$ ps

$\sigma_{th2} = 1950 \pm 20$ ps







TIME RESOLUTION

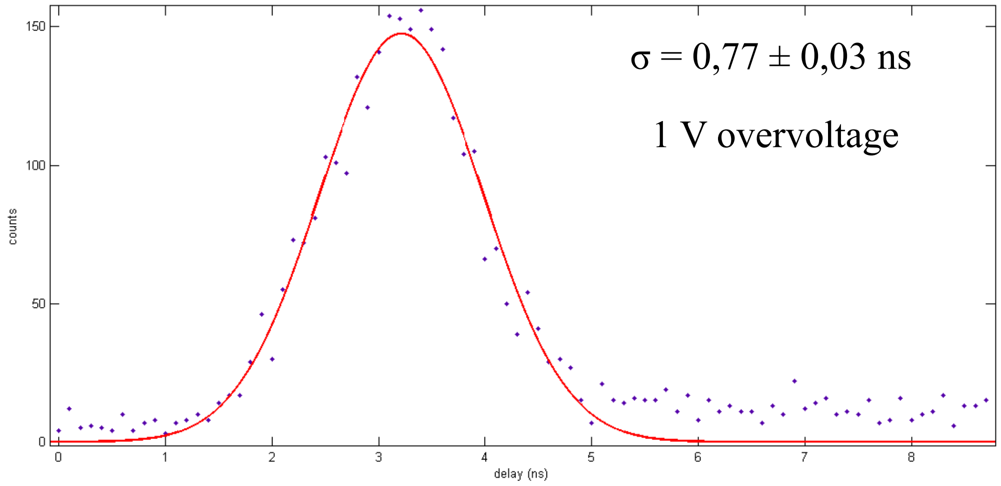
→ Coincidence between two lines of the matrices with ^{22}Na

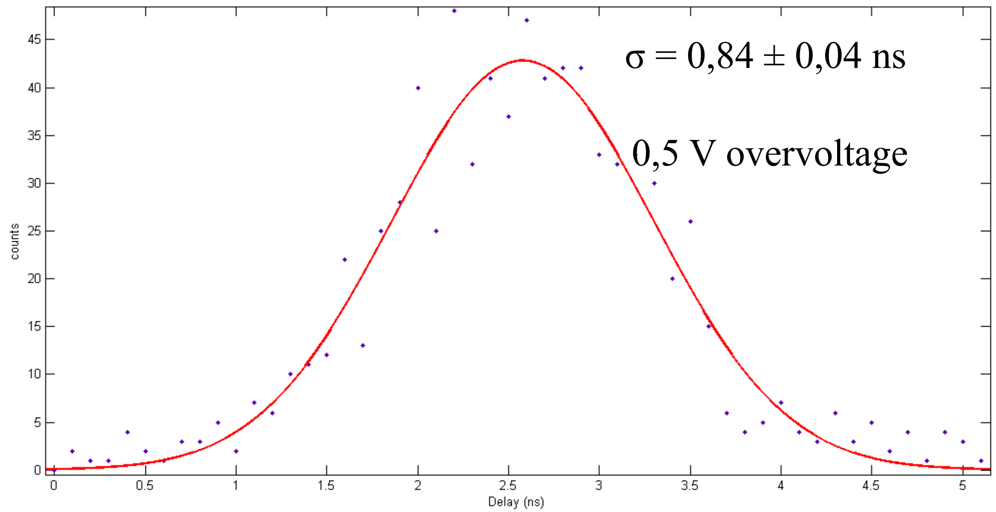
$$\sigma_{tot}^{2} = 2\sigma^{2}$$

Digital signals sent to the scope:

✓ band-width 1,5 GHz

✓ sampling of 2 GS/s



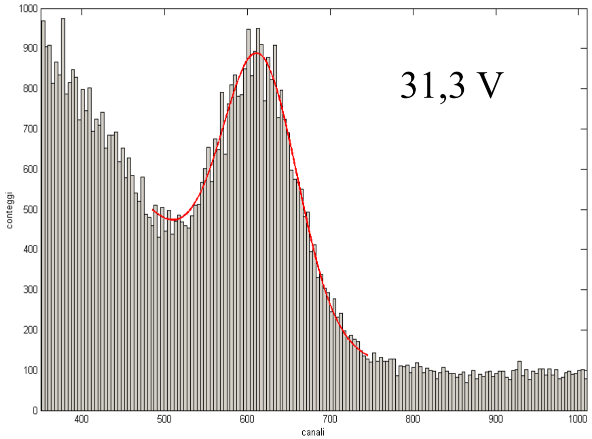


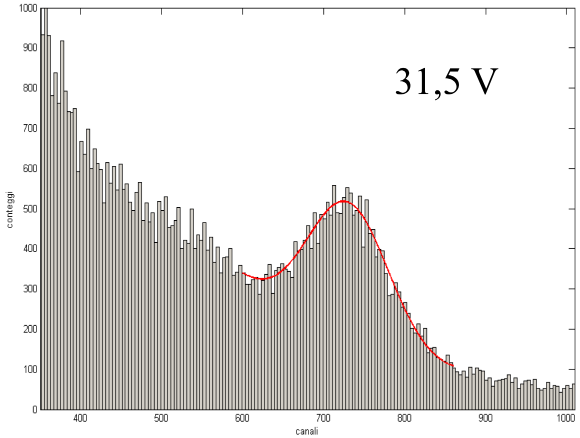
ENERGY RESOLUTION

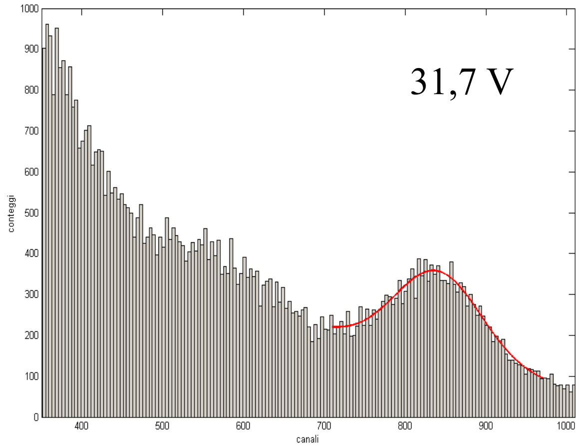
✓ Energy resolution at different bias voltages

$$Ris.En. = \frac{\sigma \cdot 2{,}355}{\left(X_{picco} - X_0\right)}$$

Single line acquisition



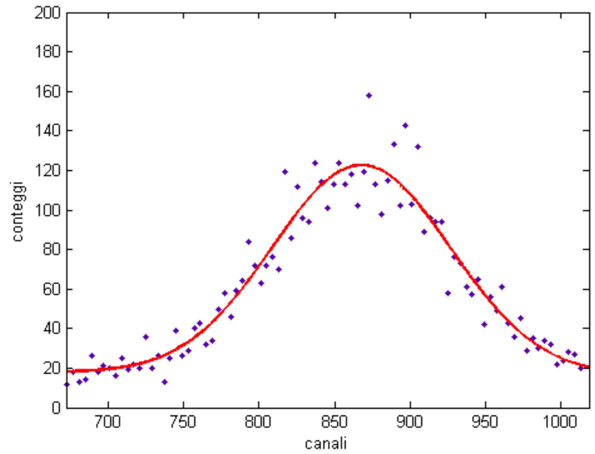




V_{bias}	31,3 V	31,5 V	31,7 V
Energy Res. (%)	19,8 ± 0,7	15,3 ± 0,4	16,6 ± 0,5

✓ Energy resolution in coincidence

Ris. En. = 16,9 ± 0,4 %,



CONCLUSION

✓ Characterization and calibration of the acquisition system

✓ Time resolution for coincidence events of $\sigma = 0{,}77 \pm 0{,}03$ ns

✓ Energy resolution of 15,3 ± 0,4 % (16,9 ± 0,4 % in coincidence)

HP3

- Involvement in task 2: SiPM-coupled advanced fiber detectors
- Involvement in task 3: Ultra-fast timing with plastic scintillators for TOF-applications