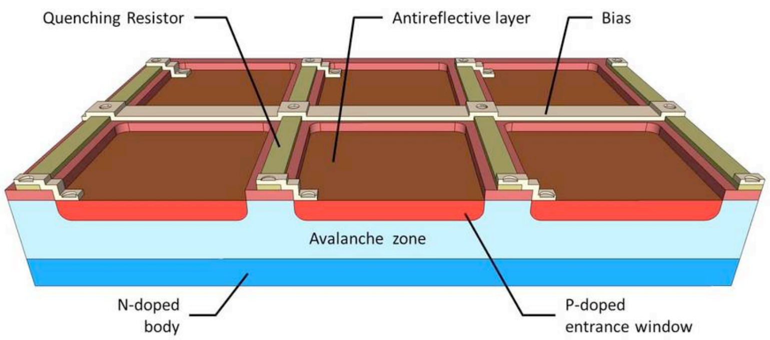
Silicon Photomultiplier (SiPM): a flexible platform for the development of high-end instrumentation

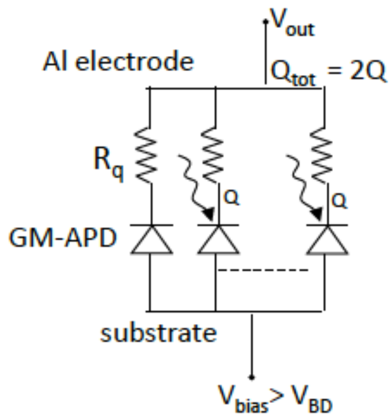
Romualdo Santoro* and M. Caccia
Università dell'Insubria, Como (Italy)

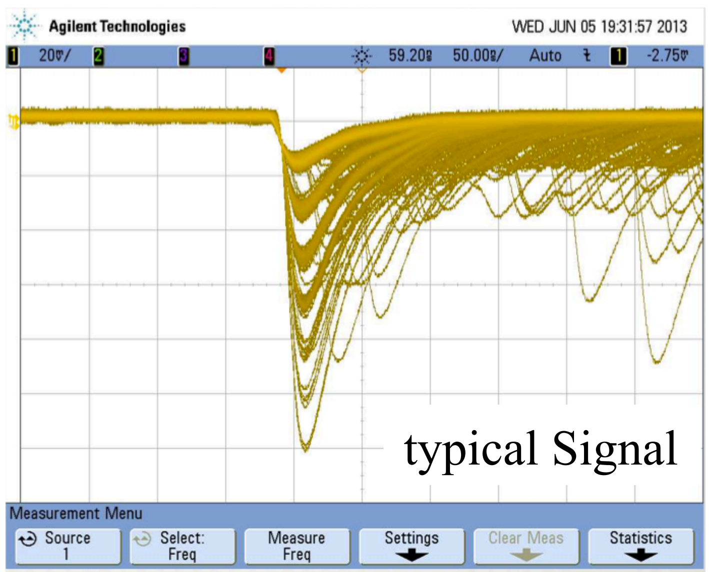
Photons detectors: SiPM

- SiPM is a High density (up to $10^4/mm^2$) matrix of diodes with a common output, working in Geiger-Müller regime
- Common bias is applied to all cells (few % over breakdown voltage)
- Each cell has its own quenching resistor (from 100kΩto several MΩ)
- When a cell is fired an avalanche starts with a multiplicative factor of about 10^5-10^6
- The output is a fast signal (t_{rise}~ ns; t_{fall} ~ 50 ns) sum of signals produced by individual cells
- SiPM works as an analog photon detector: signal proportional to the number of fired cell

SiPM: Basic principle



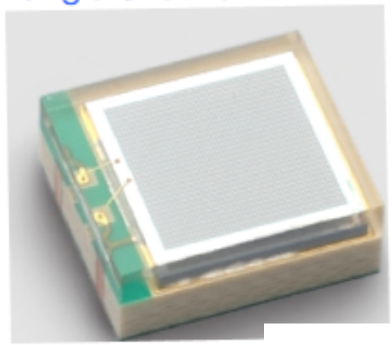




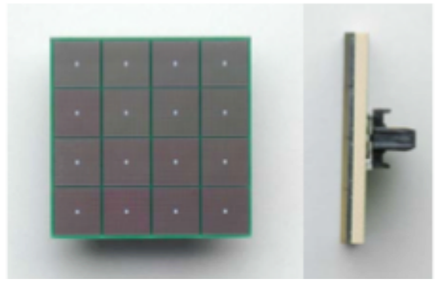
Wide range of products

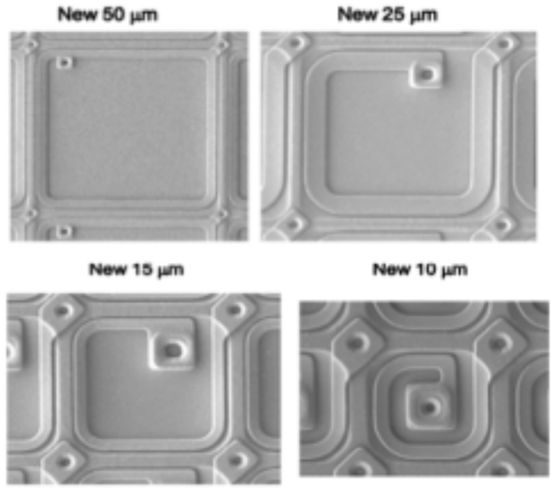
- Different geometry
  - single chip (i.e. 1x1, 3x3 and 6x6 mm^2)
  - array: (i.e. linear or squared) with common or separate output
- Different Fill factor
  - Pixel size (from 10 to 100 μm)
  - different technology (with/witout trenches)

Single Channel



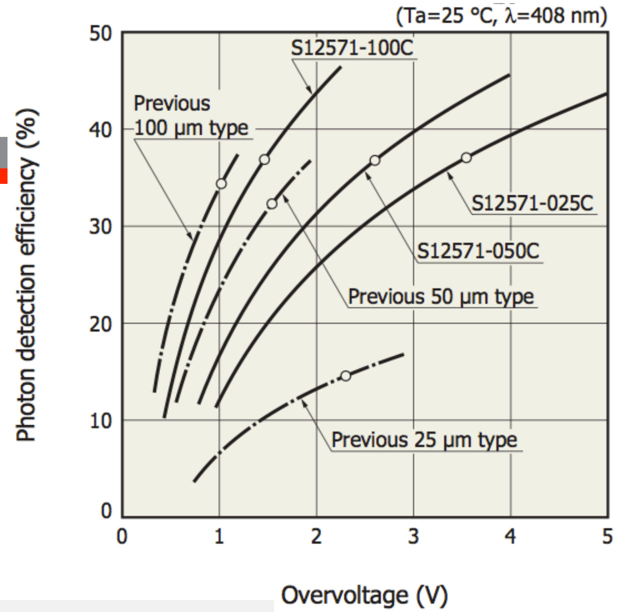
Squared array

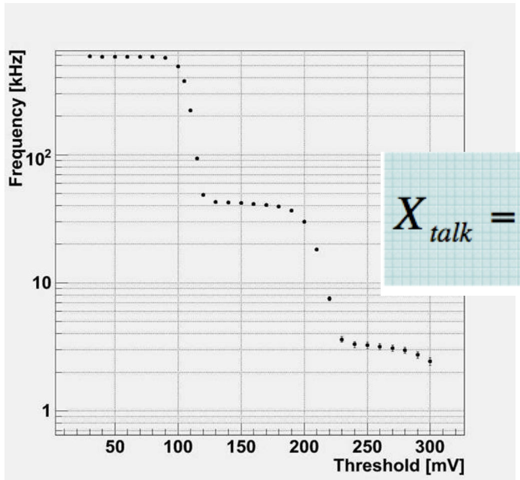




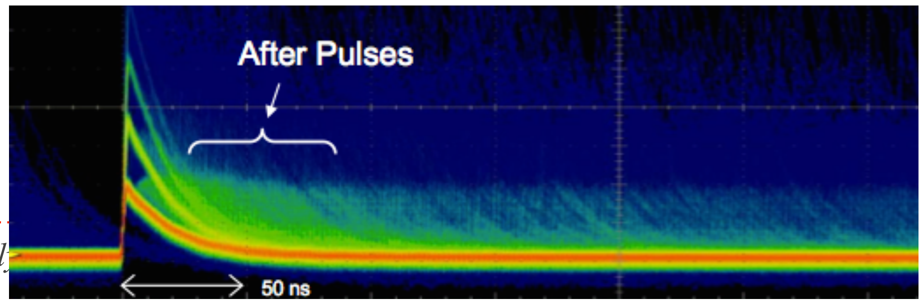
Wide range of products

- Different geometry
  - single chip (i.e. 1x1, 3x3 and 6x6 mm^2)
  - array: (i.e. linear or squared) with common or separate output
- Different Fill factor
  - Pixel size (from 10 to 100 μm)
  - different technology (with/witout trenches)
- Long list of parameters to be measured
  - QE, PDE
  - Gain vs voltage and temperature
  - DCR, After pulse and cross-talk
  - time resolution
  - …





$$X_{talk} = \frac{DCR(1.5\,ph)}{DCR(0.5\,ph)}$$



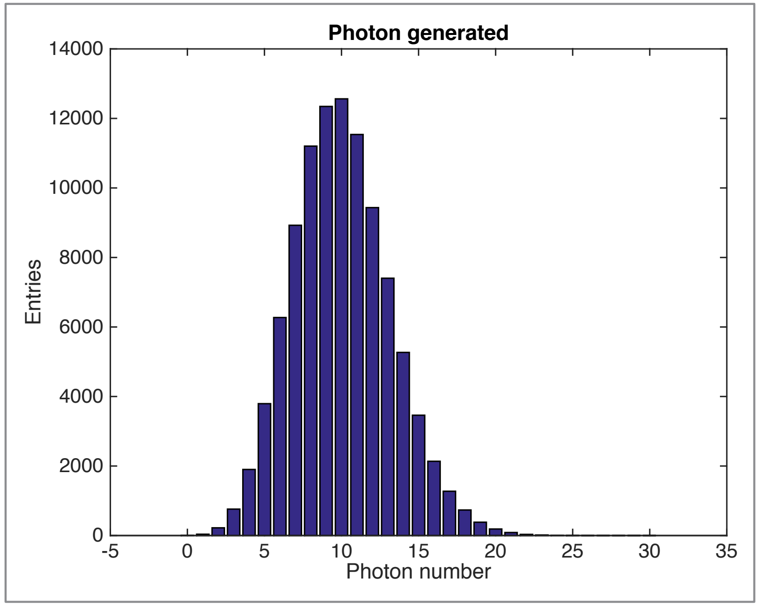
Why a fast simulation could be of interest?

- To reproduce the typical measurements done in the lab and to better understand the results especially when:
  - you characterize new sensors
  - you define new protocols
- To investigate new applications trying to better identify the sensor requirements

By the way, it isn't the real world!
There are a series of assumptions and measurements to be done on SiPMs

Simulation block diagram

1. Light (poissonian statistics)

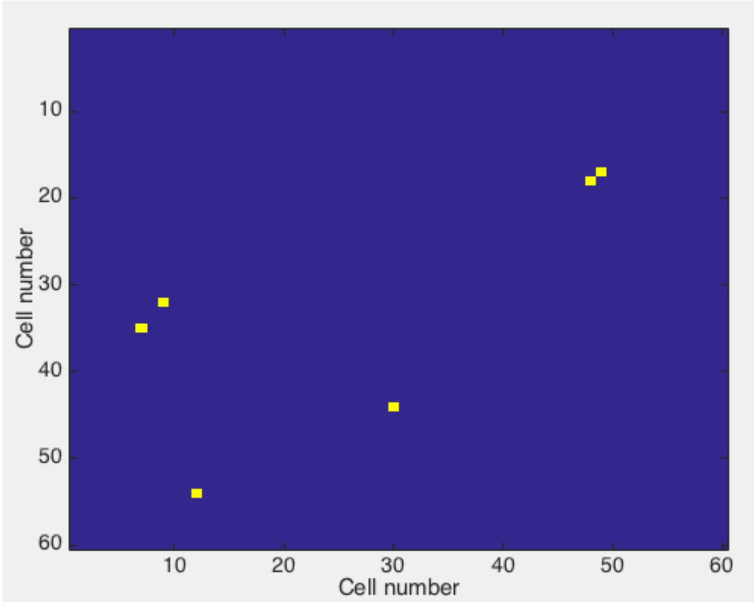


Simulation Parameters:

- Event = 10^5
- μ = 10 Photons

Simulation block diagram

1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk

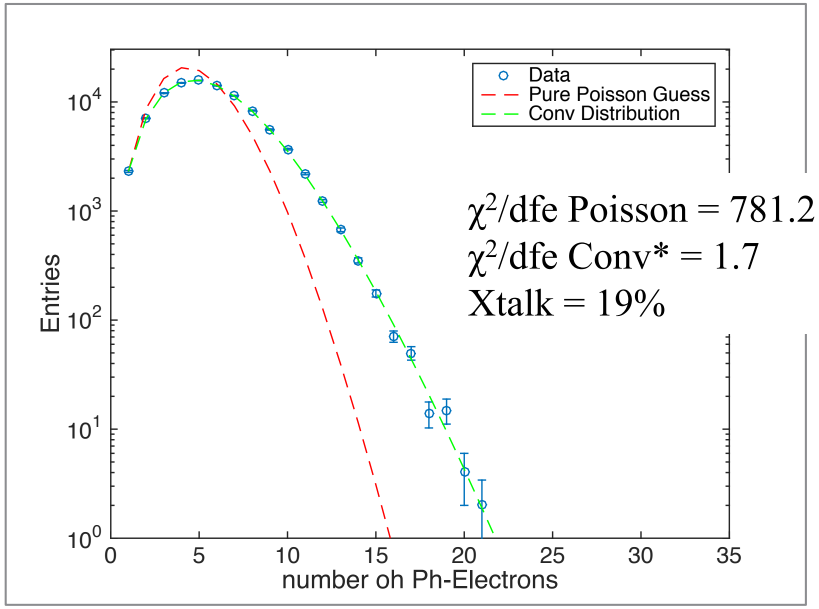


Simulation Parameters:

- number of cells = 3600
- eff =38%
- Xtalk=20%

Simulation block diagram

1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk
3. Number of pixel Hit due to Phe and Xtalk



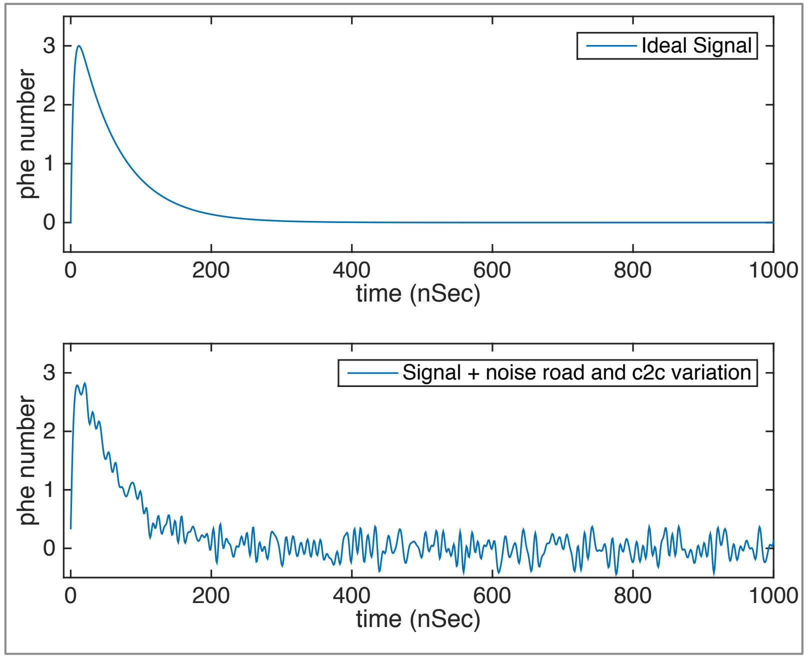
χ^2/dfe Poisson = 781.2
χ^2/dfe Conv* = 1.7
Xtalk = 19%

*Conv = S. Vinogradov et al. (NSS/MIC), 2009 IEEE

This fit nicely but I could also try the N.Borel (Erlang) see Thomas Bretz talk at this conference

Simulation block diagram

1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk
3. Number of pixel Hit due to Phe and Xtalk
4. Signal characteristics: signal tau, noise and cell2cell variation

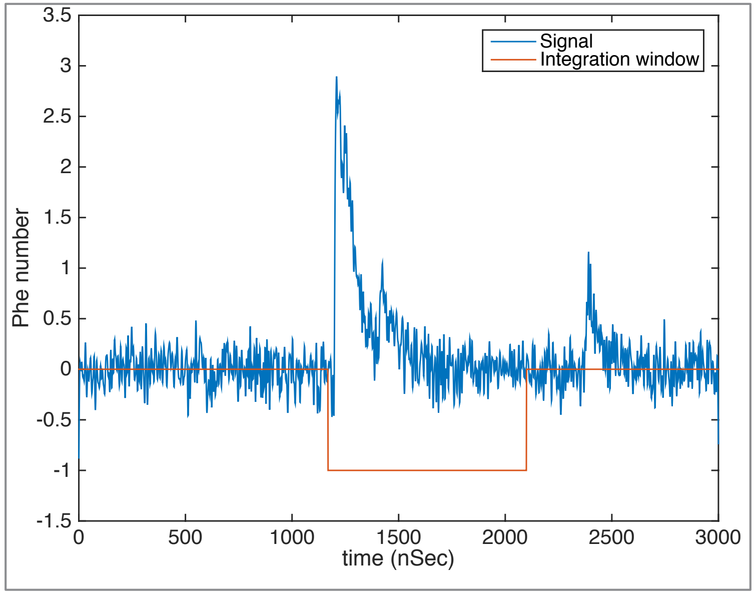


Simulation Parameters:

- τ_{signal}=60nSec
- Cell2Cell Variation=0.1phe
- SNR=10

Simulation block diagram

1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk
3. Number of pixel Hit due to Phe and Xtalk
4. Signal characteristics: signal tau, noise and cell2cell variation
5. DCR and AfterPuls + correlated xTalk



Simulation Parameters:

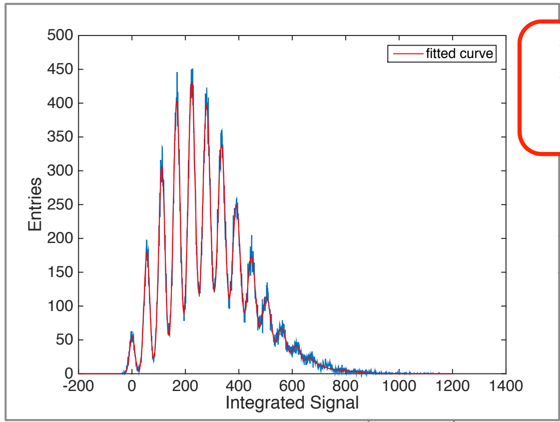
- DCR=300 kHz
- Xtalk=20%
- AfterPulse (AP)=20%
- τ_{AP}=80 (slow) and 15 (fast) @ 50% ratio

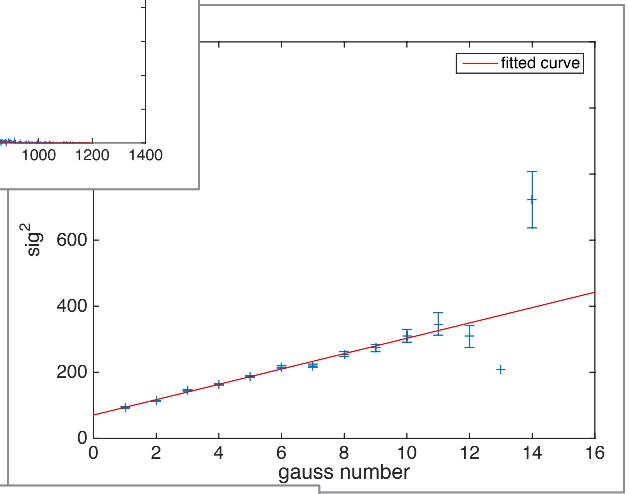
Simulation block diagram

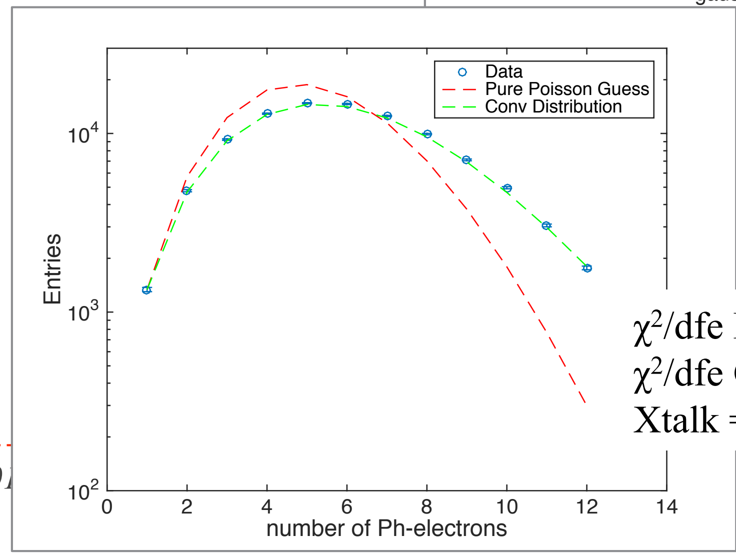
1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk
3. Number of pixel Hit due to Phe and Xtalk
4. Signal characteristics:

   signal tau, noise and cell2cell variation
5. DCR and AfterPuls + correlated xTalk
6. Analysis tool

Example of Xtalk Measurement





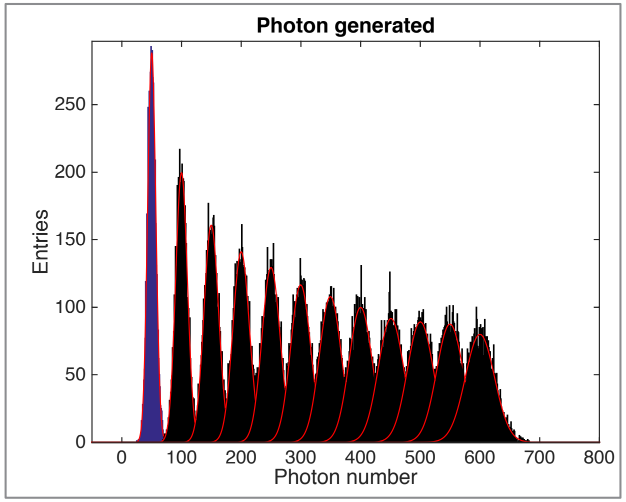


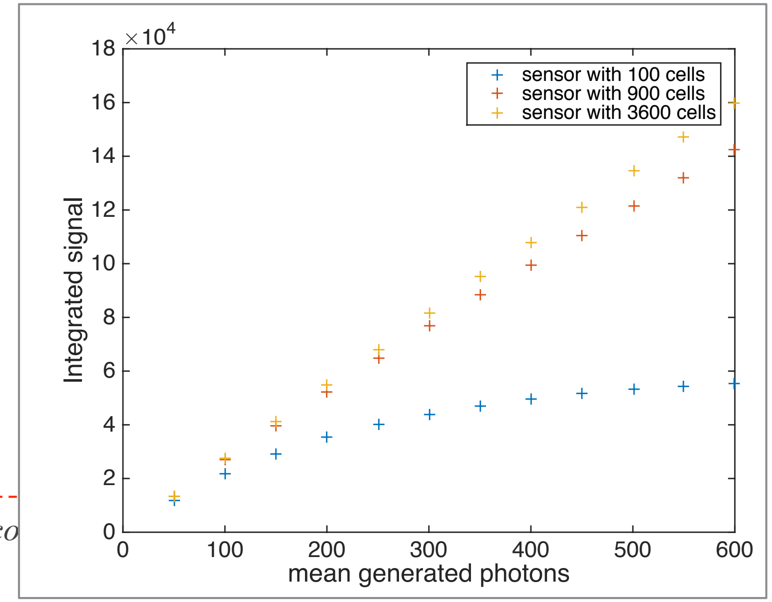
χ^2/dfe Poisson = 1141.0
χ^2/dfe Conv = 6.9
Xtalk = 19%

Simulation block diagram

1. Light (poissonian statistics)
2. Detector characteristics: number of pixel, eff, Xtalk
3. Number of pixel Hit due to Phe and Xtalk
4. Signal characteristics: signal tau, noise and cell2cell variation
5. DCR + AfterPuls + correlated xTalk
6. Analysis tool

Example of light saturation Measurement





SiPM for homeland security

- MODES_SNM has been founded by the European Commission within the Framework Program 7
- The Main Goal is the development of a system with detection capabilities of "difficult to detect radioactive sources and special nuclear materials"
  - Neutron detection with high γ rejection power
  - γ-rays spectrometry
- Other requirements
  - Mobile system
  - Scalability and flexibility to match a specific monitoring scenario
  - Remote control, to be used in covert operations

modes SNM

Modular Detector System for Special Nuclear Material

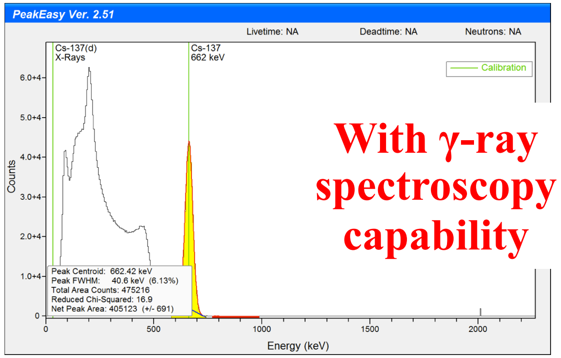
Two main Goals

- The demonstrator: a fully integrated system based on high pressure scintillating gas readout by PMT
  - Fast neutron (^4He)
  - Thermal neutron (^4He with Li converter)
  - Gamma (Xe)
- The proof of principle of PMT replacement with the innovative SiPM

→ Available on the market: http://www.arktis-detectors.com/products/security-solutions/

→ Now prototyped by Arktis and shown at NSS/MIC 2014 at Seattle

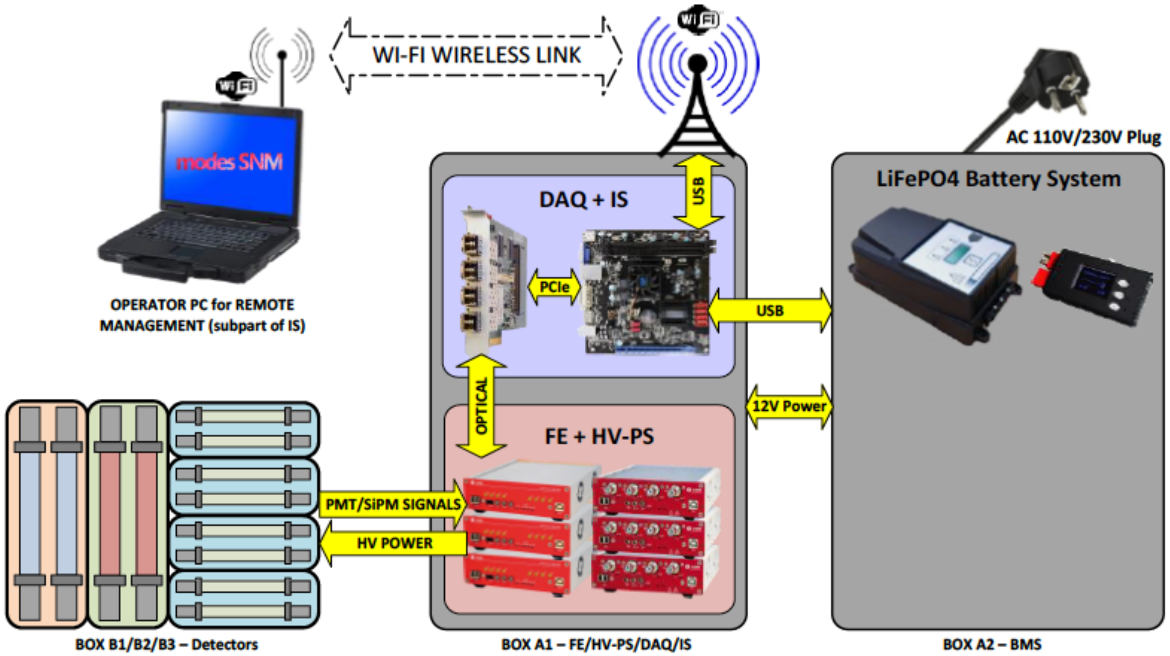
MODES_SNM System overview



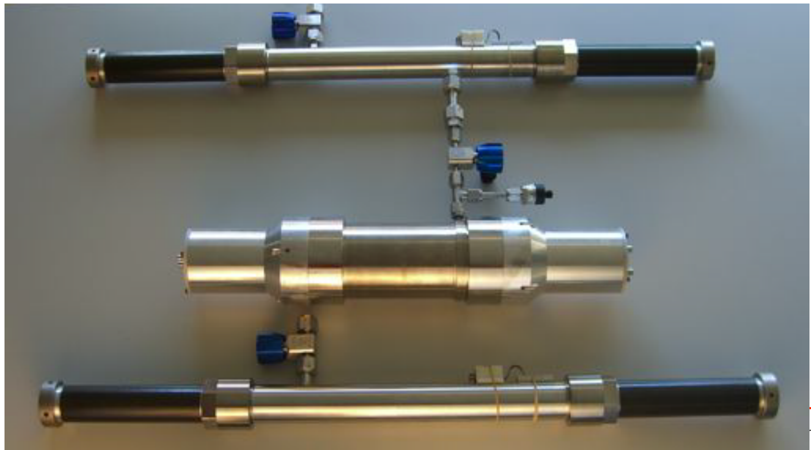
With γ-ray spectroscopy capability

Modular system optimized for:

- Fast neutron (^{4}He)
- Thermal neutron (^{4}He with Li converter)
- Gamma (Xe)



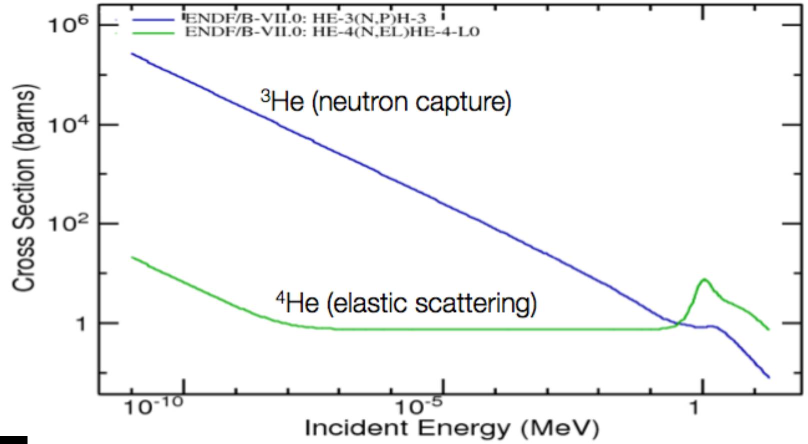
R. Santoro et al. NSS/MIC (2014)
D. Cester et al. ANIMMA (2015)

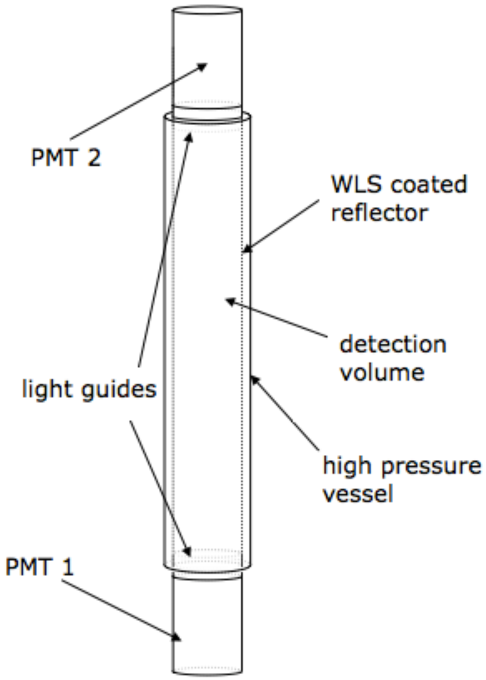


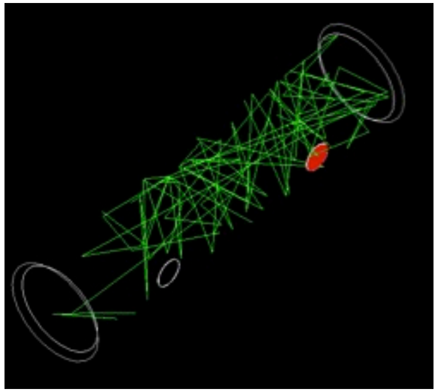
Modes used in the first-line scan at the Rotterdam seaport

Baseline technology

- The Arktis technologies is based on high pressurized ^4He for the neutrons detection
- The main key features of ^4He
  - Reasonably high cross section for n elastic scattering
  - Good scintillating properties
  - Two component decays, with τ at the ns and μs levels
  - Cheaper and easier to be procured wrt ^3He





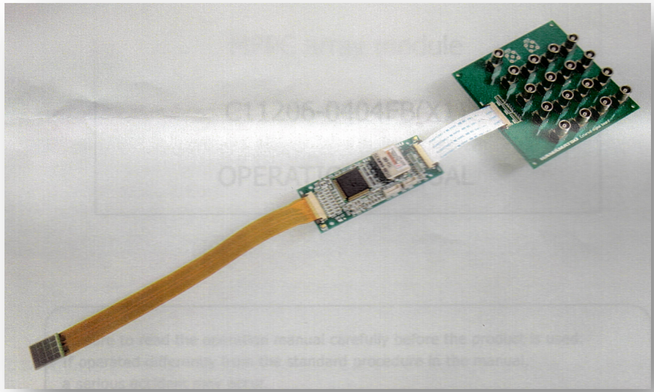


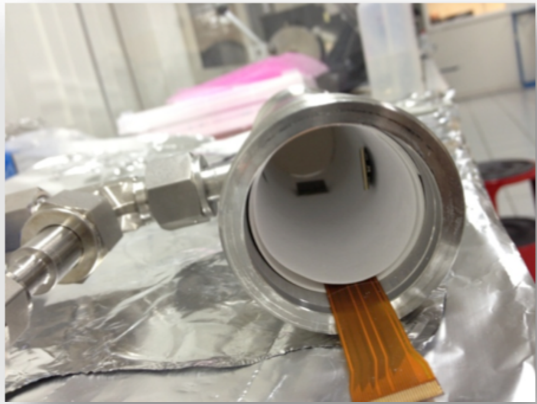
	Z	Photons/ MeV	Peak emission
^4He	2	15'000	70 nm
^{40}Ar	18	40'000	128 nm
^{131}Xe	54	46'000	175 nm
NaI(Tl)	11,53	40'000	415 nm

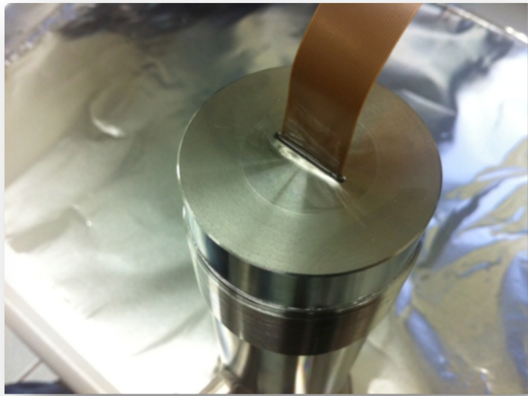
- 4.4 cm diameter x 47 cm sensitive length
- 180 bar ^4He sealed system maintaining gas purity

R. Chandra et al., 2012 JINST 7 C03035

SiPM and the proof of principle







- A short tube (19 cm) used for the proof of principle
- Filled with ^{4}He at 140 bar, an integrated wavelength shifter and two SiPMs mounted along the wall (by ARKTIS)
- Two SIPMs read-out through the Hamamatsu electronic board (C11206-0404FB)
- 2-channels 3-stage amplification with leading edge discrimination (SP5600A – CAEN)
- Digitizer with a sampling rate of 250 Ms/s 12 bit digitization (V720 – CAEN)

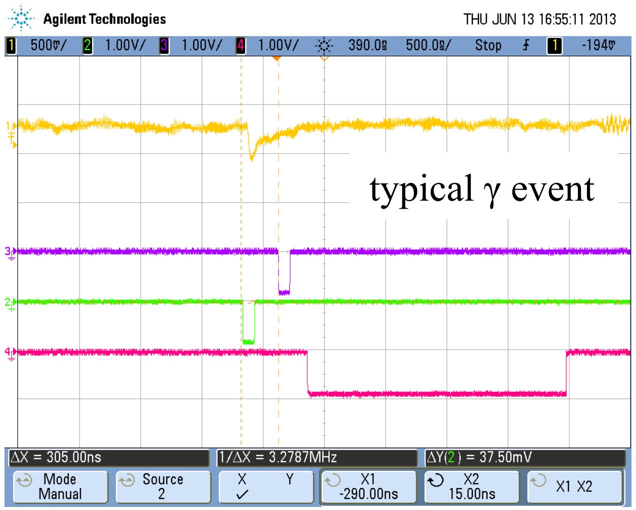
Counting measurements

Test performed measuring:

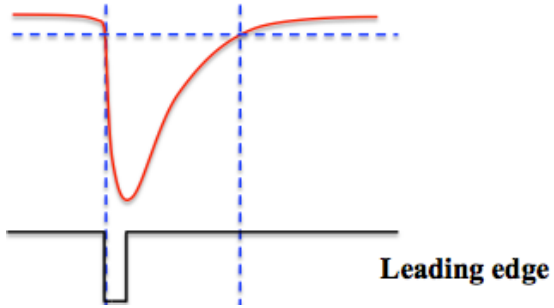
- Background, n and γ counting rate using ^{252}Cf and ^{60}Co source in contact

Two triggering scheme:

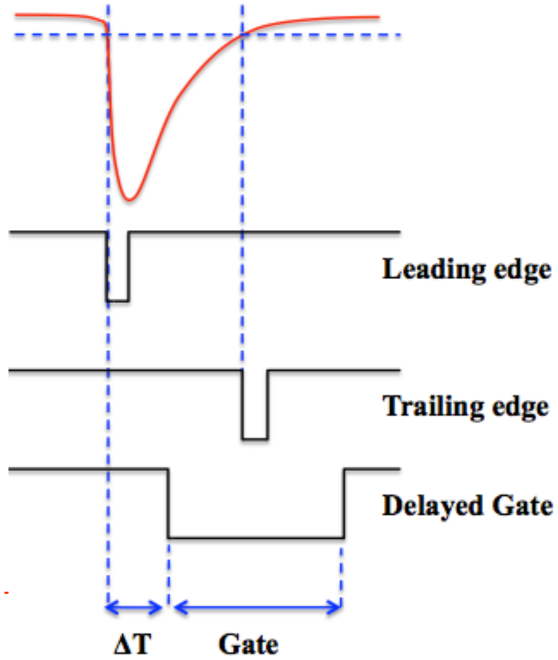
- Leading edge discrimination in coincidence
- Leading edge and delayed gate of each single SiPM in coincidence
  - Few parameters to be optimized:
    - Leading and trailing threshold
    - Delay time (ΔT)
    - Gate aperture



1st Trigger Scheme



2nd Trigger Scheme



SiPM counting measurements

Result for the different trigger scheme @ 28°C

Counting rate [Hz]	no source	^{60}Co in contact	^{252}Cf in contact
Leading edge discrimination (Ch0 ∩ Ch1) @31mV [Hz]	0.05	1.32	10.18
Delayed trigger, single detector [delay 700 ns, long gate 2 μs]	0.02	0.05	12.27
Delayed trigger, Ch0 ∩ Ch1	0.01	0.01	8.61

An amazing result, corresponding to a γ rejection power at the 10^6 level

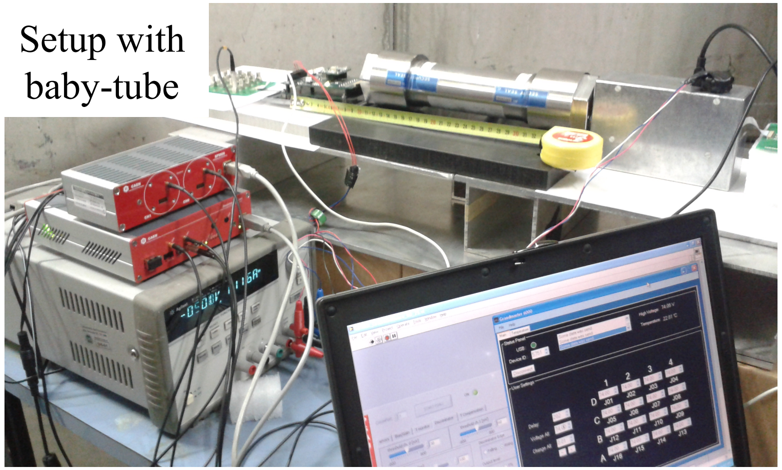
[10 counts in 1000s, for a number of γ given by acceptance*activity*time
$= 1/3 * 3 * 10^4 * 10^3 \sim 10^7$]

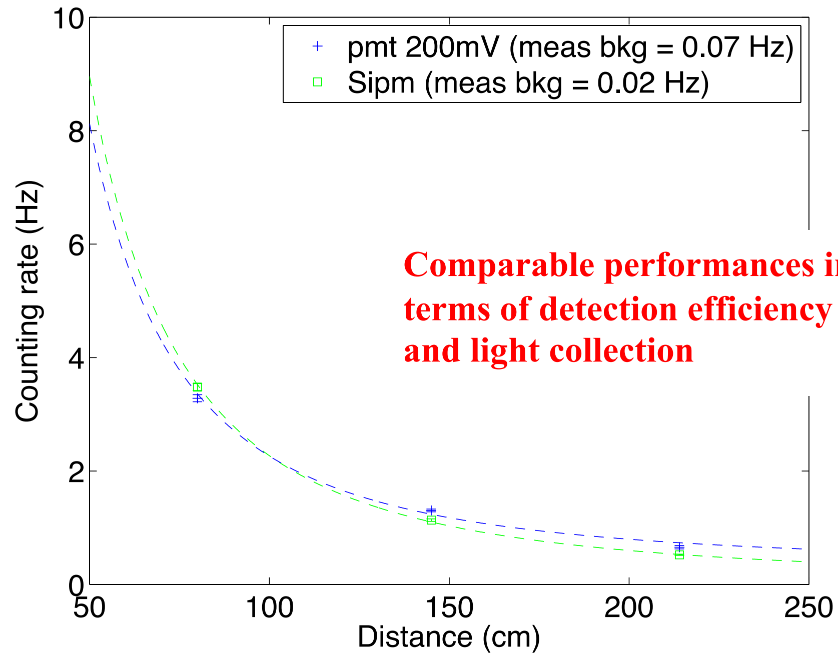
M. Caccia, R. Santoro et al. IEEE xplore, doi=10.1109/ANIMMA.2013.6727974 (2013)

SiPM VS PMT counting measurements

- Trigger: leading edge discrimination in coincidence among the 2 channels in the tube
  - Threshold set to have low bkg counting rate
  - No γ-rejection algorithm
  - Same strategy for both tubes
- The counting rate was measured at different distances from the ^{252}cf source

Setup with baby-tube



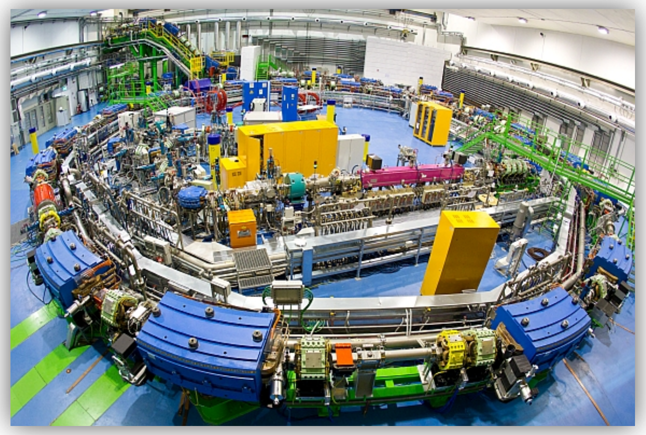


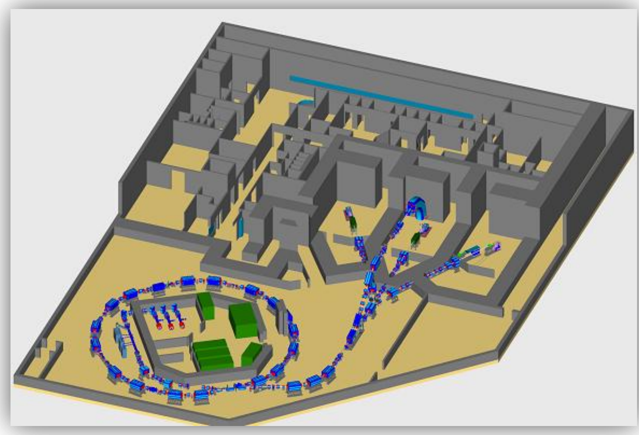
Comparable performances in terms of detection efficiency and light collection

SiPM for beam profilometry @ CNAO

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori

- Protons (250MeV) and carbon ions (4.8 GeV) beam
- Three treatments rooms

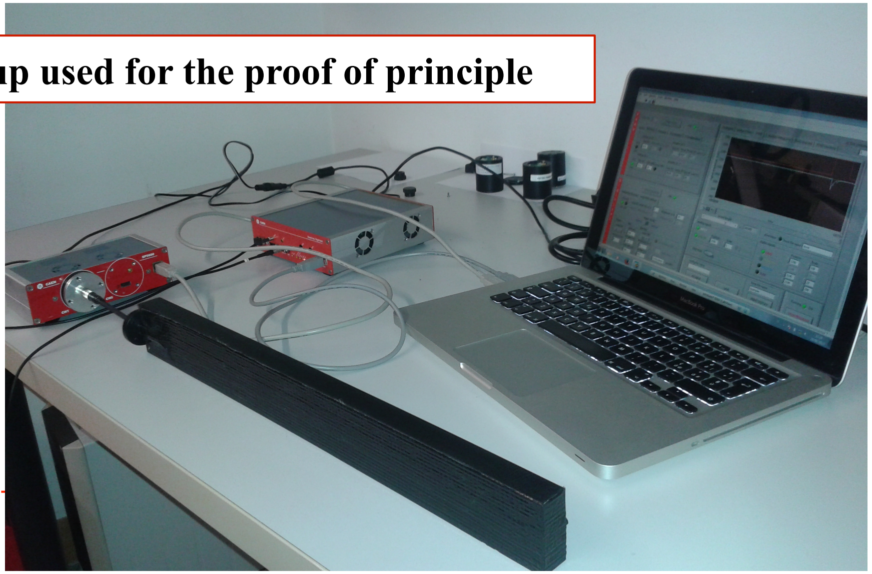




Measurement of the beam profile: wide dynamic range (≈ 4 order of magnitude)

- Scintillating fiber (d=1mm)
- SiPM (1x1mm^2)
- 1st stage amplification
- Digitizer for signal integration

Setup used for the proof of principle



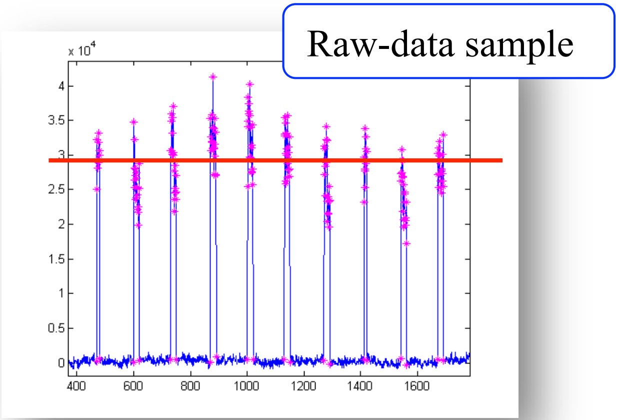
Beam profile

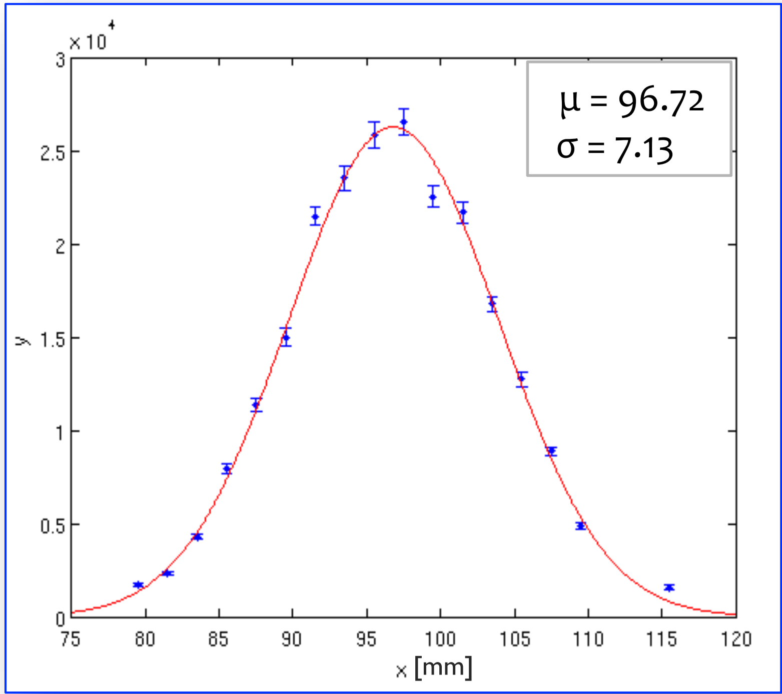
- Proton beam @ 117 MeV
- Intensity ≈ $2*10^8$ / spill (1 sec long)
- duty cycle = 20%

Proof of principle

Two methods investigated:

1. Integration mode:
   asynchronous long (≈ ms) integration windows





σ and linearity are compatible with the ones measured with the film technique

Beam profile

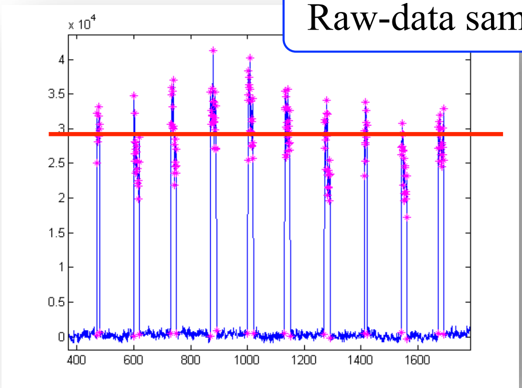
- Proton beam @ 117 MeV
- Intensity ≈ $2*10^8$ / spill (1 sec long)
- duty cycle = 20%

Proof of principle

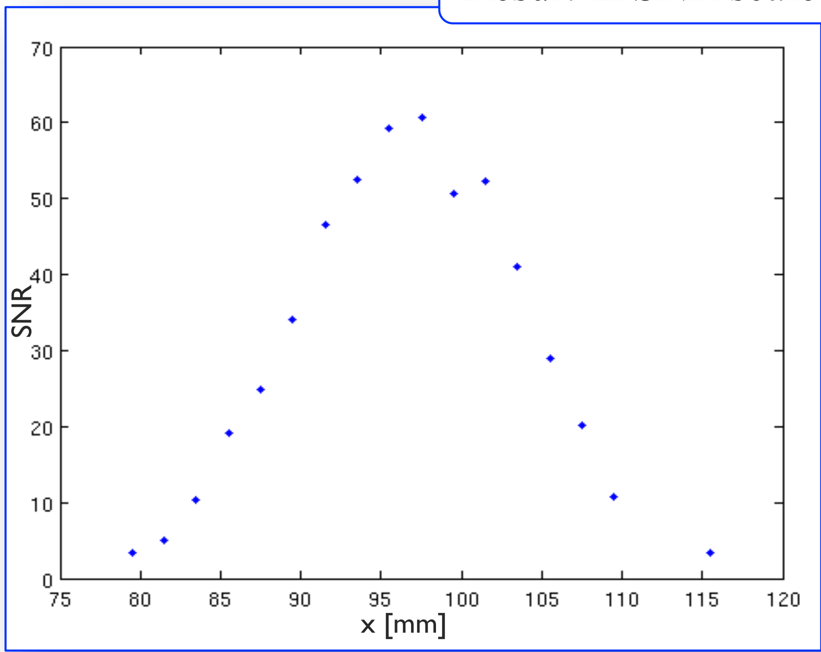
Two methods investigated:

1. Integration mode:
   asynchronous long (≈ ms) integration windows

Raw-data sample



Result in SNR scale



Not enough dinamic range!

Beam profile

- Proton beam @ 117 MeV
- Intensity ≈ $2*10^8$ / spill (1 sec long)
- duty cycle = 20%

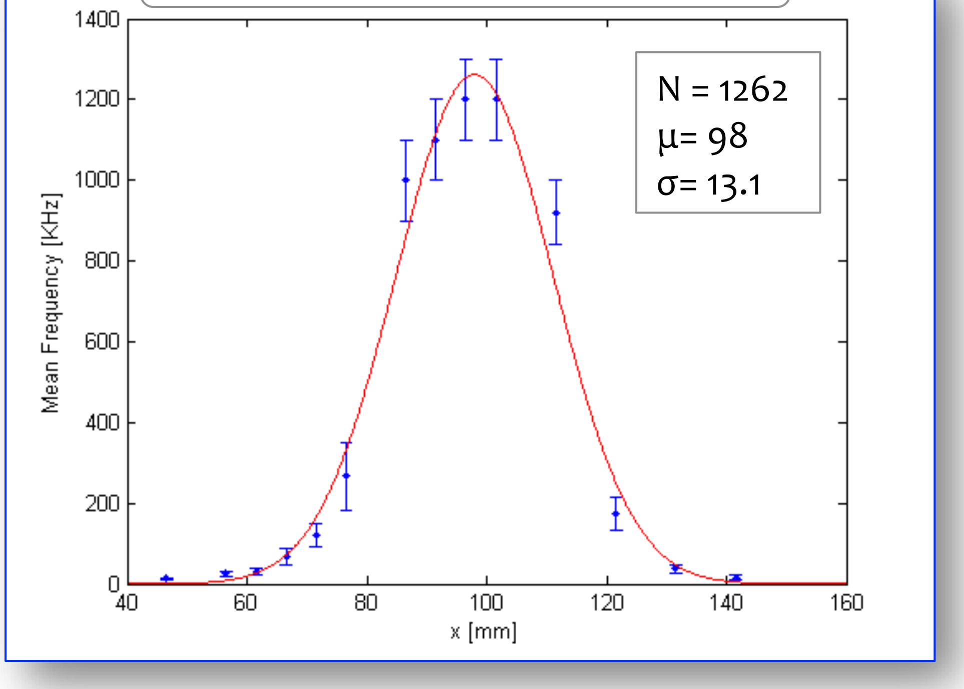
Proof of principle

Two methods investigated:

2. Counting mode:
   Leading-edge discrimination,
   Threshold set to have DCR @ Hz level

If were are not saturating we get more than 4 orders of magnitude

Different beam energy and intensity!



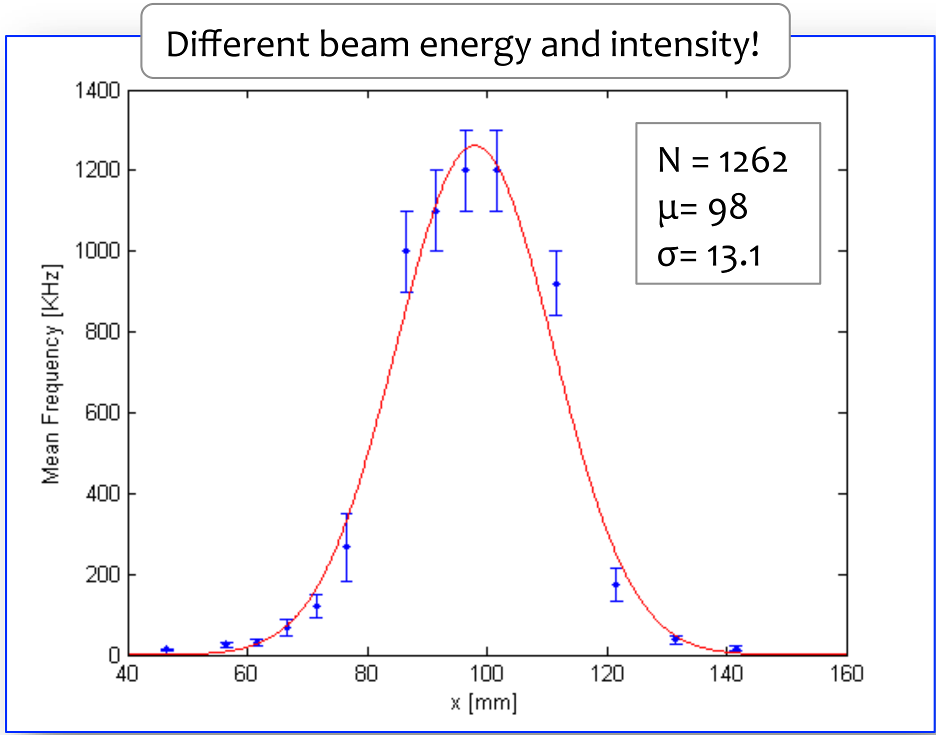
Beam profile

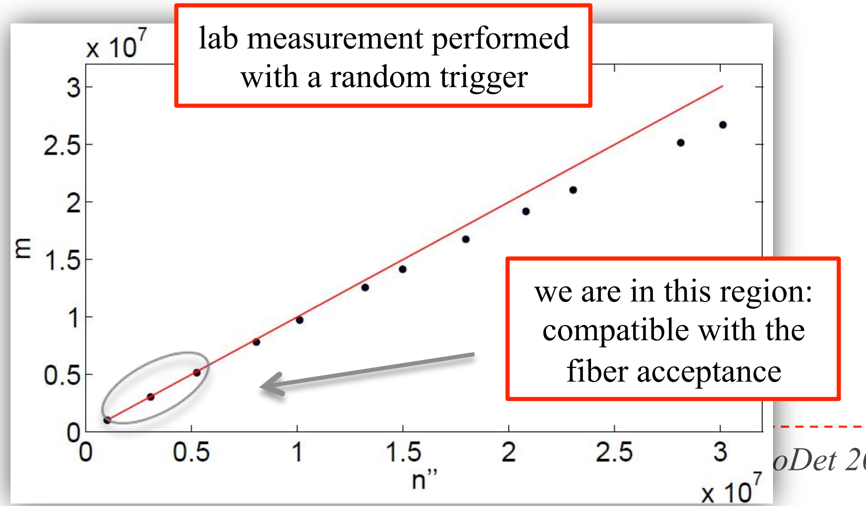
- Proton beam @ 117 MeV
- Intensity ≈ $2*10^8$ / spill (1 sec long)
- duty cycle = 20%

Proof of principle

Two methods investigated:

2. Counting mode:
   Leading-edge discrimination,
   Threshold set to have DCR @ Hz level





Few personal considerations …

- There is a growing interest for this new class of detector both in scientific & industrial communities
- A good requirements definition and a deep knowledge of the detector characteristics could make the difference when exploring for new applications
- Some times a simple and flexible setup plus a fast simulation may help in identifying the way to go