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

Romualdo Santoro
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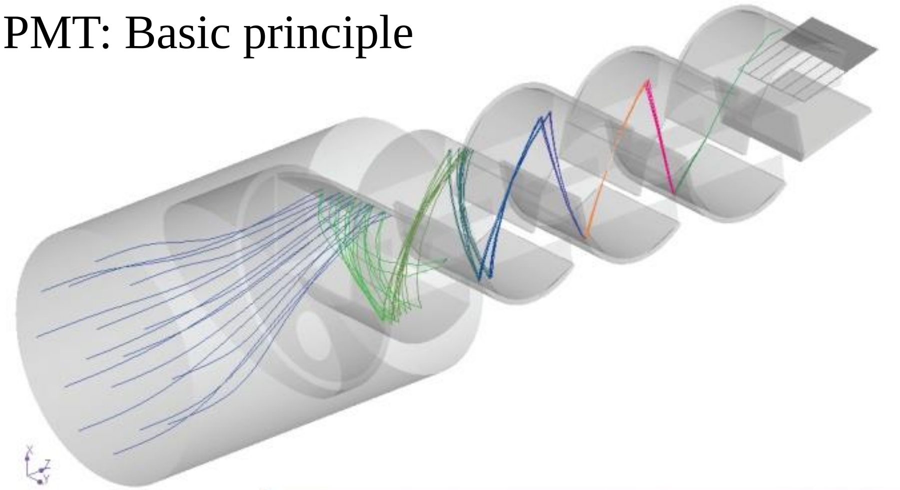
Photon detectors: PMT

PMT: Basic principle

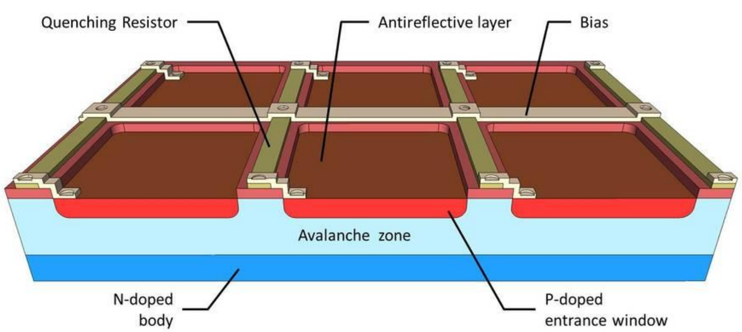


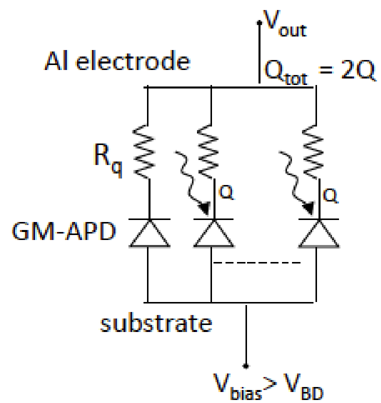
- Quite mature and robust technology
- Wide range of products with different characteristics for all the needs
- A series of parameters to be considered while choosing the proper device
  - Quantum Efficiency
  - Photoelectron Collection Efficiency
  - Gain
  - Excess Noise Factor
  - Energy Resolution
- … and a well consolidated bibliography form measurements and methods

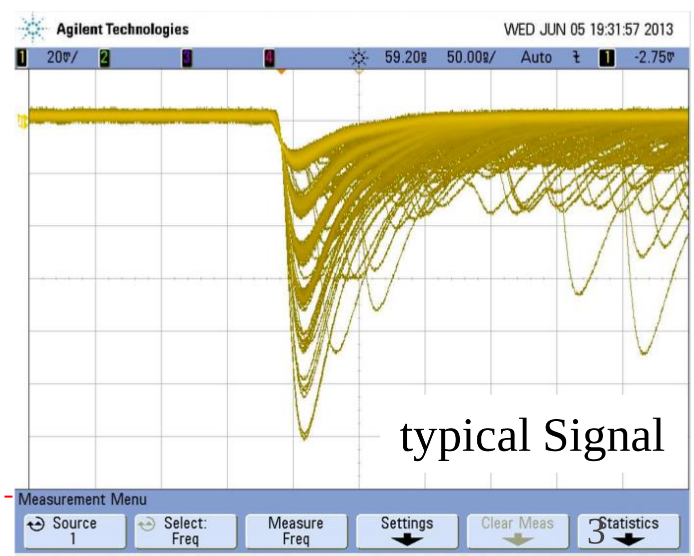
Photons detectors: SiPM

- 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







typical Signal

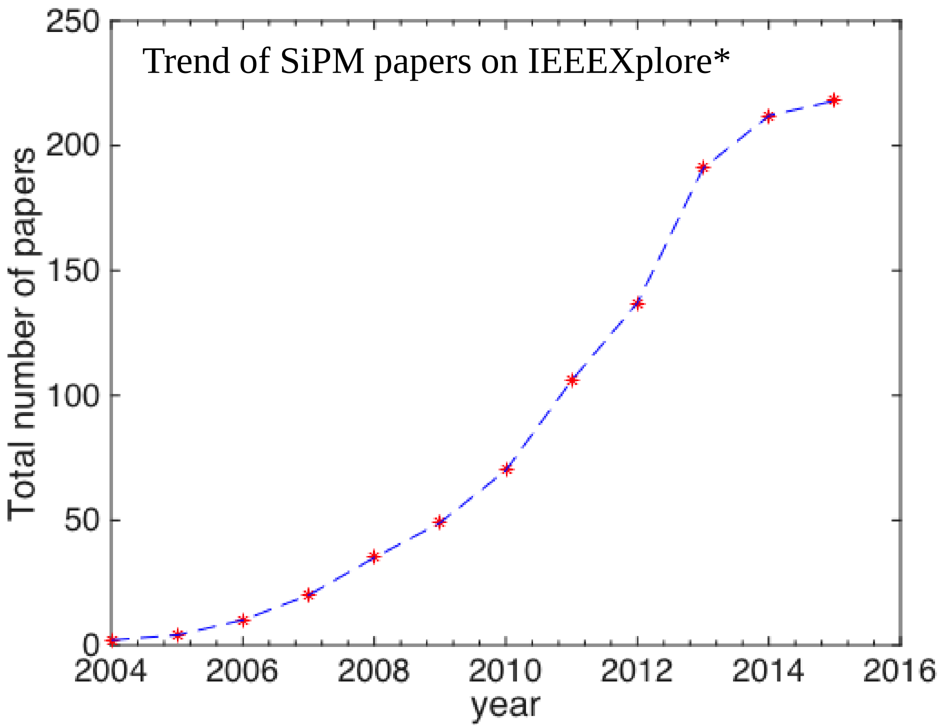
Why SiPMs are so appealing?

- High detection efficiency (single photo-electron discrimination)
- Compact and robust
- Low operating voltage and power consumption
- Low cost
- Withstanding to magnetic field

… and in fact…. they are starting to be widely used in different fields i.e. medical applications, homeland security, spectrometry, high energy physics …

As of today…

… a clearly growing interest in scientific & industrial communities, where the first is pushing for requirements and characterization methodology while the second for a better technology



* number of papers with "Silicon Photomultiplier" in the abstract or Title, tracked by IEEEXplore

List of producers

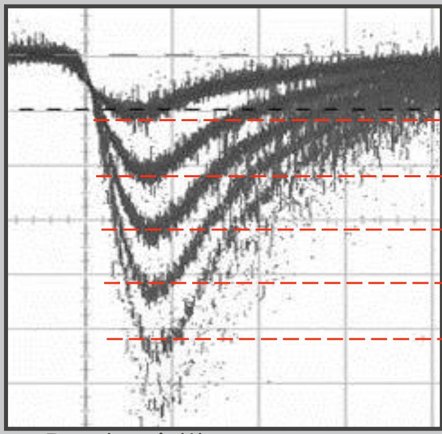
- AdvanSid
- CPTA-Advatech
- CSEM
- Excelitas
- E2V
- Ketek
- HAMAMATSU
- PHILIPS Digital Counting
- PULSAR
- SENSL
- STm
- ZEKOTEK

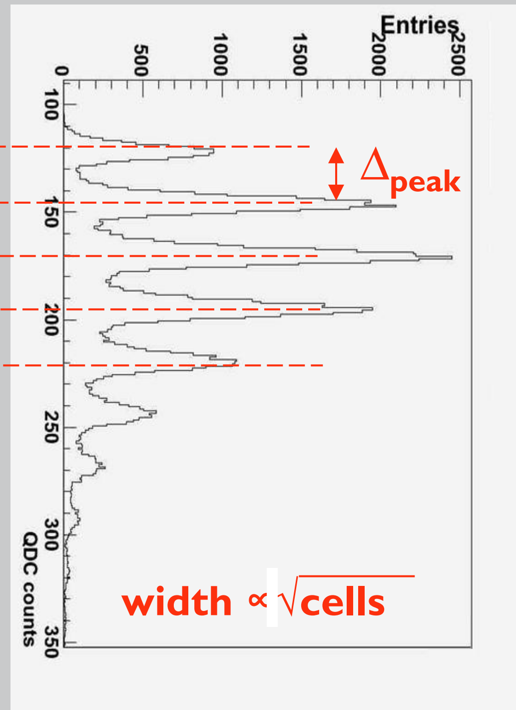
A typical characterization protocol

- ***I-V measurements*** (leakage current, quenching resistor, breakdown voltage)
- ***Noise measurements*** (vs over voltage and vs temperature):
  - dark counting rate (DCR) vs bias voltage
  - optical cross-talk (DCR vs threshold)
  - afterpulse
- ***Analysis of*** (Poissonian photon) ***spectrum*** (vs temperature)
  - resolution power (how many photons can I distinguish?) & gain
  - working point optimization (at low and large flux)
  - noise measurement (not DCR; essentially system noise and cell-to-cell variations)
  - optical cross-talk (deviations from the Poissonian distribution)
- ***linearity*** & ***dynamic range***
- ***Spectral response*** (PDE vs λ, PDE vs temperature)
- **timing properties** and time resolution (currently O(100ps))

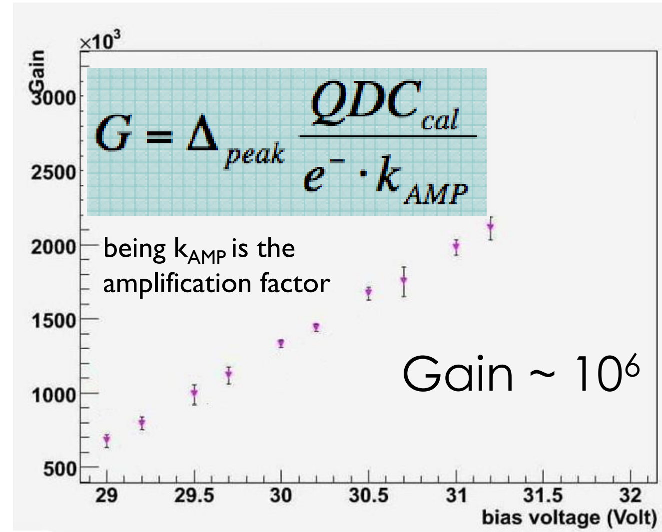
Photon Spectrum & Gain

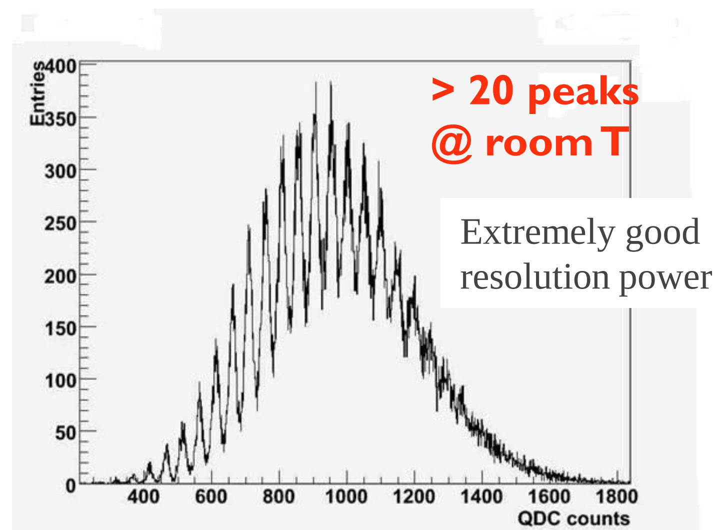
Light source: CAEN ultra-fast LED (**SP5601**) OR Pico Quant PDL 800 - light at ~ 510 nm (green)





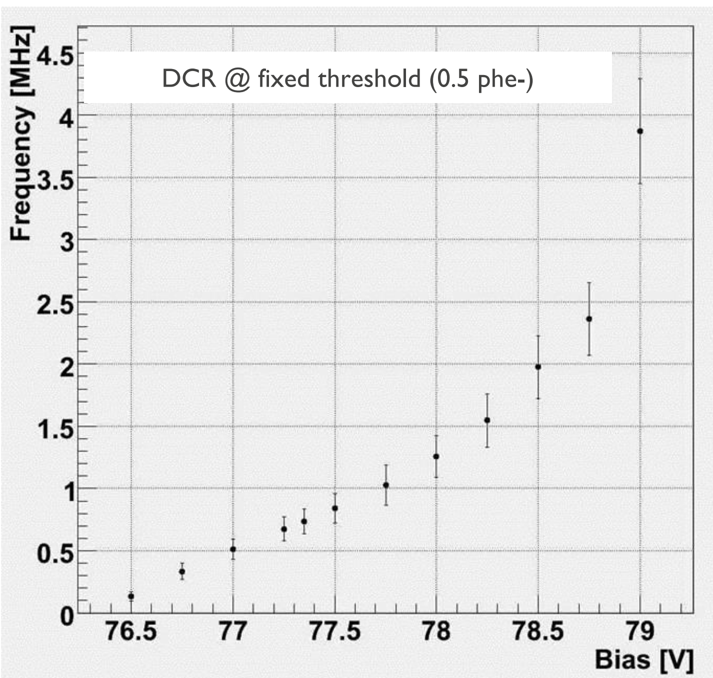
- Peak width:
  - System noise
  - Cell-to-cell gain variation (process uncertainties)
  - I_{leak} fluctuations
  - Spurious hits in the QDC integration time

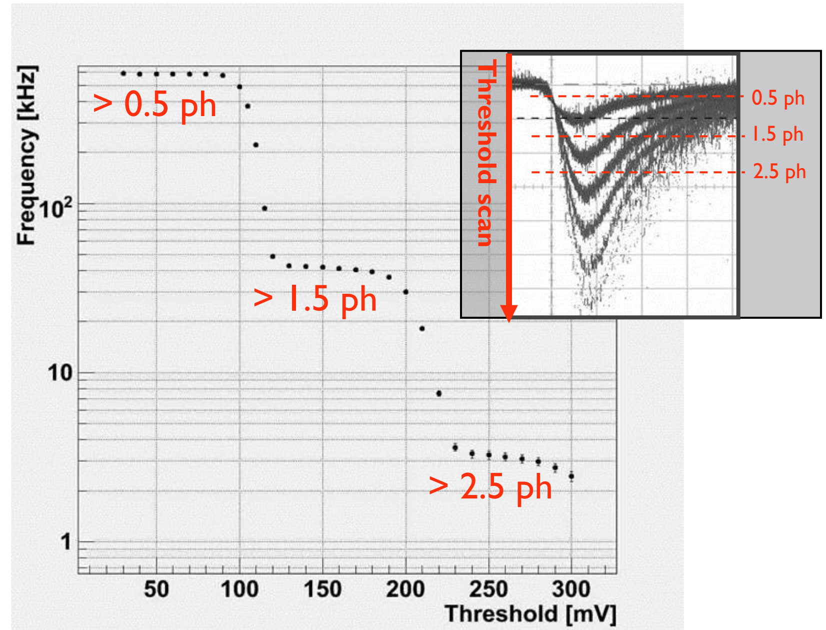




Dark Count Rate & Xtalk

The **D**ark **C**ounts (DCR) measure the rate at which a Geiger avalanche is randomly initiated by thermal emission.



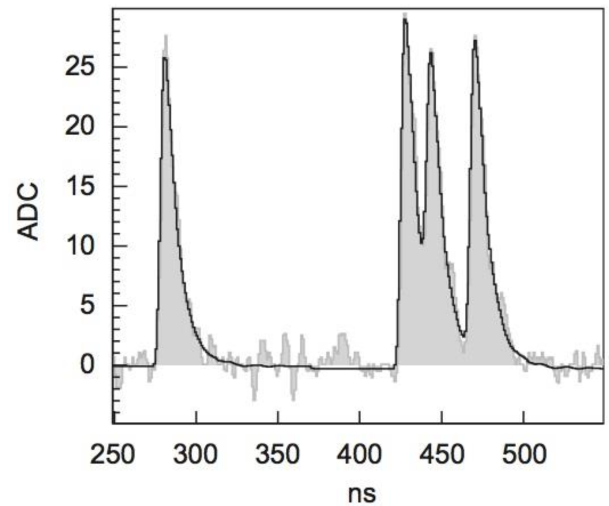


an avalanche generation can fire another cell with a photon; measuring the DCR for different thresholds is possible to define and evaluate the **Optical Cross talk** as:

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

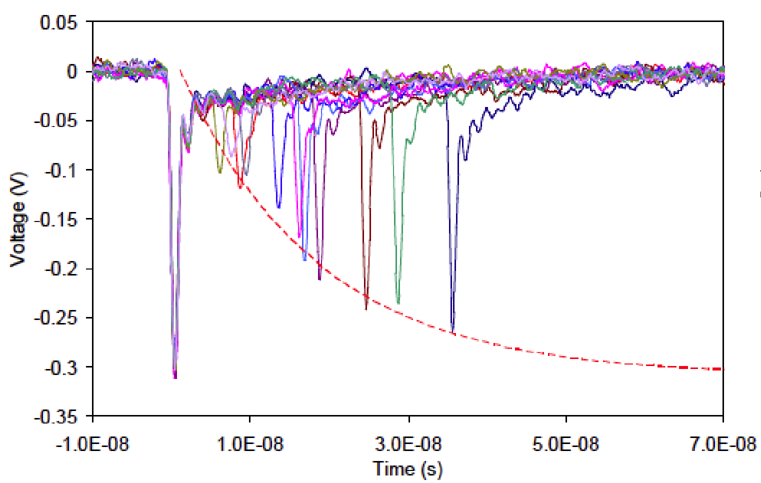
After Pulse

It is a delayed avalanches triggered by the release of a charge carrier that has been produced in the original avalanche and has been trapped on an impurity



Output of a HAMA MPPC 11-50, digitized by a CAEN V1729 waveform digitizer, as reported by Y. Du, F. Retiere (NIM A 596 (2008) 396–401)

A quantification of the effect essentially proceeds through an analysis of the pulses time structure, expected to be Poissonian without the after pulse phenomenon:



After Pulses measured on the same pixel v.s. time
The exponential recovery time is clearly shown
(C.Piemonte)

After Pulse

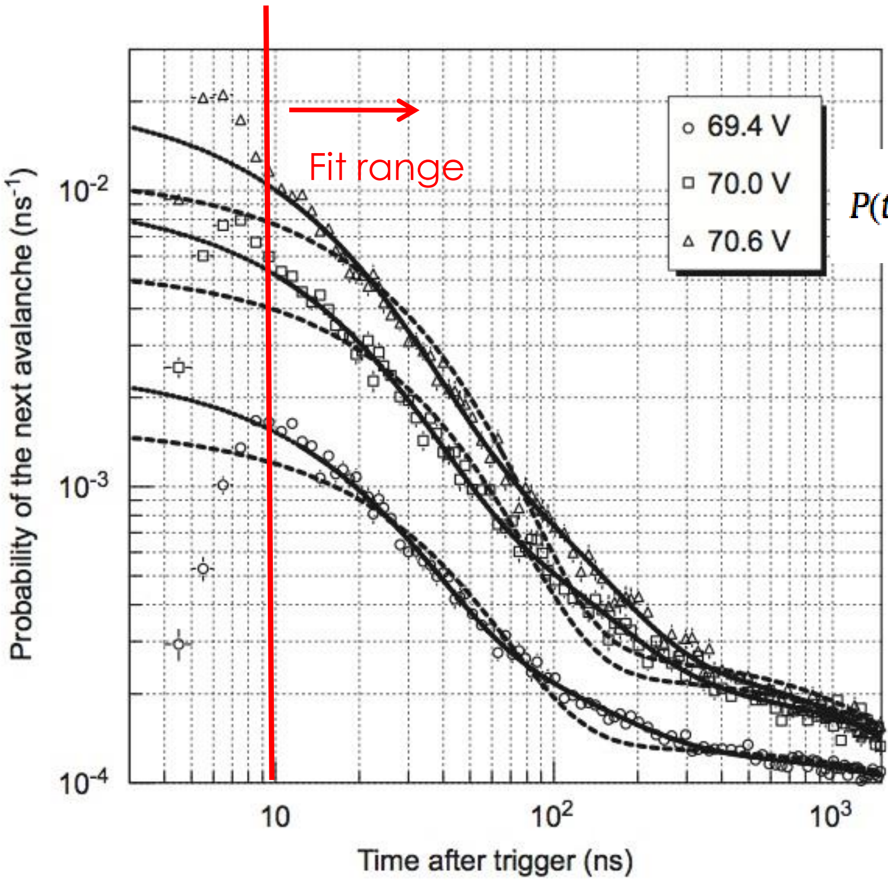


Fig. 4. Timing distribution of the first pulse following the trigger. The dotted lines are fits with a single after-pulsing time constant, while the solid lines included two time constants. The dashed lines show the two exponential function behaviors beyond the fit range.

What is plotted on the Y axis is:

$$P(t) = \int_0^t [1 - P_{AP}(x)]\, dx P_{DN}(t) + \int_0^t [1 - P_{DN}(x)] \times dx P_{AP}(t).$$

Where:

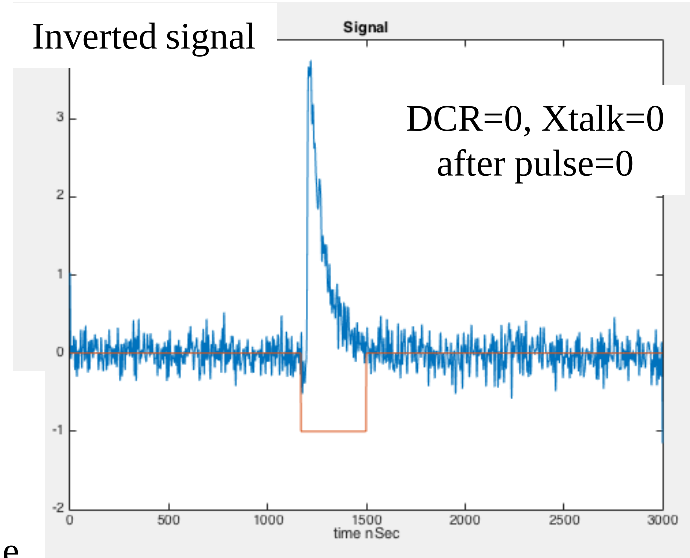
$$P_{AP}(t) = \sum_{i=1}^{\infty} \frac{\lambda^i}{i!} e^{-\lambda} \frac{i}{\tau} e^{-t \cdot i/\tau}$$

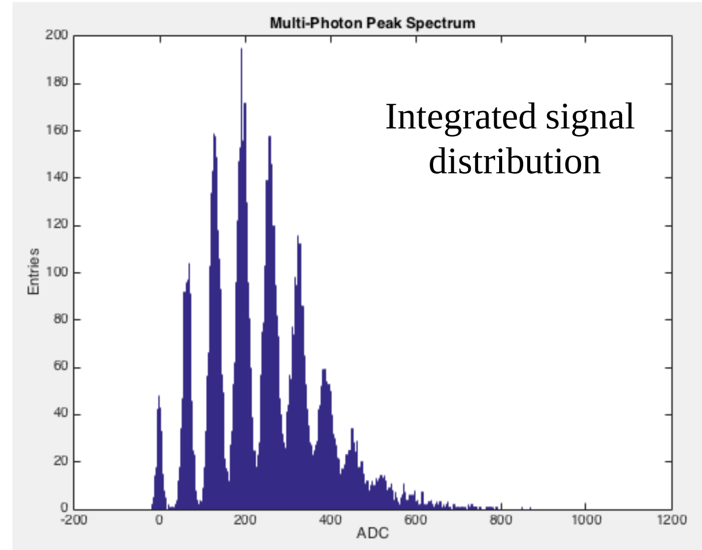
$$P_{DN}(t) = Re^{-Rt}$$

Are the After Pulse and Dark Noise probabilities

Y. Du, F. Retiere (NIM A 596 (2008) 396–401)

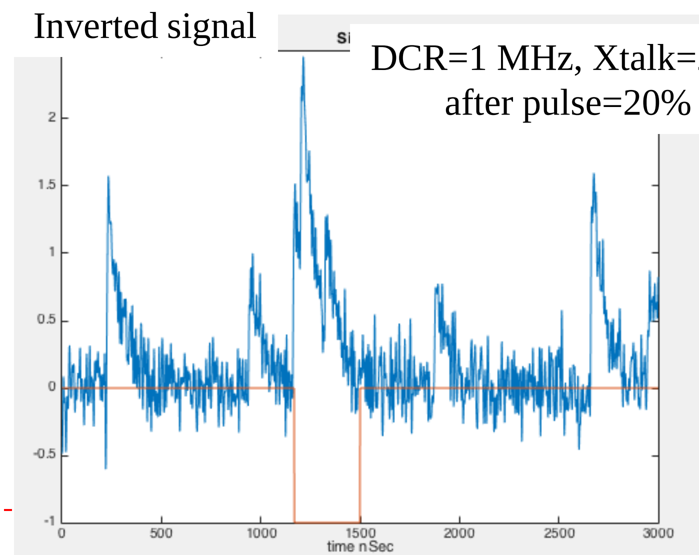
Simulated Signal

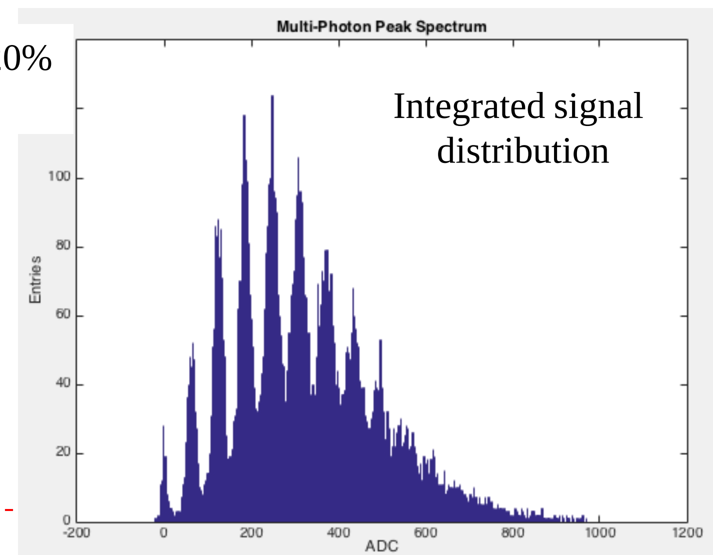




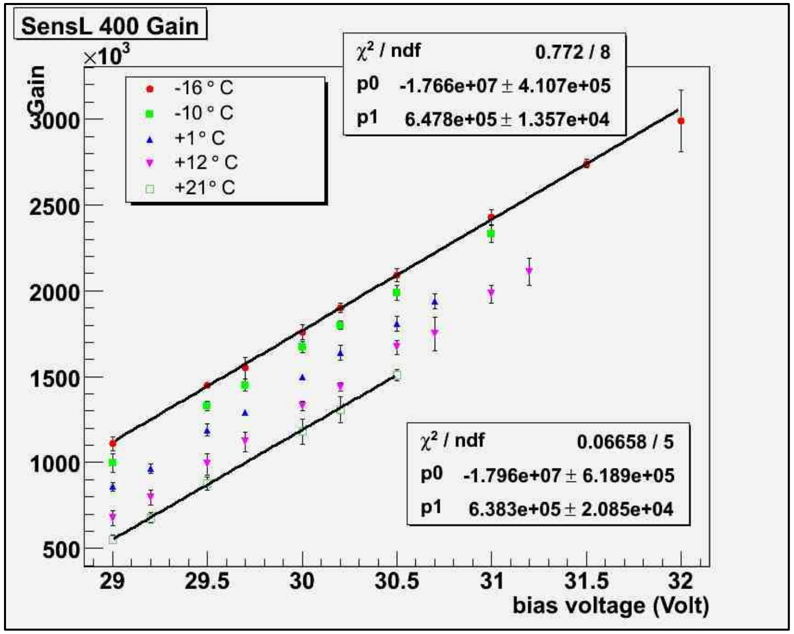
Toy settings:

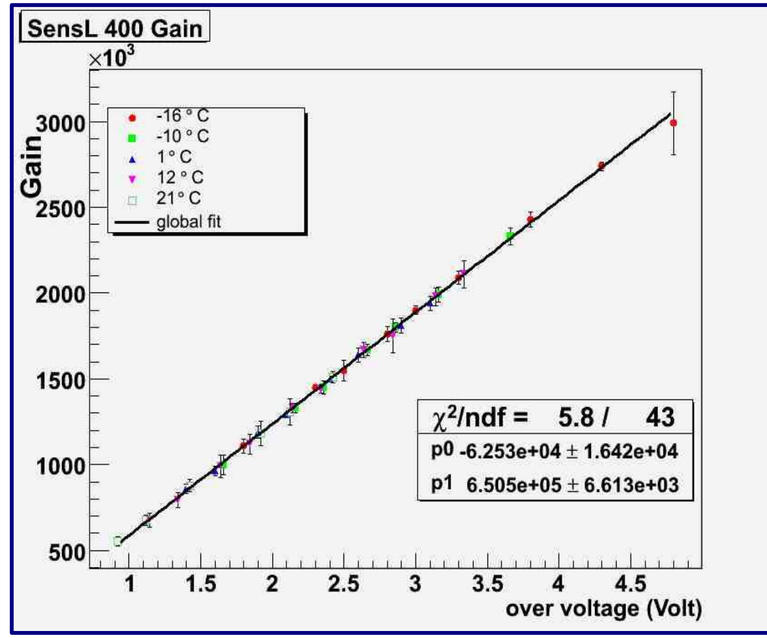
- SNR=10
- Tau=70nSec
- CellToCell = 0.1 phe
- sampling 1 nSec
- gate =320nSec





Gain temperature variations





$$\frac{dV}{dT} = -\frac{dG}{dT}\frac{1}{\frac{dG}{dV}}$$

$$V_{BD} = \frac{dV}{dT}\left(T - T_{RT}\right) + V_{RT}$$

Breakdown Voltage rescaled accounting for temperature variation

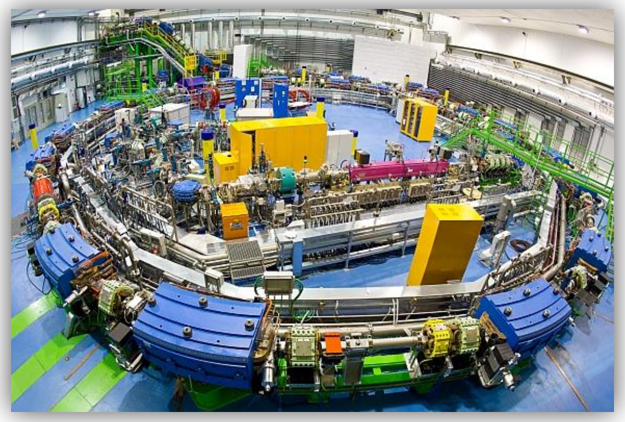
M. Ramilli: IEEE NSS Conf. (2008), pp. 2467

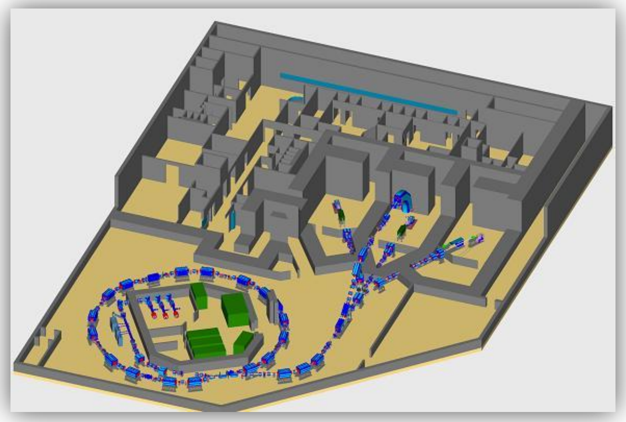
What can be done with such a device?

Beam profile at 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

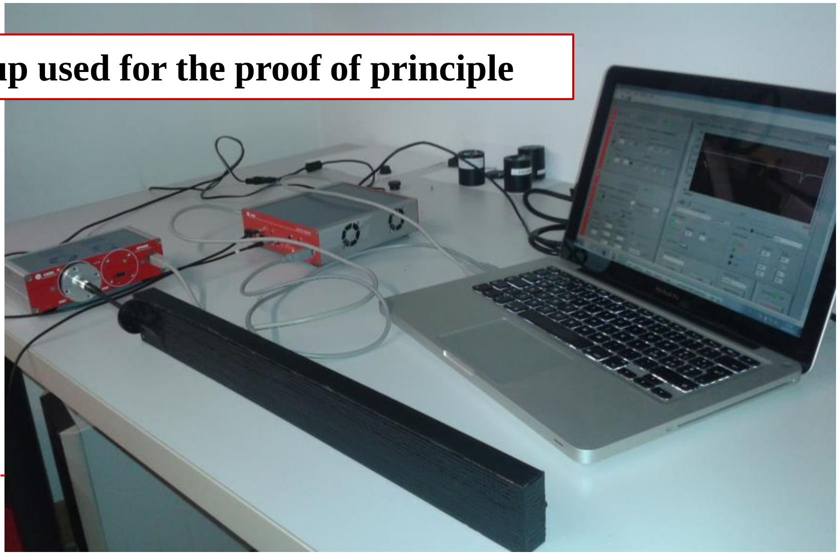




Measurement of the beam profile: wide dynamic range (≈ 4 order of magnitude)

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

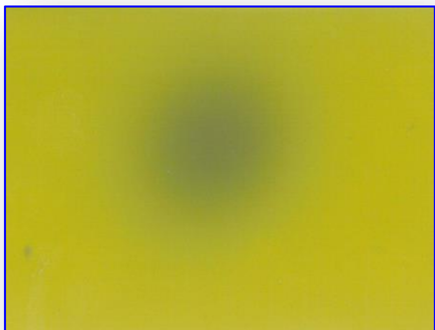
Setup used for the proof of principle

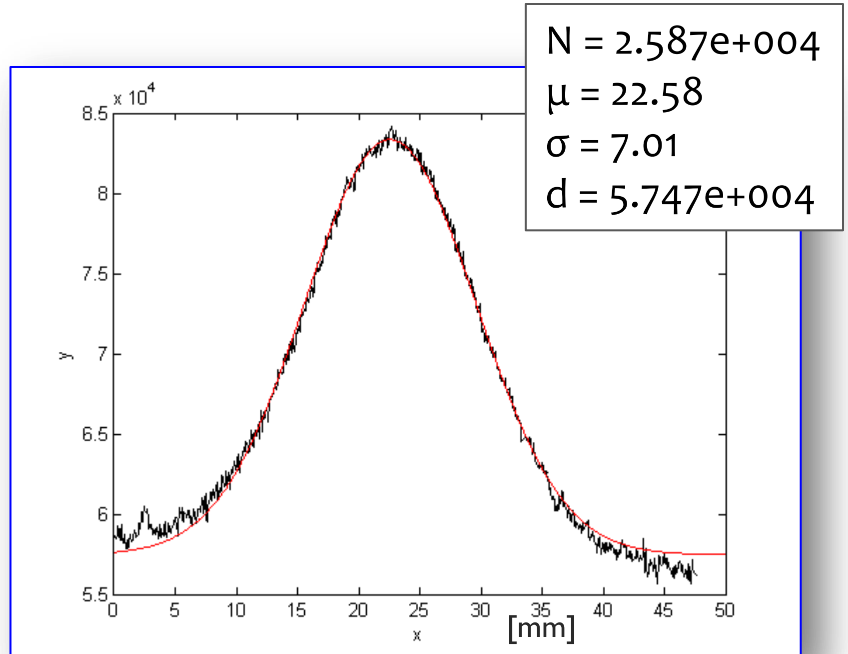


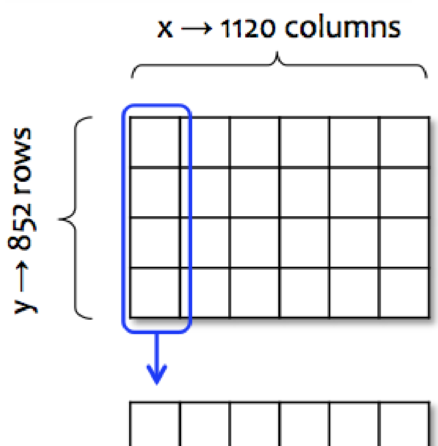
Beam Image

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

Film image digitized







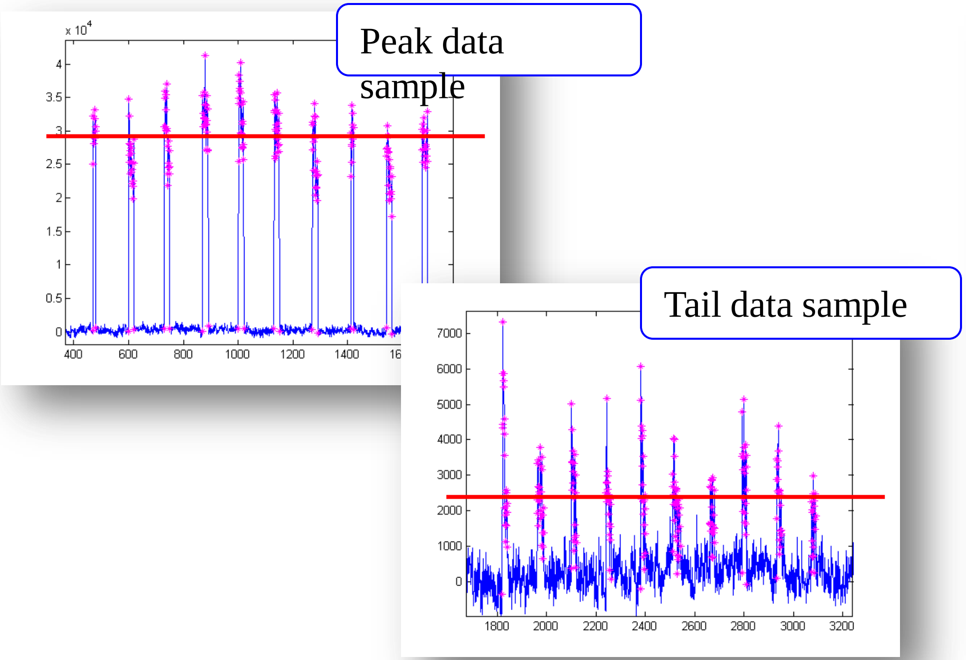
Horizontal projection of the red component

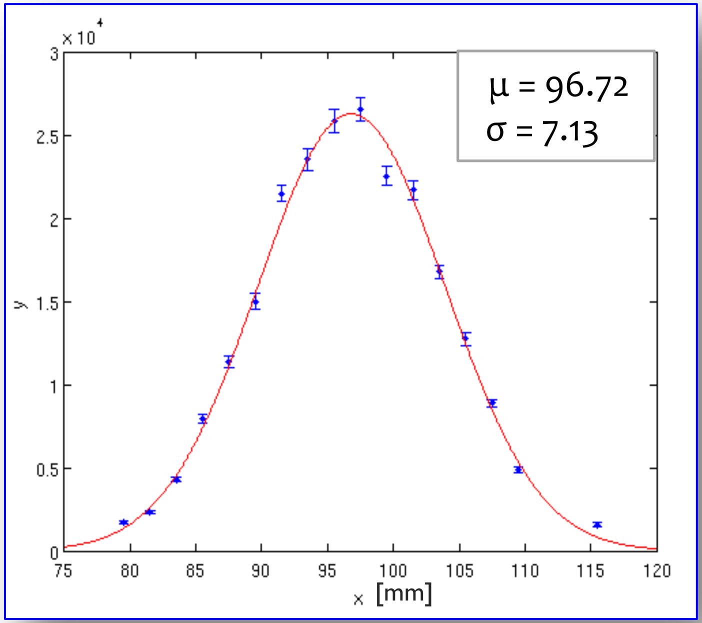
- Profile is estimated as the sum along the y (To be compared with the SiPM method)
- The fit is done with gauss + const

Beam profile: integration mode

The procedure

- Baseline estimation: mean and std with the first 300 points
- Baseline subtraction + smoothing (3 points moving average)
- Identify the the first and last point for each peak
- The mean value in all the spills is used for the beam profile

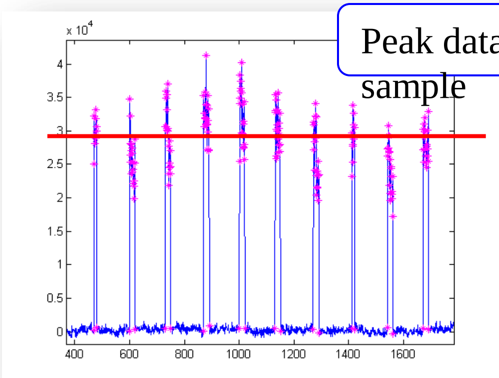




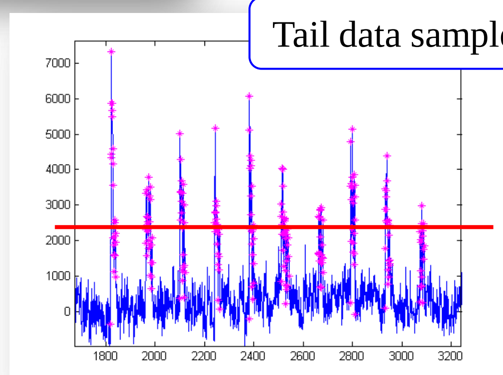
Beam profile: integration mode

Sensitivity

- Beam profile in SNR unit: from 3 (tail) to 60 (peak)

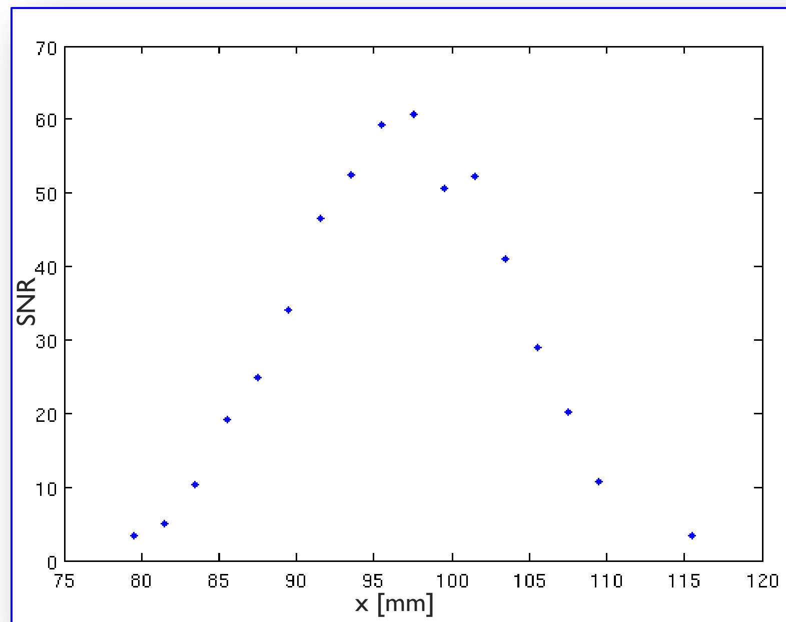


Peak data sample



Tail data sample

$$\frac{\textbf{Mean} \text{ of every value above threshold}}{\sigma \text{ background}}$$



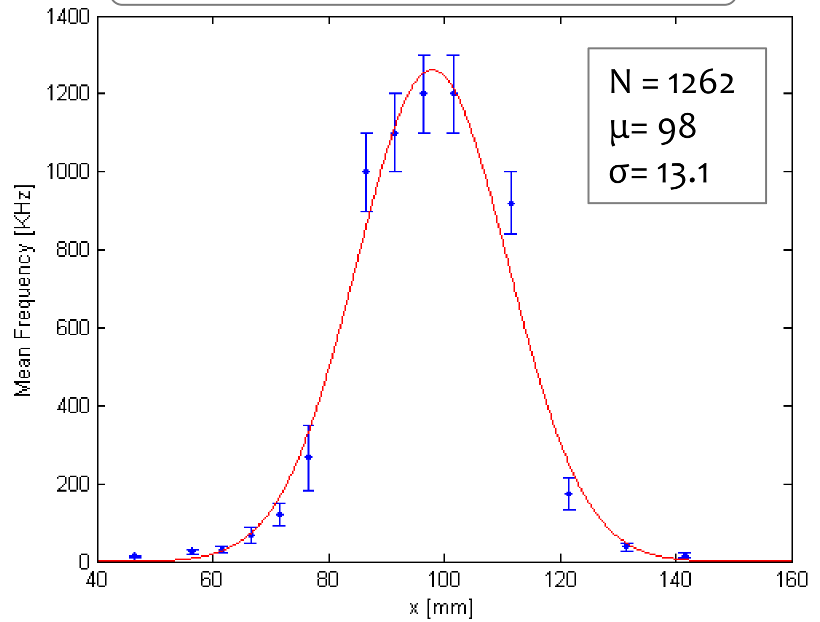
Beam profile: counting mode

The procedure

- Leading-edge discriminations with ad-hoc threshold
  - Dark count at Hz level
- Mean value an standard deviation over different points in the spill

Position [mm]	Mean Frequency [KHz]	Std Frequency [KHz]
46,54	12,7	2,1
56,54	25	7,7
61,54	29,4	8,7
66,54	67,9	21,4
71,54	121	27,4
76,54	266,3	84,6
86,54	1000	100
91,53	1100	100
96,52	1200	100
101,52	1200	100
111,54	919,6	79,9
121,54	174,6	40,7
131,54	37,9	10,4
141,55	16,1	4,4

Different beam energy and intensity!

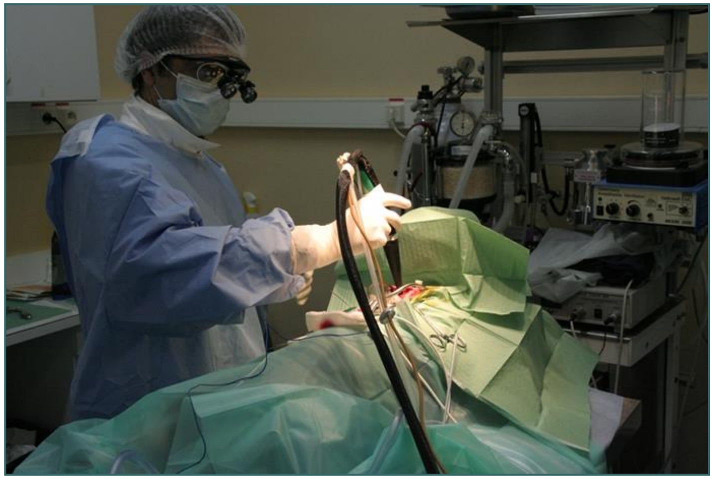


we get the 4 orders of magnitude

Development of Intra-operative Beta Probes

- N. Hudin, NDIP 2011
- F Bogalhas et al., Phys. Med. Biol. 54 (2009) 4439–4453

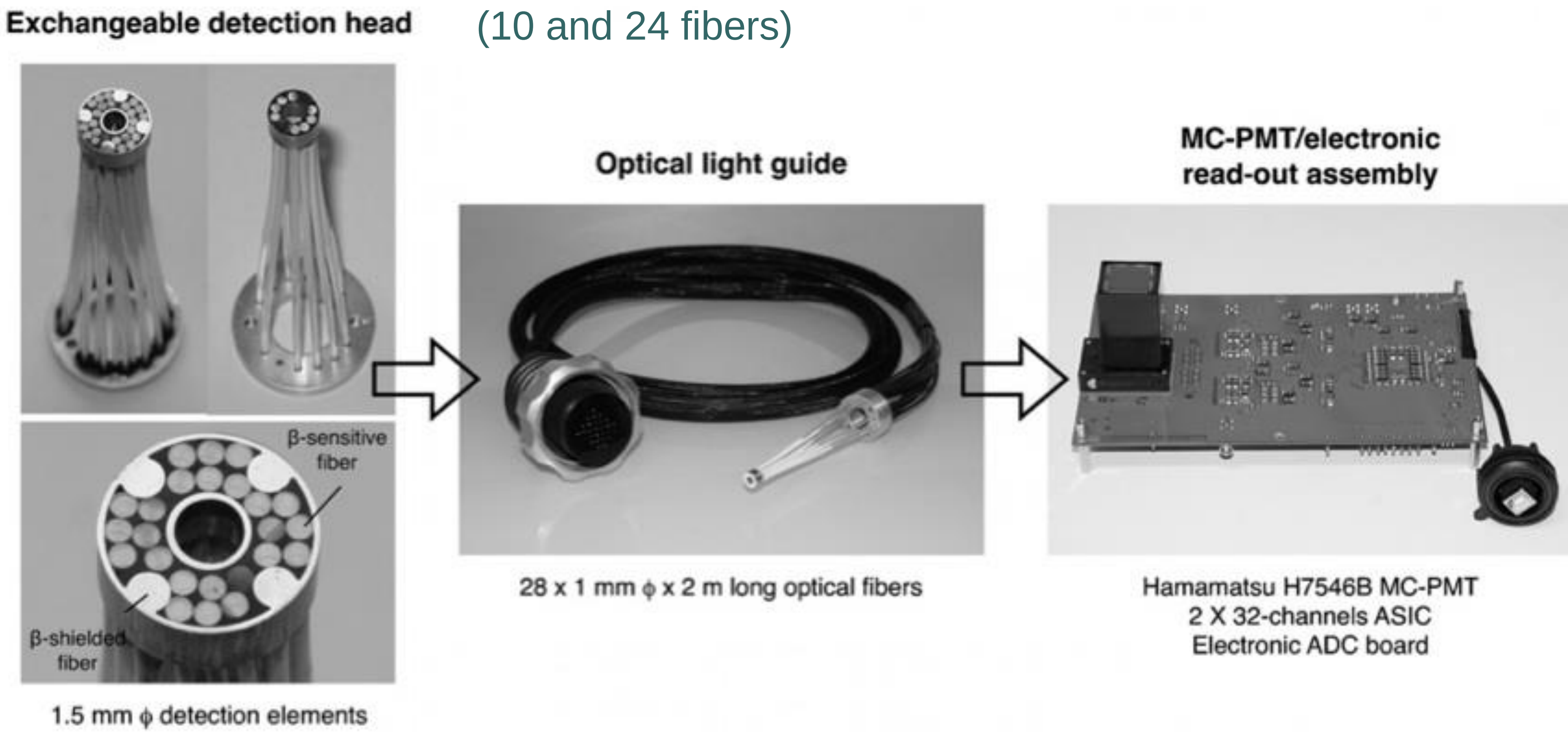
The precise localization and complete surgical excision of tumors are one of the most important procedures in the treatment of cancer. In that context, the goal is to develop new intra-operative probes to help surgeons to detect malignant tissues previously labeled with beta-emitting radiotracers.



A first prototype was designed and constructed using multi-anode PMT; now, the use of SiPM is being pioneered.

the MA-PMT based probe

(10 and 24 fibers)



Main result on the MA-PMT based probe

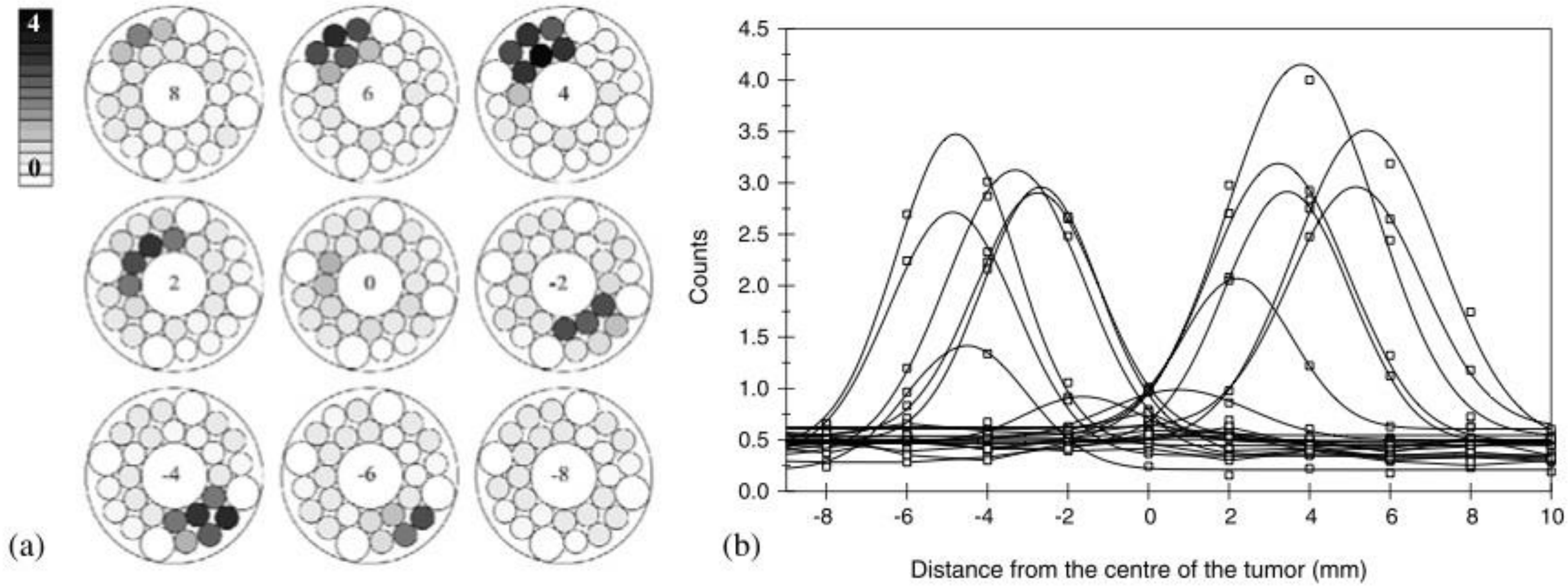
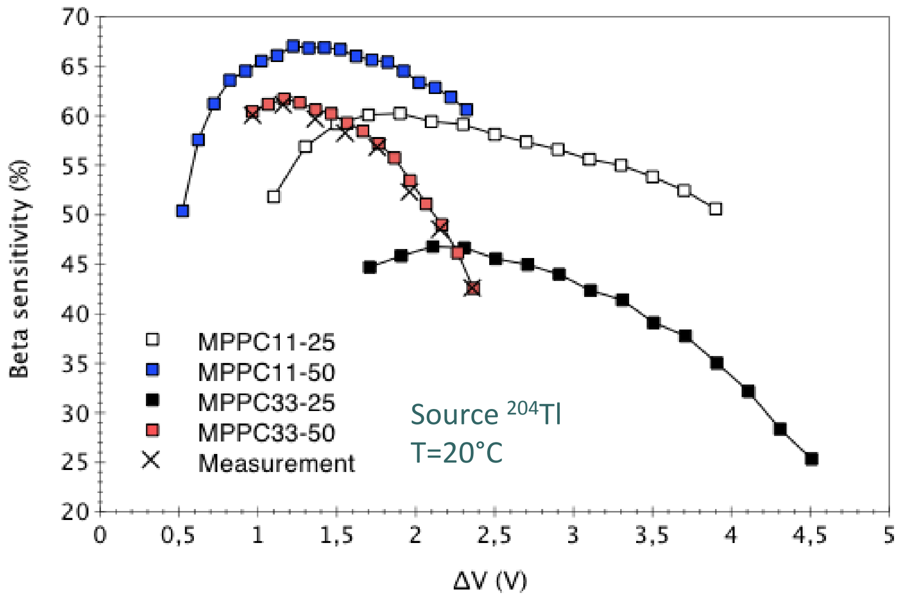
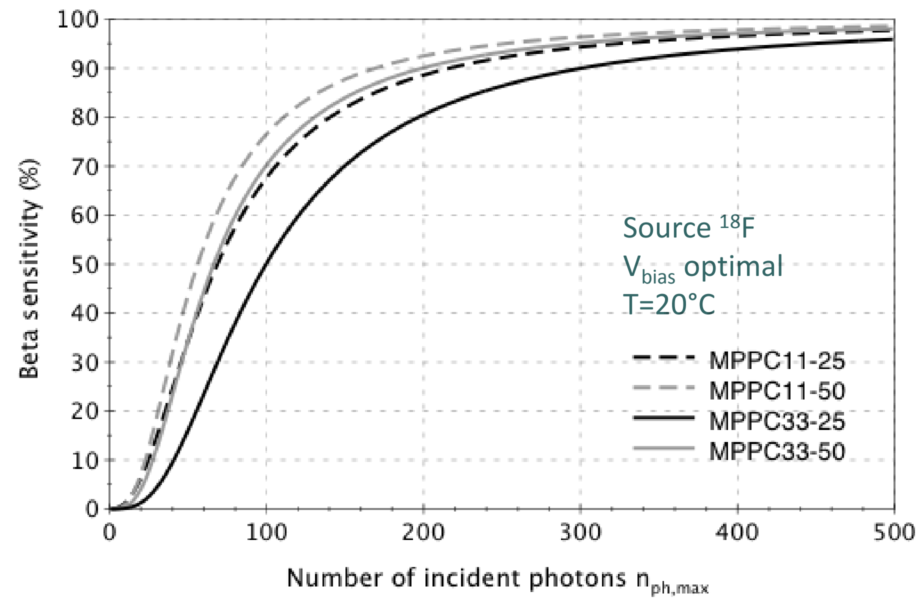


Figure 6. Image sequence (a) and count profiles (b) measured as the probe (large detection head) was used in 2 mm scanning steps over the 5 mm diameter tumour disc (an uptake ratio of 8:1).

The radiotracer concentration in the brain phantom and the normal region was set to 34 kBq ml^{-1} and the concentration in the tumour discs was scaled to achieve the corresponding uptake ratio (58.5 kBq ml^{-1}, 106 kBq ml-1, and 280 kBq ml^{-1}).

Preliminary result of a fiber+SiPM (MMPC) based element





- Very good agreement between the measured and modeled beta sensitivity
- Optimal ΔV depends on the features of the SiPM device but is independent on T and $n_{ph,max}$
- The sensitivity drops as the Over-voltage increases since the thresholds to keep the noise constant has to be raised (noise level 1 Hz!)

- Minimal $n_{ph,max}$ value to reach a beta sensitivity of 90% ranges from 170 for different sensors
- MPPC33-50 appears as the best compromise between sensitivity and light collection efficiency

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

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Revenue Irish Tax & Customs

Narodowe Centrum Badań Jądrowych Świerk

University of Liverpool

arktis Radiation Detectors

CAEN Tools for discovery

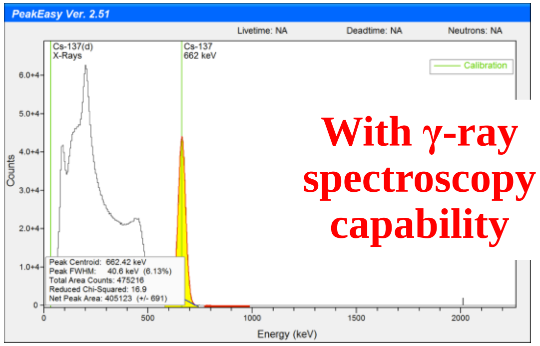
Two main Goals

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

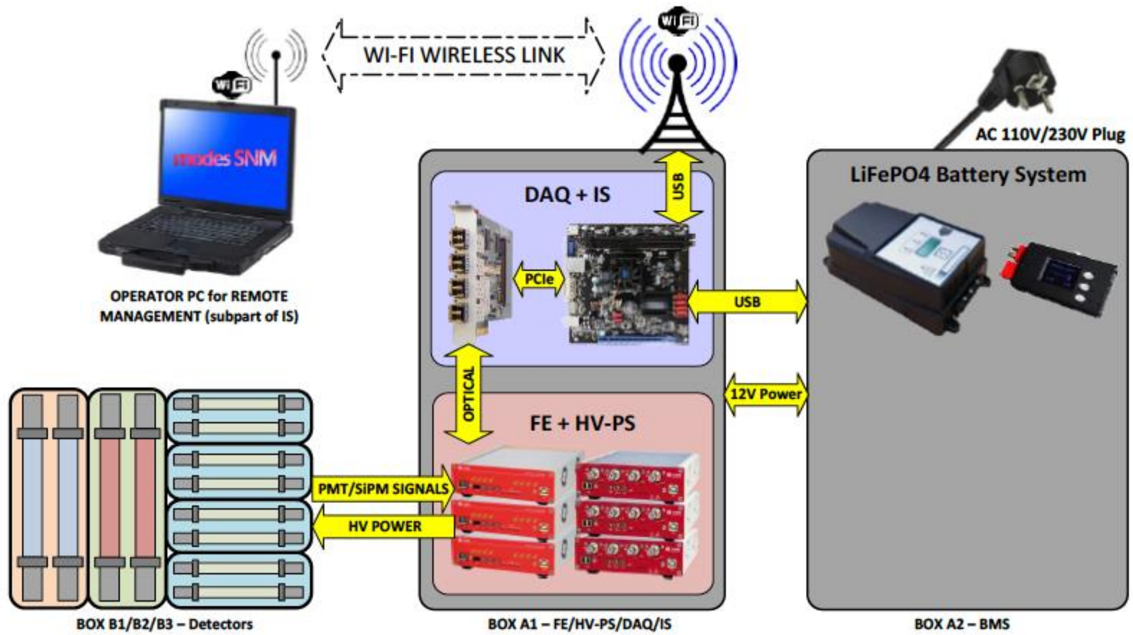
Available on the market: http://www.arktis-detectors.com/products/security-solutions/

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:

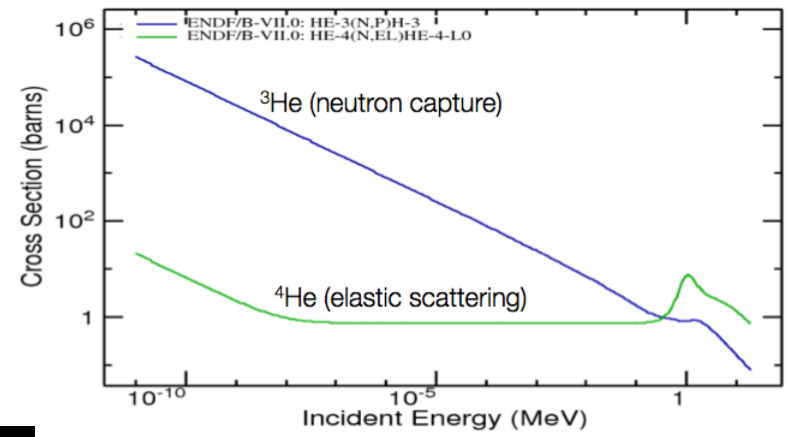
- Fast neutron (^4He)
- Thermal neutron (^4He with Li converter)
- Gamma (Xe)

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

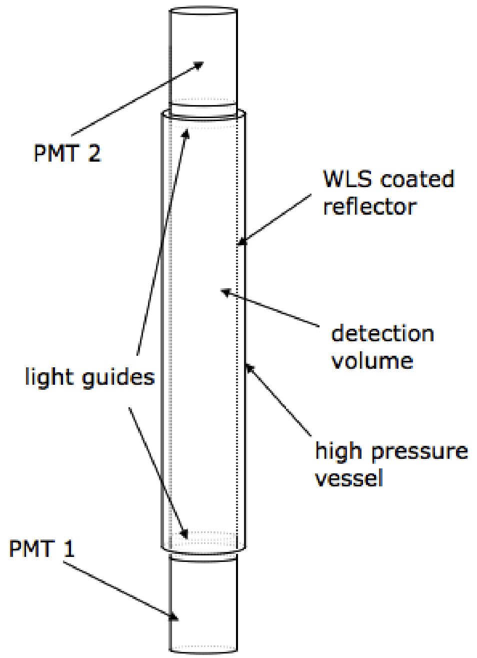
Modes used in the first-line scan at the Rotterdam seaport

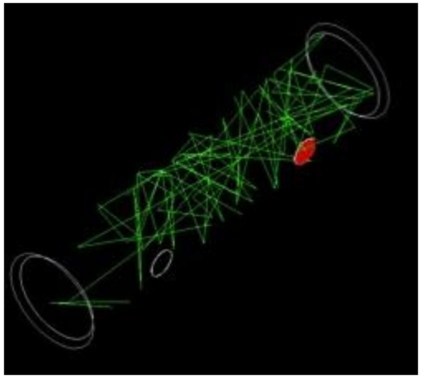
Baseline technology

- The Arktis technologies is based on high pressurized ^{4}He for the neutrons detection
- The main key features of ^{4}He
  - 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 ^{3}He



	Z	Photons/ MeV	Peak emission
^{4}He	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

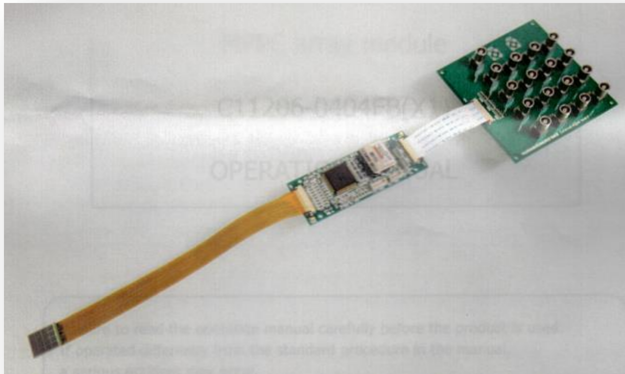


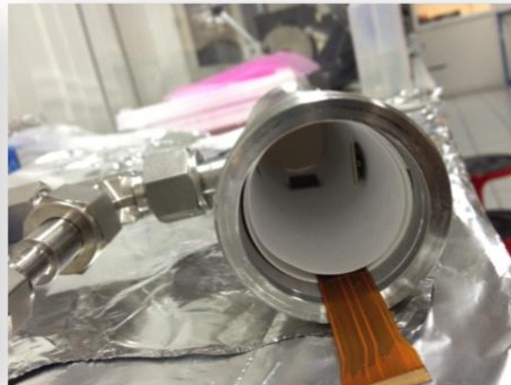


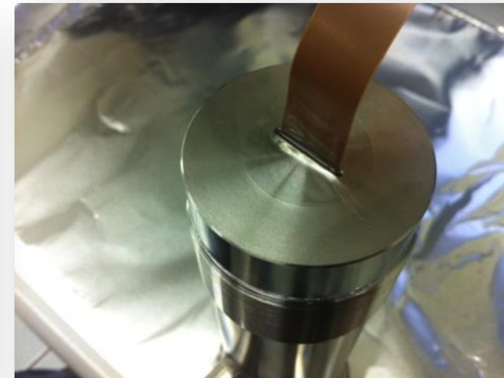
- 44 cm diameter x 47 cm sensitive length
- 180 bar ^{4}He sealed system maintaining gas purity

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

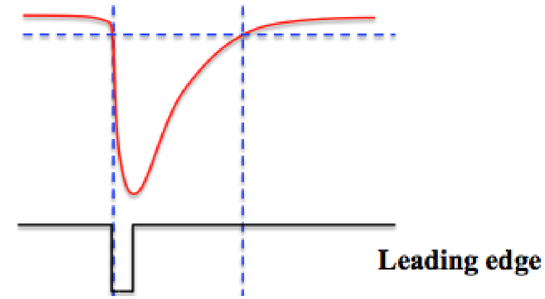
Test performed measuring:

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

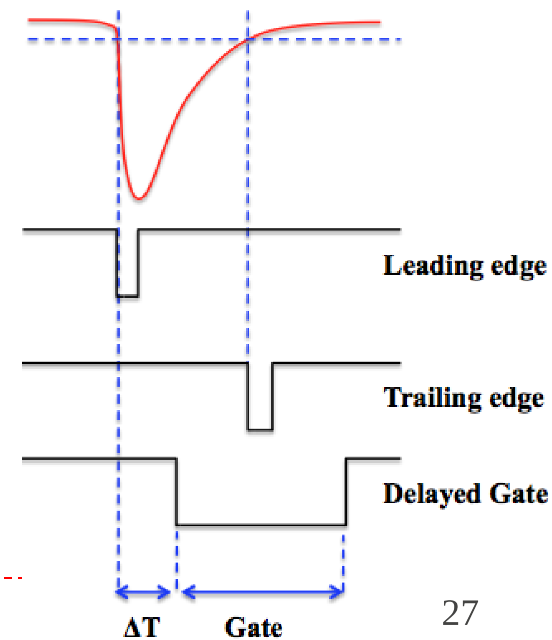
Two triggering scheme:

- Trailing edge discrimination in coincidence
- Trailing 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

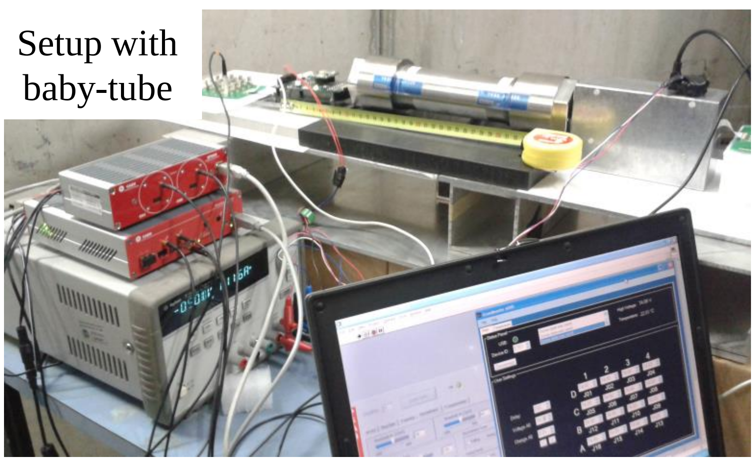
[10 counts in 1000s, for a number of γ given by acceptance*activity*time $= 1/3 * 3 * 10^4 * 10^3 \sim 10^7$]

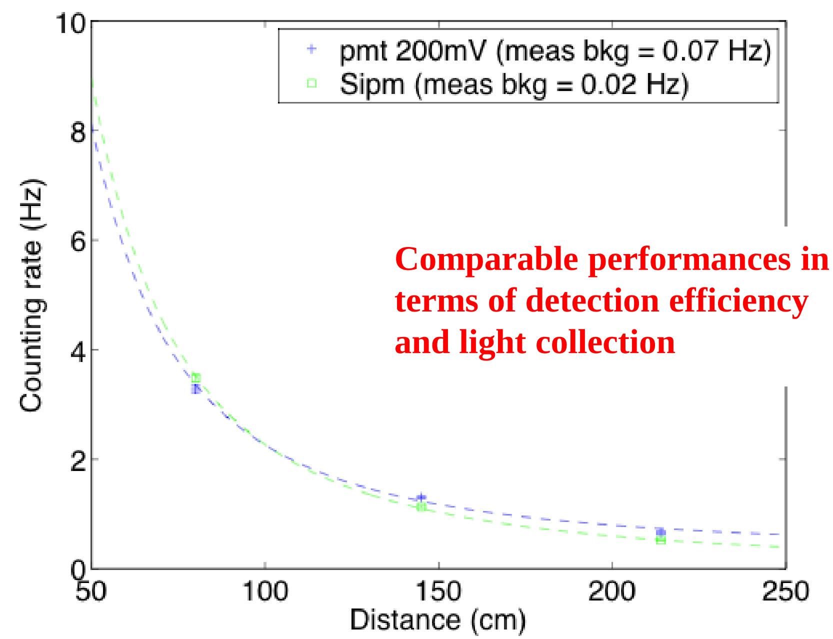
M. Caccia, R. Santoro et al. IEEE xplore, doi=10.1109/ANIMMA.2013.6727974 (2013)

SiPM VS PMT counting measurements

- Trigger: pulse-height discrimination and 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





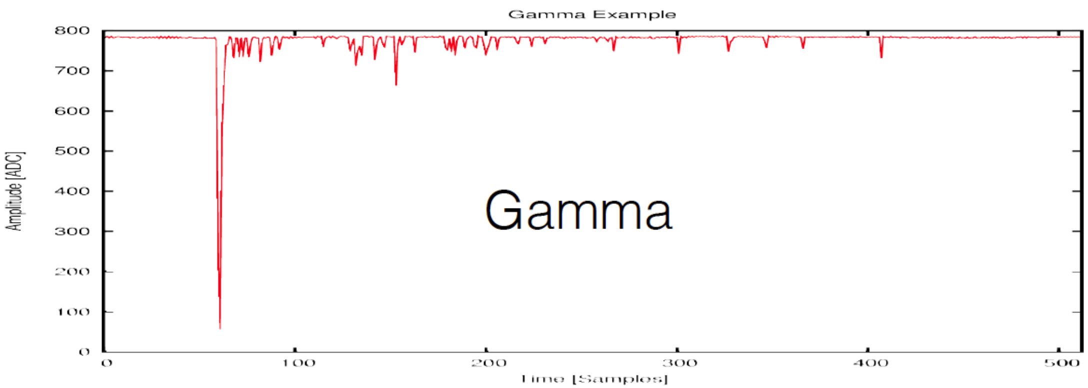
Few personal considerations …

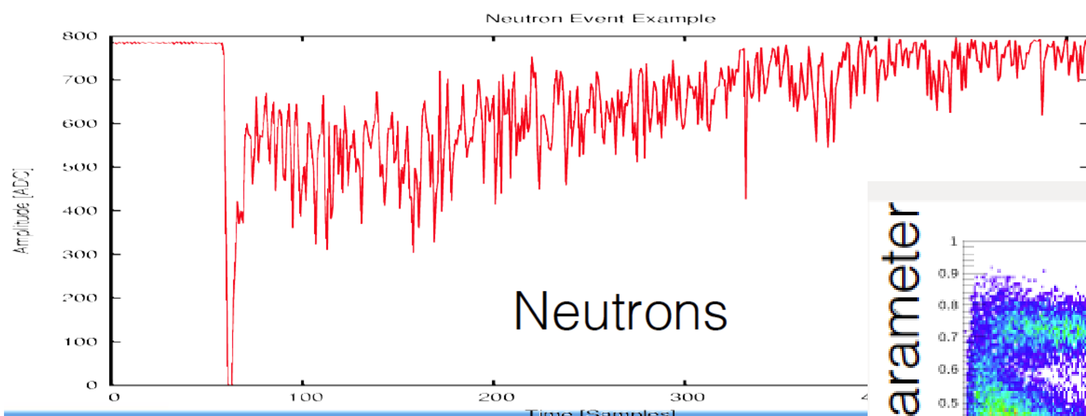
- There is a growing interest for this new class of detector both in scientific & industrial communities
- There is still a lot to do, but a good definition of the requirements and a deep knowledge of the detector characteristics could make the difference for the specific solution
- They shouldn't be seen as a simple replacement of PMT

… as someone else said …
"Think different"

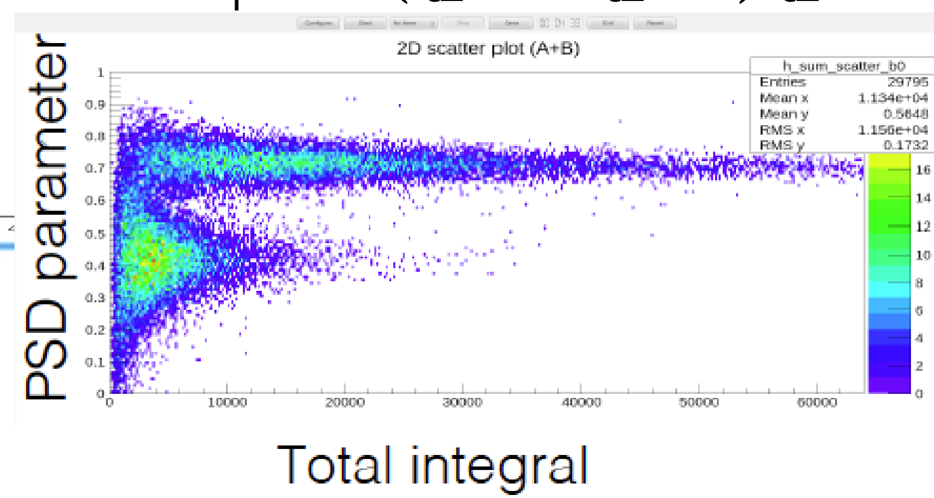
Spares

Neutron/γ separation





PSD=(Q_total – Q_short)/Q_total

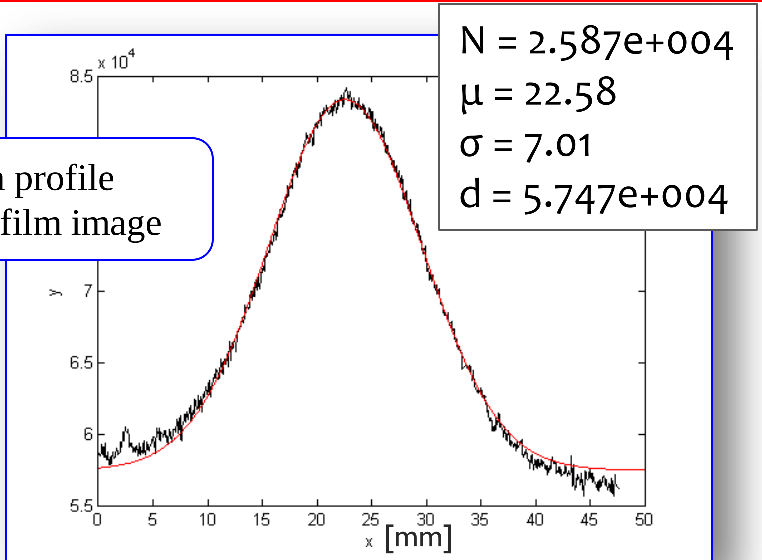


Decision tree

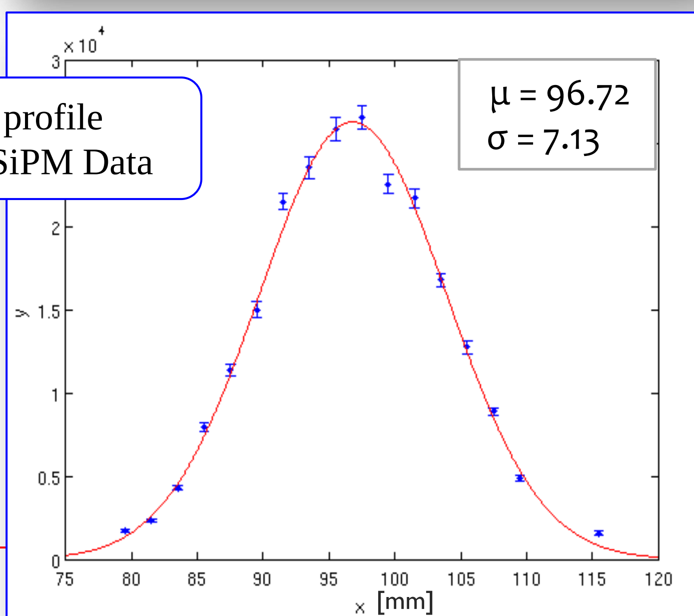
Type of event	Gamma Alarm	Neutron Alarm	Thermal Neutron Alarm	Message to the operator
Radioactive Source	**YES**	**NO**	**NO**	**Type of source (within the implemented library)**
NORM	**YES**	**NO**	**NO**	**Type of NORM (within the implemented library)**
Heavy lead shielded neutron source	**NO**	**YES**	**NO**	**Lead shielded neutron source**
Poly shielded Neutron source	**YES**	**NO**	**YES**	**Poly shielded neutron source**
Poly and lead shielded Neutron source	**NO**	**NO**	**YES**	**Poly-Lead shielded neutron source**
^{252}Cf source	**YES**	**YES**	**NO**	**^{252}Cf source**
Am/Be or Pu/Be source	**YES**	**YES**	**NO**	**(alpha,n) neutron source**
Pu source	**YES**	**YES**	**NO**	**Pu source**
U source	**YES**	**NO**	**NO**	**U source**

Saturation check

Beam profile from film image



Beam profile from SiPM Data



$$\mathbf{F} = \frac{Y_{\text{Integration}}(x=x_i)}{Y_{\text{image}}(x=x_i)}$$