Silicon Photomultipliers:

Introducing the **Silicon** age in low light detection

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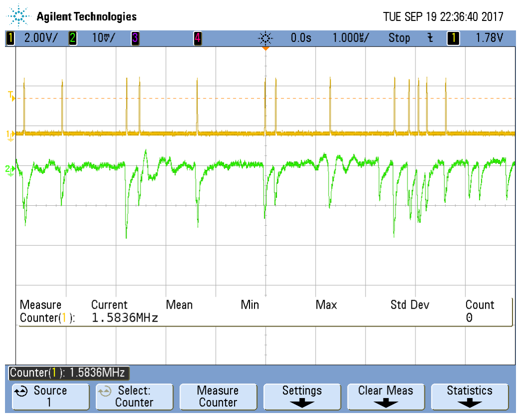
Part 2: applications (a limited number of)

Rudjer Boskovic Institute
October 24th, 2018

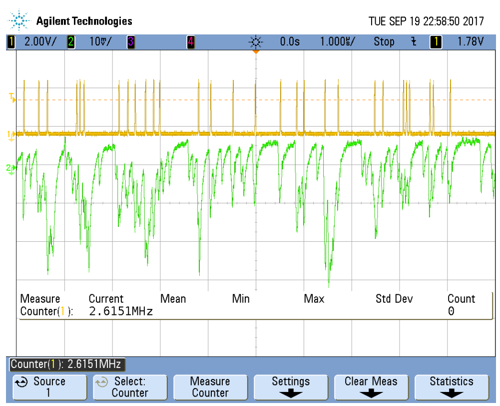
Benedetta Cappa Marinetti - Velocità di motoscafo, 1919

Applications (a limited number of)

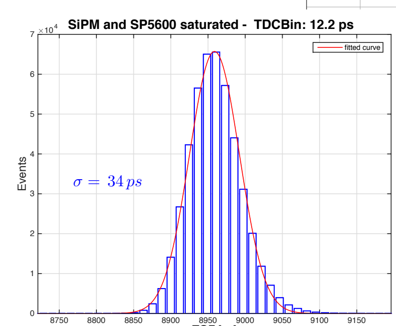
- Pulse mode:

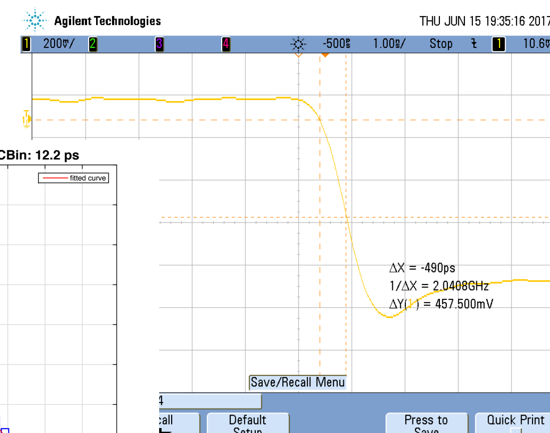


- Current mode:



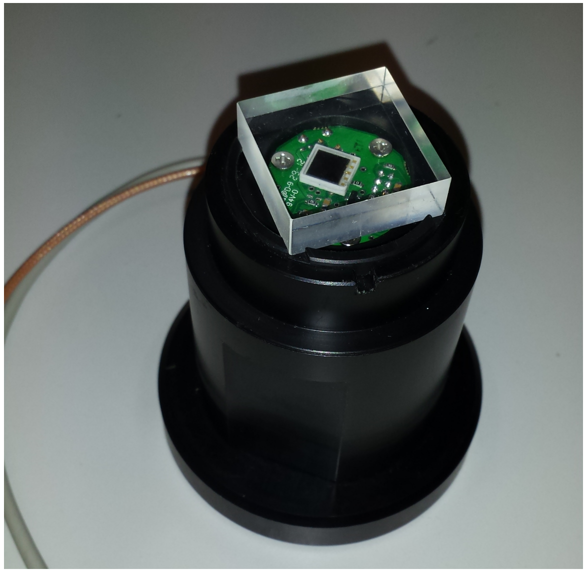
- Timing

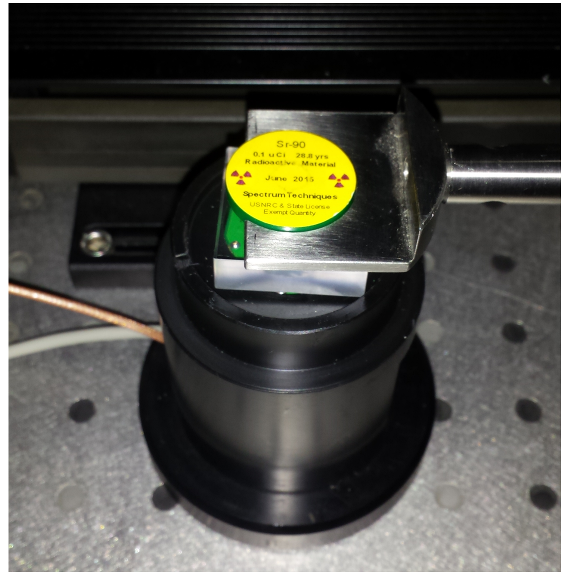




p.s. extremely biased by my activity & experience!

A Friday afternoon exercise (1/3):
Thickness measurement by β absoprtion (aka β gauging)





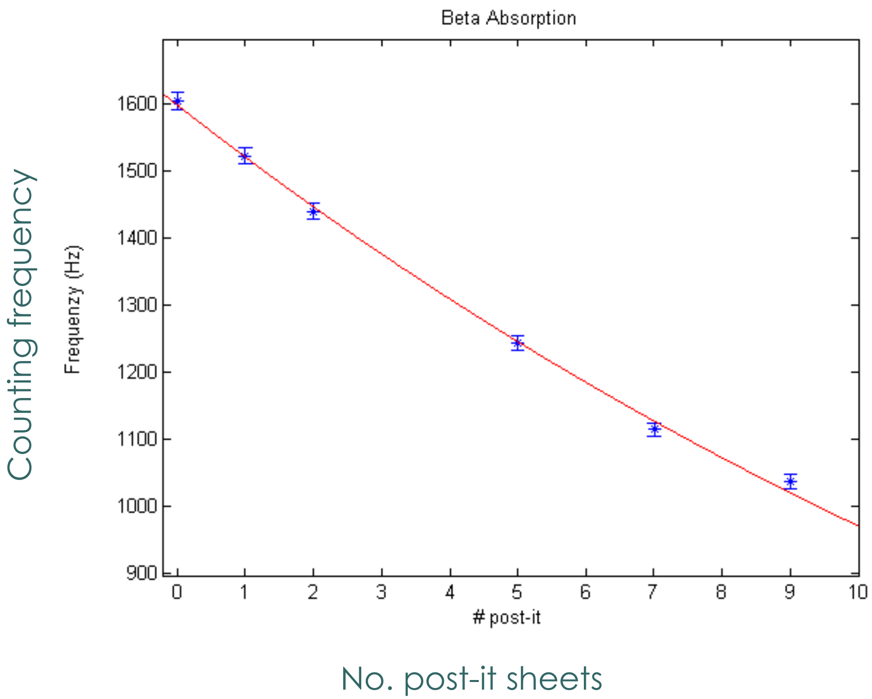
- 6x6 mm^2 SiPM
- 1 cm thick plastic scintillator

- 37 kBq ^{90}Sr source

- post-it sheets
  interleaved between the source and the scintillator

Can I count the number of sheets by the counting rate?

A Friday afternoon exercise (2/3):
Thickness measurement by β absoprtion (aka β gauging)



$$\nu = ae^{-bn}$$

a = 1600 Hz
b = 0.05
n = number of post-it sheets

→ in 250 ms I can tell you at 3σ level if I have 1 or 2 post-it
→ In 25'' I can detect a thickness variation at the 10% level

Is it serious?

A Friday afternoon exercise (2/3):
Thickness measurement by β absoprtion (aka β gauging)

Radioisotope sensor for measuring the density of paper and cardboard web based on the isotope Kr 85 A361 CAN LEB1

Brief description

Radioisotopic density sensor of sheet materials A361 CAN (LEB-1) is designed for use in automated quality control system "A-3000" for the continuous and non-contact technological control paper web density or other sheet materials.

Application range — paper web density continuous monitoring for the papermaking and other sheet materials process control.

5014i Beta Continuous Ambient Particulate Monitor

Measure PM-10, PM-2.5 or PM-1 mass concentrations with the Thermo Scientific™ 5014i Beta Continuous Ambient Particulate Monitor. The 5014i distinguishes itself from other beta measurement methods by utilizing a continuous (non-step wise) mass measurement with a proven industry standard which provides for long-term unattended operation. To accurately address potential water bias and volatile loss, the Dynamic Heating System allows the user to hold the sample temperature at a fixed value or below a relative humidity threshold.

Radiation Protection – an exemplary illustration for the UK

The TN15™ high sensitivity thermal neutron detector utilizes a state-of-the-art Silicon photomultiplier (SiPM) and offers world-leading specification in a compact form. The TN15™ surpasses the performance of a 100mm long 13mm ^{3}He tube at 4 atmospheres.

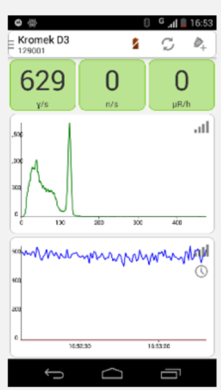
Specifications:	
Equivalent to 100mm x 13mm Ø ^{3}He at 4 atmospheres	
Photo-sensor	SiPM array
Thermal Neutron Sensitivity	>50%
Maximum throughput	10,000 cps
Power consumption	250 mW
Dimensions	131mm x 33mm x 24mm
Weight	110 gram
Temperature range	-10 to 40°C

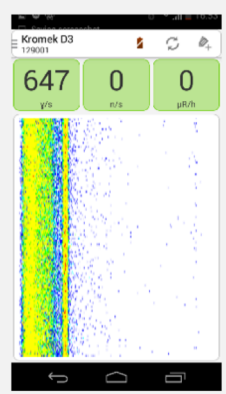
TN15 ™ by KROMEK, Sedgefield
County Durham, UK
www.kromek.com

The 2015 blockbuster

D3S

- Compact Bluetooth gamma neutron detector for $400
- All technology available at OEM level
  - Gamma module
  - Neutron module
  - Bluetooth MCA
    - All designed for ultra low power
- All software can be supplied badged or further developed as required
  - Android application
  - Fully secure web application including GPS



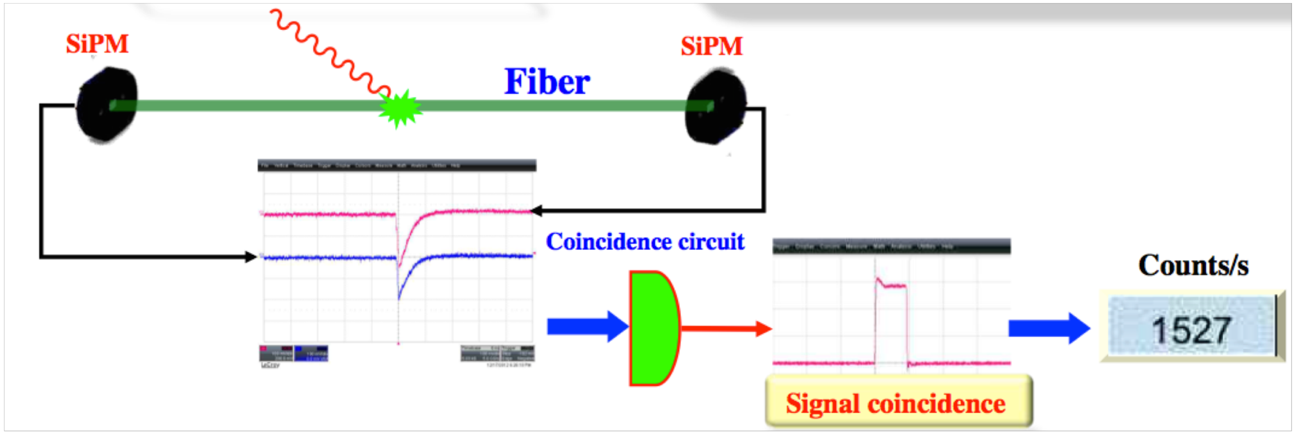


About Nuclear Waste

Paolo Finocchiaro, Nuclear Physics News,
http://dx.doi.org/10.1080/10619127.2014.941681

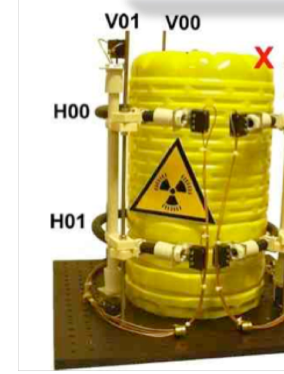
❖ Goal: online monitoring of radiation emitted by nuclear waste drums

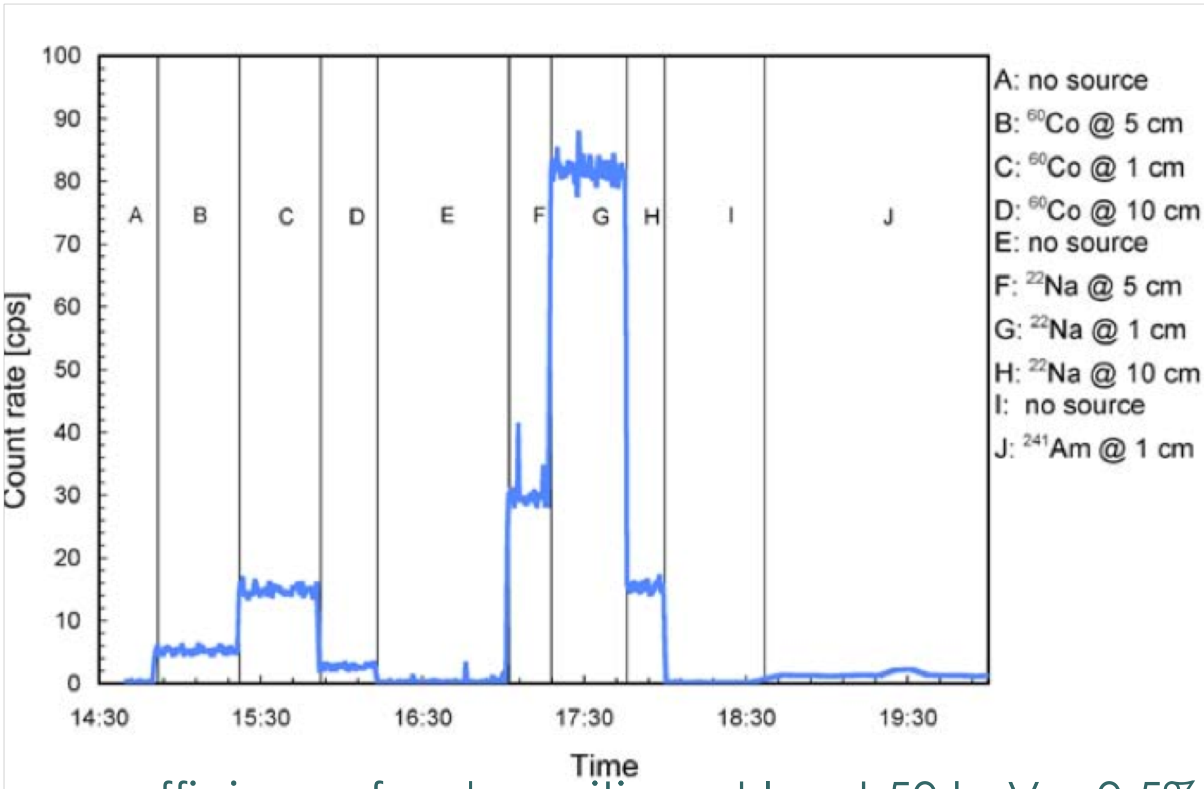
❖ Method: “annular” detector, made out of a plastic scintillating fiber connected to SiPM at both ends



Italian National Institute of Nuclear Physics (INFN) & SOGIN s.p.a

Qualification results:



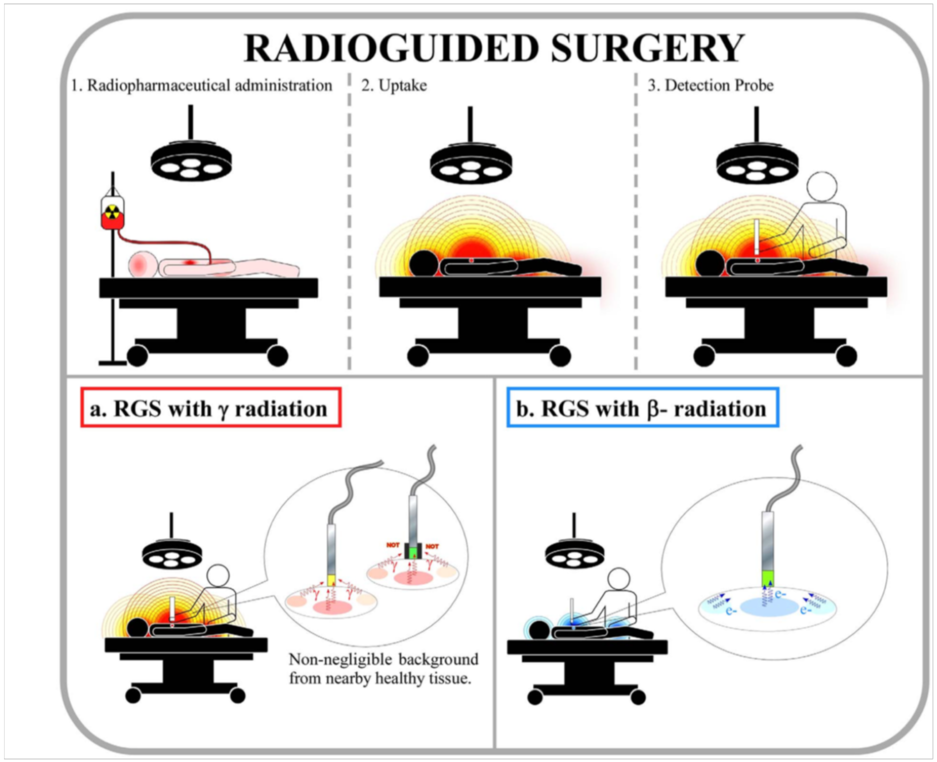


- ^{60}Co, 35 kBq
- ^{22}Na, 243 kBq
- ^{241}Am, 36 MBq
- ^{137}Cs, 231 kBq

- efficiency for depositing at least 50 keV ~ 0.5%
- mean deposited energy ~ 180 keV, i.e. 1800 photons (light yield ~ 10^4 photons/MeV)
- mean detected signal ~ 40 photo-electrons
- random coincidence rate ~ 1Hz

RadioGuided Surgery (RGS)

1. F Bogalhas et al., Phys. Med. Biol. 54 (2009) 4439–4453
2. Solfaroli Camillocci et al., NATURE SCIENTIFIC REPORTS | 4 : 4401 | DOI: 10.1038/srep04401 (2014)
3. H. Sabet et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 5, OCTOBER 2015



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 β *or* γ radiotracers.

RGS with β^- (ref.2)

Focused on brain tumor (meningioma) for two reasons:

- It is particularly receptive to synthetic somatostatin analogues, such as DOTATOC, that can be labelled with the β^- emitting ^{90}Y
- The concentration of "standard" β^+ emitting isotopes (e.g. 18F-FDG used for PET) is quite high in the brain, inducing a significant background

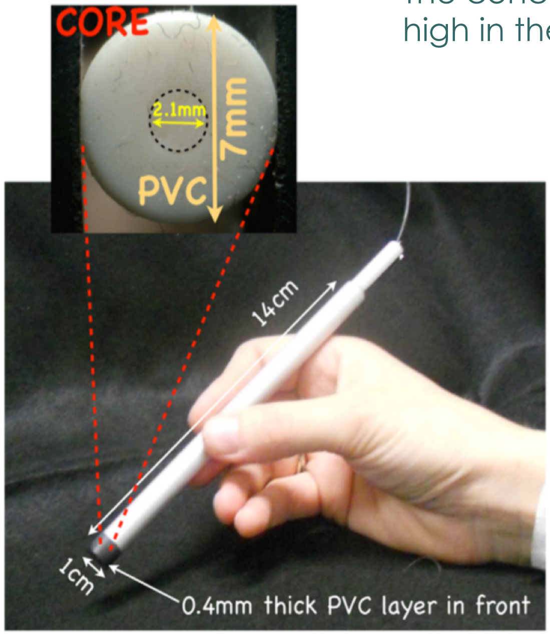


Figure 2 | First prototype of the intraoperative β^- probe. The core is a cylindrical scintillator (diameter 2.1 mm, height 1.7 mm) of poli-crystalline p-terphenyl. A ring of PVC wraps the scintillator and shields it against radiation coming from the sides. The device is encapsulated inside an easy-to-handle aluminum body as protection against mechanical stress and it is protected against light by a thin PVC layer.

Results from phantoms with a specific activity corresponding to what can be expected in clinical applications

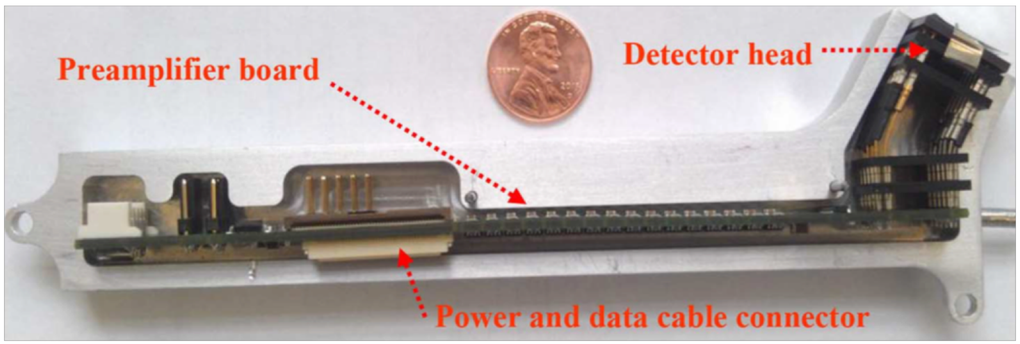
Phantom	Diameter (mm)	Height (mm)	Volume (ml)	Rate (cps) 22 kBq/ml	T (s) 22 kBq/ml	Rate (cps) 5 kBq/ml	T (s) 5 kBq/ml
Residual	6	3.5	0.10	31.6	1	6.6	2
H1	4	1	0.01	12.4	2	2.6	>10
H2	4	2	0.02	17.7	1	3.7	4
H3	4	3	0.04	20.1	1	4.2	4

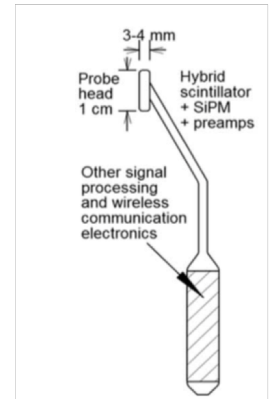
Time required to get False Negative < 5% and False Positive ≈ 1%

RGS with β^+ (ref.3) (1/2)

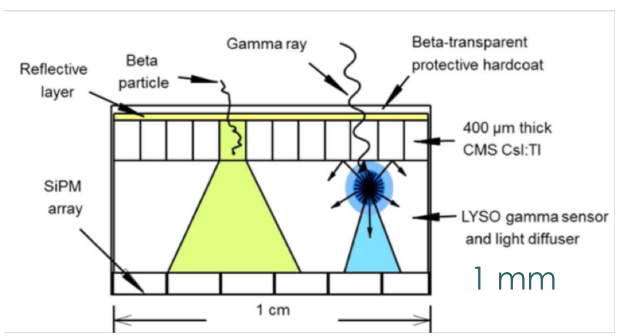
An IMAGING DEVICE engineered to detect β^+ emitting isotopes irrespective from the γ background

❖ Conceptual design & prototype of the probe





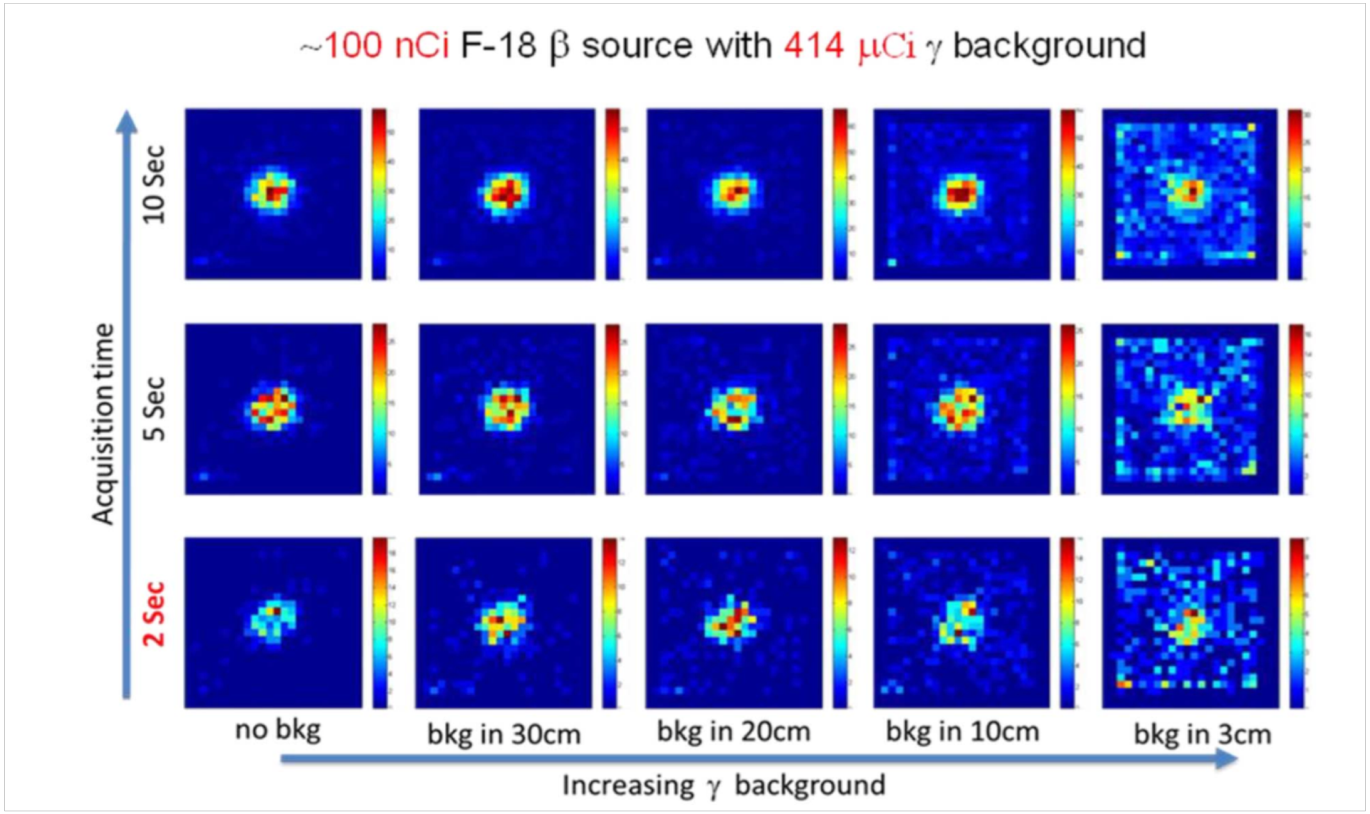
❖ A head designed to identify and discriminate β^+ from γ



- CsI to detect β^+ rather than plastic scintillator for the light yield (53 photons/keV vs 10 photons/keV); $\bar{E}_{\beta^+}$= 250 keV, E_{max}= 635 keV
- β^+ vs γ discrimination profiting from the difference in the time constant of the CsI (800 ns) vs LYSO (40 ns)

RGS with β^+ (ref.3) (2/2)

Images of a ^{18}F droplet ($\approx 1mm\ diameter$) @different background levels



Still a bit qualitative (on spatial resolution and sensitivity) but definitely intriguing

Response to a constant flux:
Dosimetry in mammography

C. Cappellini et al., 2008 IEEE Nuclear Science Symposium Conference Record & NIM 607 (2009), 75–77

Dosimetry in mammography is utmost important and this is somehow proven by the ongoing debate on the relevance of mammography screening

…but currently existing instruments are limited:

- Standard Termo-Luminescent Detectors require to be analyzed after examination, degrade with time
- MOSFET detectors suffer from low stability and degrade with each irradiation
- Ionization chamber devices need relatively high voltage (cannot be used in contact with the patient), not tissue equivalent

precise measurements of the actual dose being received by a patient without distorting the X-ray beam and introducing any artefacts in the image

Some functional requirements:

- dose rate range (2 ÷ 150 mGy/s)
- dose range (0.5 mGy - 180 mGy)
- sensitivity (5%)
- overall accuracy (±10%)
- tolerance to environmental variation & stability

Prototype qualification

Conceptual design of the prototype tested @ PTW – secondary standard lab for dosimetry:

Scintillator

(tile or fiber)

Ligth guide
Ø 1 mm
clear fiber

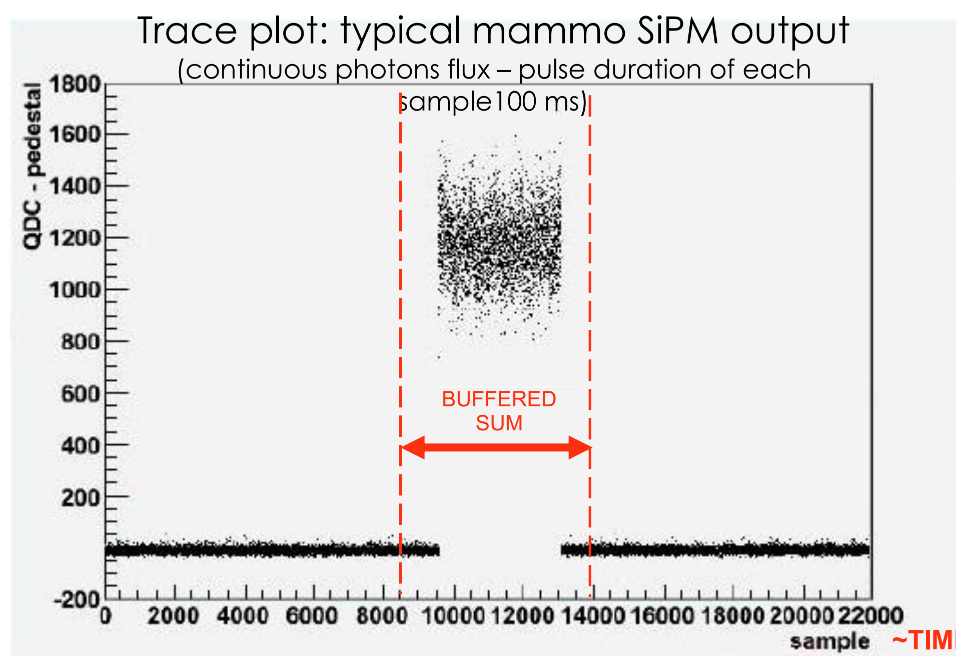

FC connector & SiPM

Electronics

PHISYCAL OBSERVABLE:
“buffered” signal sum

Sum of samples signals selected by an edge detector algorithm + left & right buffer

⇒ proportional to the DOSE

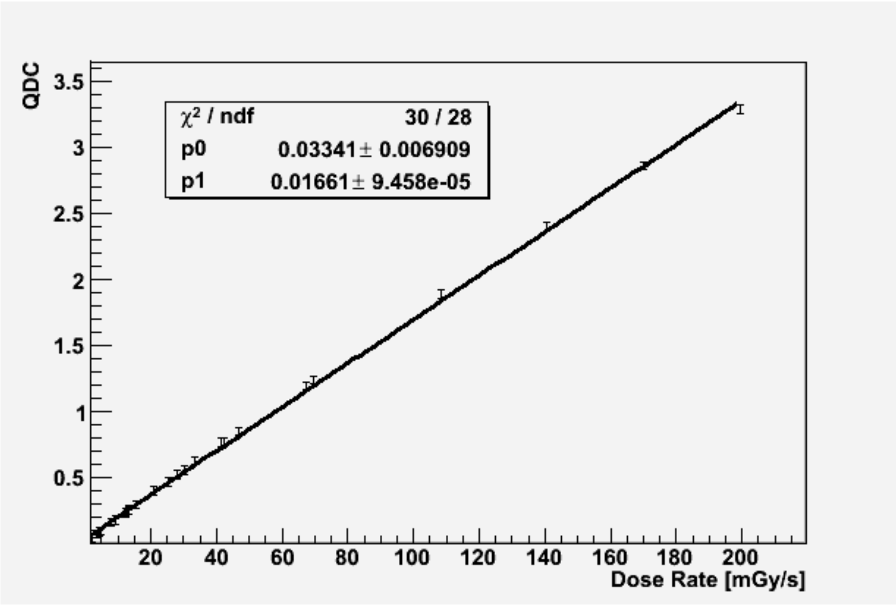


summary of the results

Two different set-up (optimized for dynamic range & λ):
- 1mm scintillator tile
- Blue scintillator fiber

coupled with MPPC (400 cells, 1x1 mm^2)

Irradiation: 0,22 ÷ 217 mGy/s



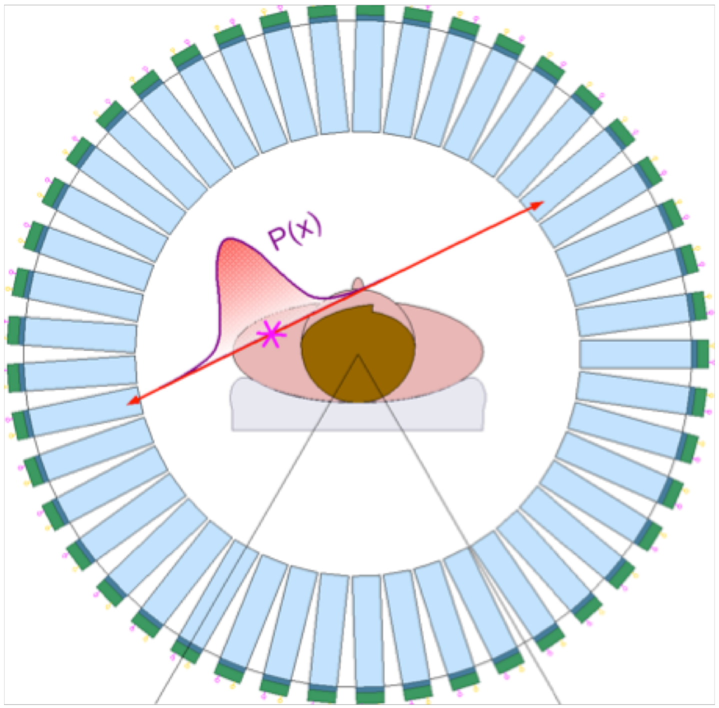
	Fiber + Hamamatsu MPPC
Precision(%)	2.31 ± 0.03
Sensitivity^A (mGy/s)	2.05 ± 0.03
MDS^B (mGy/s)	0.458 ± 0.007
Linear Dinamic range (mGy/s)	> 200

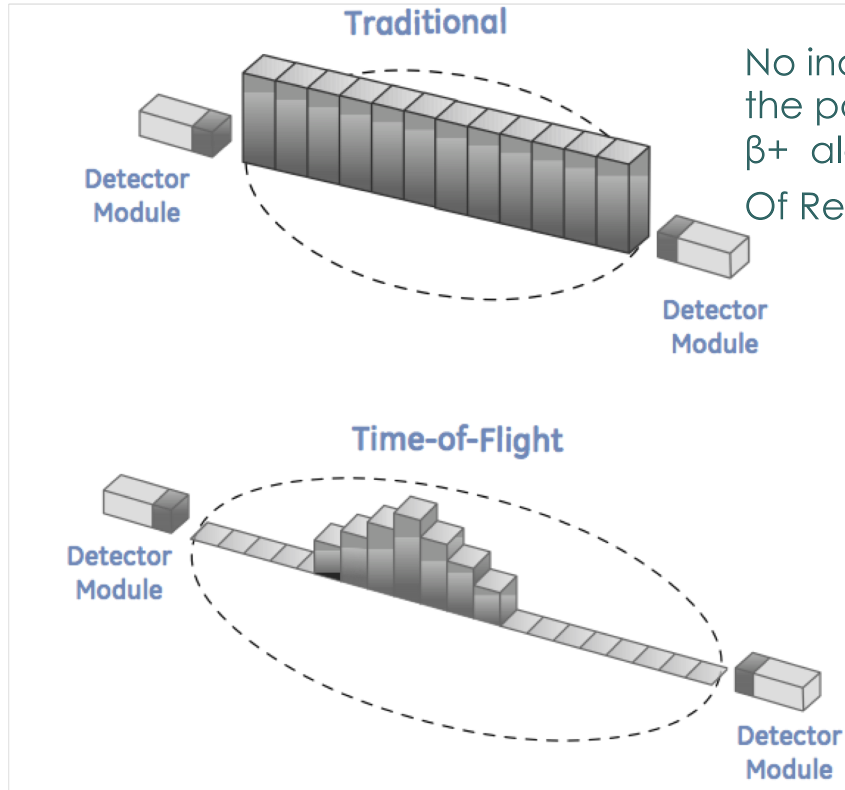
^{A}Sensitivity: Precision / system gain

^{B}MDS: minimum signal distinguishable from the noise

Time-of-flight Positron Emission Tomography (TOF-PET) & LIDAR

M. Conti, Physica Medica (2009) 25, 1-11





No indication about the position of the β+ along the Line Of Response (LOR)

The functional imaging tool, based on the detection of pair of γ rays emitted back-to-back by the annihilation of the β+ emitted by the ^{18}F, chemically bound to FDG

Identify the position of the β+ along LOR by the differenc ein the time of arrival of the photons

TOF-PET is a HOT topic: 1510 papers in 2008-2013 (Google Scholar) + significant investments by funding agencies & companies

The gain in the image quality between a conventional and a TOF-PET system may be quantified as [Conti]:

$$G = \frac{SNR_{TOF}}{SNR_{non-TOF}} = \sqrt{\frac{D}{c*CTR}}$$

- D = volume being inspected
- c = speed of light
- CTR – Coinicidence Time resolution

CTR	G
1 ns	1.6
500 ps	2.3
100 ps	5.2

500 ps ← Current machines

100 ps ← TARGET

[S. Gundacker et al., NIM A 737 (2014) 92–100]

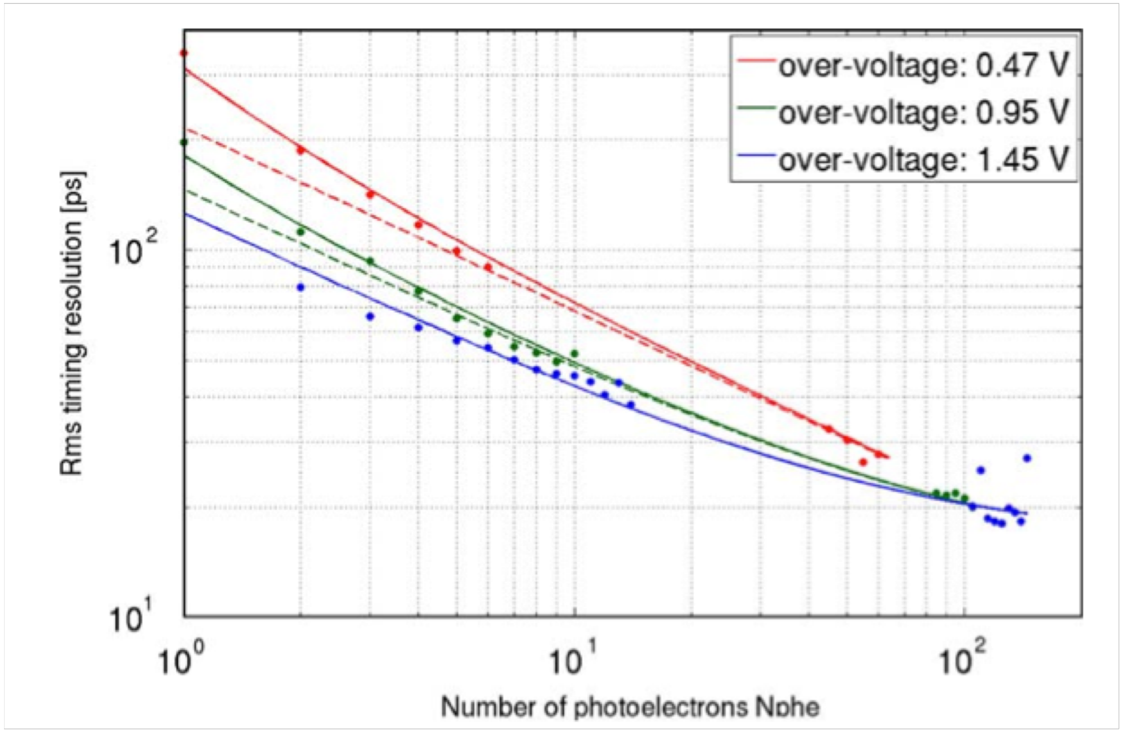
SiPM do play a role, since the timing resolution of a sensor my roughly be written as:

$$\sigma_t = (output\ signal\ fluctuations)/(signal\ slope)_{trigger}$$

Exemplary illustration of results obtained with the HAMAMATSU SiPM [R. Vinke et al. NIM A 610 (2009) 188–191]:

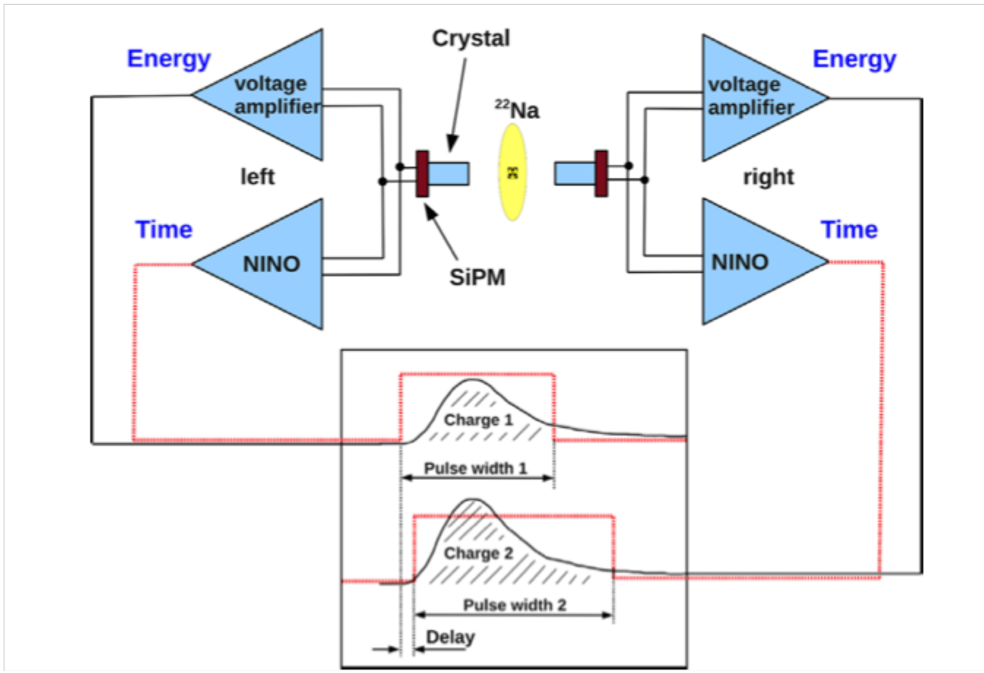
Time resolution wrt a laser shot (worth thinking of it for ranging & LIDAR)

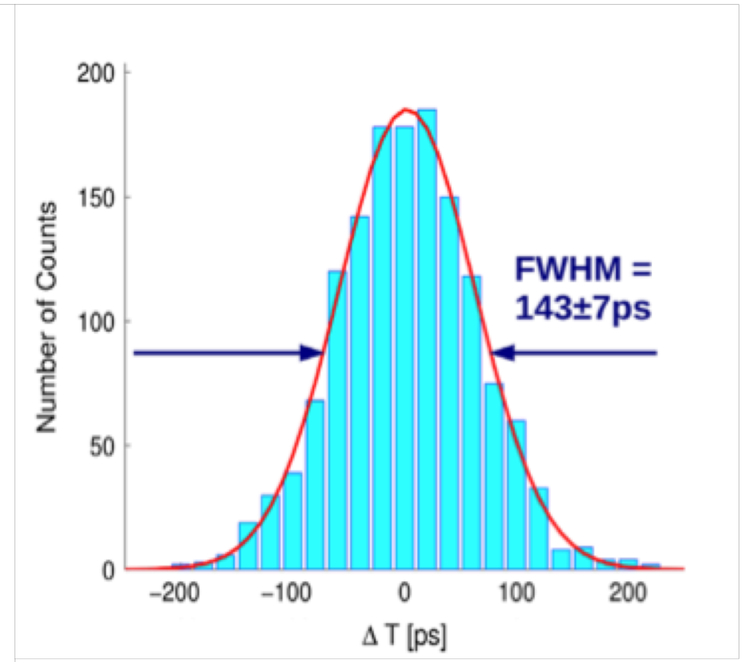
[1x1 mm², 50 micron cell pitch]



Currently, a SInglePhotonTimingResolution ≈ 35 ps has been reported (Acerbi et al., IEEE Transaction in Nuclear Science, 10.1109/TNS.2014.2347131

Timing properties of the sensor are not the full story and the scintillator does play a role [S. Gundacker et al., NIM A 737 (2014) 92–100]:





- [3x3 mm^2, 50 micron cell pitch]
- 2x2x10 mm^3 LSO crystal

Actual resolution, accounting as well for the Photon Travel Spread (PTS) resulting by the point-of-interaction and scintillation light time spread

Small animal PET/CT scanning is also a significant market

(valued $790 million in 2012, and estimated to grow at an annual growth rate of 14.5% over the next five years)

- The price for different small-animal PET systems ranges between $400,000 and $1,200,000, depending on the PET system configuration
- No. of crystals/scanner:~ 30000

JOURNAL OF NUCLEAR MEDICINE TECHNOLOGY • Vol. 40 • No. 3 • September 2012

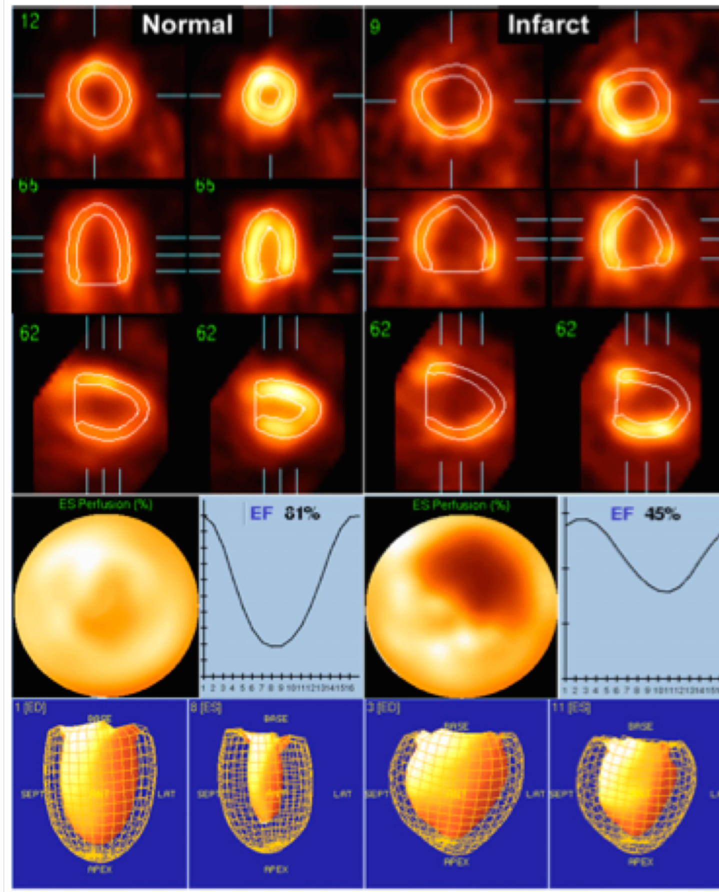
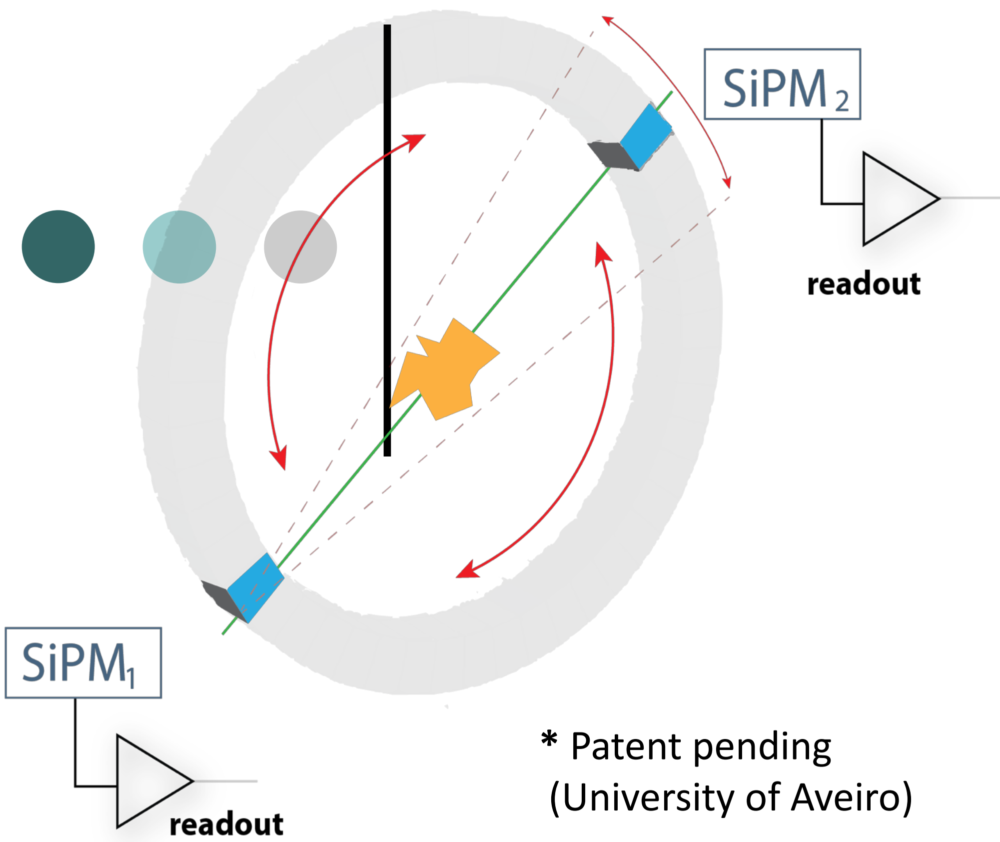


FIGURE 5. Electrocardiogram-gated ^{18}F-FDG studies in normal and infarcted rats obtained using clinical cardiac analysis software QGS (56). Polar maps display end-systolic ^{18}F-FDG uptake. Ejection fractions for normal and infarcted rats are 81% and 45%, respectively. ED = end-diastolic; EF = ejection fraction; ES = end-systolic. (Adapted with permission of (55).)

the easyPET concept *



* Patent pending (University of Aveiro)

- based on a single pair of detectors (LYSO + SiPM)
- detectors mounted on rotating structure with 2 degrees of freedom, allowing reconstruction of source position
- axial FOV: small animals (mice/rats)
- system geometry removes parallax errors, eliminating the need of DOI measurement
- allows highly granular detector assemblies for enhanced performance

easyPET provides a very cost-effective solution for entry level systems, due to the extreme reduction in the nr. of detectors and complexity of the overall apparatus

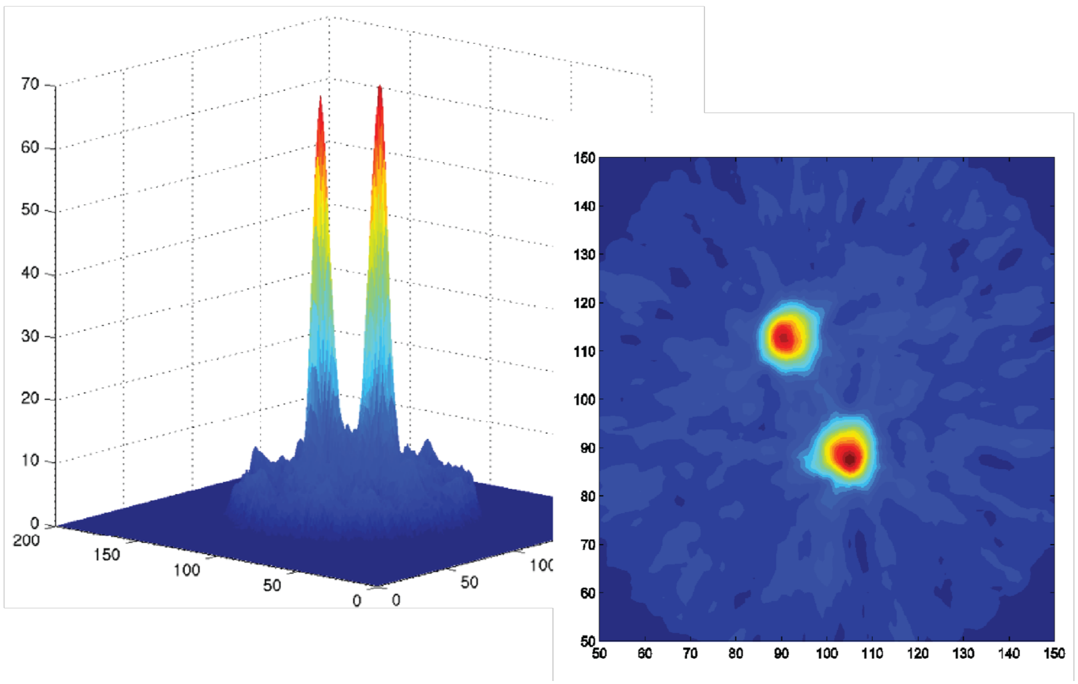
universidade de aveiro

partners:

CAEN Tools for Discovery

current status:

fully functional
educational system developed *



- Arduino UNO microcontroller
- MATLAB interface: control and online imaging
- Two ^{22}Na sources, 5 µCi
- 2.7 mm Ø, 9 mm apart
- forward projection (no filtered reconstruction)
- position resolution < 1.5 mm FWHM, uniform over the whole FOV

* Licensing under way for didactic/educational purposes

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CAEN Tools for Discovery

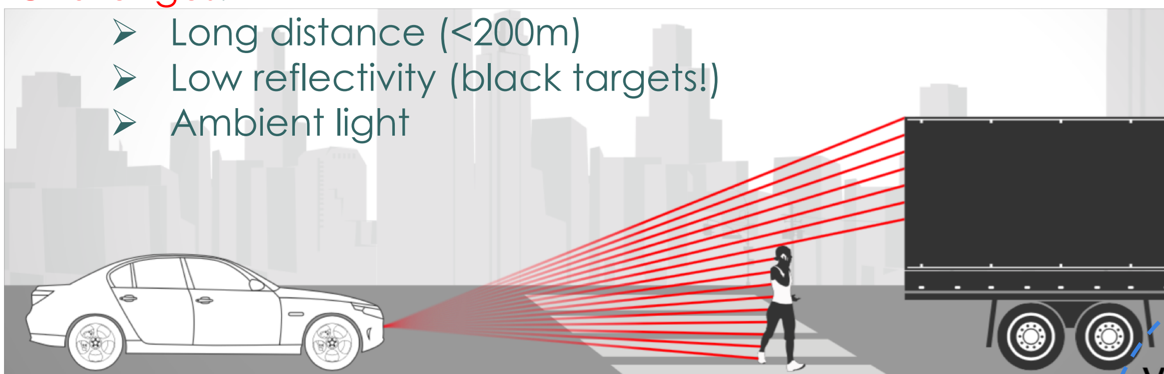
SiPM for Time of Flight LIDAR

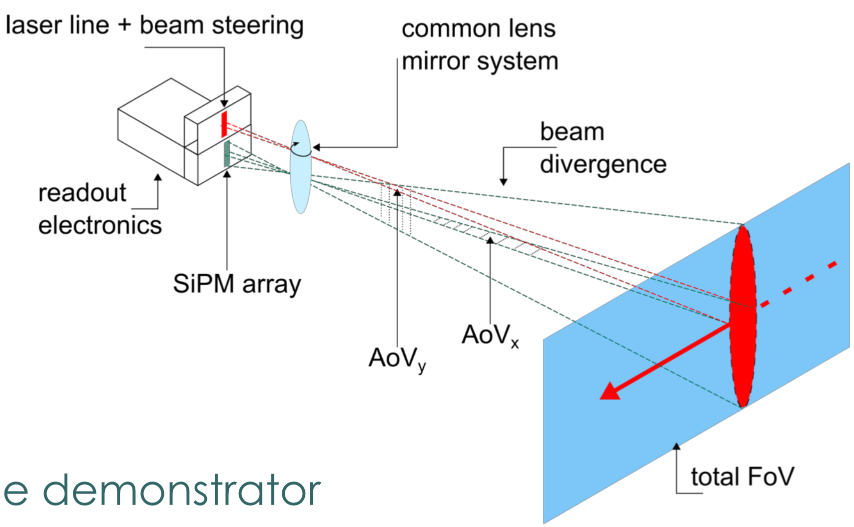
For an excellent paper showing the advantages of SiPM, see
S. Vinogradov, Evaluation of performance of silicon photomultipliers in LIDAR applications, doi: 10.1117/12.2264935

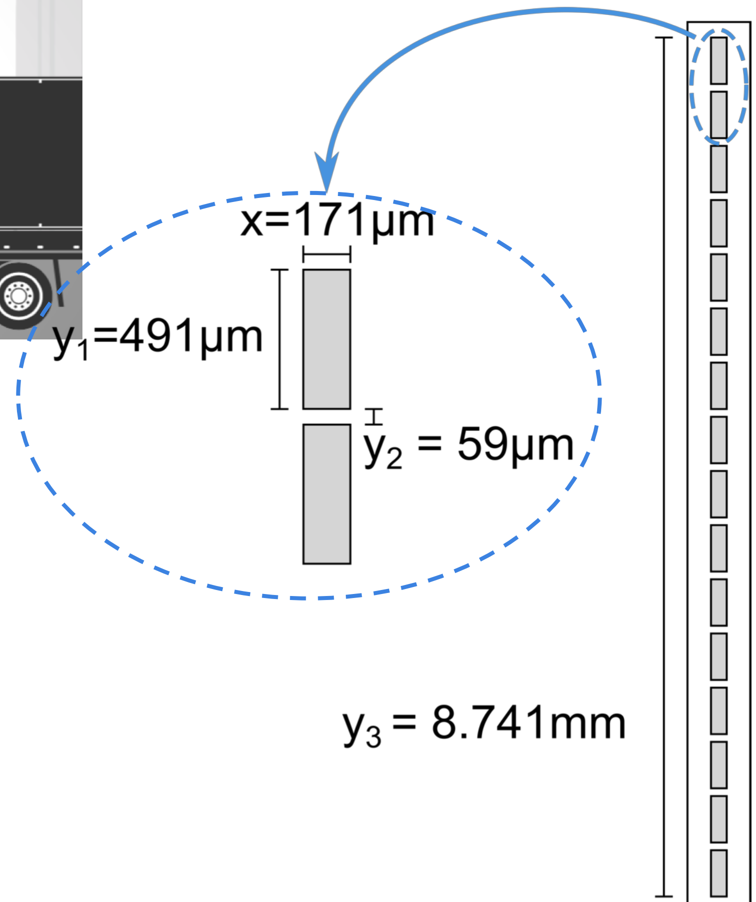
The basic principle

Challenges:

- Long distance (<200m)
- Low reflectivity (black targets!)
- Ambient light





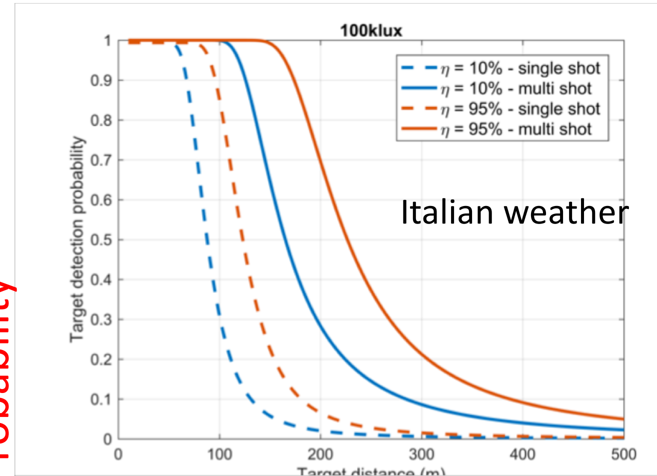


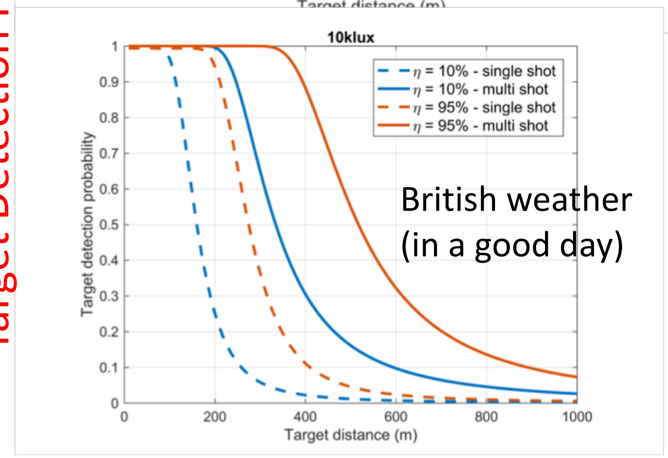
The demonstrator

SensL LiDAR System Parameters

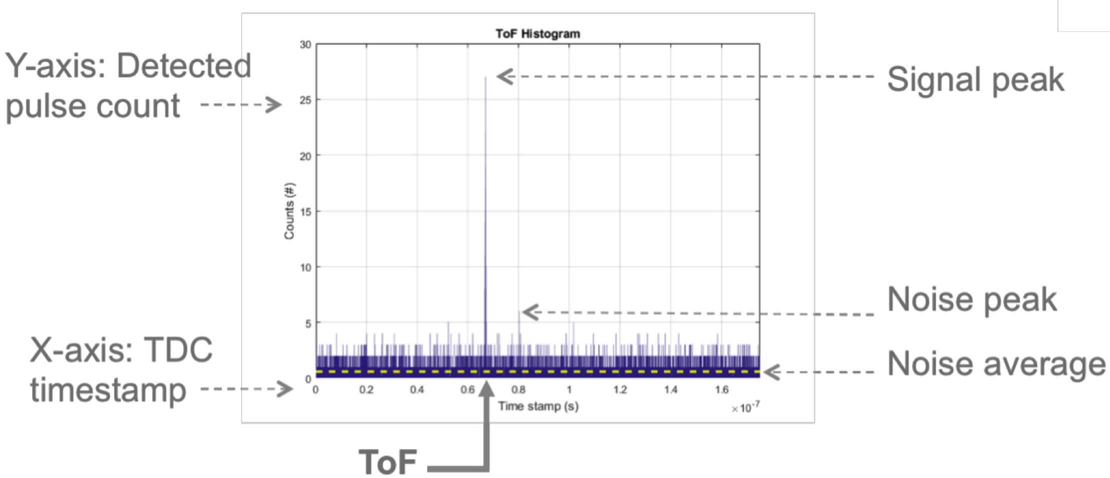
Parameter	Value
Array size	1×16
SiPM pixel length x	171 µm
SiPM pixel height y_1	491 µm
Pixel spacing y_2	59 µm
Total array length y_3	8.741 mm
SPAD cells per pixel N_{cells}	133
PDE @ 905 nm	8.4 %
SPAD cell dead time τ_{dead}	23ns
SiPM pixel gain G	10^6
SiPM rise time τ_{rise}	100 ps
Laser divergence	$0.1^\circ \times 5^\circ$
Laser peak power P_{laser}	400 W
Laser pulse width τ_{pulse}	1 ns
Laser pulse repetition rate PRR	500 kHz
Frames per second	30 fps
Optical aperture D_{lens}	22 mm
Scanning angle of view	$80^\circ \times 5^\circ$
Static angle of view $AoV_x \times AoV_y$	$< 0.1^\circ \times 5^\circ$
Angular resolution	$0.1^\circ \times 0.312^\circ$
Optical bandpass $\lambda \pm \Delta\lambda$	(905 ± 25) nm

Target Detection Probability



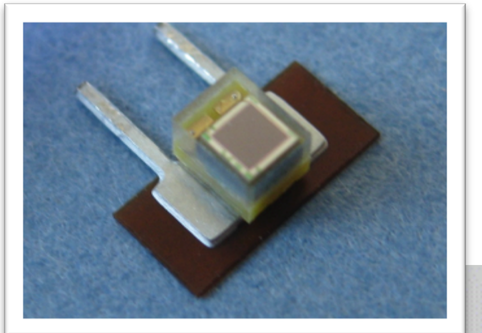


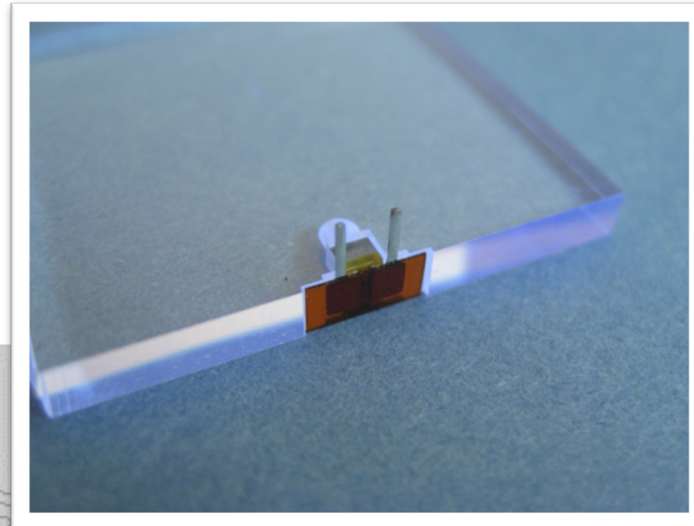
1 Lux = 1 lumen/m^2; A 25 W compact fluorescent light bulb puts out around 1700 lumen

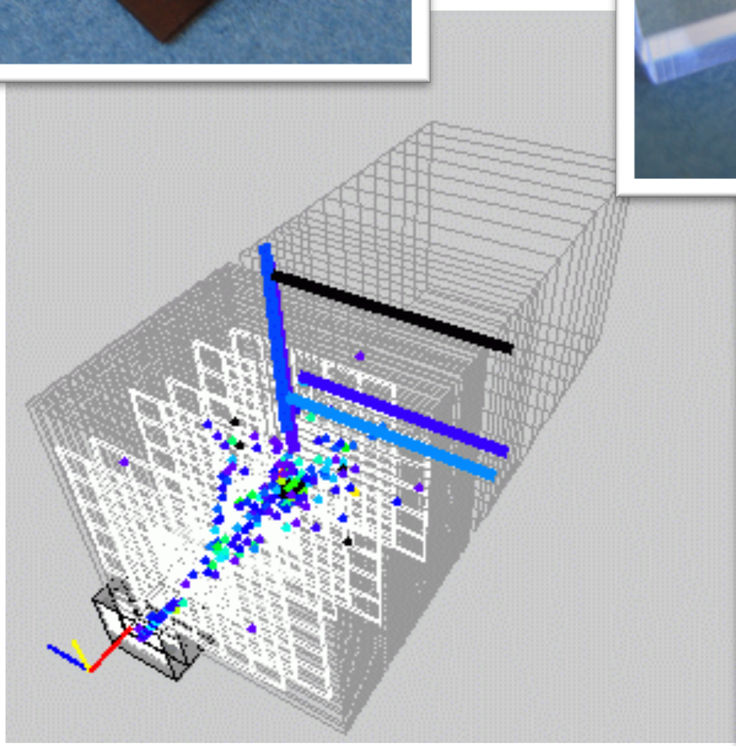


The returned signal reaches the level of the background noise, and so a multi-shot technique can be used to improve the performance and increase the probability of detection. Currently, the TOF distribution is built over 20 shots.

Last but not least: High Granularity Calorimetry for High Energy Physics [the domain of CALICE, even if we also entered the game]

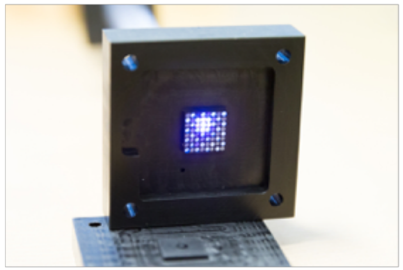
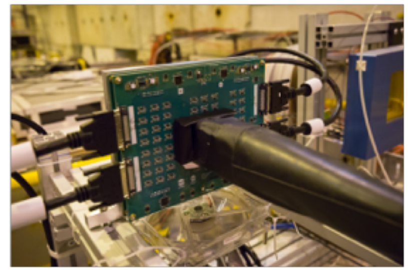
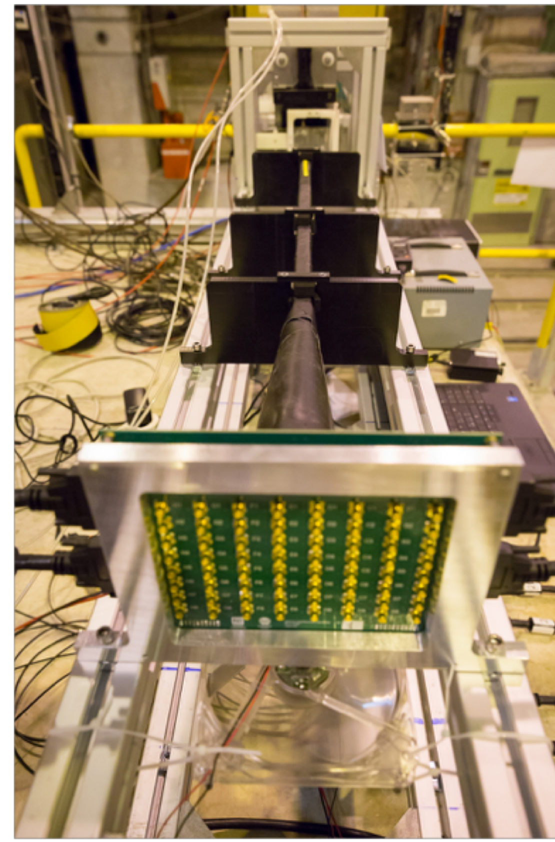
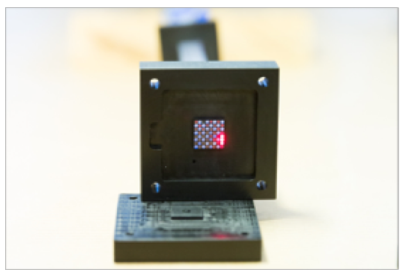
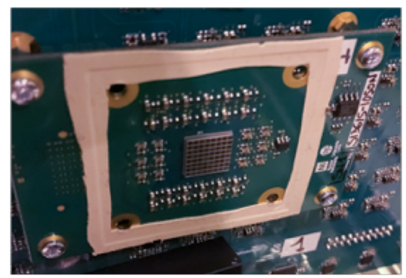
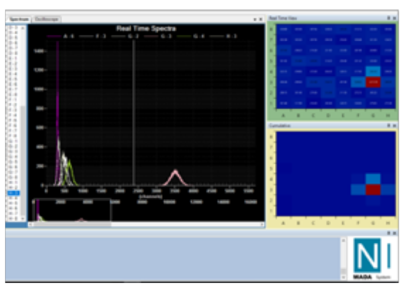


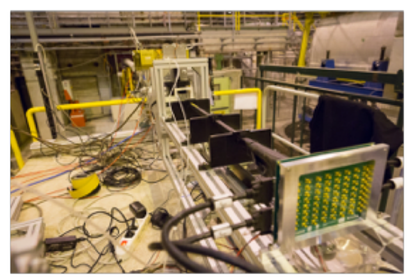




A SiPM based Dual Readout Calorimeter module (DREAM)
(http://highenergy.phys.ttu.edu/dream/)

A small DREAM by now…

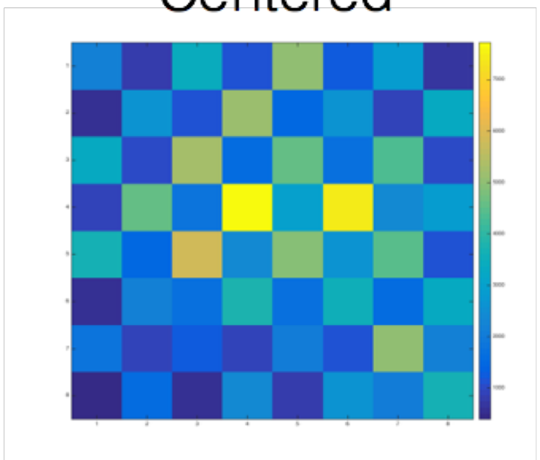









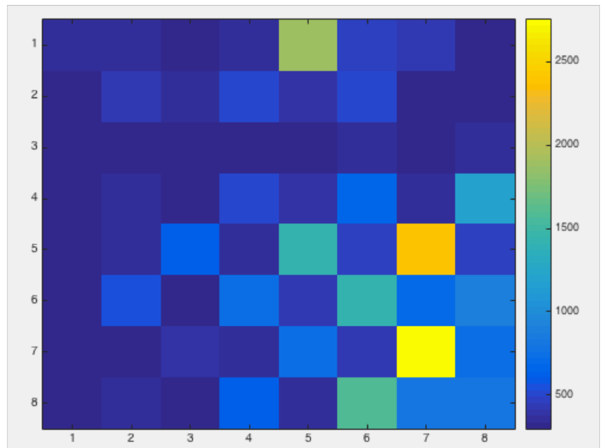
on beam at CERN in October 2016 & July 2017

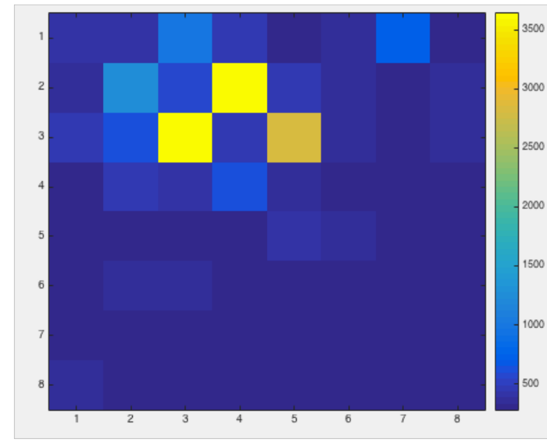
And we made it (and the best is yet to come)!

Centered



Off-centered





A muon

40 GeV electrons

What did we do since we got started with SiPM, in 2006?

- RAPSODI, a Framework Program 6 EC project:
  - Real-time dosimetry in mammography (with PTW-Freiburg)
  - Indoor radon concentration (with JP-SMM, Cz)
  - Gamma detection for security (with FORIMTECH-CH)
- Partnership with CAEN.s.p.a. for the development of a SiPM kit for Science & Education (http://www.caentechnologies.com/jsp/Template2/CaenProd.jsp?parent=61&idmod=1023)
- MODES-SNM, a Framework program 7 EC project on Homeland Security (ARKTIS detectors & CAEN)
- Two Homeland security projects [KROMEK, AWE (UK Atomic Weapons establishment)]
- Dual Readout Calorimetry (Texas Tech, Iowa State Uni., INFN, Nuclear Instruments)
- Radio-guided surgery (Light Point Medical, UK, completed)
- EasyPET 2D with CAEN and University of Aveiro (3D on the way)
- Dual Energy Bone densitometry (partnership with an Italian Company)
- Industrial Automation (Partnership with a Swiss company)
- Chemiluminescence (in partnership with 2 research institutions from Italy)
- Dosimetry and QC of radiotherapy machines with scintillating fibers (Ireland)
- “friendly” relationship with HAMAMATSU Europe & the other producers

Take Home Message: when you see a wave…

Never forget it is made out of drops!

Once more, thank you for listening!

Never forget it is made out of drops!

http://icasipm.org

Once more, thank you for listening!