Dipartimento di Fisica
Università di Torino
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The Power of One
Part 2

Exemplary systems &applications

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2+1exemplary systems, in increasing order of complexity (and cost)

1. Cheap & Chic: The ARDUSiPM

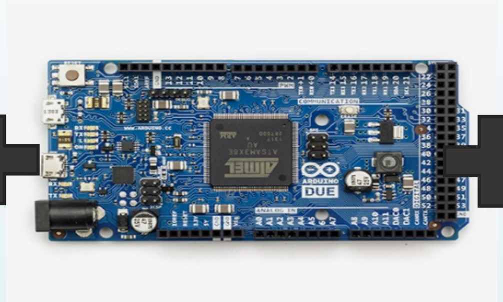
- V.Bocci et al., "The ArduSiPM a compact trasportable Software/Hardware Data Acquisition system for SiPM detector" http://arxiv.org/abs/1411.7814 (**DOI:** 10.1109/NSSMIC.2014.7431252)
- V. Bocci et al., "A low cost network of spectrometer radiation detectors based on the ArduSiPM a compact transportable Software/Hardware Data Acquisition system with Arduino DUE.» http://arxiv.org/abs/1506.01915" (**DOI:** 10.1109/ANIMMA.2015.7465621)

https://www.facebook.com/groups/ardusipm/

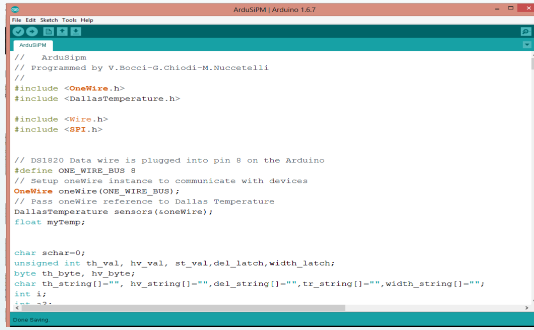
Scintillator

Photons Sensor (SiPM)

Custom Electronics (ArduSiPM Shield)



Arduino DUE



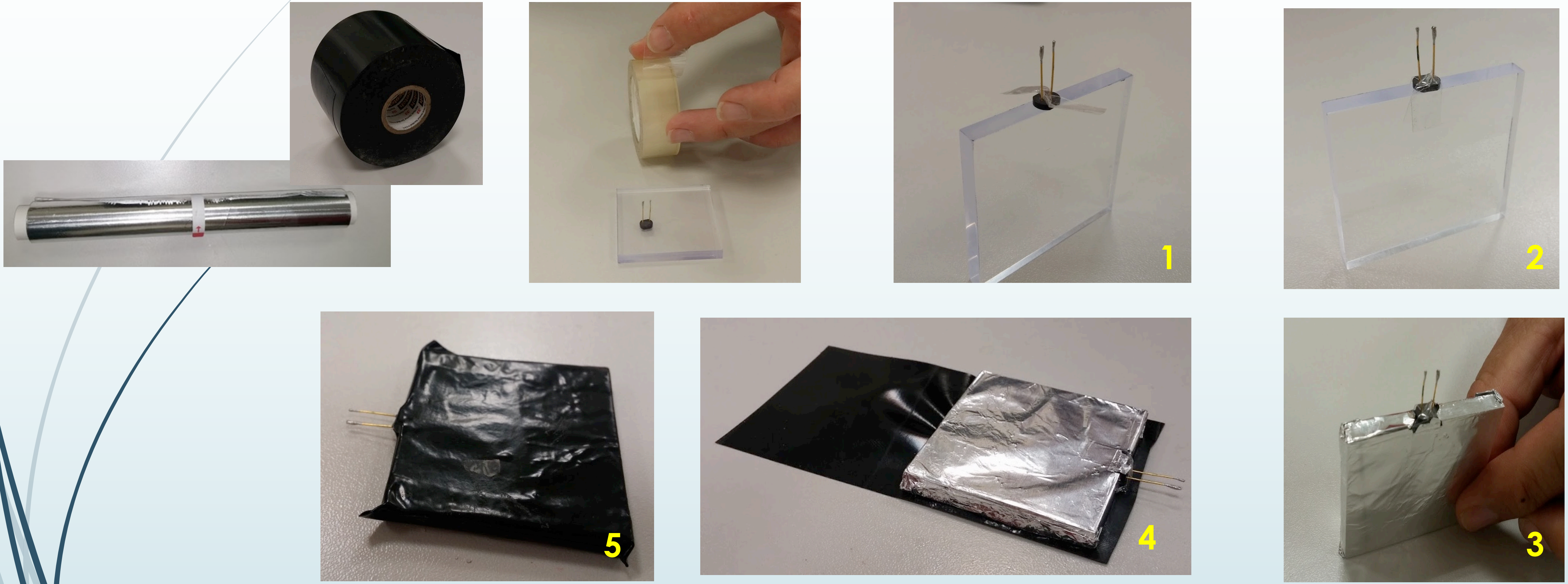
ArduSiPM Software

Particle Detector

ArduSiPM

A 564.99 EUR toy you can buy at www.robot-domestici.it

Intended for the genuine “makers”…



Build your own particle detector in 5 steps

But good enough for the professionals:

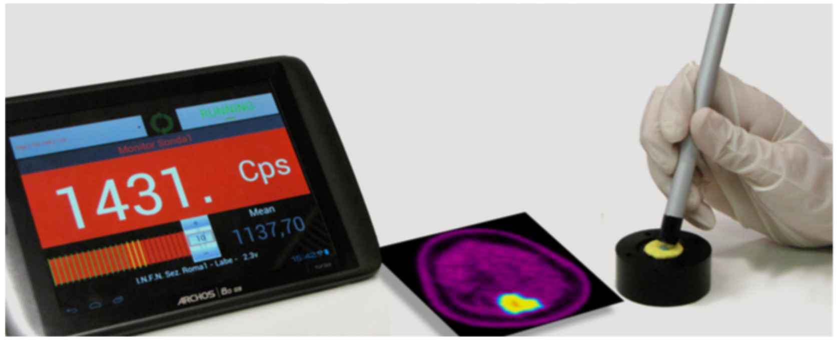
1.

nature.com > scientific reports > articles > article

SCIENTIFIC REPORTS

A novel radioguided surgery technique exploiting β^- decays

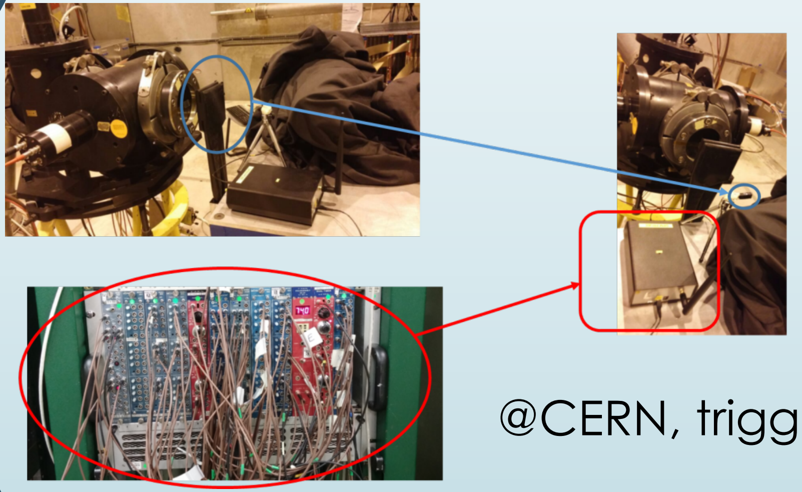
E. Solfaroli Camillocci, G. Baroni, F. Bellini, V. Bocci, F. Collamati, M. Cremonesi, E. De Lucia, P. Ferroli, S. Fiore, C. M. Grana, M. Marafini, I. Mattei, S. Morganti, G. Paganelli, V. Patera, L. Piersanti, L. Recchia, A. Russomando, M. Schiariti, A. Sarti, A. Sciubba, C. Voena & R. Faccini



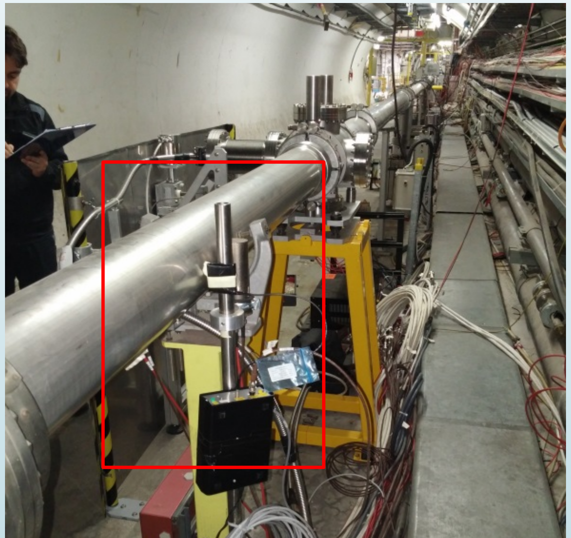
Wi-Fi data transmission to an ANDROID App

SCIENTIFIC REPORTS | 4 : 4401 | DOI: 10.1038/srep04401

2.



@CERN, trigger at the H8 beam line



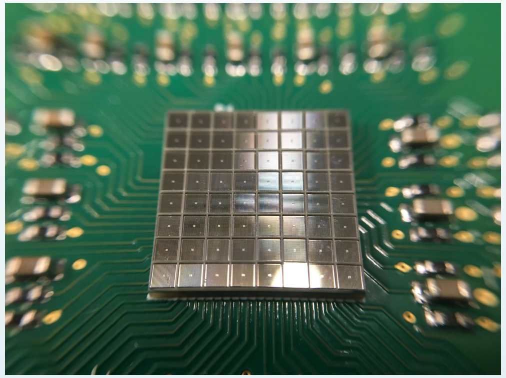
Beam loss monitor at the sps

2. Quite sophisticated (but not horribly expensive): a MADA based 64 channel system for the HAMAMATSU SiPM "imager"

Nuclear Instruments &

UNIVERSITAS · STUDIORUM INSUBRIAE

http://www.nuclearinstruments.eu



The S13615-1050N-08 array
(8x8 channels, 1 mm^2 pixels)

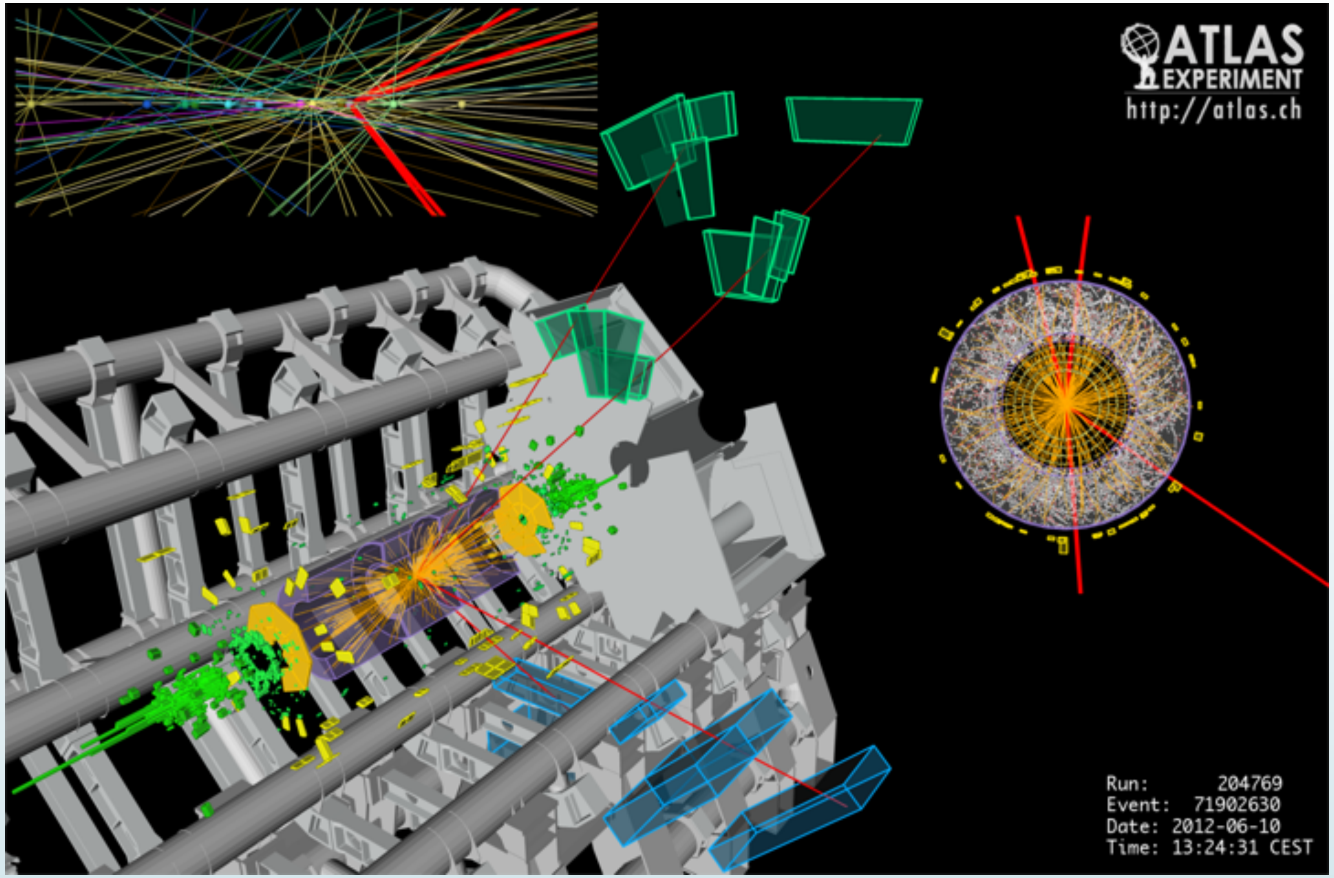
Features of the Main board:

- Snap-in detector daughter card
- 64 channels readout board.
- Trans-impedance amplifier circuit with 1µs shaping time and selectable gain
- Integrated differential cable drivers
- Programmable HV voltage generator
- Fine control of the HV bias independent for each channels (0, -3v)
- Temperature sensor placed on the detector board
- Identifier eeprom on both amplifier and detector board

Features of the MADA:

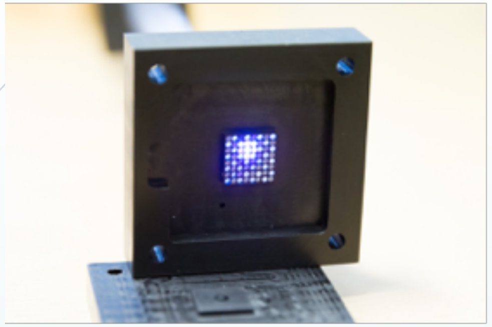
- The MADA is a multichannel read out system
- 32 80Msps/14-bit ADC, used to acquire up to 32 analog inputs.
- FPGA based charge integration algorithm.
- The output of the board is a list of event timecode and intergated charge measured on all pixels.

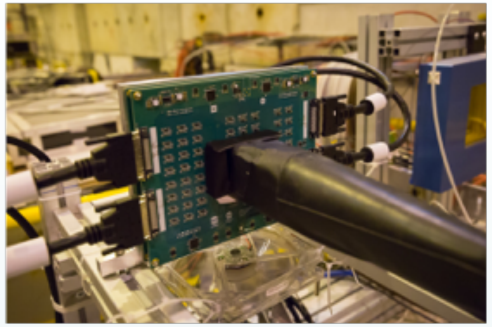
Why did we do it? Well, because we have a DREAM (http://highenergy.phys.ttu.edu/dream/) - Richard Wigmans (TTU) & John Hauptman (Iowa State University)

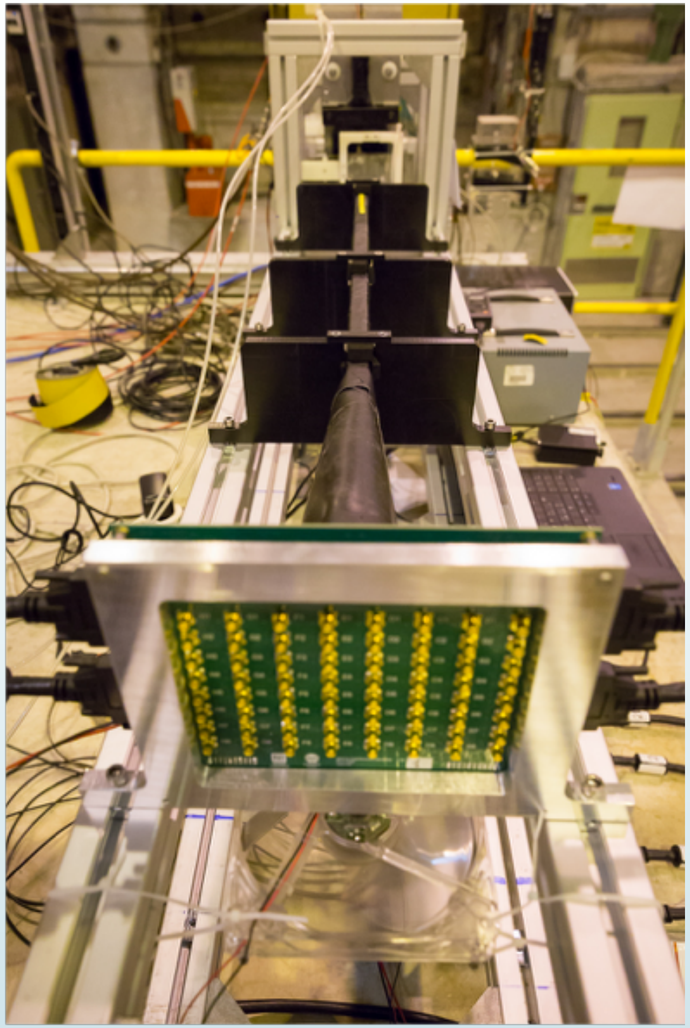


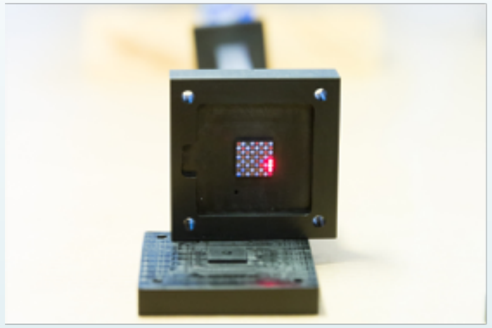
Event display of a H -> 4muon candidate event with m(4l) = 124.1 (125.1) GeV.
The event was recorded by ATLAS on 10-Jun-2012, 13:24:31 CEST in run number 204769 as event number 71902630. Muon tracks are colored red.

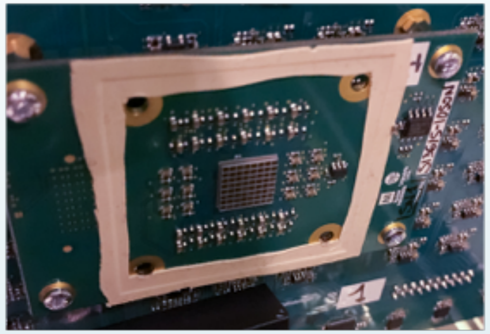
It is a small DREAM by now…

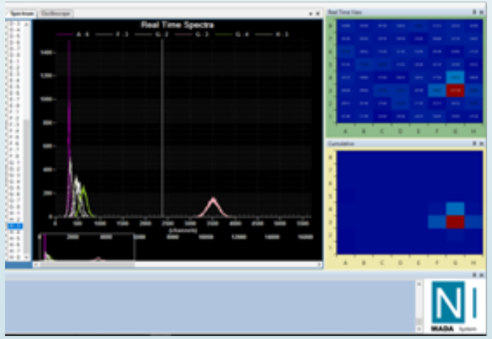


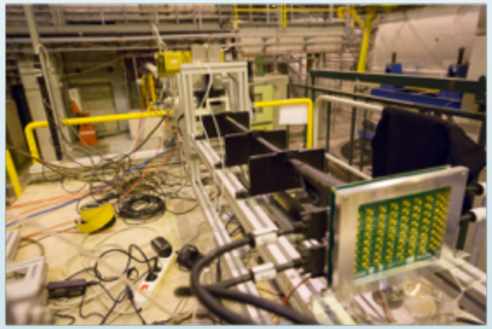








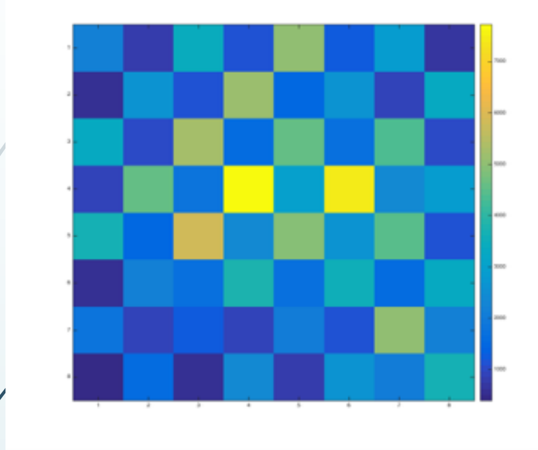




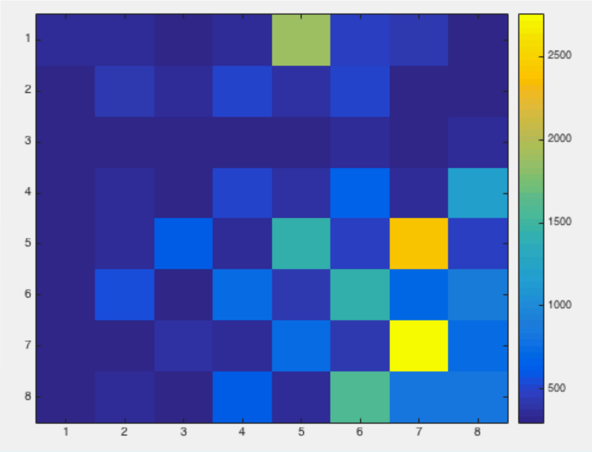
But in June 2016 we were told to have a chance to test it on beam at CERN in October

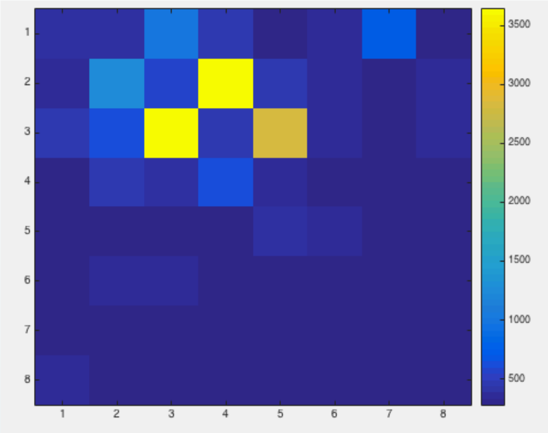
And we made it!

Centered



Off-centered

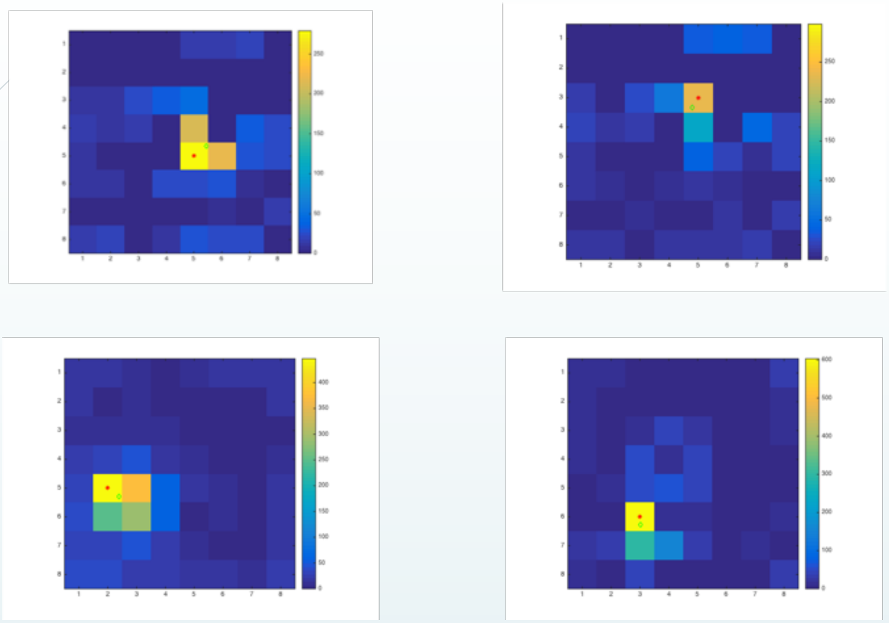


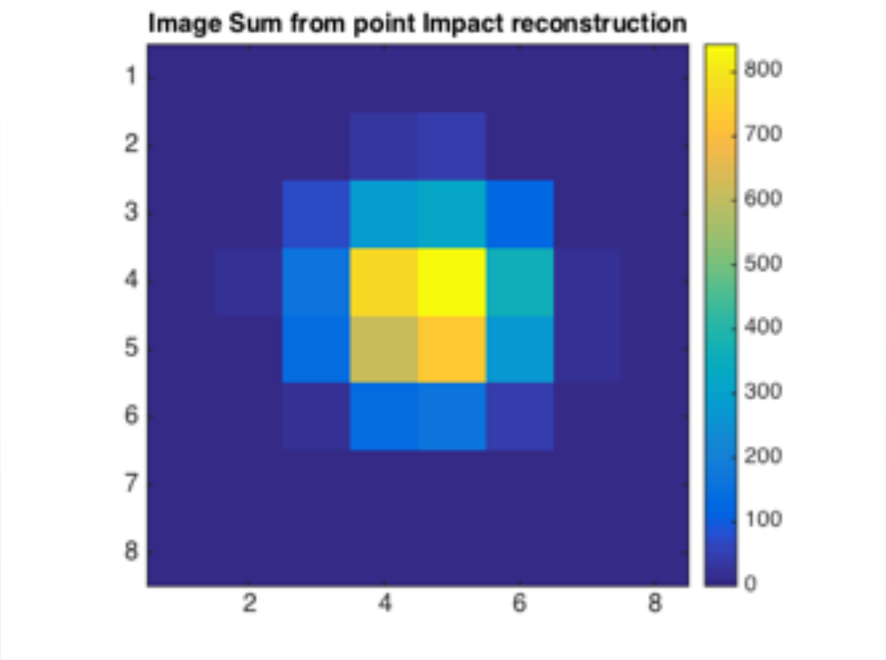


40 GeV electrons

A muon

Quantum² imaging of a radioactive source





And once you have it, there’s a lot more you can do

[images of single β particles from a 90Sr radioactive source impacting on a thin scintillator coupled to the array. The reconstruction of the impact points allow to visualize the source activity profile]

Single photon Sensitive device

biotech

bioluminescence

Single molecule detection

imaging

Metrology

Detector Calibration

Quantum standards

Hyper-spectral imaging

Primary radiometric scales

Quantum info processing

imaging

cryptography

computing

Single photon sources

Medical Physics

Imaging

radioactivity

Nuclear Medicine

Military

Night Vision

Security

Chem-Bio Threat

Meteorology

Remote Sensing

Lidar

Environmental monitoring

Space

Ch. Telescope Array

IR detectors

Robust imaging devices

Electronics

Lighting

Displays

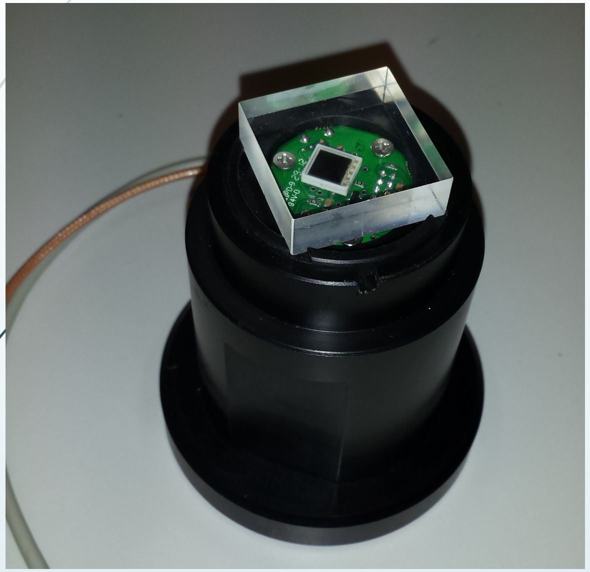
Entertainement

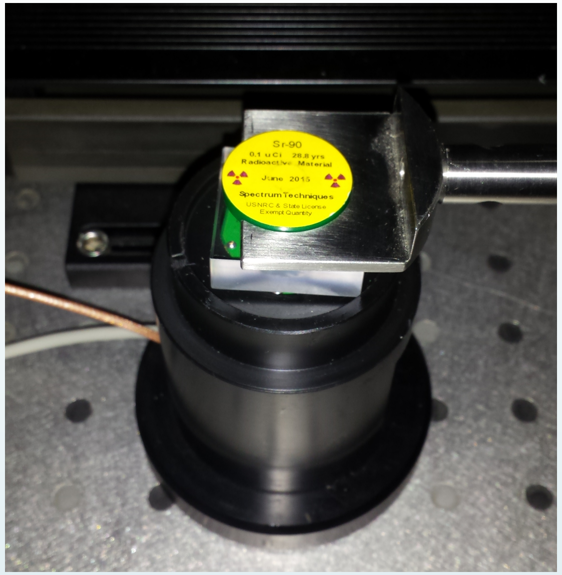
Summary Table from http://www.photoncount.org

Before we start, we shall consider that the SiPM can be used in (at least) 3 different modes of operation:

- Pulse mode (analog or digital (if counting only is required))
- Continuous mode
- Timing

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





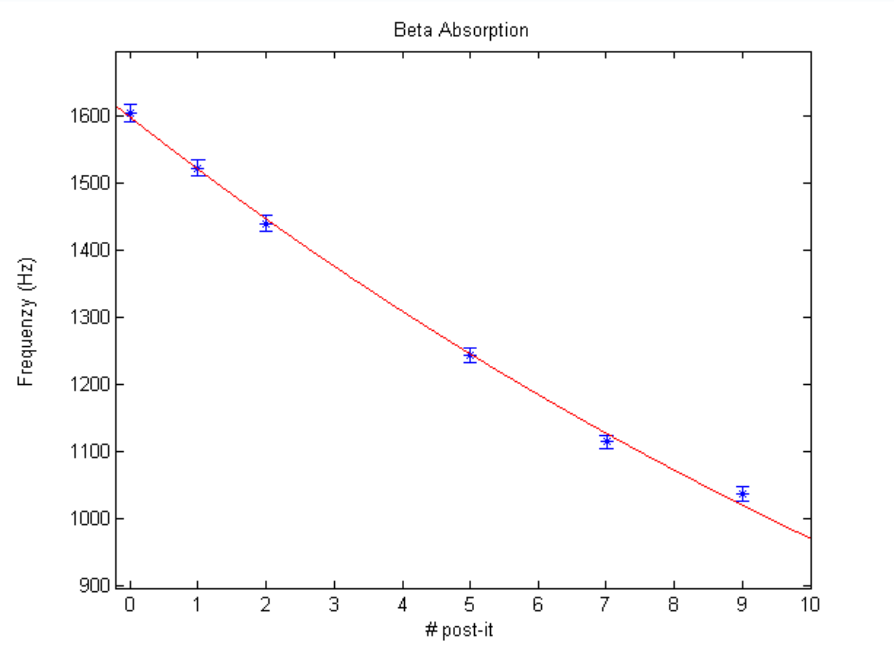
- 6x6 mm^2 SiPM
- 1 cm thick plastic scintillator

- 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)



Counting frequency

No. post-it sheets

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

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 (3/3):
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.

Contact Sales
+1 866 282 0430 | Submit a product question

Contact Support
+1 866 282 0430 | Submit a support or service question

Pulse Mode (counting): 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.

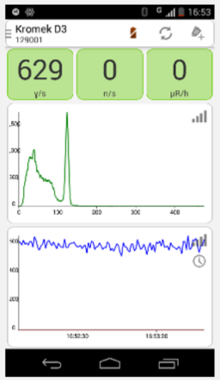
Specifications:	
Equivalent to 100mm x 13mm Ø ^{3}He at 4 atmospheres	
Photo-sensor	SiPM array
Thermal Neutron Sensitivity	>50%
Maximum throughput	10,000 cps
Power consumption	250 mW
Dimensions	131mm x 33mm x 24mm
Weight	110 gram
Temperature range	-10 to 40°C

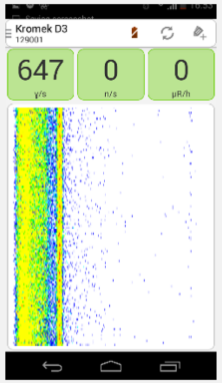
TN15 ™ by KROMEK, Sedgefield County Durham, UK
www.kromek.com

The 2015 blockbuster (counting & spectrometry)

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



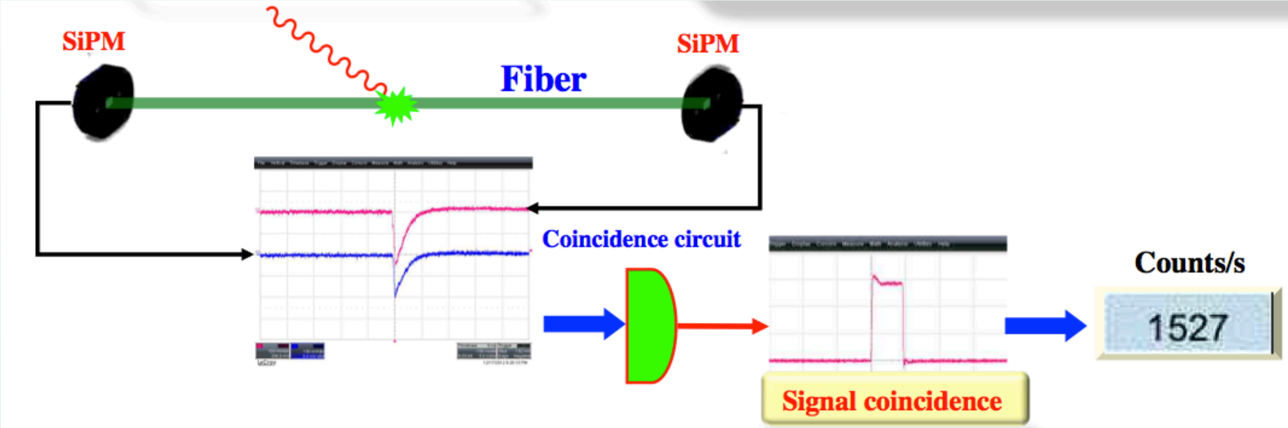


Pulse mode (counting): a monitor for Nuclear Waste drums

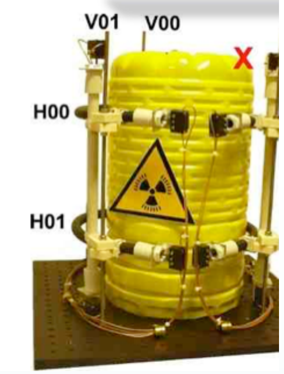
Paolo Finocchiaro, Nuclear Physics News,
http://dx.doi.org/10.1080/10619127.2014.941681

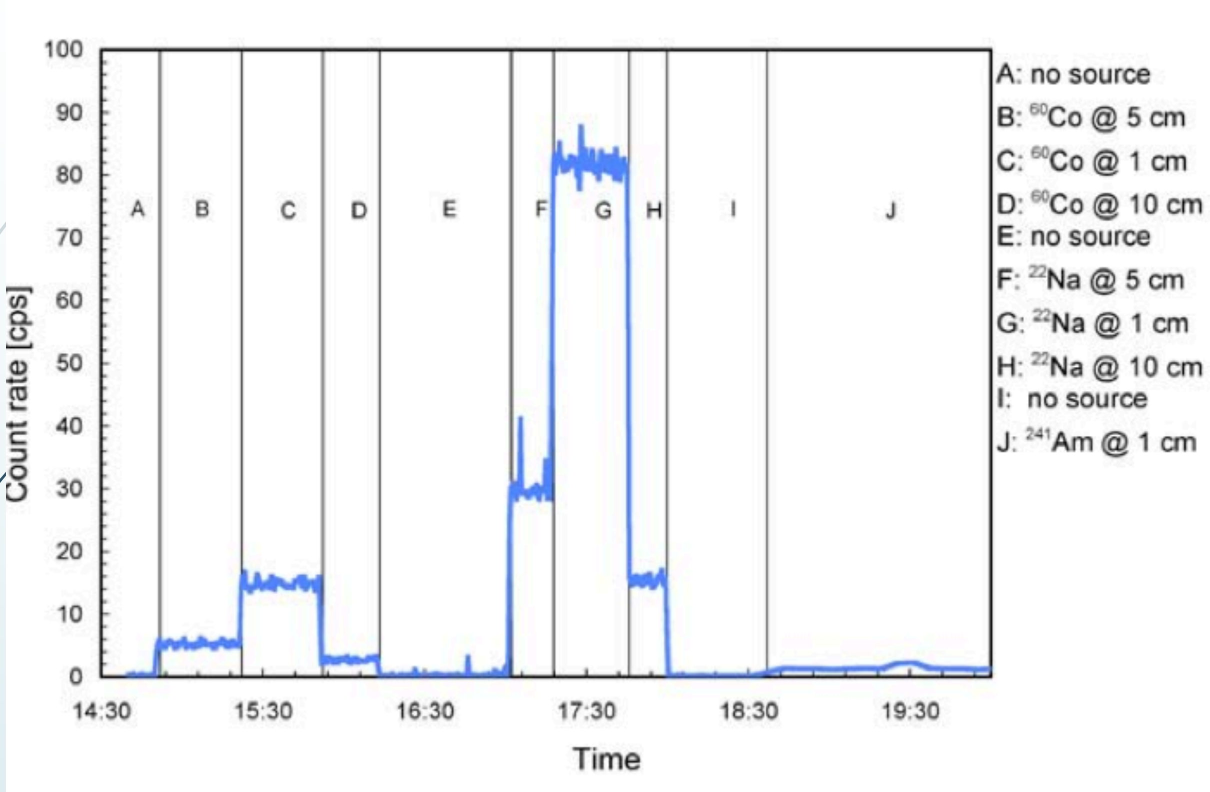
❖ Goal: online monitoring of radiation emitted by nuclear waste drums

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



Qualification results:





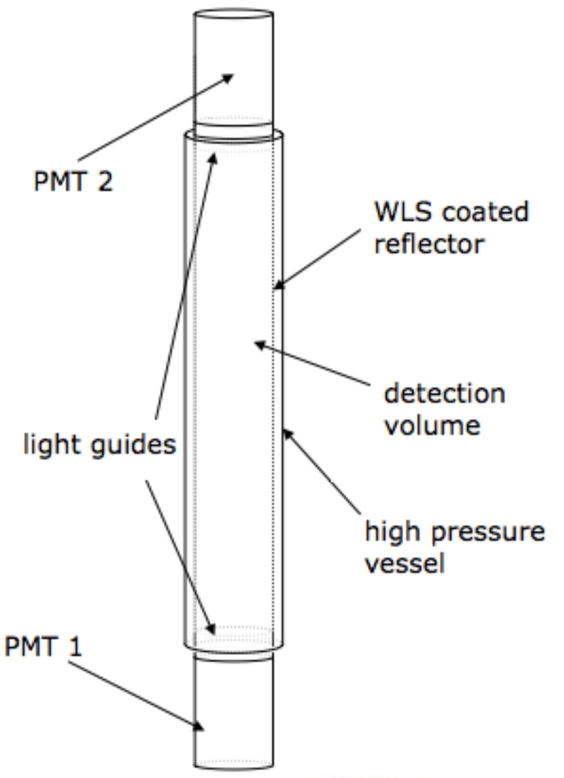
- ^{60}Co, 35 kBq
- ^{22}Na, 243 kBq
- ^{241}Am, 36 MBq
- ^{137}Cs, 231 kBq

- 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

Pulse mode: Homeland security. Silicon photomultiplier readout of a scintillating noble gas neutron detector (2012-2014)

[M. Caccia et al. ANIMMA2013, MODES-SNM DOI: 10.1109/ANIMMA.2013.6727974

http://www.modes-snm.eu/



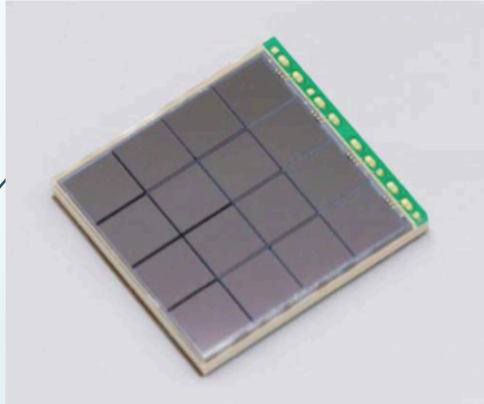
Special Nuclear Material detection by identifying a flux of fast neutrons in a high-pressure tube filled with high pressure (180bar) ^{4}He scintillating gas

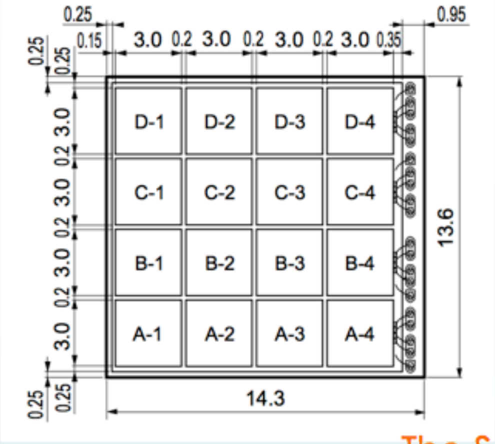
	State of the art	This proposal	Comment
Thermal neutron detection	He-3 proportional counter (until 2009) Replacement technology candidates under evaluation	Noble gas scintillation detector lined with neutron capturing material such as Gd	He-3 proportional counters have become obsolete due to the high cost of the filling gas. This proposal will develop a novel thermal neutron detector based on Arktis technology
Fast neutron detection (new concept, see below)	No such detectors included in current radiological screening systems	Pressurized He-4 scintillation detector	Detection of fast neutrons allows larger standoff distances and increased sensitivity for highly shielded SNM [4]
Gamma detection	PVT or NaI(Tl)	Pressurized Xe scintillation detector	Improved energy resolution, less temperature dependence, lower cost, better ruggedness [13]

Project Objectives

MPPC for MODES

GROWING UP...





The S11829-3344MF
monolithic array of SiPM units

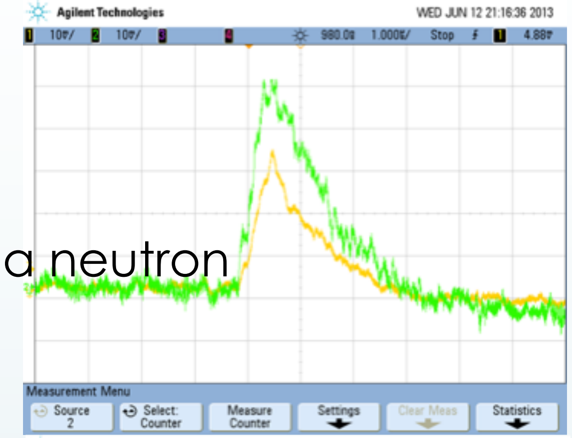
■Specifications

Parameter	Condition	Value	Unit
Number of elements		16 (4 x 4)	elements
Effective active area / channel		3 x 3	mm
Pixel pitch		50	µm
Number of pixels / channel		3600	-
Number of pixels / device		57600	-
Fill factor		61.5	%
Photon detection efficiency *	λ=440 nm	50	%
Dark current / channel	per channel	3	µA
Terminal capacitance / channel		320	pF
Gain		7.5×10^5	-

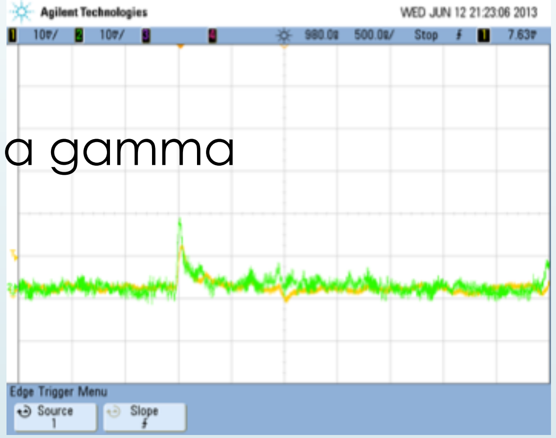
* Includes cross-talk and after-pulse

Main drive:
- increased light detection efficiency
- engineering optimization

Qualification of a prototype detector



Signal by a neutron



Signal by a gamma

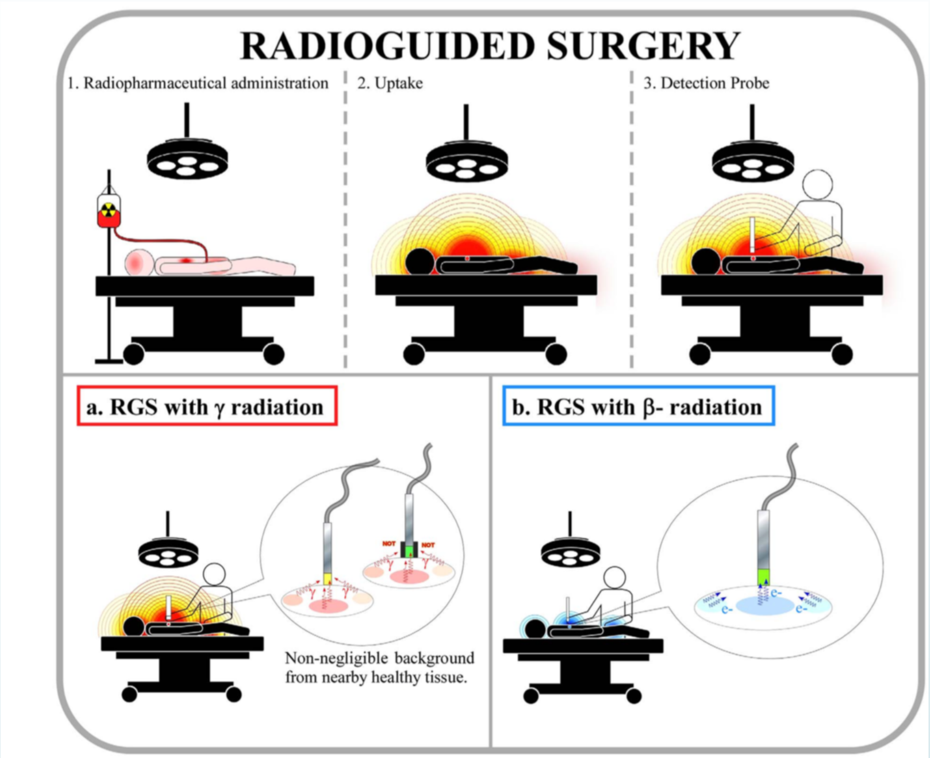
Main Result	single arm	coincidence
γ rejection power	92%	99%
n selection efficiency	94%	88%

Corresponding to:

- ❖ fast neutron detection efficiency ~3%
- ❖ gamma rejection at the 10^6 level

Pulse mode: 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

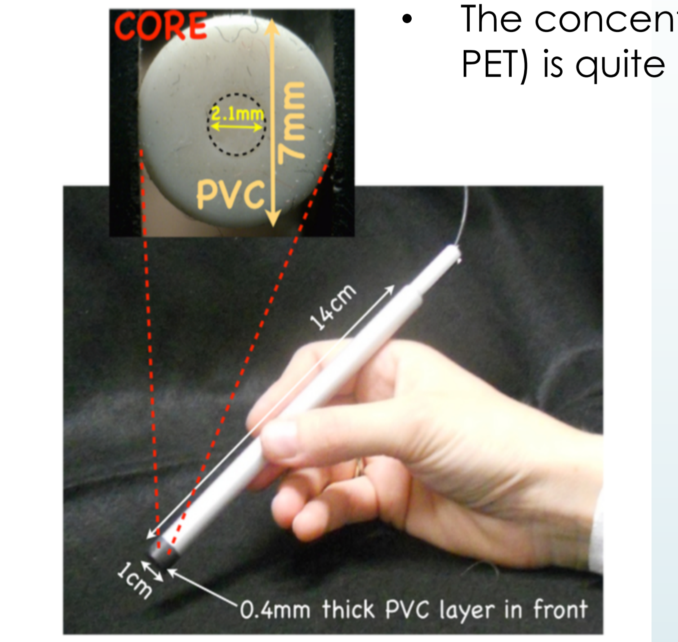


Figure 2 | First prototype of the intraoperative β^- probe. The core is a cylindrical scintillator (diameter 2.1 mm, height 1.7 mm) of poli-crystalline p-terphenyl. A ring of PVC wraps the scintillator and shields it against radiation coming from the sides. The device is encapsulated inside an easy-to-handle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

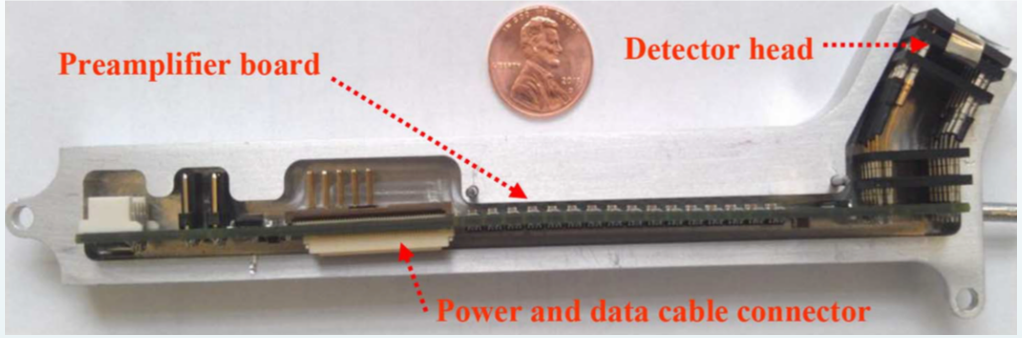
Phantom	Diameter (mm)	Height (mm)	Volume (ml)	Rate (cps) 22 kBq/ml	T (s) 22 kBq/ml	Rate (cps) 5 kBq/ml	T (s) 5 kBq/ml
Residual	6	3.5	0.10	31.6	1	6.6	2
H1	4	1	0.01	12.4	2	2.6	>10
H2	4	2	0.02	17.7	1	3.7	4
H3	4	3	0.04	20.1	1	4.2	4

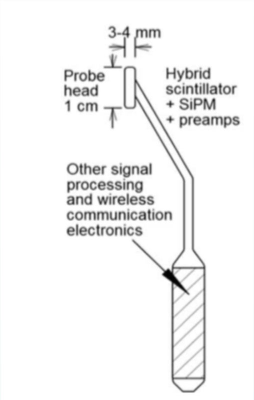
Time required to get False Negative < 5% and False Positive ≈ 1%

RGS with β^+ (ref.3) (1/2)

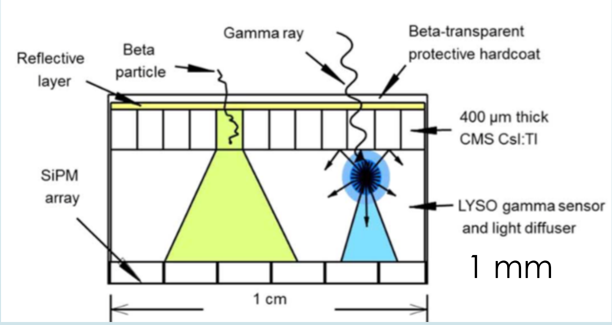
An IMAGING DEVICE engineered to detect β^+ emitting isotopes irrespective from the γ background

- Conceptual design & prototype of the probe





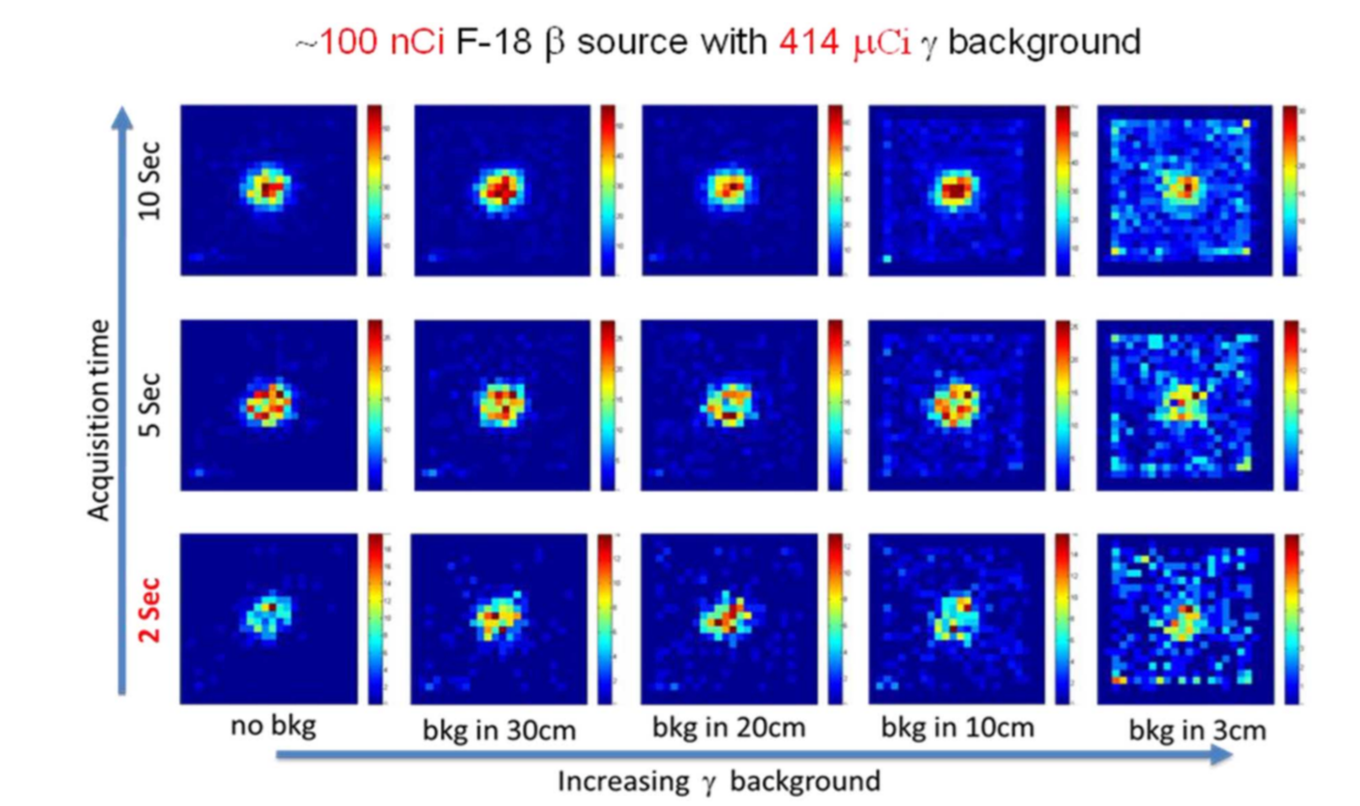
- A head designed to identify and discriminate β^+ from γ



- 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

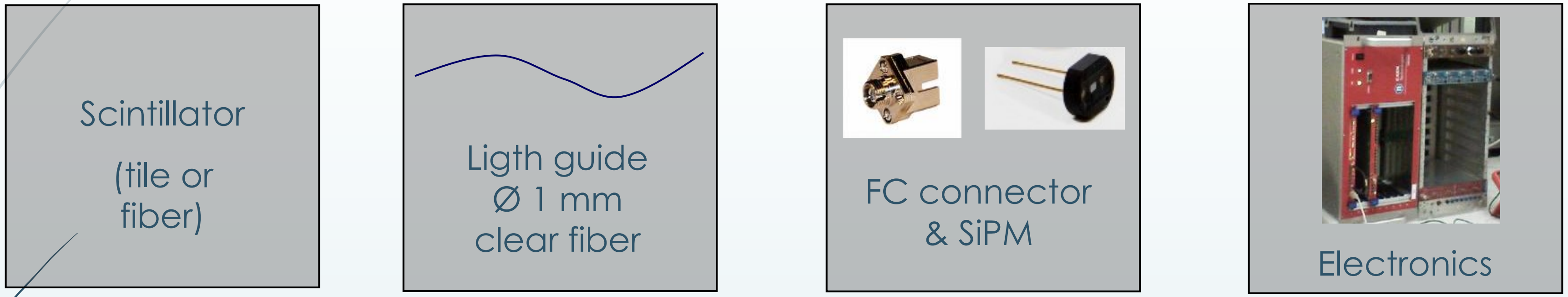
Some *functional requirements*:

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

PTW

Prototype qualification

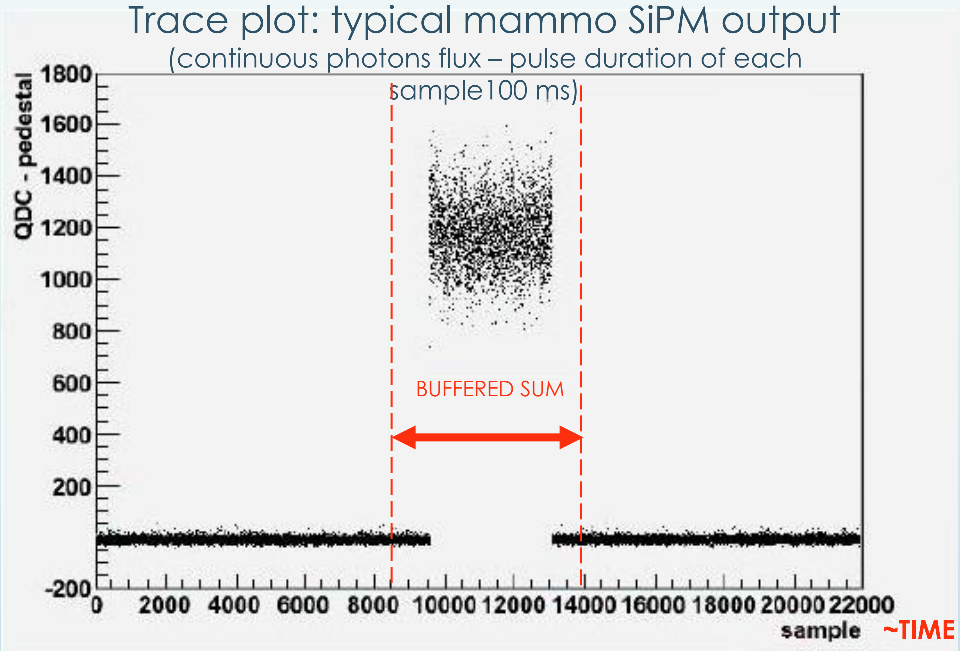
Conceptual design of the prototype tested @ PTW – secondary standard lab for dosimetry:



PHISYCAL OBSERVABLE:
"buffered" signal sum

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

⇒ proportional to the DOSE



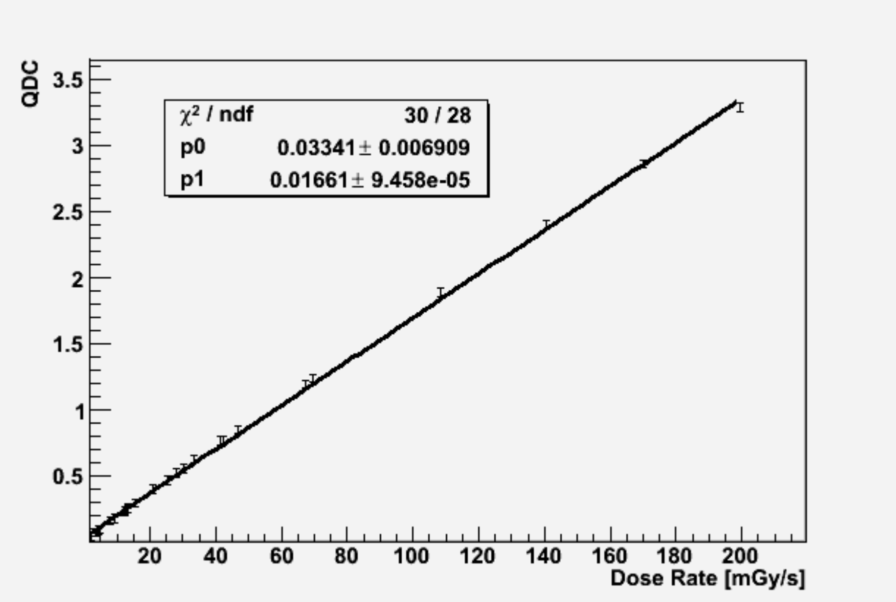
summary of the results

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

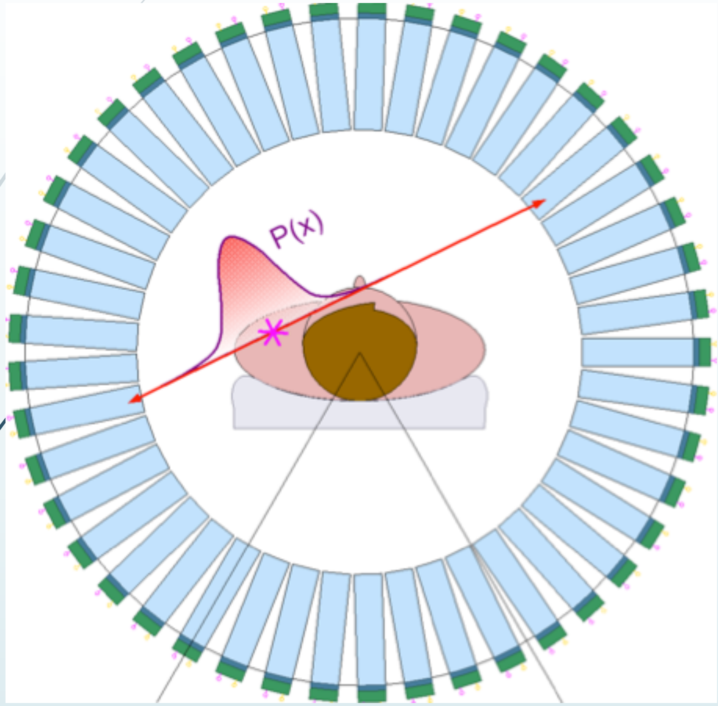


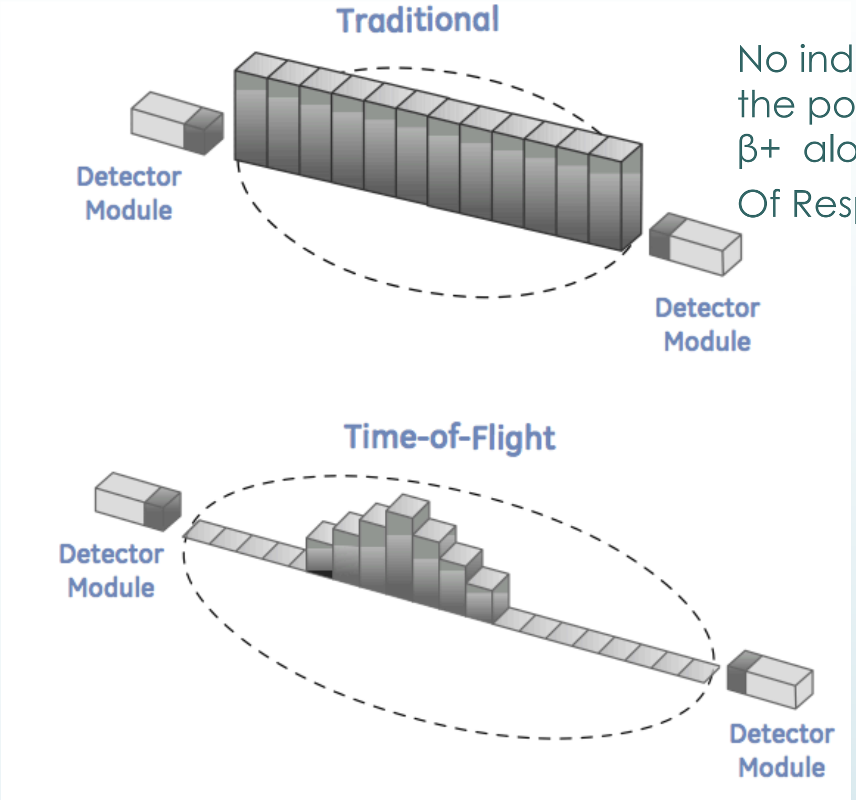
	Fiber + Hamamatsu MPPC
Precision(%)	2.31 ± 0.03
Sensitivity^A (mGy/s)	2.05 ± 0.03
MDS^B (mGy/s)	0.458 ± 0.007
Linear Dinamic range (mGy/s)	> 200

^{A}Sensitivity: Precision / system gain

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

Time-of-flight Positron Emission Tomography (TOF-PET) 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]:

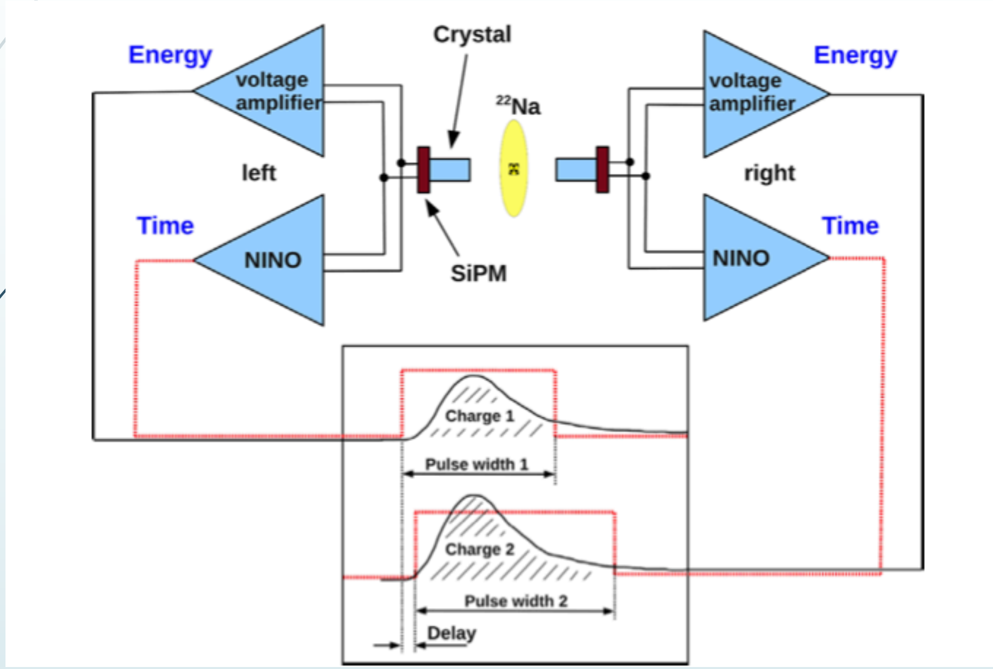
$$G = \frac{SNR_{TOF}}{SNR_{non-TOF}} = \sqrt{\frac{D}{c*CTR}}$$

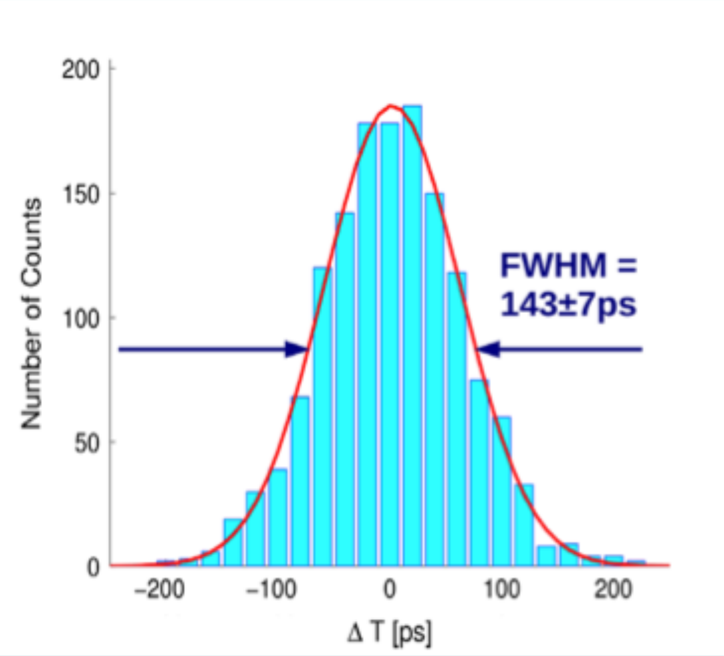
- D = volume being inspected
- c = speed of light
- CTR – Coinicidence Time resolution

CTR	G	
1 ns	1.6	
500 ps	2.3	← Current machines
100 ps	5.2	← TARGET

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

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]:





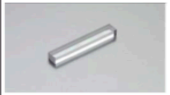
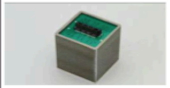
•[3x3 mm^2, 50 micron cell pitch]
• 2x2x10 mm^3 LSO crystal

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

Actually, HAMAMATSU is well aware of the relevance of crystals:

LFS scintillation crystals: Industry product comparison

Parameter \ Crystal*	Tl:NaI	BGO	LSO	GSO	LYSO	LFS
Density, g/cm^3	3.67	7.13	7.4	6.71	7.1	**7.35**
Effective at. number	51	74	66	57	66	**64**
Attenuation length, cm	2.6	1.11	1.14	1.38	1.12	**1.15**
Decay constant, ns	230	300	40	30–60	41	**< 33**
Max emission, nm	415	480	420	430	420	**425**
Light yield (NaI:Tl=100%)	100	7–12	40–75	20	70–80	**80–85**
Refractive index	1.85	2.15	1.82	1.85	1.81	**1.81**
Energy resolution ^{137}Cs, %	8	12–14	10–14	9.5	8.0	**8**
Absorbed γ-ray irradiation dose, rad (rad. hardness, %/cm)†	10 (?)	10^{2-3} (?)	10^8 (7)	10^{8-9} (6)	10^8 (7)	**10^8 (2)**
Hygroscopicity	strong	No	No	No	No	**No**
Hardness, Moh	2	4.5	5.8	5.7	5.8	**5.8**
Cleavage	(100)	none	none	(100)	none	**none**
Boule size, mm	∅400x600	∅100x250	∅75x200	∅75x150	∅75x150	**∅90x250**

Item	Image
LFS 3x3mm 1x1ch	
LFS 3x3mm 4x4ch	
S12572-050J MPPC-LFS 3x3mm 1x1ch	
S12642-0404JB-50 MPPC-LFS 3x3mm4x4ch	

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

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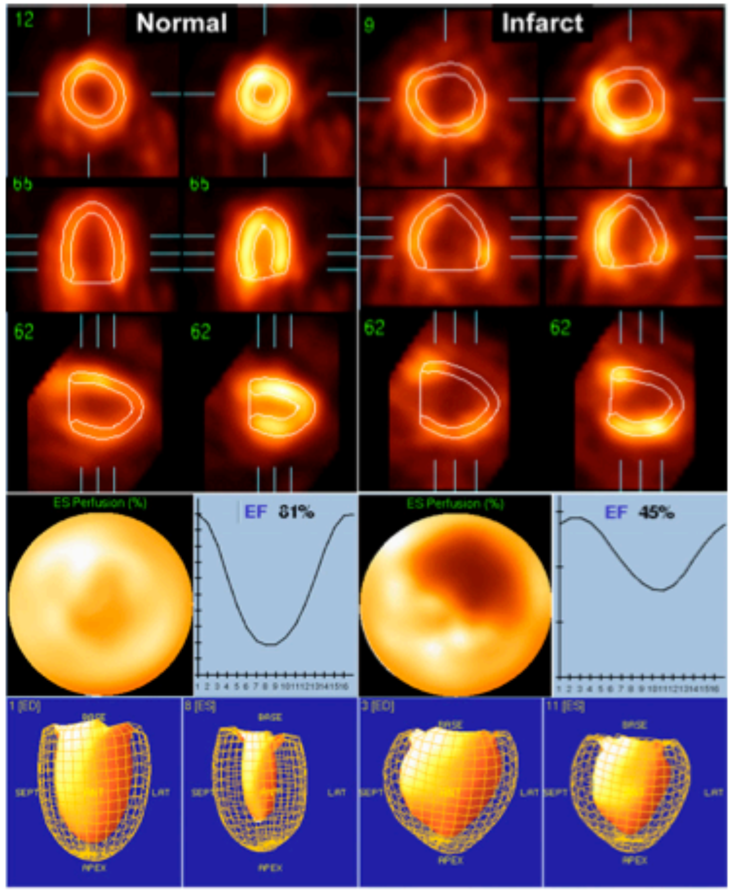
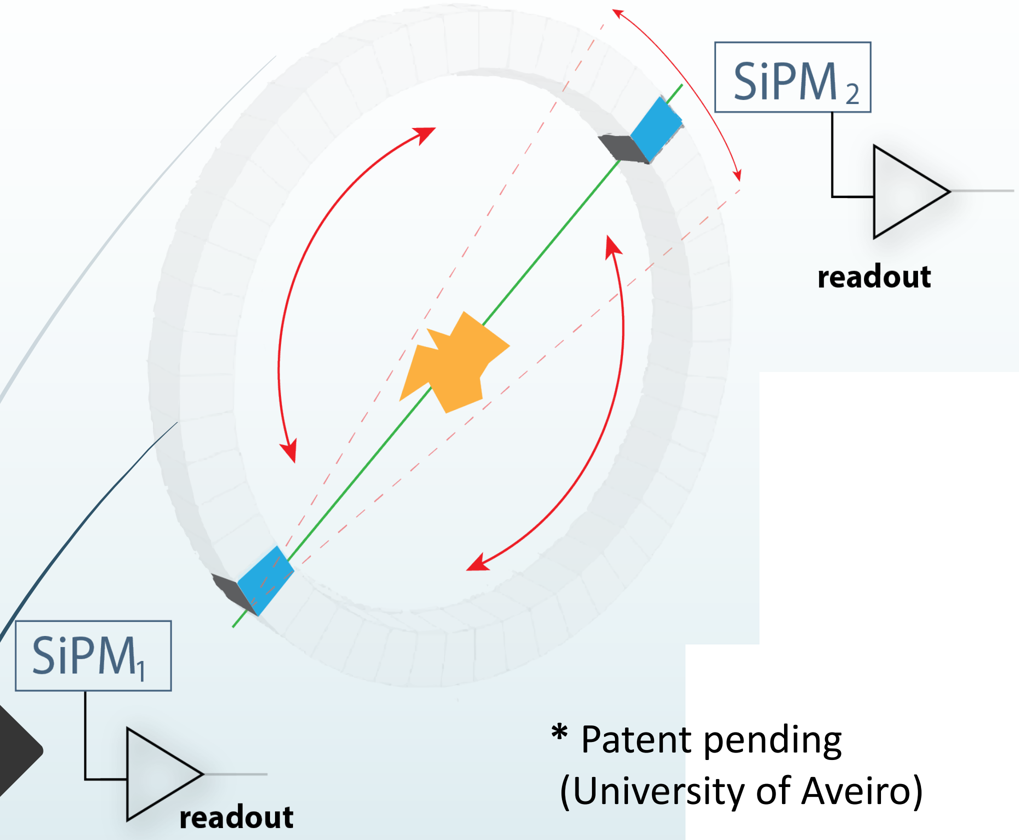


FIGURE 5. Electrocardiogram-gated ^{18}F-FDG studies in normal and infarcted rats obtained using clinical cardiac analysis software QGS (56). Polar maps display end-systolic ^{18}F-FDG uptake. Ejection fractions for normal and infarcted rats are 81% and 45%, respectively. ED = end-diastolic; EF = ejection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

partners:

universidade de aveiro

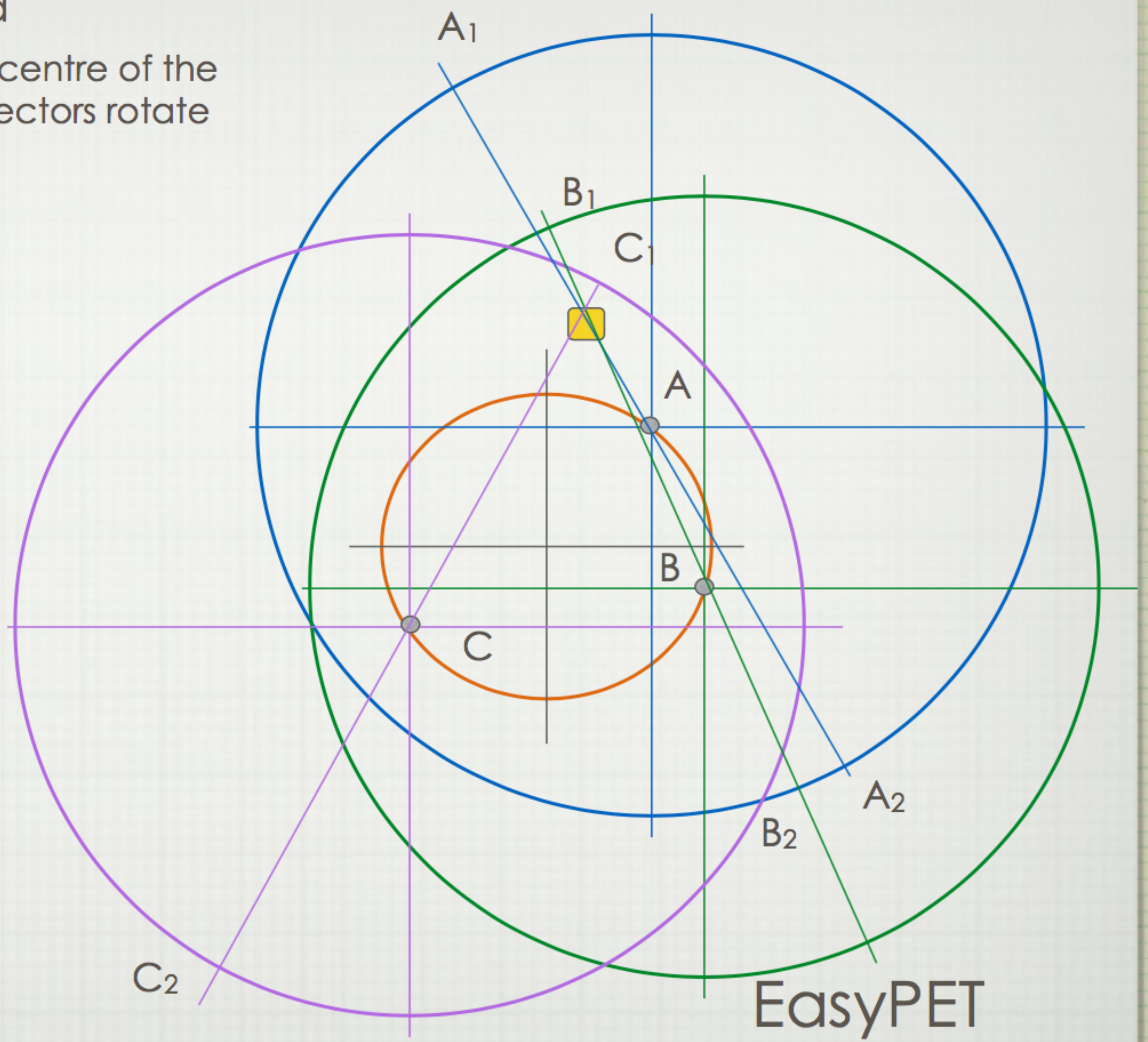
CAEN Tools for Discovery

Radioactive ^{22}Na seed

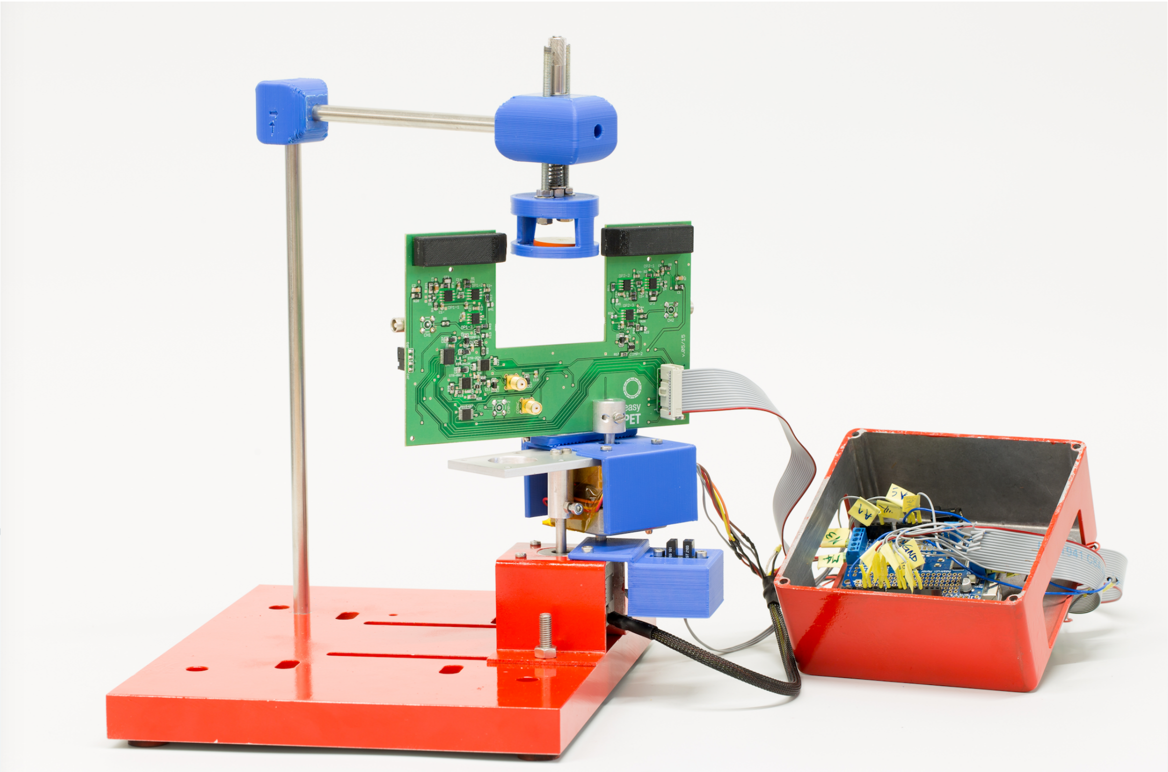
Circle along which the centre of the axis between the 2 detectors rotate

Basic Principle:

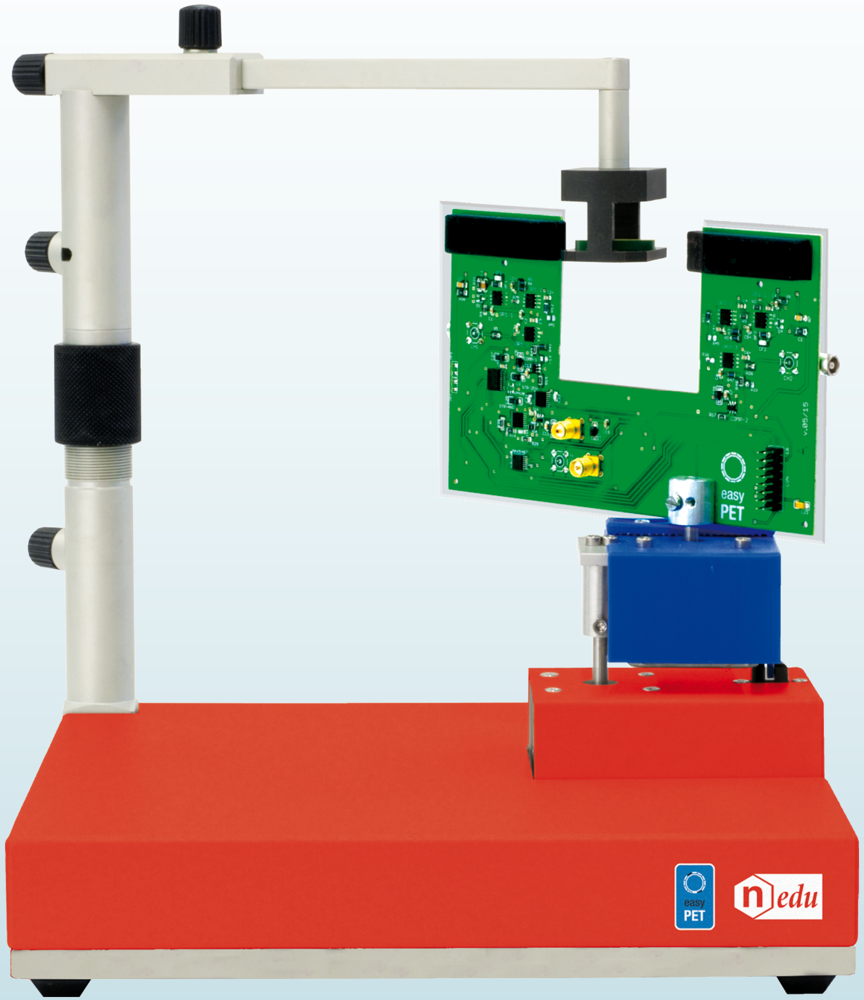
- the system is based on 2 detectors, aligned at a distance corresponding to the diameter of the big circles(e.g. A_1A_2)
- the 2 detectors undergo a full φ rotation around the center
- moreover, the center of the big circles after every azimuthal scan moves along the small circle
- ∀ position of the center(e.g. A,B, C), a φ scan of the detectors will identify the Line of Response, corresponding to maximum in the coincidence rate of events. The azimuth of the LOR is a function of the position of the center (e.g. A_1A_2, B_1B_2, C_1C_2)
- The intersection of the LOR's identifies the position of the source, on the base of 2 detectors only rather than a full ring



EasyPET



The prototype (2015)

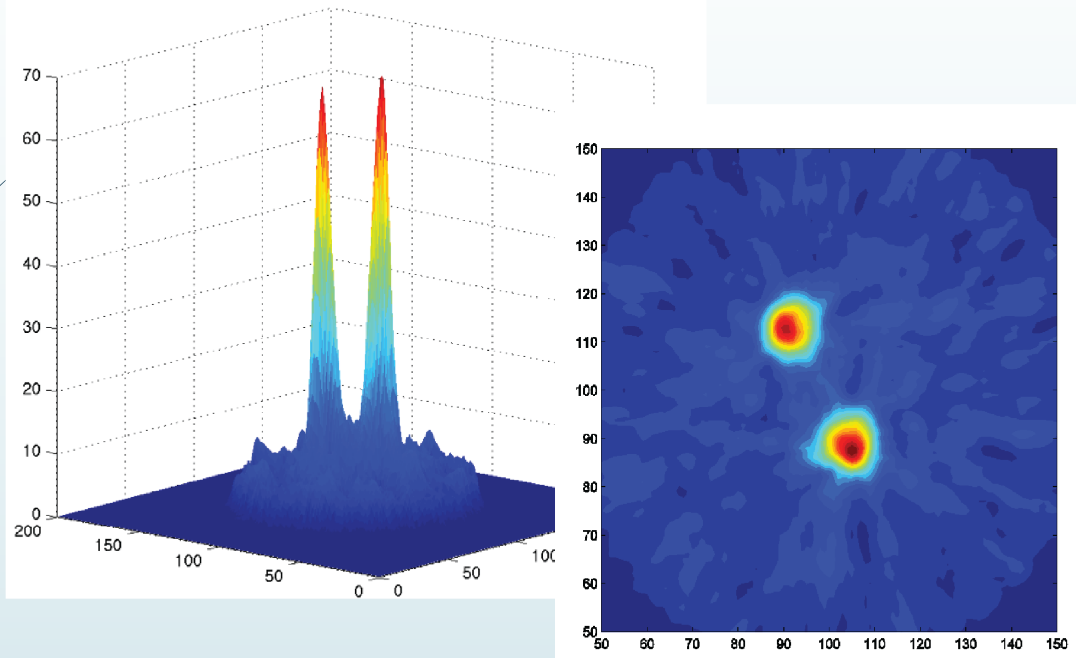


The product (2017)

current status:

fully functional educational system developed*

- 2D prototype designed, engineered and commissioned
- 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

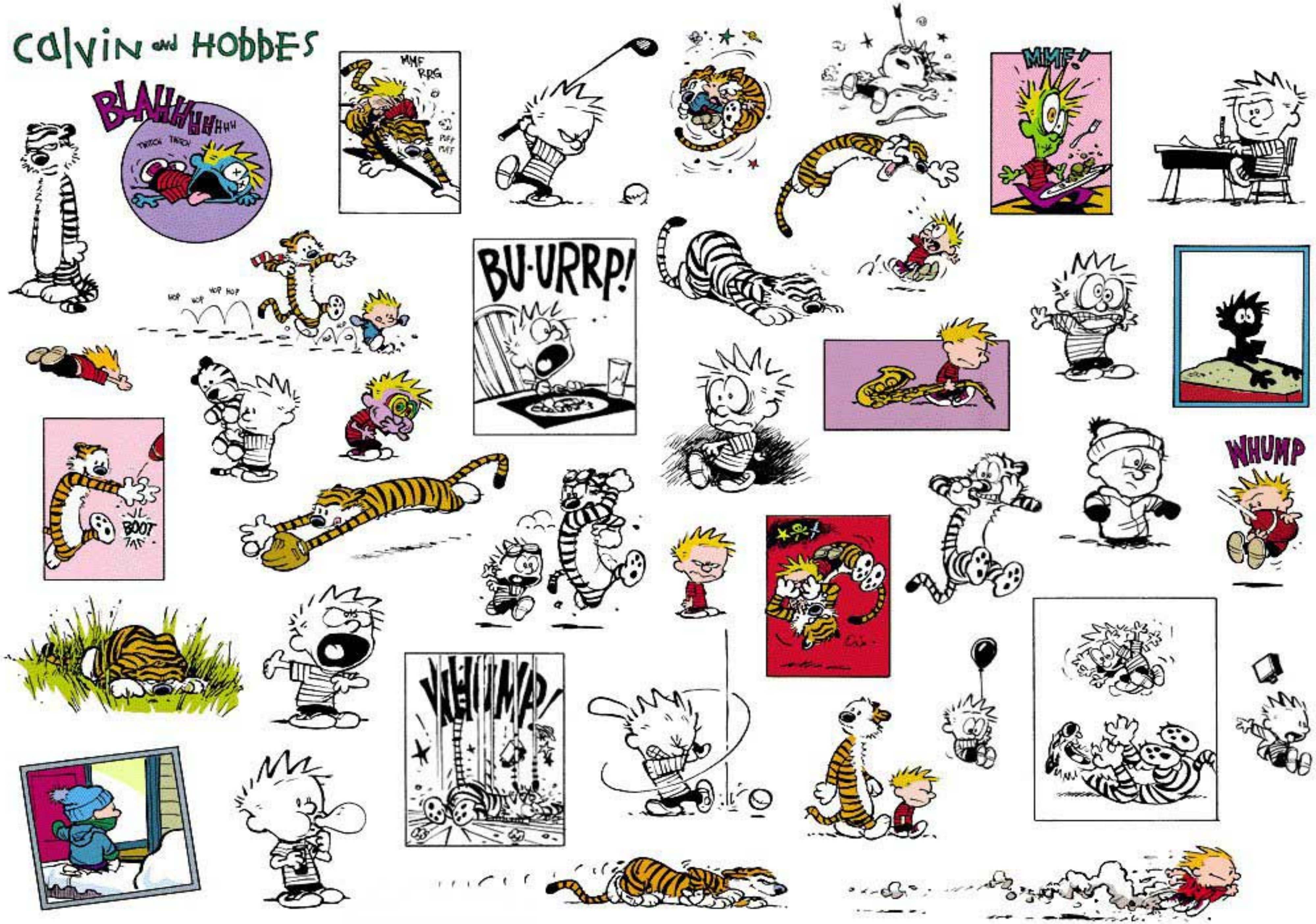
partners:

universidade de aveiro

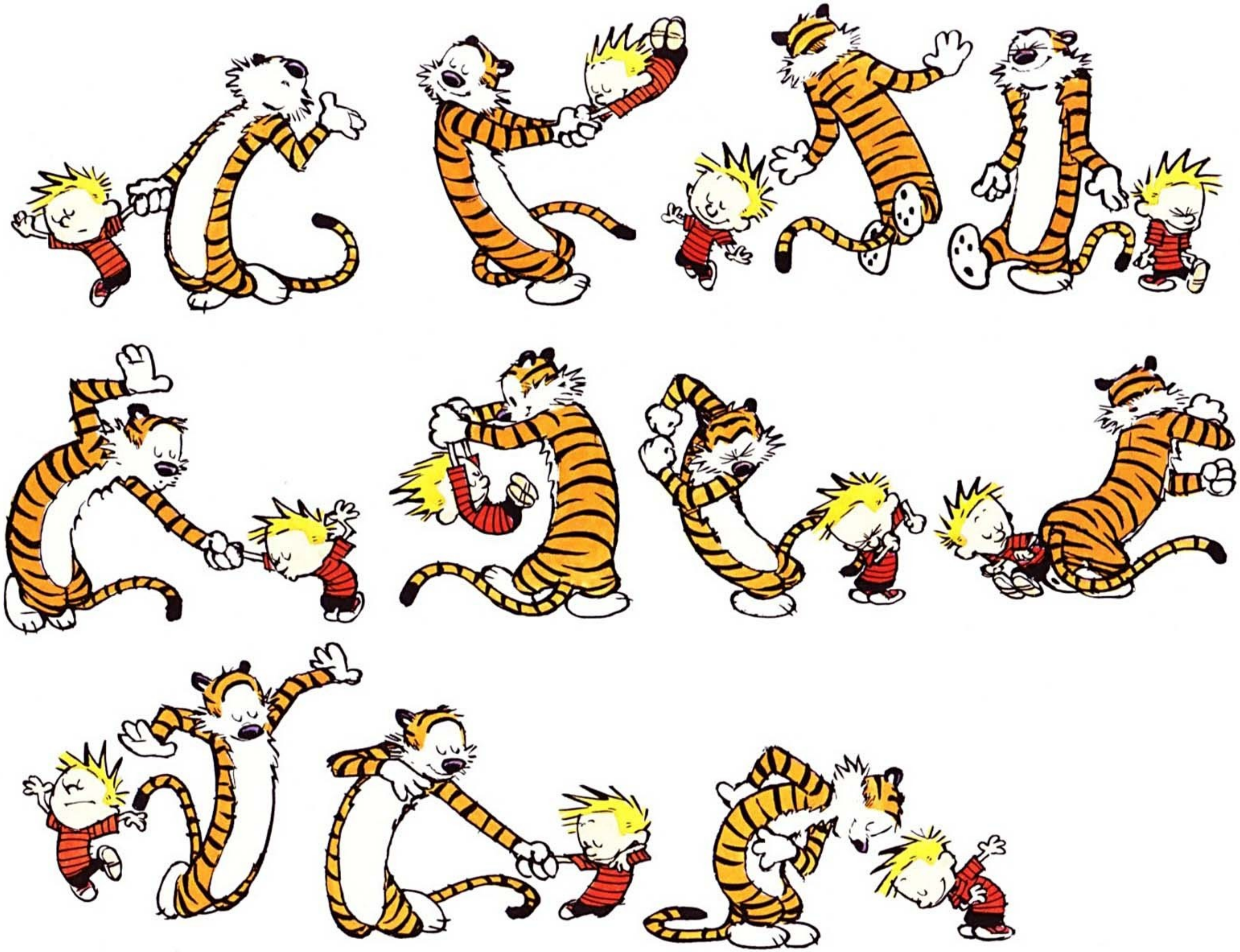
CAEN Tools for Discovery

What are current projects today (March 2017, not prioritized)?

- Homeland security [KROMEK, AWE (UK Atomic Weapons establishment)]
- Dual Readout Calorimetry (Texas Tech, Iowa State Uni., INFN, Nuclear Instruments)
- A super-classified project (ssshhhhhh….)
- Radio-guided surgery (Light Point Medical, UK, nearly completed)
- EasyPET 3D
- Fresh after the 2016 Technology Days:
  1. Bone densitometry (Italy)
  2. Industrial Automation (Switzerland)
  3. Landscape topography (Sweden)
  4. Fluorescence Lifetime Imaging (Switzerland)
  5. Dosimetry and QC of radiotherapy machines with scintillating fibers (Ireland)



Typical reactions when people are approached



But at end of the day, you & your partner may be quite happy…