Axial PET a new concept for brain and small animal imaging

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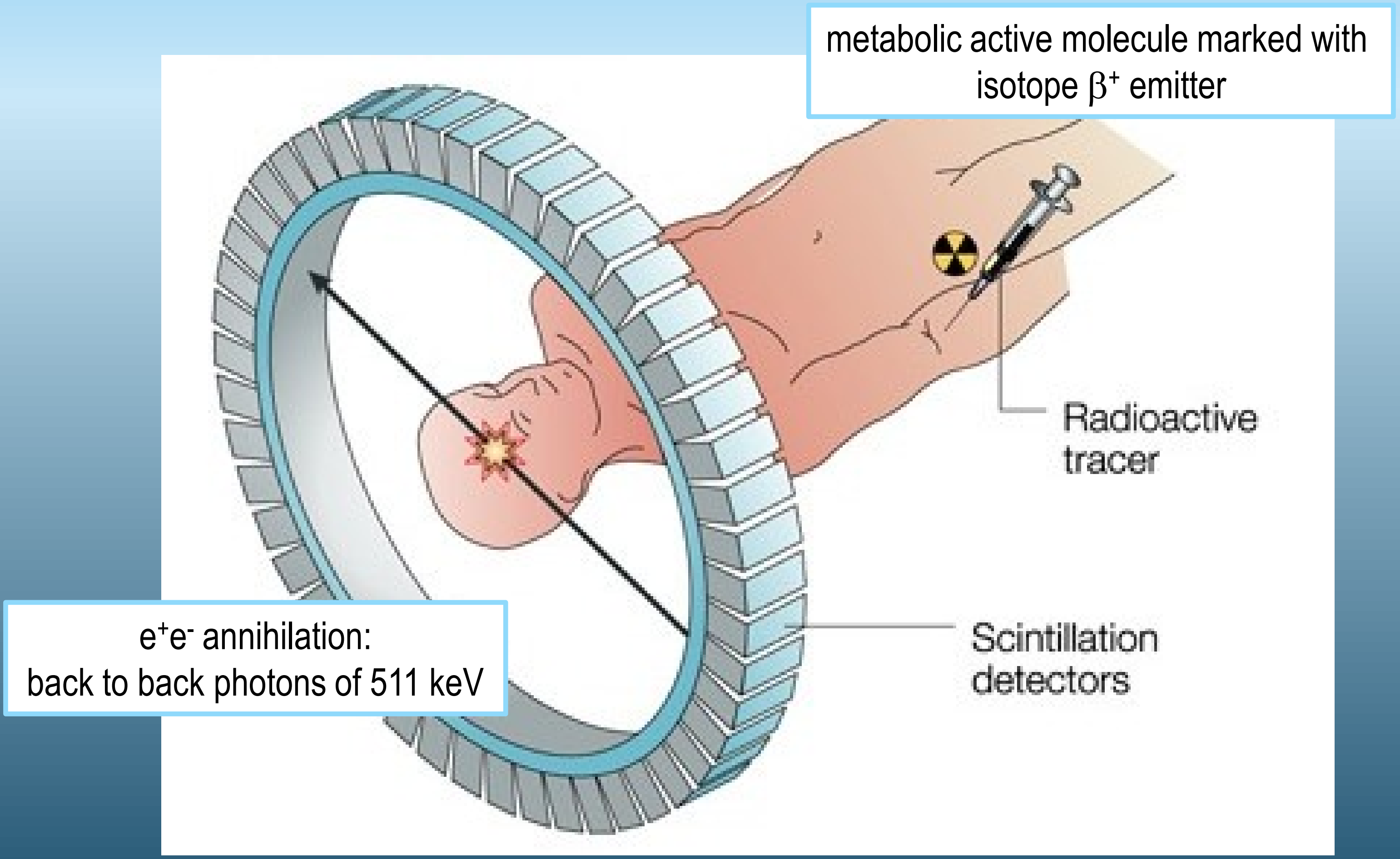
Marie Curie for Particle Detector

Outlook

- *The concept*
  - ✧ **Standard PET and the novel Axial-PET concept**
- *The demonstrator*
  - ✧ **Components and construction**
    - ➢ Digression
  - ✧ **Silicon Photo Multipliers**
    - ➢ Going back to Ax-PET
- *Characterization and performances*
- *Conclusions*

PET: Positron Emission Tomography

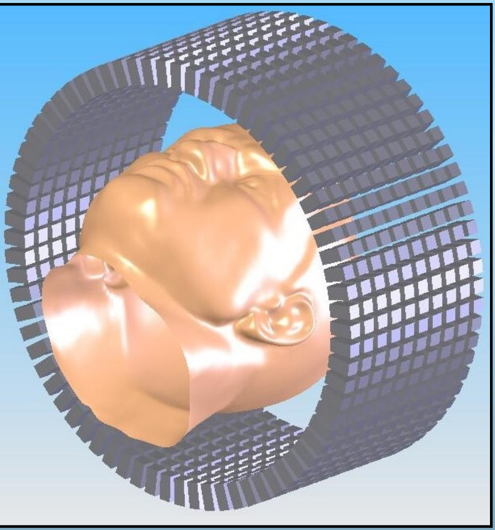


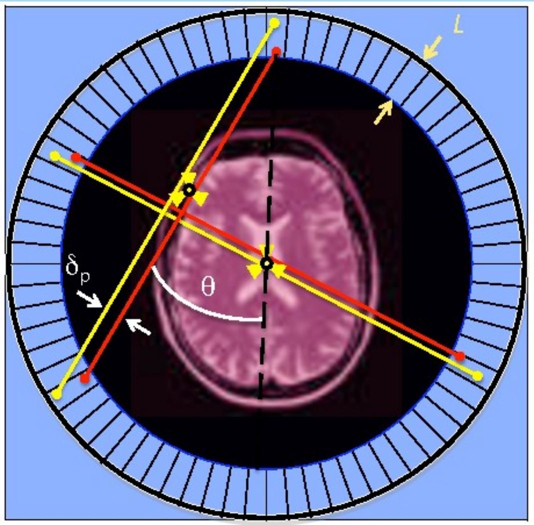
THE CONCEPT

From standard (radial) PET to Axial PET

Conventional PET
(radial arrangement of scintillator detectors)

New geometry AXIAL PET

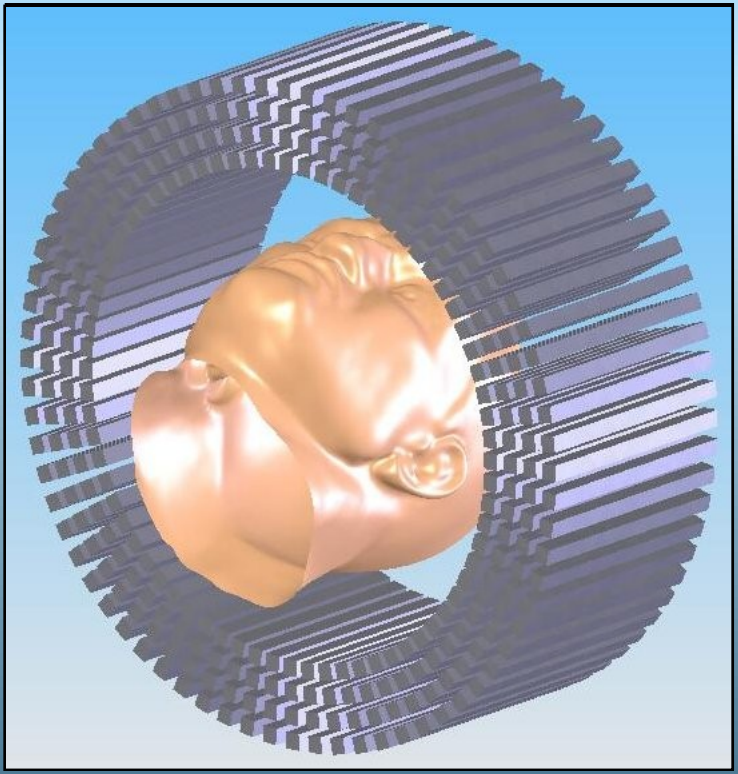




Compromise btw.
spatial resolution (*R*) and sensitivity (*S*)

✧ Long crystals (big *L*) => **high *S***, **poor *R***
- parallax error : $\delta_p = L \sin\theta$
- no depth of interaction (*DOI*) information

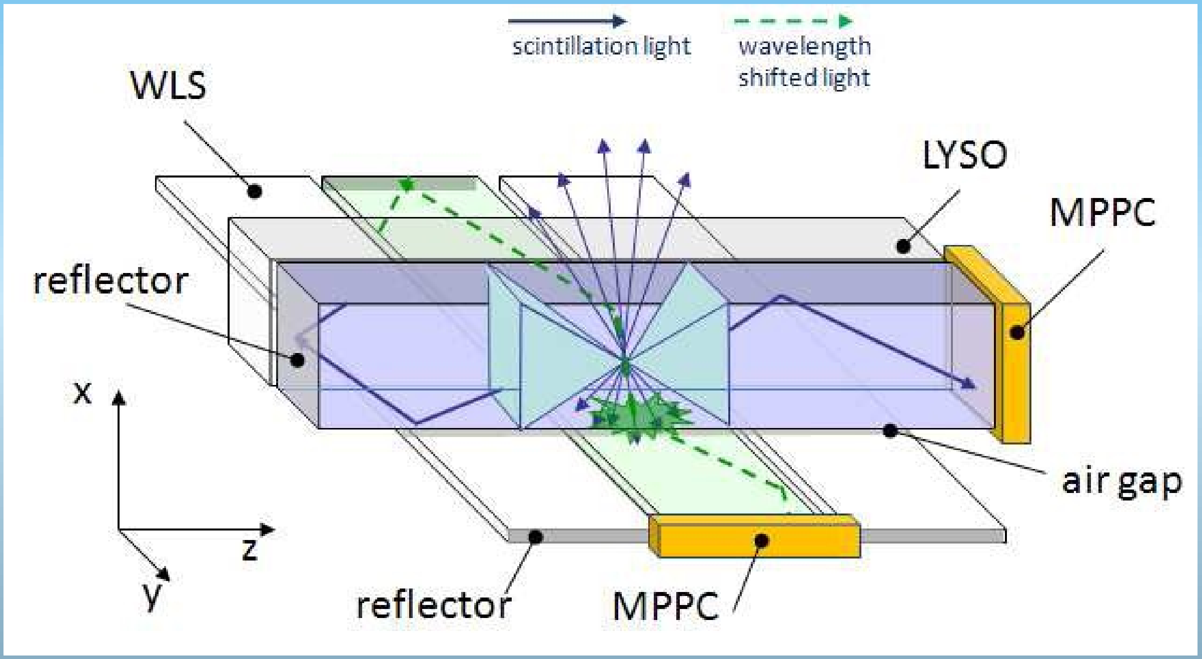
✧ Small crystals (small *L*) => **high *R***, **poor *S***
- detection efficiency: $\varepsilon = 1 - e^{-L/\lambda}$



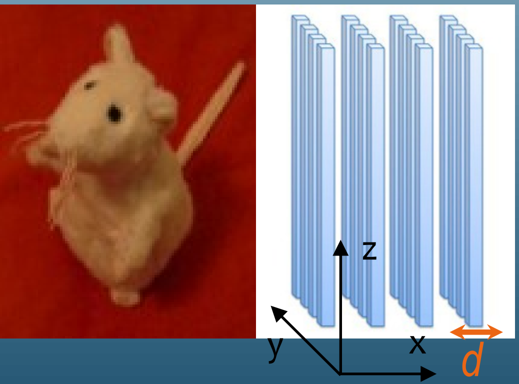
✧ Long crystals (*L* >> *L_radial*)
✧ Axially arranged around the body
✧ Different layers

The concept: transaxial coordinate (x,y)

**3D localization of
the photon interaction point
without compromising
between
spatial resolution and sensitivity**



1. TRANSAXIAL COORDINATE (x,y)

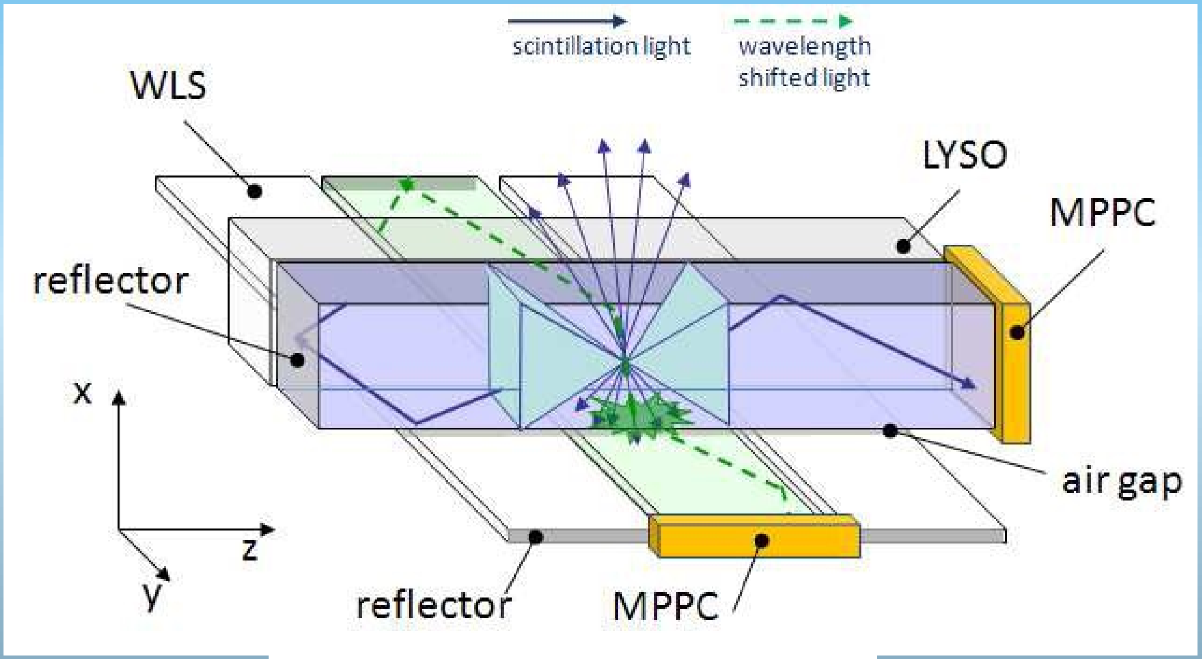


scintillating crystals

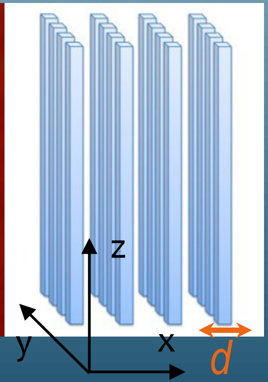
- ✧Transaxial coordinate from position of the hit crystal
- ✧Transaxial resolution $d/\sqrt{12}$ FWHM
- ✧To increase spatial resolution
  => Reduce crystals size (*d*)
- ✧To increase sensitivity
  => Add additional layers

The concept: axial coordinate (z)

3D localization of
the photon interaction point
without compromising
between
spatial resolution and sensitivity

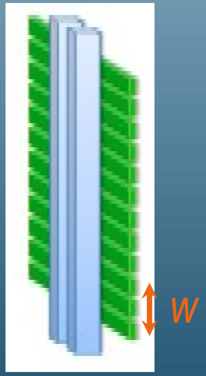


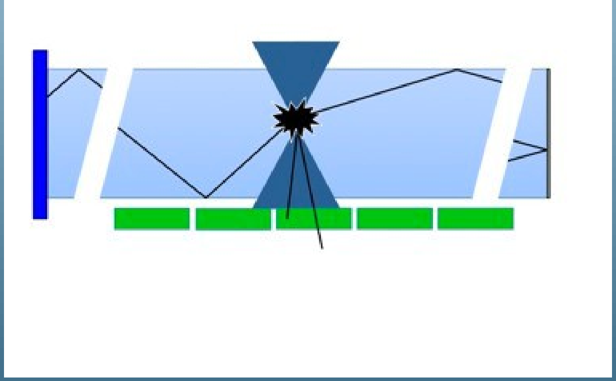
2. AXIAL COORDINATE (z)



scintillating crystals

wave length shifter (wls) array





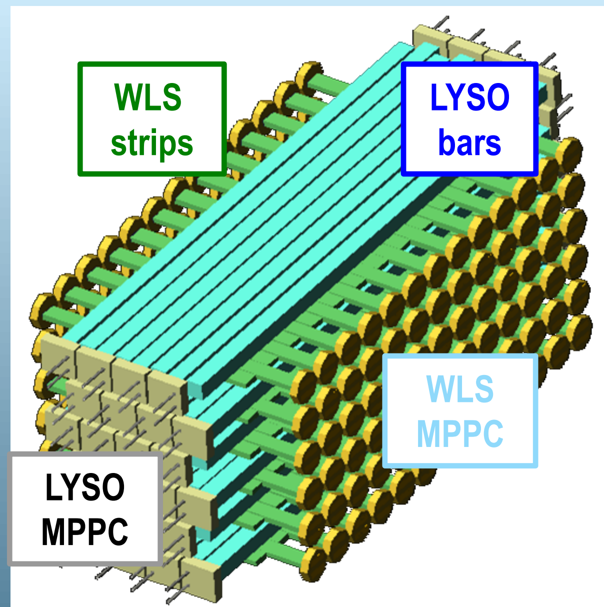
✧Axial coordinate: center of gravity method
✧Axial resolution < *w* (goal: < mm)

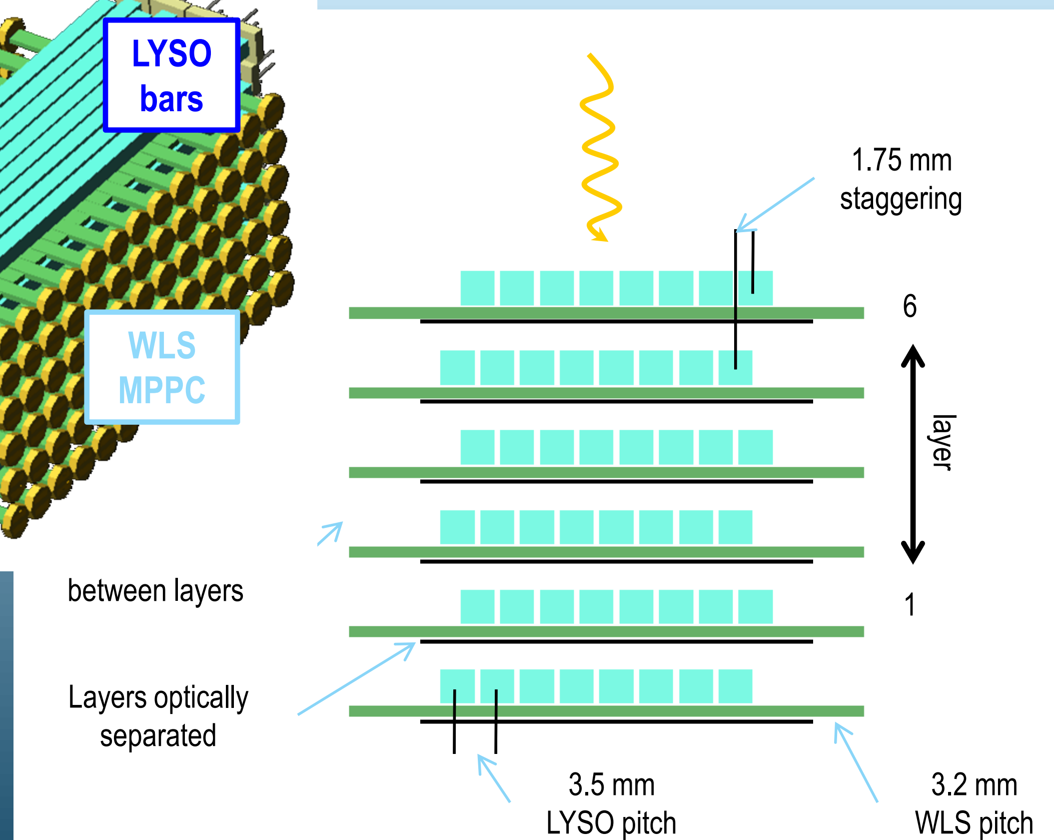
THE DEMONSTRATOR

The Ax-PET module

- **Two identical modules**. Each module:
  - 48 LYSO bars (6 layers x 8 crystals)
  - 156 WLS strips (6 layers x 26 strips)

  } 2 modules -> 408 channels





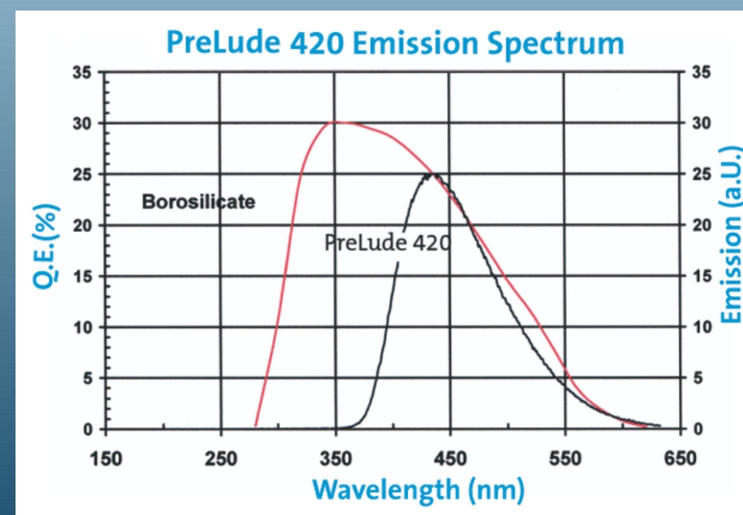
Crystals and WLS strips
read out on alternate sides
to allow maximum packing density

The Ax-PET components: LYSO crystals

Crystal material:
LYSO
Manufacturer:
Saint-Gobain
Dimensions:
3 × 3 × 100 mm^3

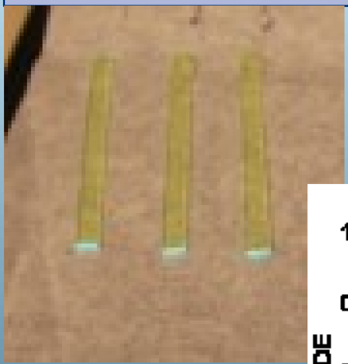
SCINTILLATOR CRYSTALS:

- ✧ Inorganic **LYSO crystals (Lu1.8Y0.2SiO5: Ce, Prelude 420 SaintGobain)**
- ✧ High atomic number
- ✧ High density (〉 = 7.1 g/cm^3)
- ✧ ⎣ @511 keV ~ 1.2 cm
- ✧ Quick decay time (⎪ = 41 ns)
- ✧ High light yield (32000 © / MeV)
- ✧ **3 x 3 x 100 mm^3**



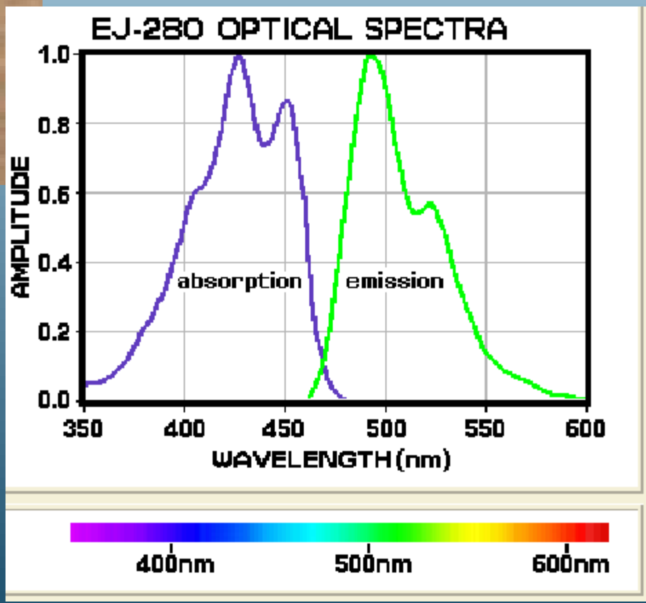
The Ax-PET components: WLS strips

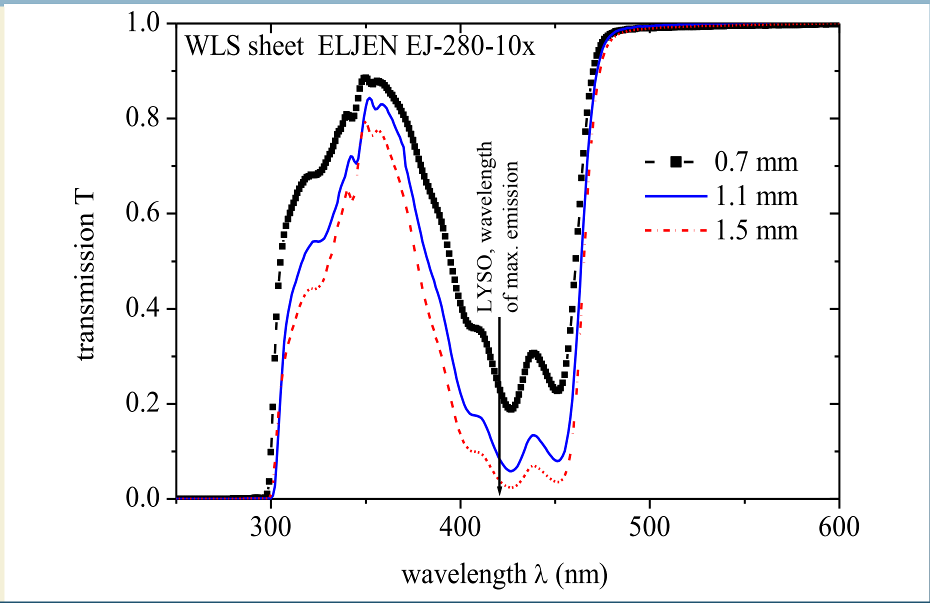
WLS material:
Polyvinyltoluene + dopant
Manufacturer:
ELJEN Technology
Dimensions:
0.9 × 3 × 40 mm^3



WAVE LENGTH SHIFTING STRIPS (WLS):

- ✧ ELJEN EJ-280-10x
- ✧ Shift light from blue to green
- ✧ Density: 1.023 g/cm^3
- ✧ Absorption length for blue light: 0.4 mm
  (10 x standard concentration)
- ✧ Index of reflection: 1.58
- ✧ Decay time: 8.5 ns
- ✧ **0.9 x 3 x 40 mm^3**





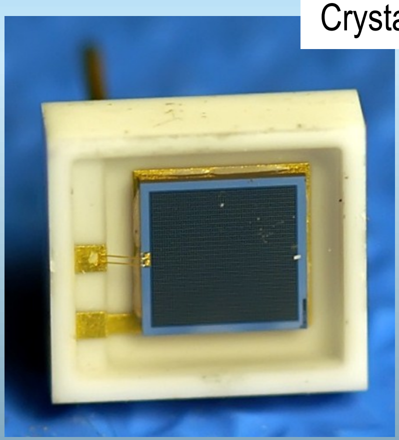
The Ax-PET components: the photon-detectors

MPPC
Manufacturer: Hamamatsu

Operational voltage: ~70 V

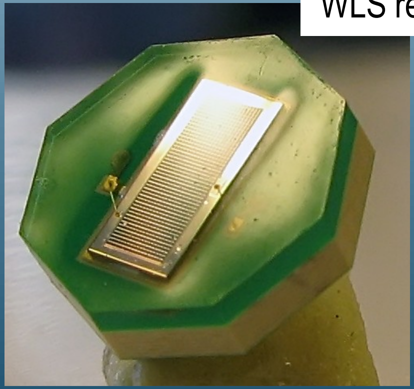
MPPC LYSO: S10362-33-50-C
active area: 3 x 3 mm^2
3600 pixels of 50 x 50 μm^2
Gain: 5.7 x 10^5
Ceramic package 5.9 x 6.6 mm^2

Crystal readout



MPPC WLS: MPPC-OCTAGON-SMD custom made
active area: 3.22 x 1.19 mm^2
1200 pixels of 70 x 70 μm^2
Gain: 4 x 10^5
Octagonal plastic package

WLS readout



“Digression”

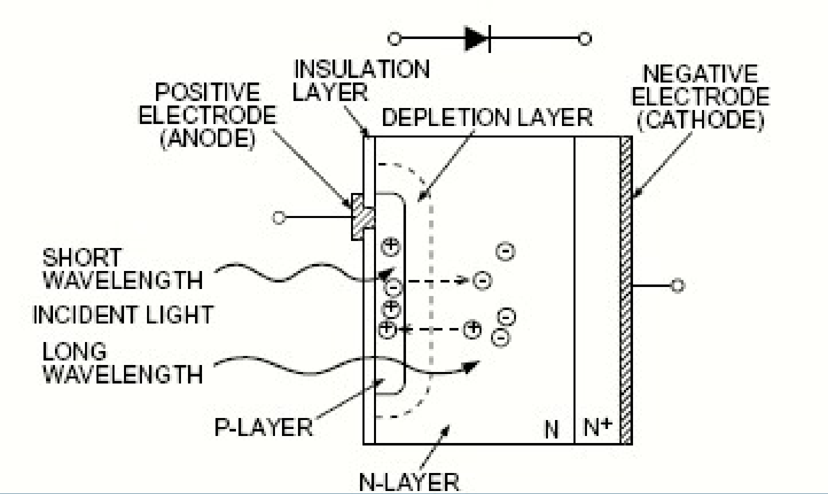
PHOTON DETECTION

- Silicon Photo Multiplier: SiPM
- Geiger mode Avalanche Photodiode: G-APD
- Multi Pixel Photon Counter

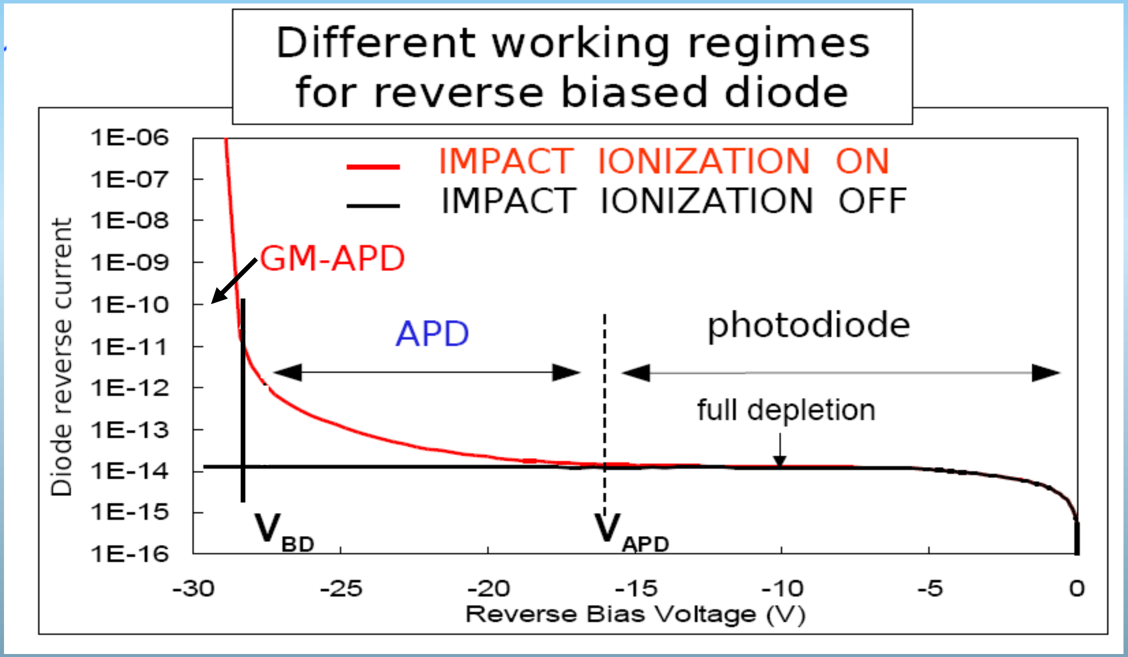
from EDIT lectures

PIN photodiode

- Solid state detector (silicon)
- Internal photoeffect
  - p-i-n photodiode
    intrinsic piece of semiconductor sandwiched between two heavily (oppositely) doped regions.
  - Two charge sheets (on the n+ and p+)
    field which tend to separate charges produced in the depleted region.
  - Charges detected as a current



From photodiode to Geiger mode Avalanche Photo Diode



Photodiode

- $0 < V_{bias} < V_{APD}$ (few volts)
- $G = 1$
- Operate at high light level (few hundreds of photons)

APD

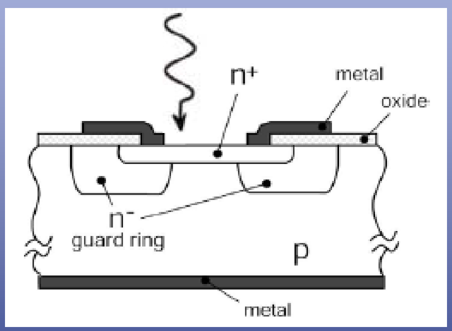
- $V_{APD} < V_{bias} < V_{BD}$
- $G = M$ (50 - 500)
- Linear-mode operation

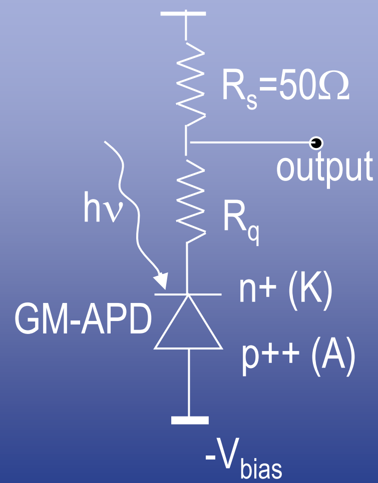
G-APD

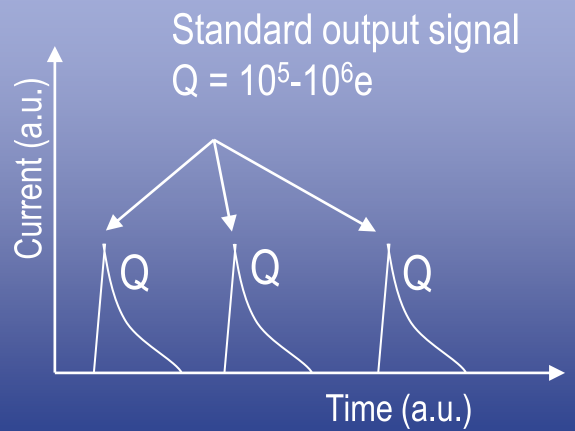
- $V_{bias} > V_{BD}$ ($V_{bias}-V_{BD}$ ~ few volts)
- $G \Rightarrow \infty$
- Geiger-mode operation
- Can operate at single photon level

Geiger mode Avalanche Photo Diode

- Singe photon detector operating in Geiger mode
- Photon counting





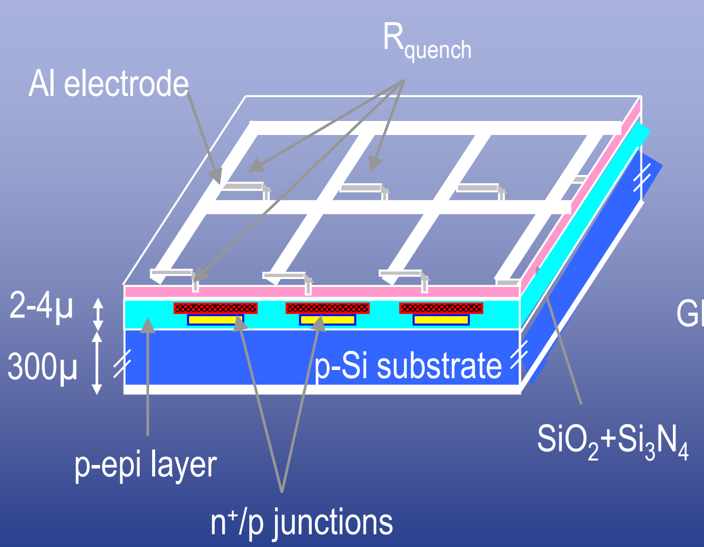


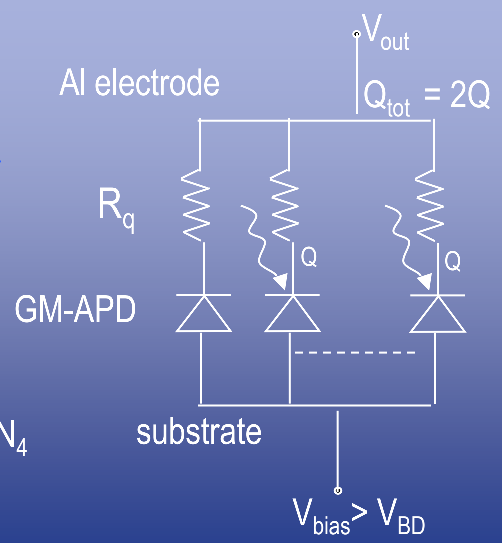
Binary device

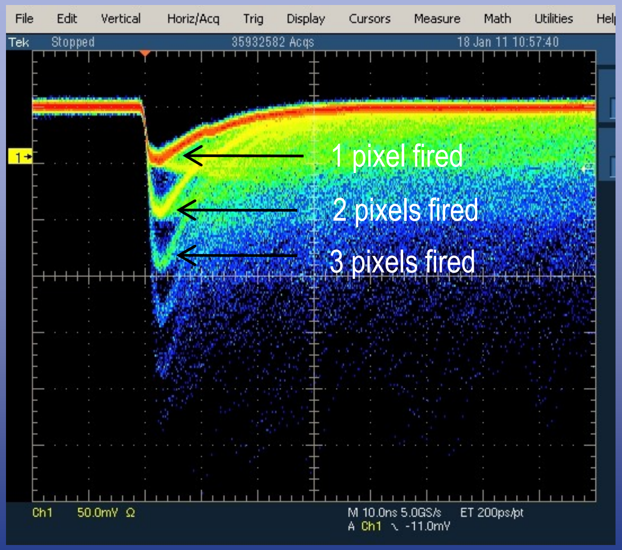
- If one or more simultaneous photons fire the GM-APD, the output is anytime a standard signal: $Q \sim C(V_{bias} - V_{BD})$
- GM-APD does not give information on the light intensity

Silicon Photo Multipliers

- Matrix of n pixels connected in parallel (e.g. few hundreds /mm^2) on a common Si substrate
- Each pixels = G-APD in series with R_{quench}







Quasi-analog device:

- If simultaneously photons fires different pixels, the output is the sum of the standard signals: $Q \sim \Sigma Q_i$
- SiPM gives information on light intensity

Silicon Photo Multipliers performances overview

Advantages

\+ high gain (10^5-10^6) with low voltage (<100V)

\+ low power consumption (<50μW/mm^2)

\+ fast (timing resolution ~ 50 ps RMS for single photons)

\+ insensitive to magnetic field (tested up to 7 T)

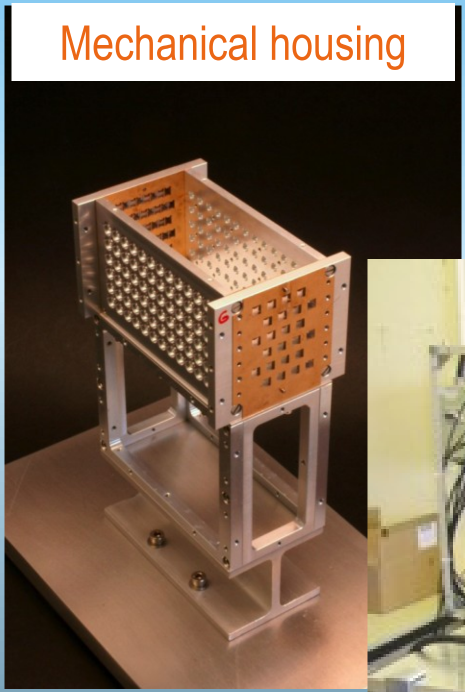
\+ high photon detection efficiency (30-40% blue-green)

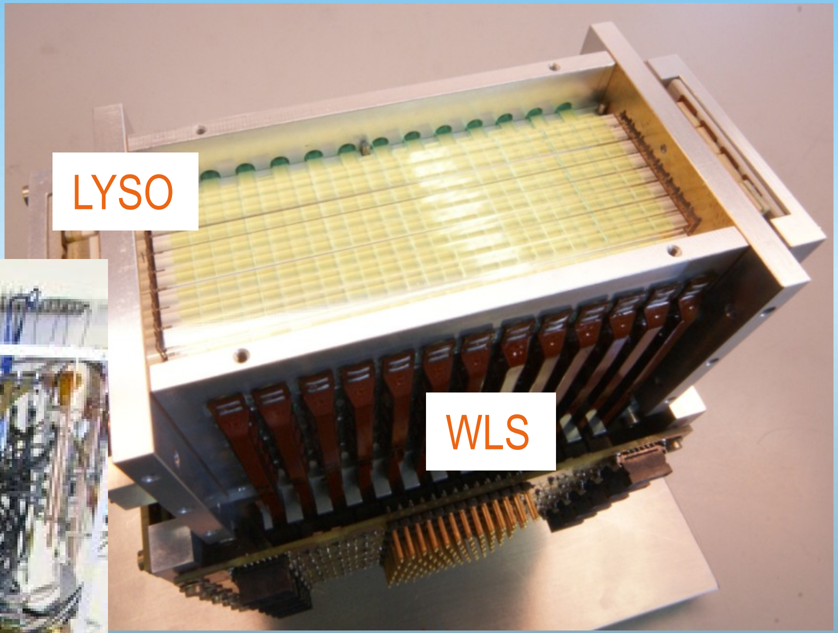
Possible drawbacks

- high dark count rate (DCR) at room temperature
  - 100kHz – 1MHz/mm^2
  - thermal carriers, cross-talk, after-pulses
- temperature dependence
  - V_{BD}, G, R_q, DCR

Going back to Ax-PET

Ax-PET module



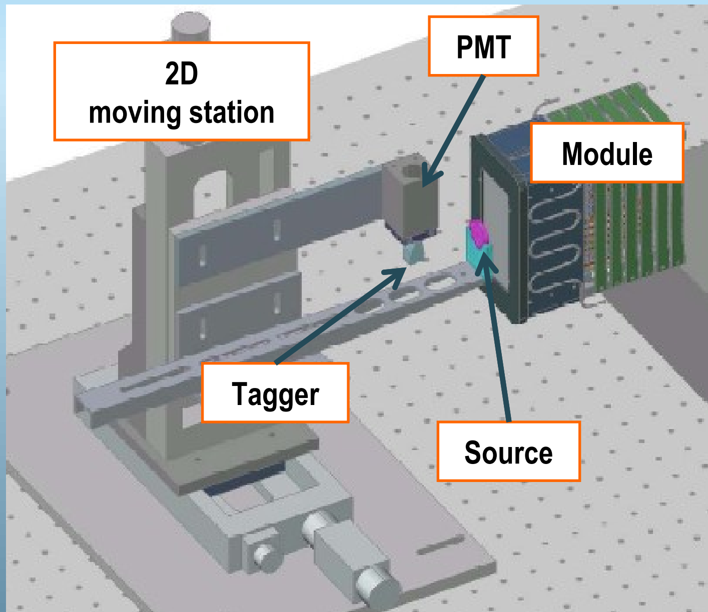


CHARACTERIZATION AND PERFORMANCES

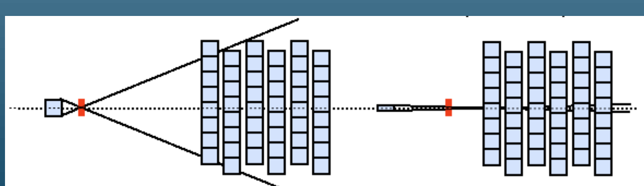
Ax-PET demonstrator characterization

^{22}Na source (ø = 250µm; A = ~900 kBq)

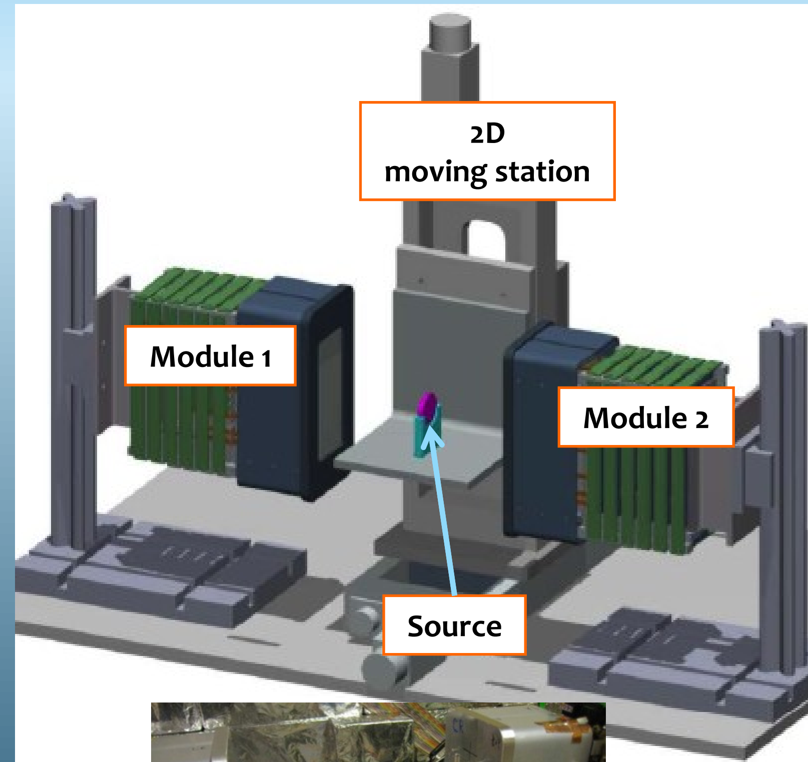
Single module characterization

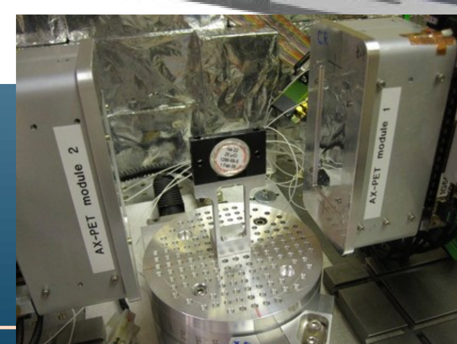


- ✧ Module in coincidence with a tagging scintillator
- ✧ Use of different tagging crystals



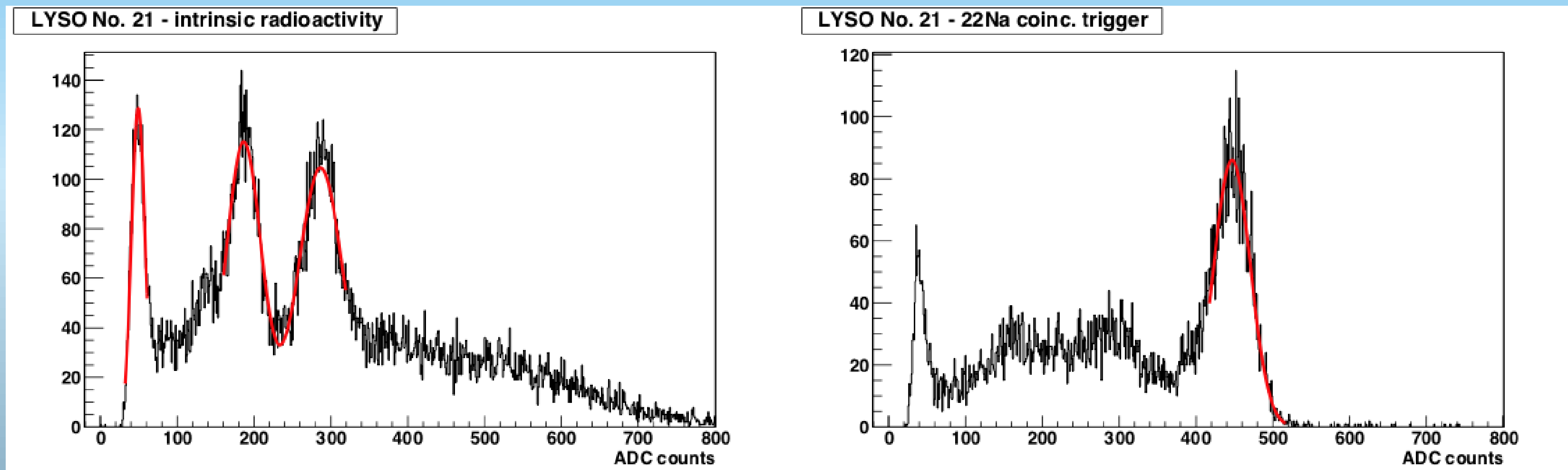
Two module characterization

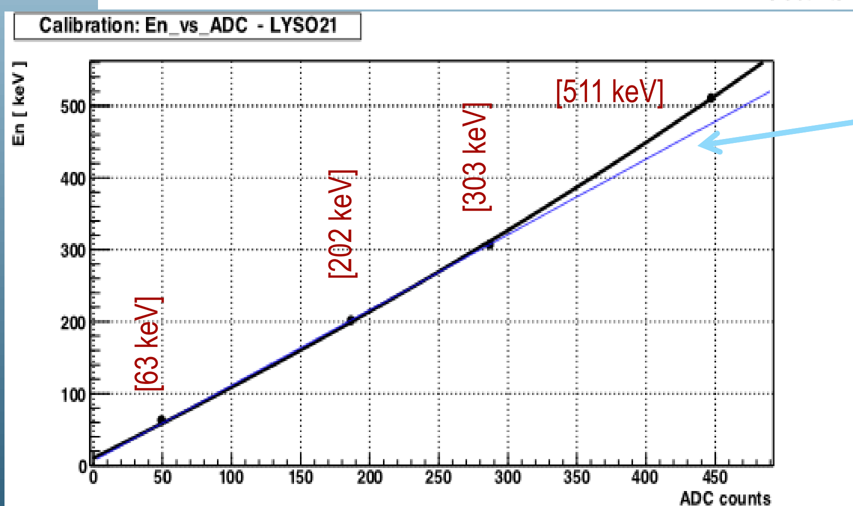




The energy calibration

Intrinsic Lu radioactivity + Photopeak → "self-calibrating" device





Deviation from linearity due to MPPC saturation (3600 pixels) ~ 5% effect

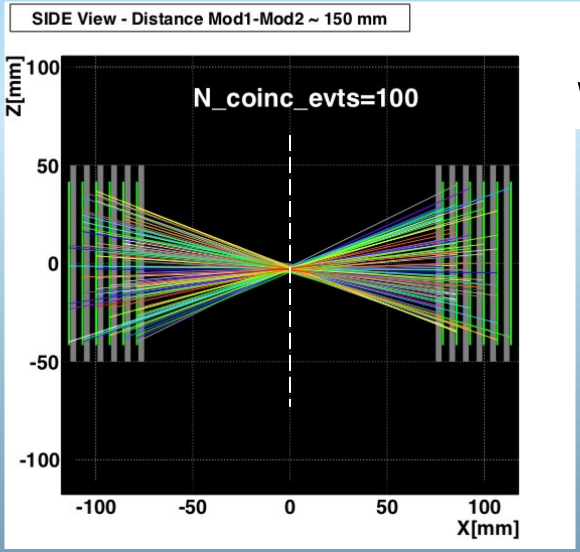
Parameterization: logarithmic function

$$En(ADC) = E_0 - a \cdot \ln\left(1 - \frac{ADC}{b}\right)$$

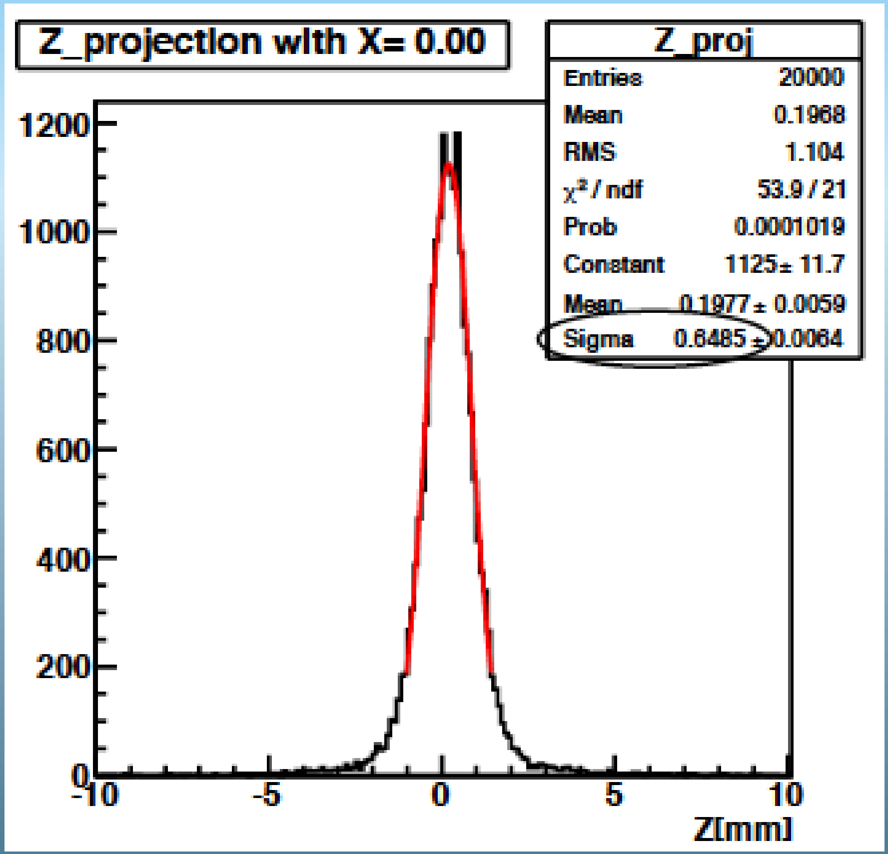
E < R_FWHM > ~ 11.6% @511 keV (averaged on all crystals)

The axial resolution

- Photoelectric events only (1 hit crystal per module)
- Draw "LOR" (pure geometrical)



Intersection
with central plane



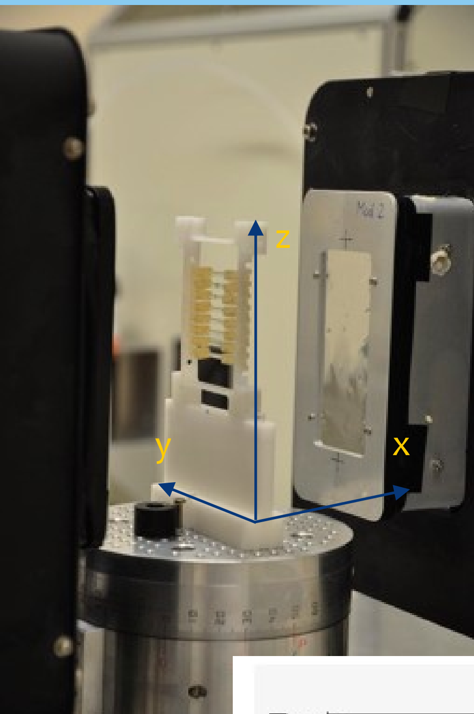
(R_FWHM) z ~ 1.5 mm

- intrinsic resolution
- positron range
- non collinearity
- (source dimensions; ø = 250µm)

Z < R_FWHM > ~ 1.35 mm

$$R_{\text{intr}} = \sqrt{R_{meas}{}^2 - R_{\rho}{}^2 - R_{180}{}^2}$$

Image reconstruction: capilaries



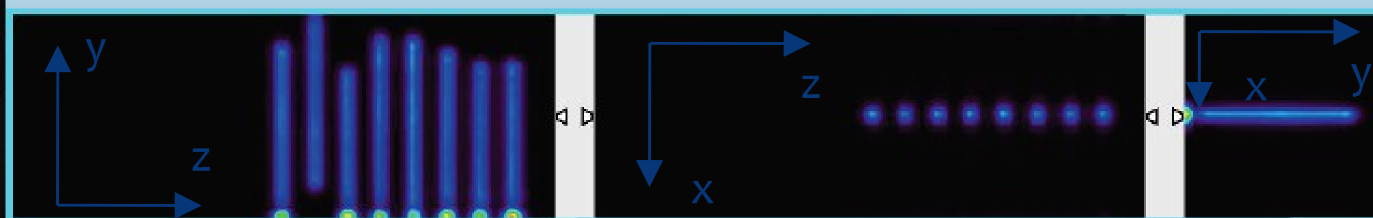
Phantom: 8 capillaries (// WLS)

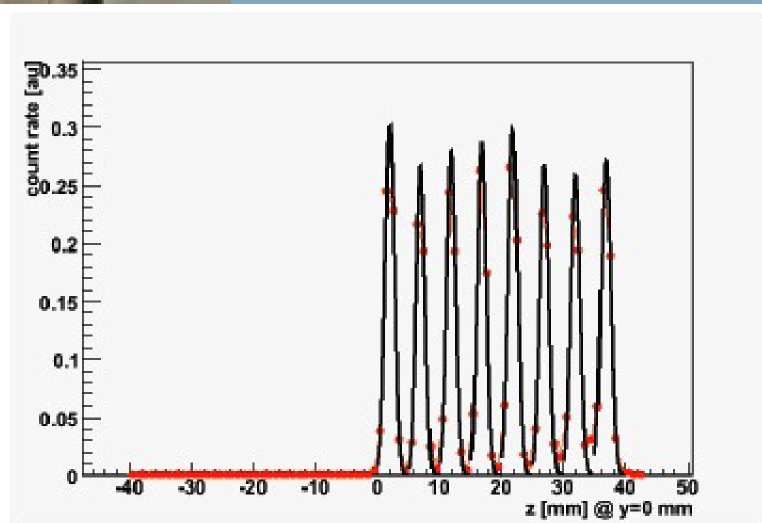
capillary (x8): ***L* = 3 cm; Diam = 1.4 mm; Pitch = 5 mm**

17 positions of the phantom, θ in [0°, 170°]

FOV: 30 x 30 x 83 vox^3 = 30 x 30 x 83 mm^3

30 iterations





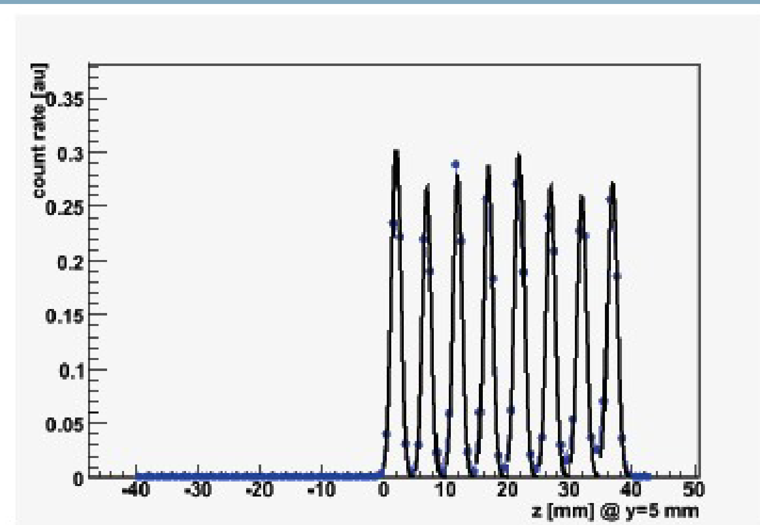
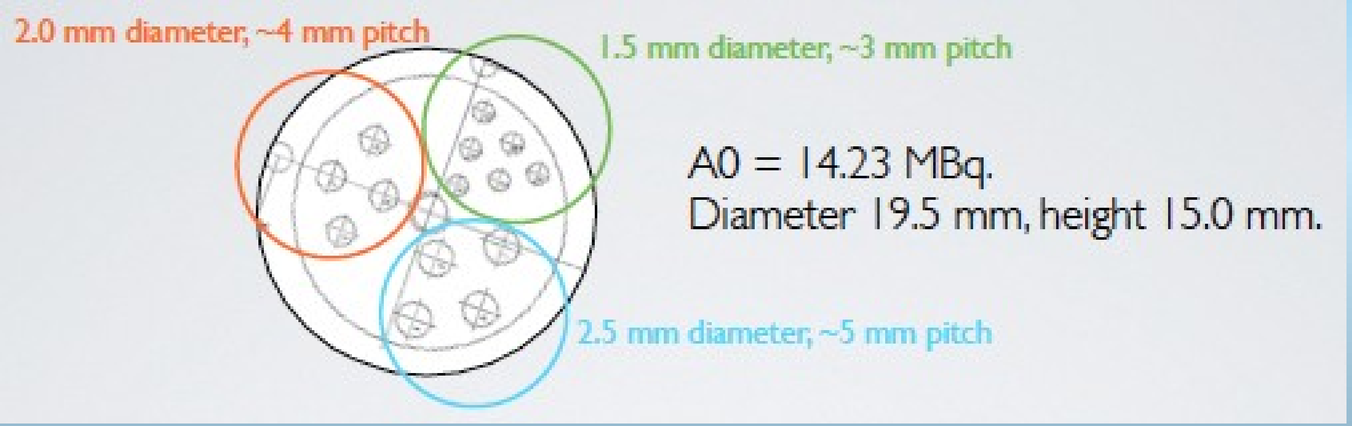
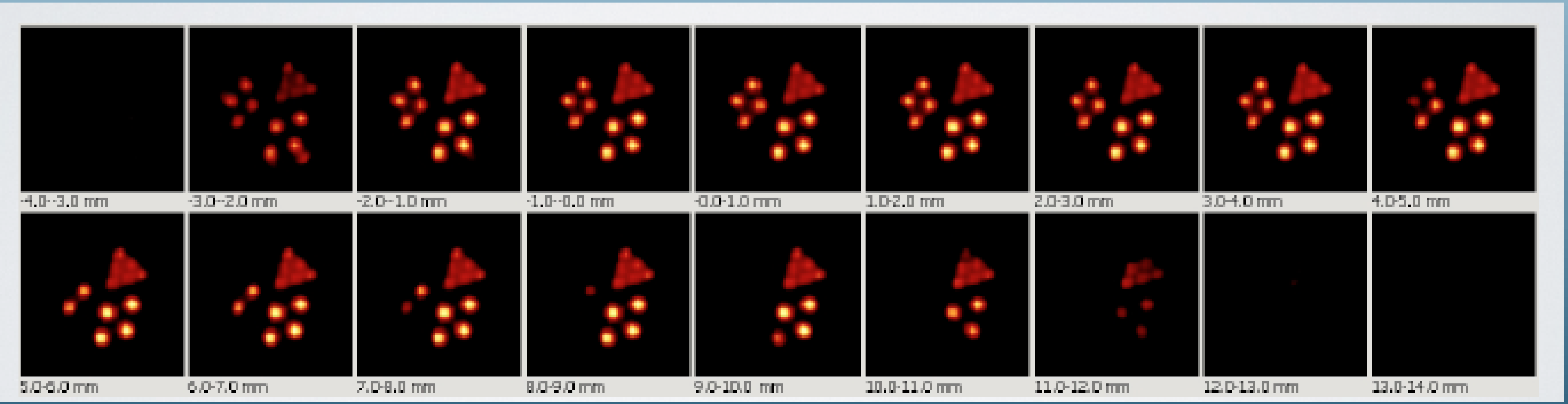


Image reconstruction: Micro-Derenzo





Conclusion

Novelty of AX-PET

1. As calorimeter

   “unconventional” use of WLS to collect escaping scintillation light / bare scintillators

2. New PET with axial geometry

   ✧ Sensitivity and Resolution decoupled

   ✧ DOI (Depth Of Interaction) direct measurement => parallax free system

   ✧ Resolution / Sensitivity tunable with granularity / Nr. layers

   ✧ Possibility to identify ICS (Inter Crystal Scattering) => Tag & discard ICS evts. (Resolution fully maintained) OR Tag & reconstruct ICS evts. (Sensitivity increased)

Status and Performance of AX-PET

1. Demonstrator (2 modules) built and characterized (individually / in coincidence) with sources
2. PERFORMANCES

   ✧ Energy resolution: R_FWHM 11.6 % (@511 keV)

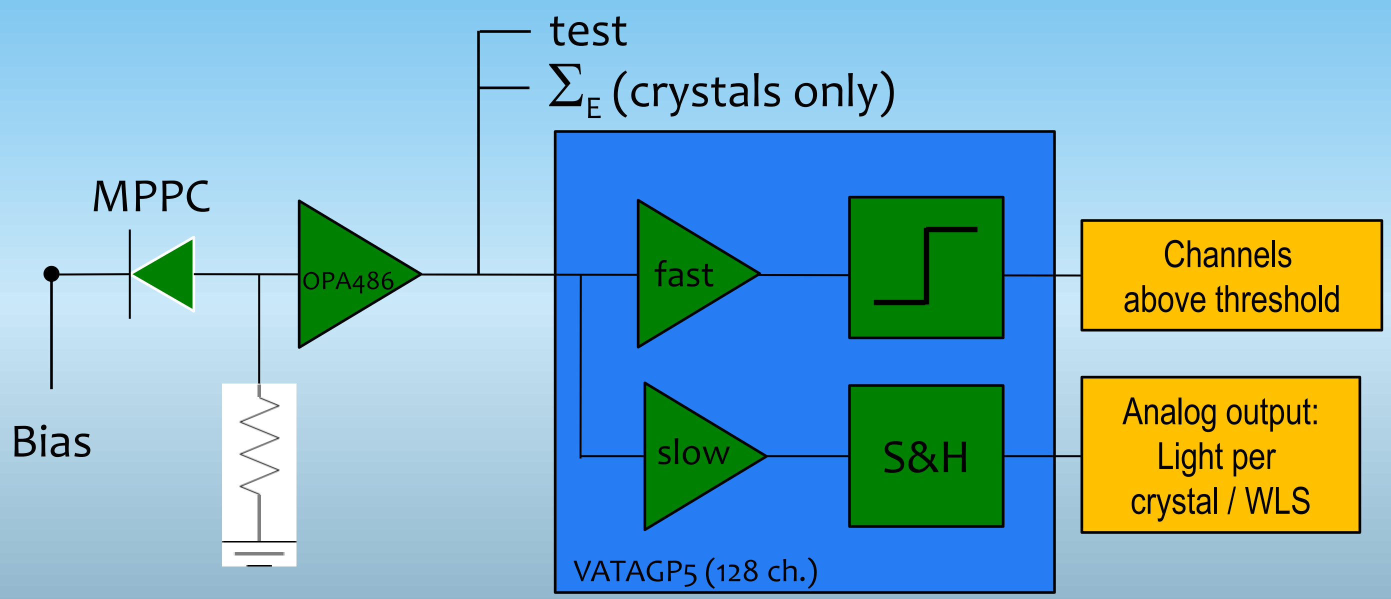
   ✧ Intrinsic spatial resolution : R_FWHM ~ 1.35 mm

   ✧ First reconstructed images

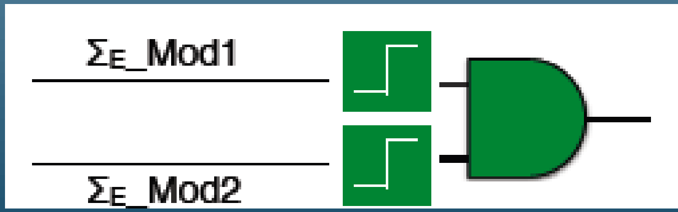
Tanks for your attention

BACK UP SLIDES

Readout and trigger

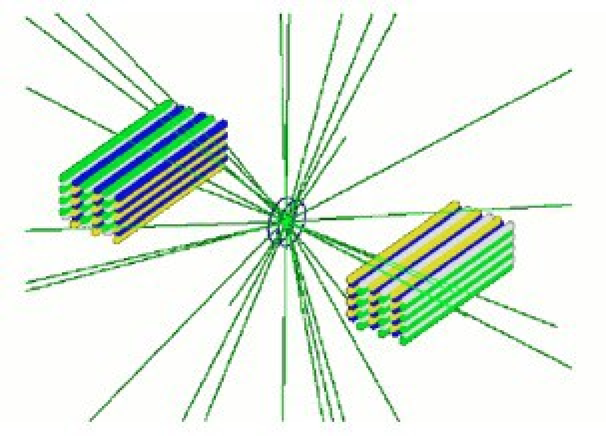


- **Custom designed DAQ system** - Individual analogue readout of MPPC output
- **Amplifiers**: OPA486 (Lyso) / OPA487 (WLS) - Fast energy sum of all the crystals module
- **VATA GP5 chip**: 128-ch charge sensitive integrating [AXPET : x4 VATA GP5 chips]
- **EXTERNAL TRIGGER** (NIM logic) :
  Coincidence of the two 511 keV annihilation photons (one per module), with high energy discrimination threshold on the module energy sum



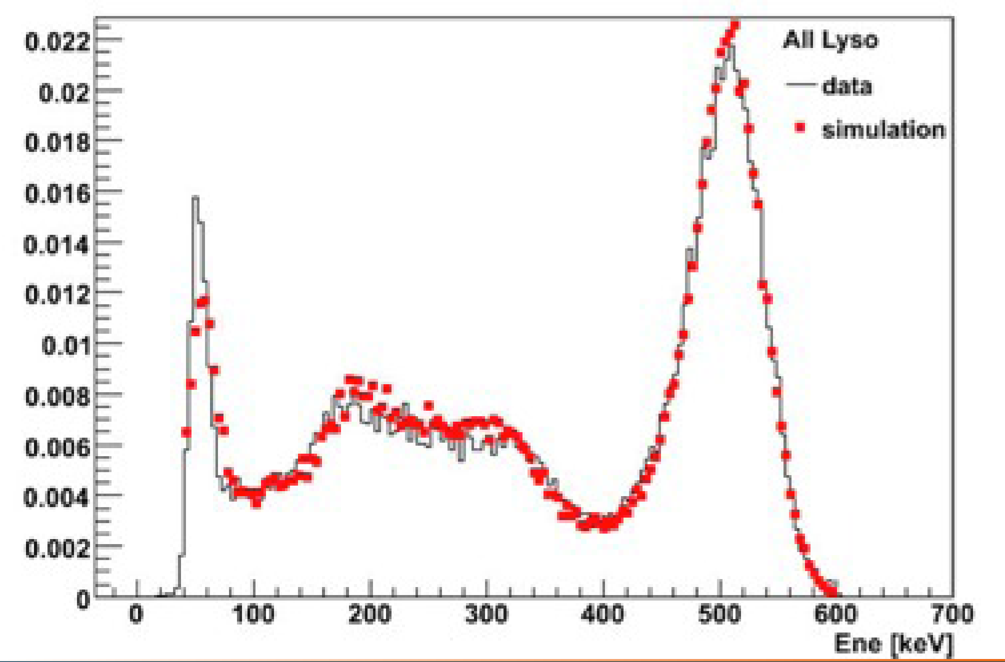
Simulation of the camera

AXPET (2 modules in coincidence)
fully modeled by **dedicated Monte Carlo simulations**



GATE simulation package
(GEANT4 application for tomographic emission,
including time-dependent phenomena e.g. detector movement)

AXPET challenges:
✧ non conventional PET design
✧ WLS parameterization in the digitizer
✧ Sorter for the coincidences



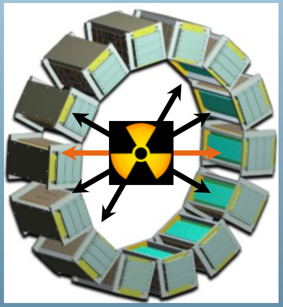
Ax-PET demonstrator characterization

Goal of the project : Build and fully characterize a demonstrator for the AX-PET concept

Not a full scanner, but **2 modules**
=> to mimic the full scanner:
2 modules in coincidence + rotating source

Dedicated simulations,
✧ **2 modules + validation of the simulation**
✧ Full scanner simulation for the final performances

a) small FOV coverage:
- 2 modules fixed, back to back position (180°)
- rotating source in the center of FOV



b) extended FOV coverage:
- allow coincidences btw 2 modules not at 180°
- 1st module fixed
- 2nd module rotating (θ=180°+/- 60°)
- rotating source