The AX-PET Demonstrator : Performance and first results

Chiara Casella
ETH Zurich
on behalf of the AX-PET Collaboration

12th Topical Seminar on
Innovative Particle and Radiation Detector
June 7th, 2010 - Siena

AX-PET : AXial Positron Emission Tomography

A novel geometrical concept for a high resolution, high sensitivity PET scanner

- **AX-PET**
  - why axial ?
  - experimental concept
  - AX-PET ingredients

- **AX-PET DEMONSTRATOR** (not a full scanner, 2 PET modules)

- **AX-PET PERFORMANCE**
  - assessed from dedicated test setups
  - spatial, energy, timing resolution

- **VERY FIRST RECONSTRUCTED IMAGES of extended objects**

AX-PET COLLABORATION

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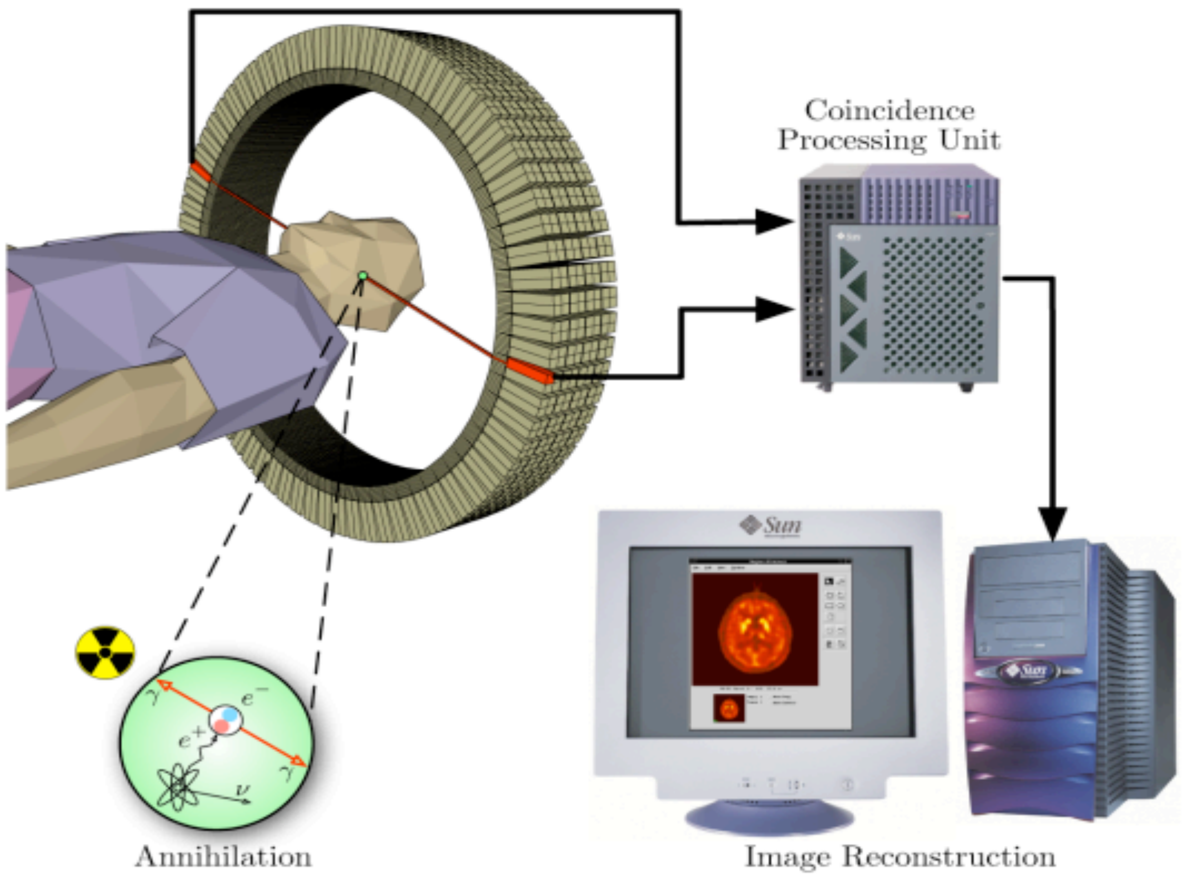
[h] *University of Rome "La Sapienza", I-00185 Rome, Italy*

PET: Positron Emission Tomography



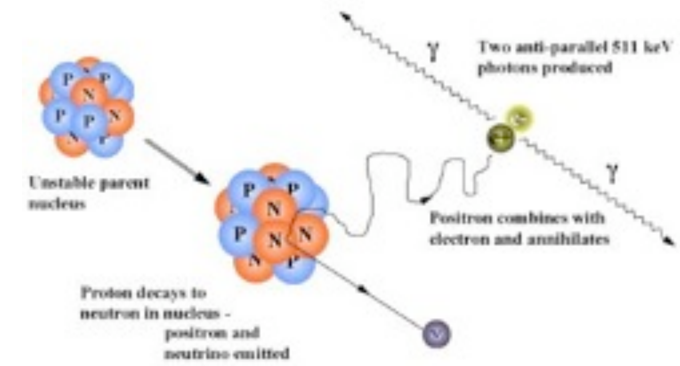
- **in-vivo functional imaging technique**

- a biologically active compound labeled with a proton rich isotope (e.g. ^{18}F, ^{11}C, ^{15}O, ^{13}N...) is injected into the body

- $p \rightarrow n + e^{+} + \nu_e$

  $e^{+}e^{-} \rightarrow \gamma\gamma$

  $(E_{\gamma} = 511\ keV)$



- detection principle :
  detection of the coincidence of two back to back photons (511 keV each)

- imaging reconstruction software => 3-dim image of the radiotracer concentration in the body

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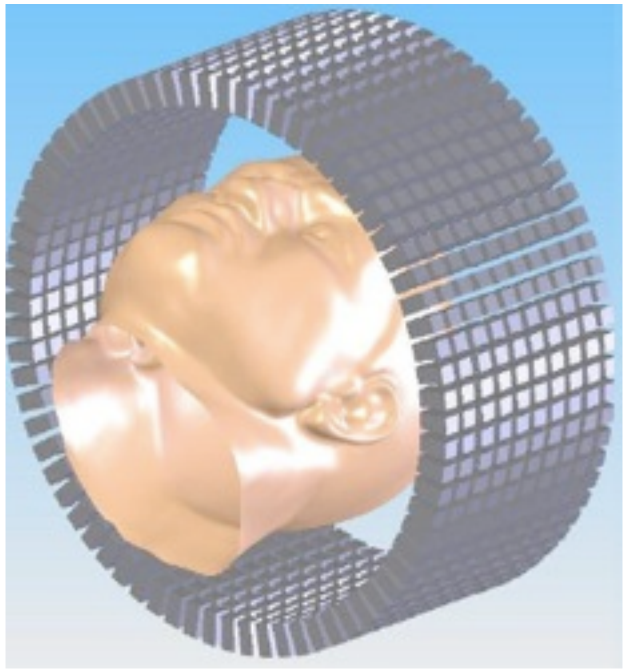
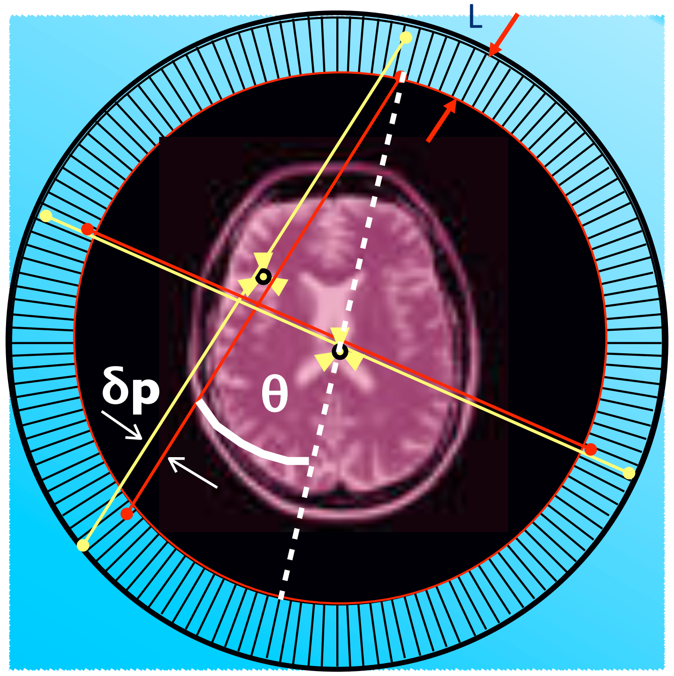
IDEAL PET SCANNER REQUIREMENTS :
- 2π full coverage
- maximum spatial resolution (up to the limits imposed by the physics of the β+ annihilation)
- maximum sensitivity
- good energy resolution
- good time performance
- ...

From standard (i.e. radial) to axial PET

conventional PET

(radial arrangement of scintillator detectors)





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: $\varepsilon = 1 - e^{-L/\lambda}$

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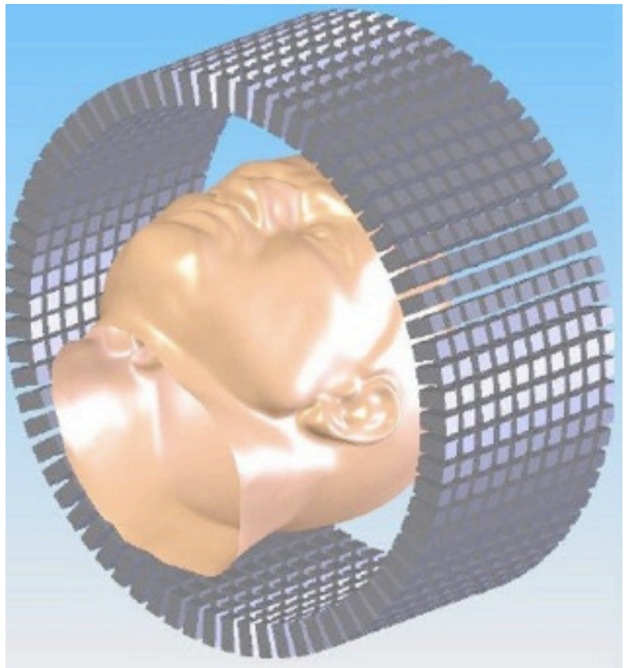

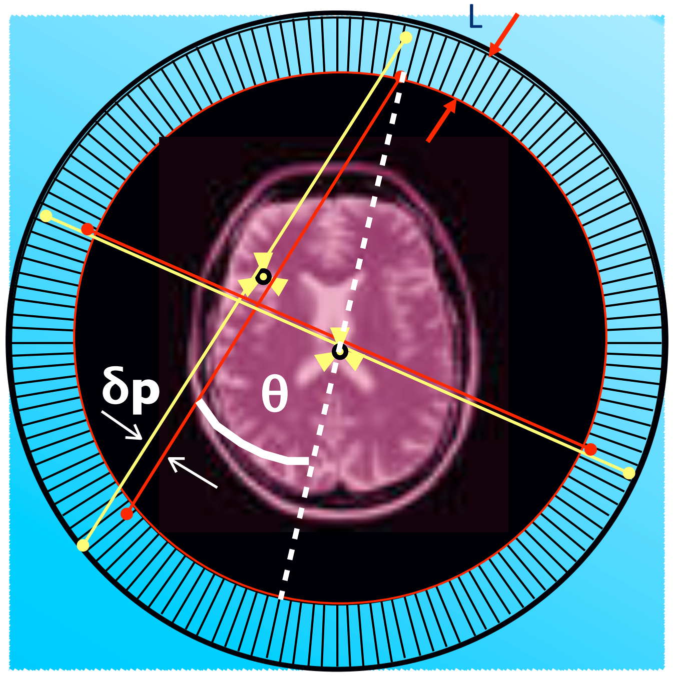

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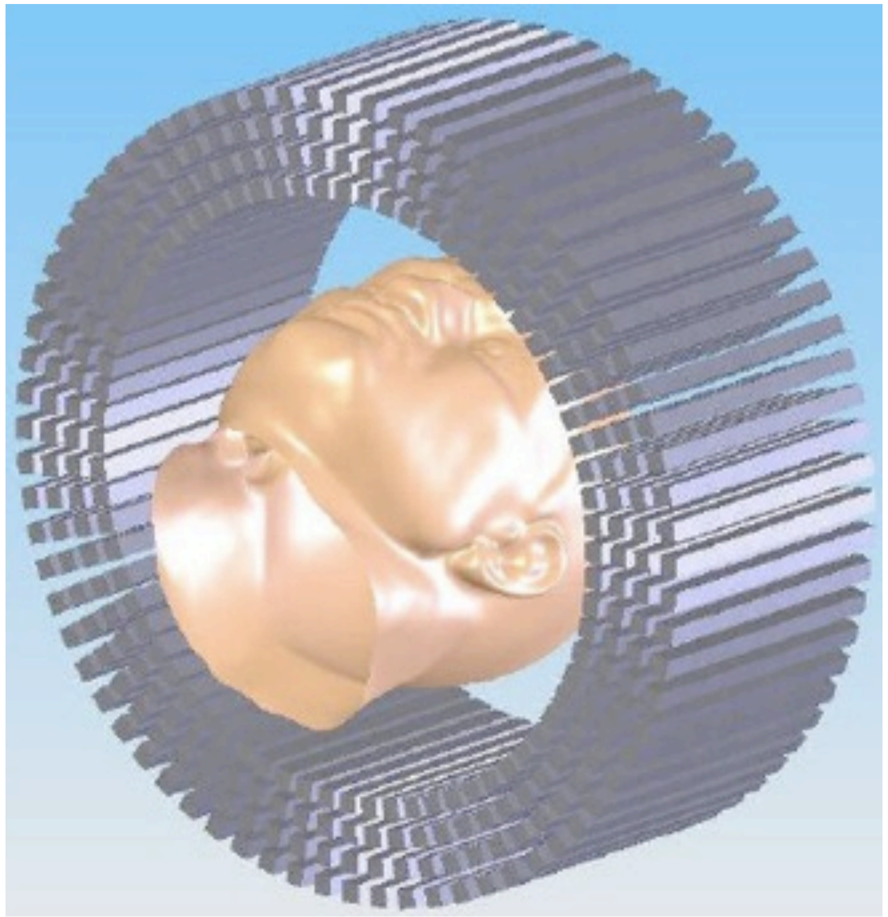
=> new geometry:

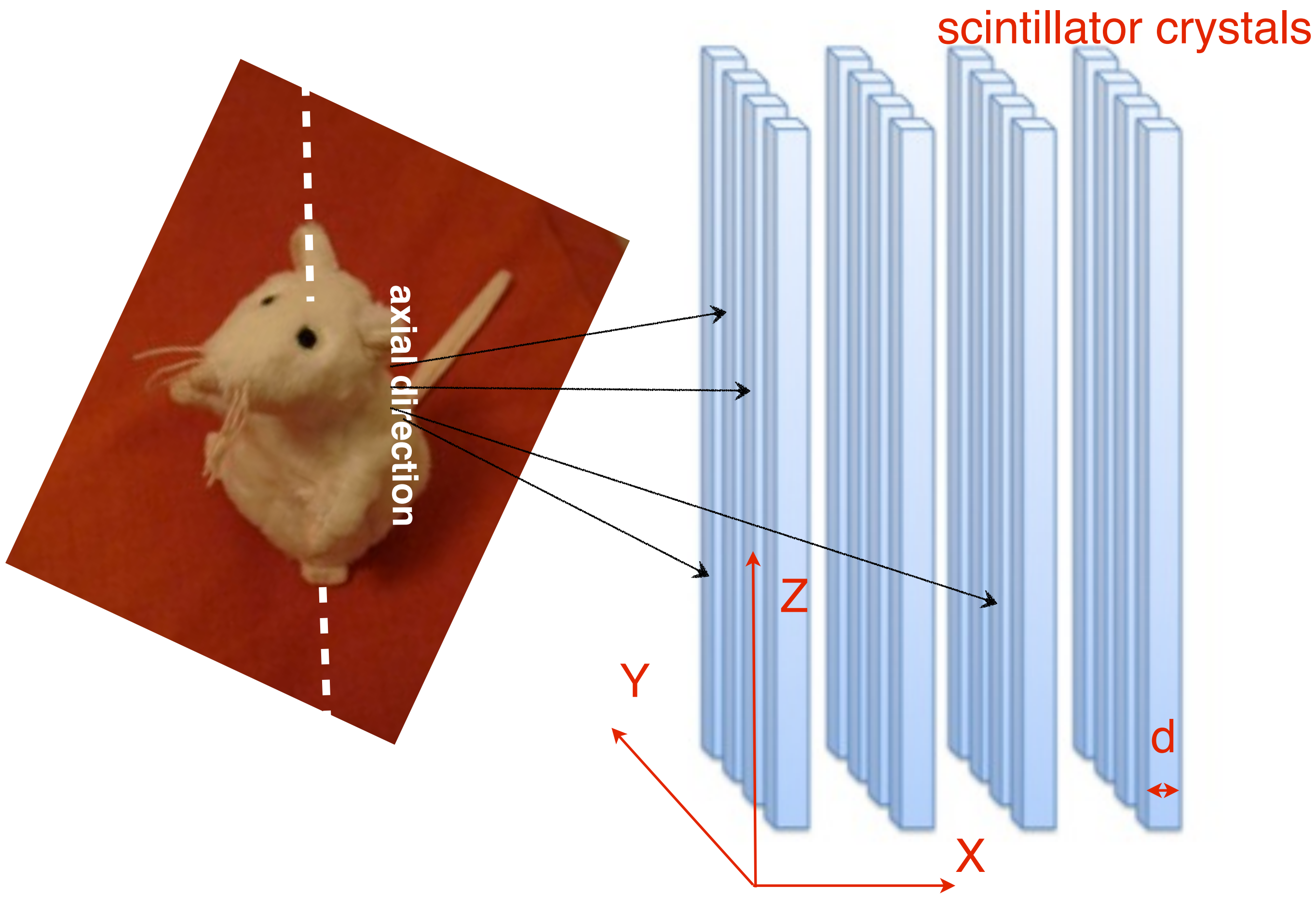
AXIAL PET



- long crystals
- axially arranged around the body

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

(1) TRANSAXIAL COORDINATE (x,y)



- Transaxial coordinate: from position of the hit crystal
- Transaxial resolution = d/√12 FWHM

- To increase spatial resolution => Reduce crystals size (d)
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AX-PET CONCEPT

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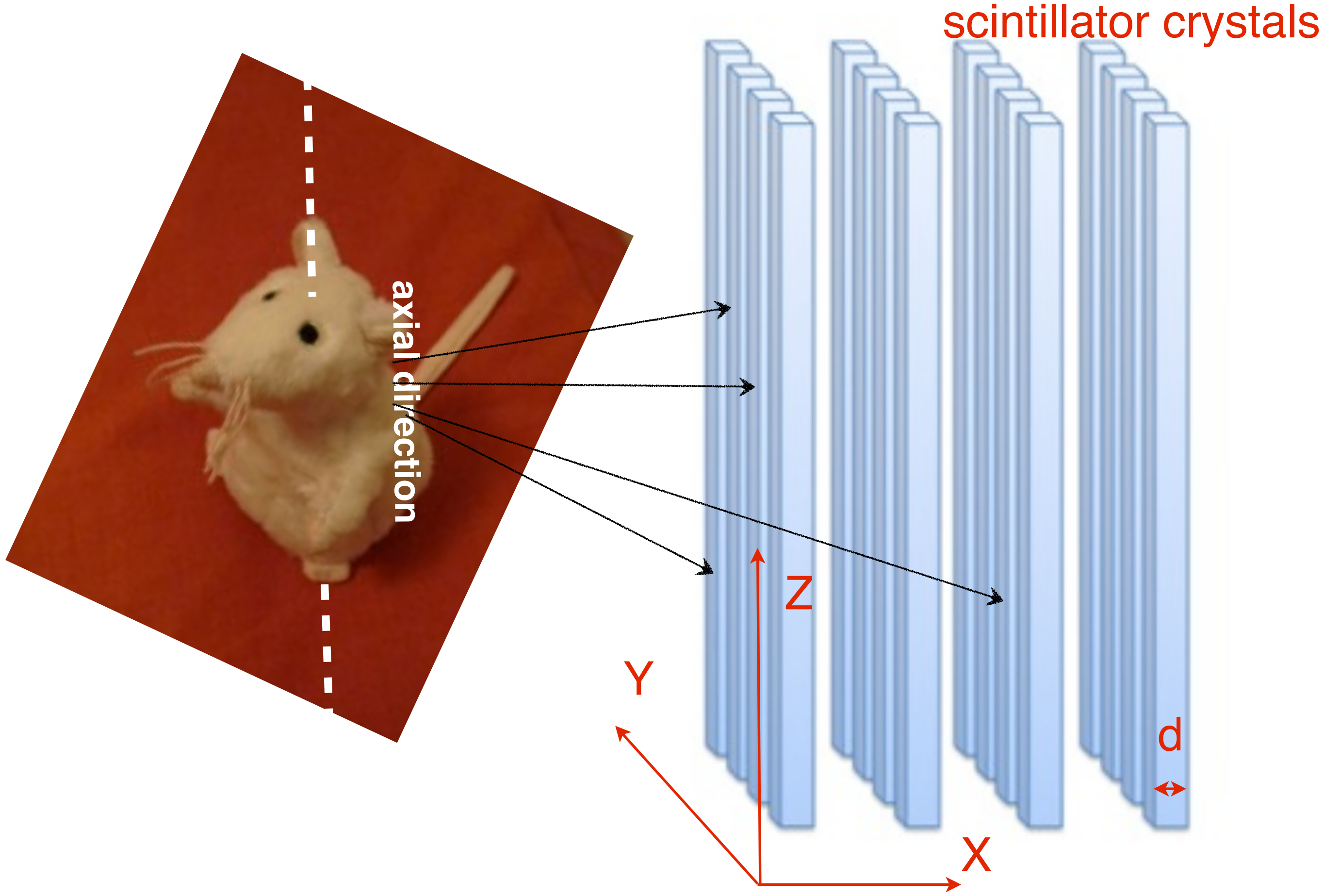

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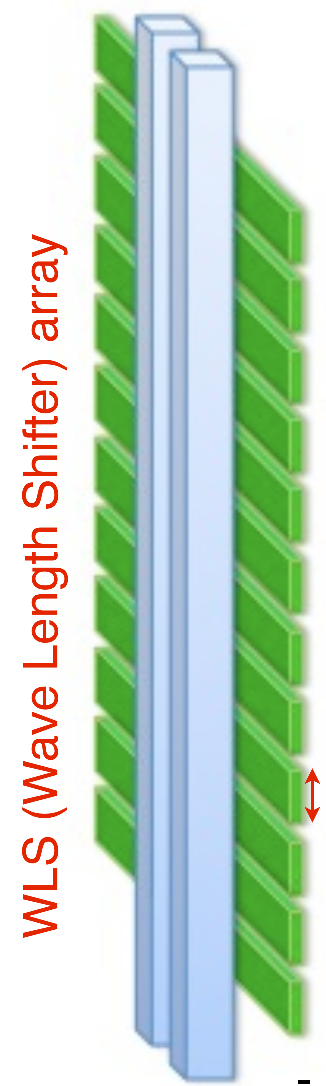
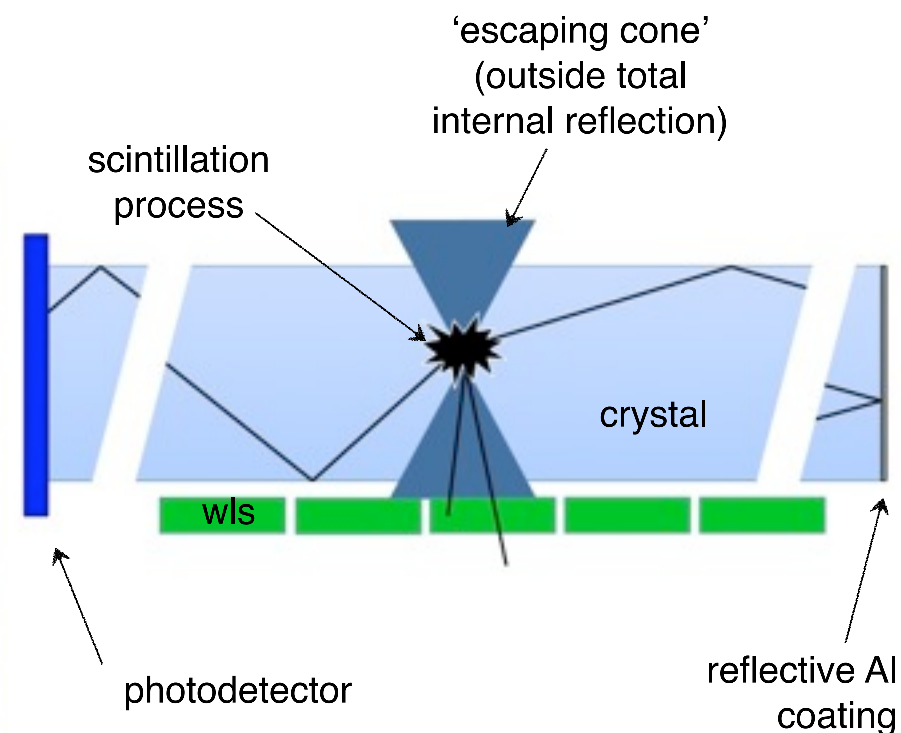
(2) AXIAL COORDINATE (z)





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

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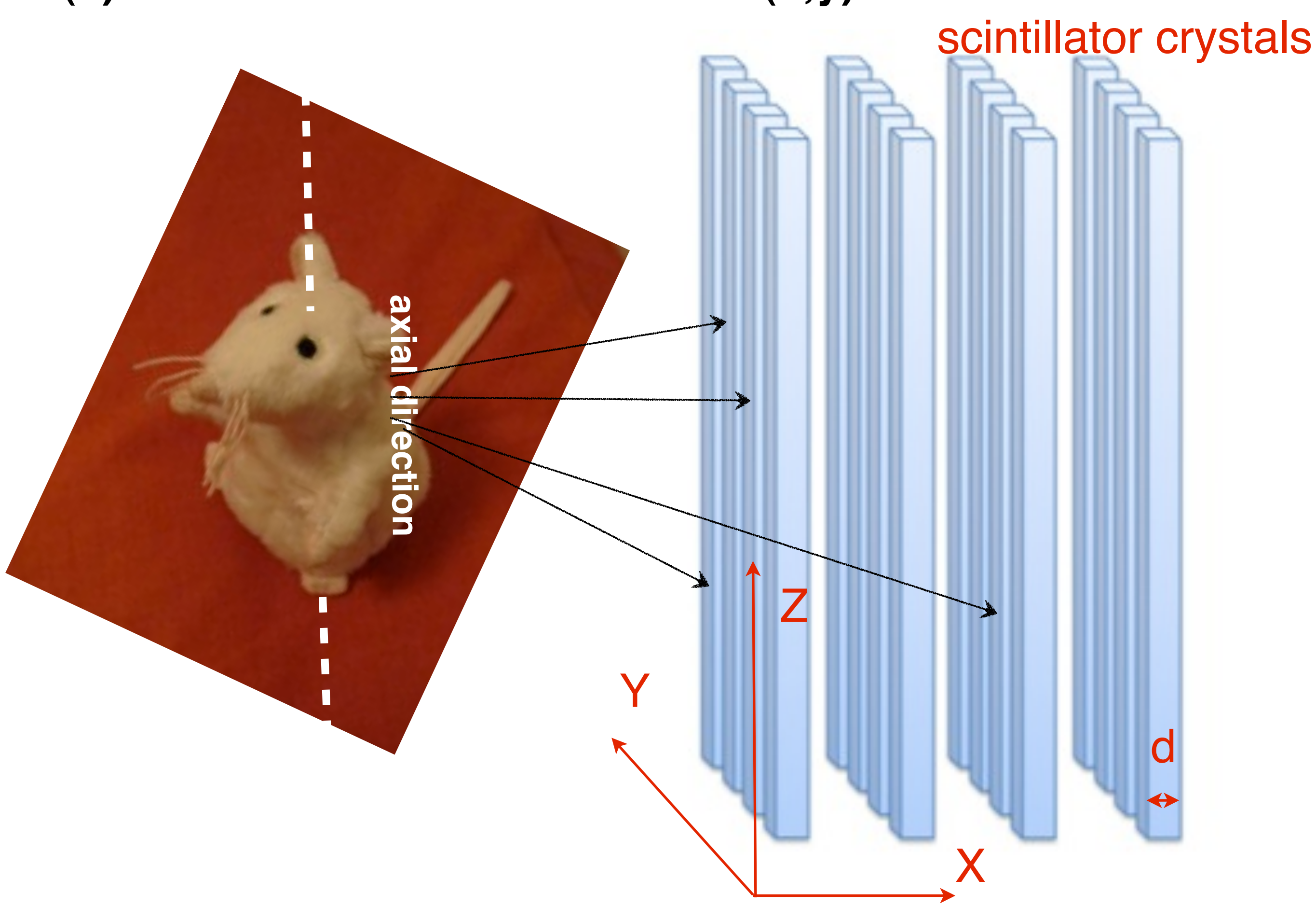

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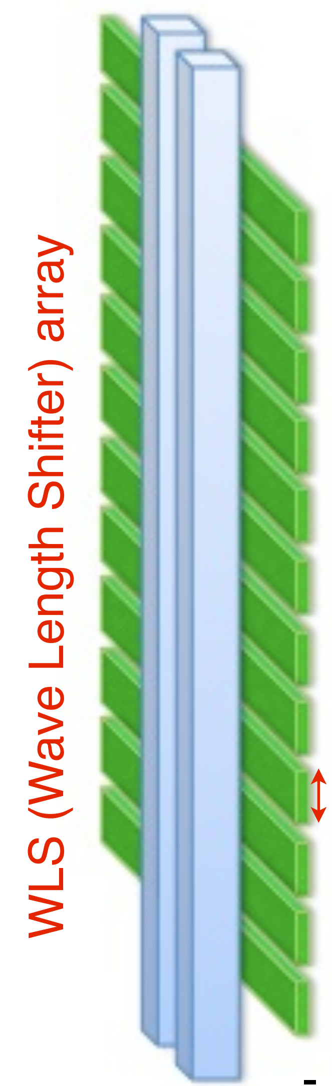

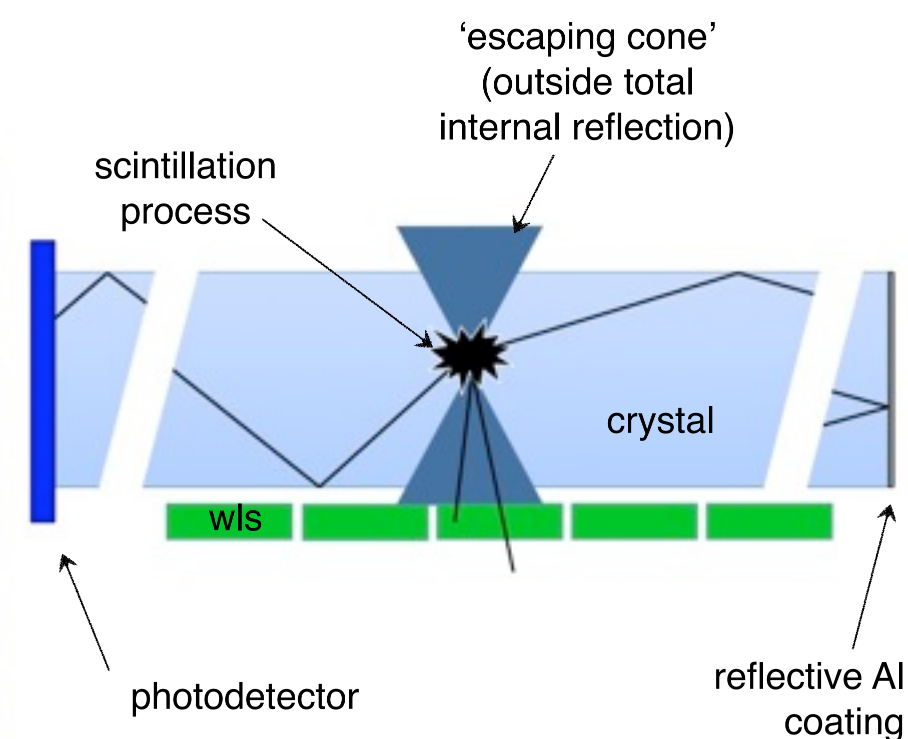

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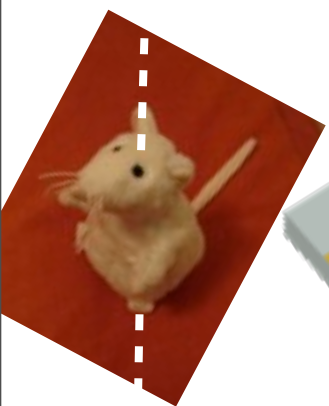
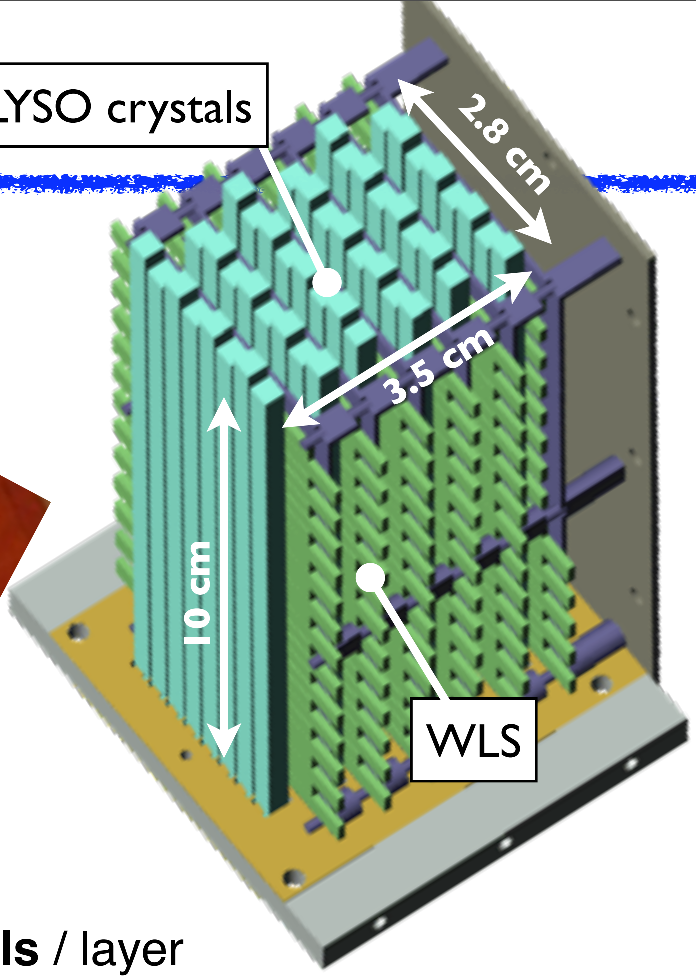
=>

from scintillator crystals : x , y, Energy deposition
from WLS strips : z

AX-PET MODULE





MODULE :

- **6 layers**
- **8 crystals** / layer
- **26 WLS** / layer
- 48 crystals + 156 WLS = **204 channels**
- staggering in the crystals layout

- SCINTILLATOR CRYSTALS :

- Inorganic **LYSO** ($Lu_{1.8}Y_{0.2}SiO_5$: Ce, Prelude 420 Saint Gobain) **crystals**
  - high atomic number
  - high density (ρ = 7.1 g/cm³)
  - λ @511 keV ~ 1.2 cm
  - quick decay time (τ = 41 ns)
  - high light yield (32000 γ / MeV)
- **3 x 3 x 100 mm³**

- WAVE LENGTH SHIFTING STRIPS (WLS) :

- ELJEN EJ-280-10x
- highly doped (x10 compared to standard) to optimize transmission
- **0.9 x 3 x 40 mm³**

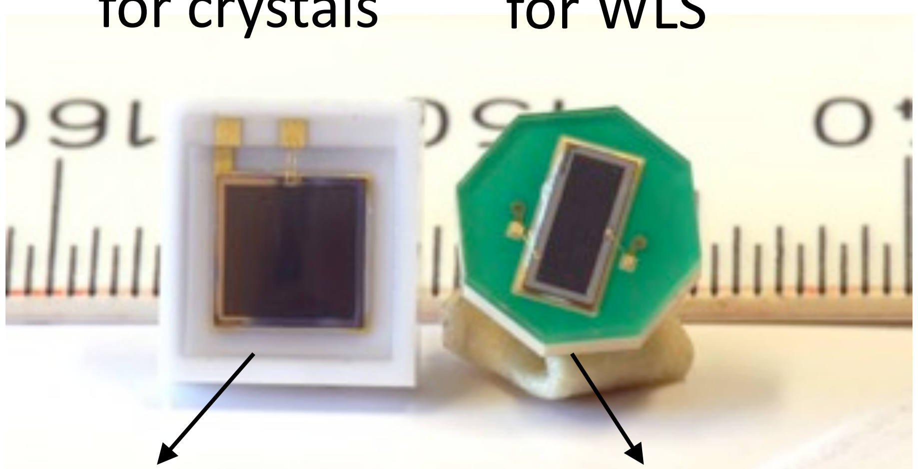
- Each crystal and WLS strip is readout individually by its own photodetector

PHOTODETECTORS

- MPPC (Multi Pixel Photon Counter) from Hamamatsu

- also known as **SiPM / G-APD**
  - high PDE (~ 50%) √
  - high gain (10^5 to 10^6) √
  - insensitive to magnetic field √
  - compact size √
  - low bias voltages (~ 70V) √
  - temperature dependent √
  - dark rate √

for crystals for WLS



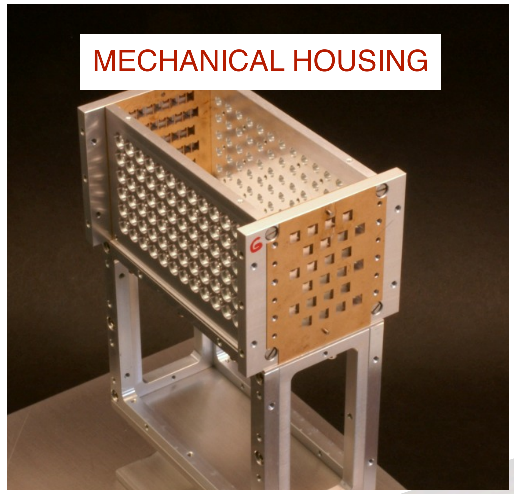
MPPC S10362-33-050C :

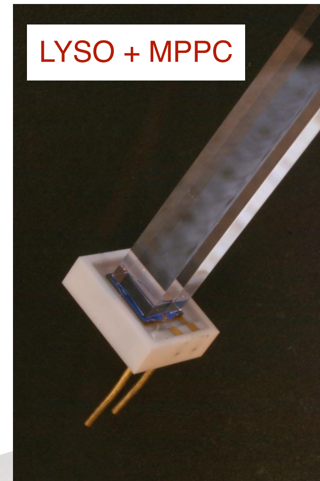
- 3x3 mm² active area
- 50 µm x 50 µm pixel
- 3600 pixels
- Gain ~ 5.7 x 10^5

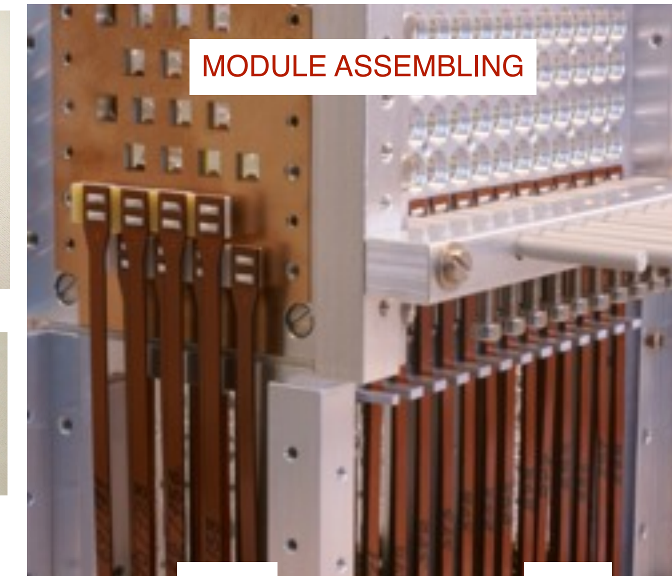
MPPC 3.22×1.19 Octagon-SMD :

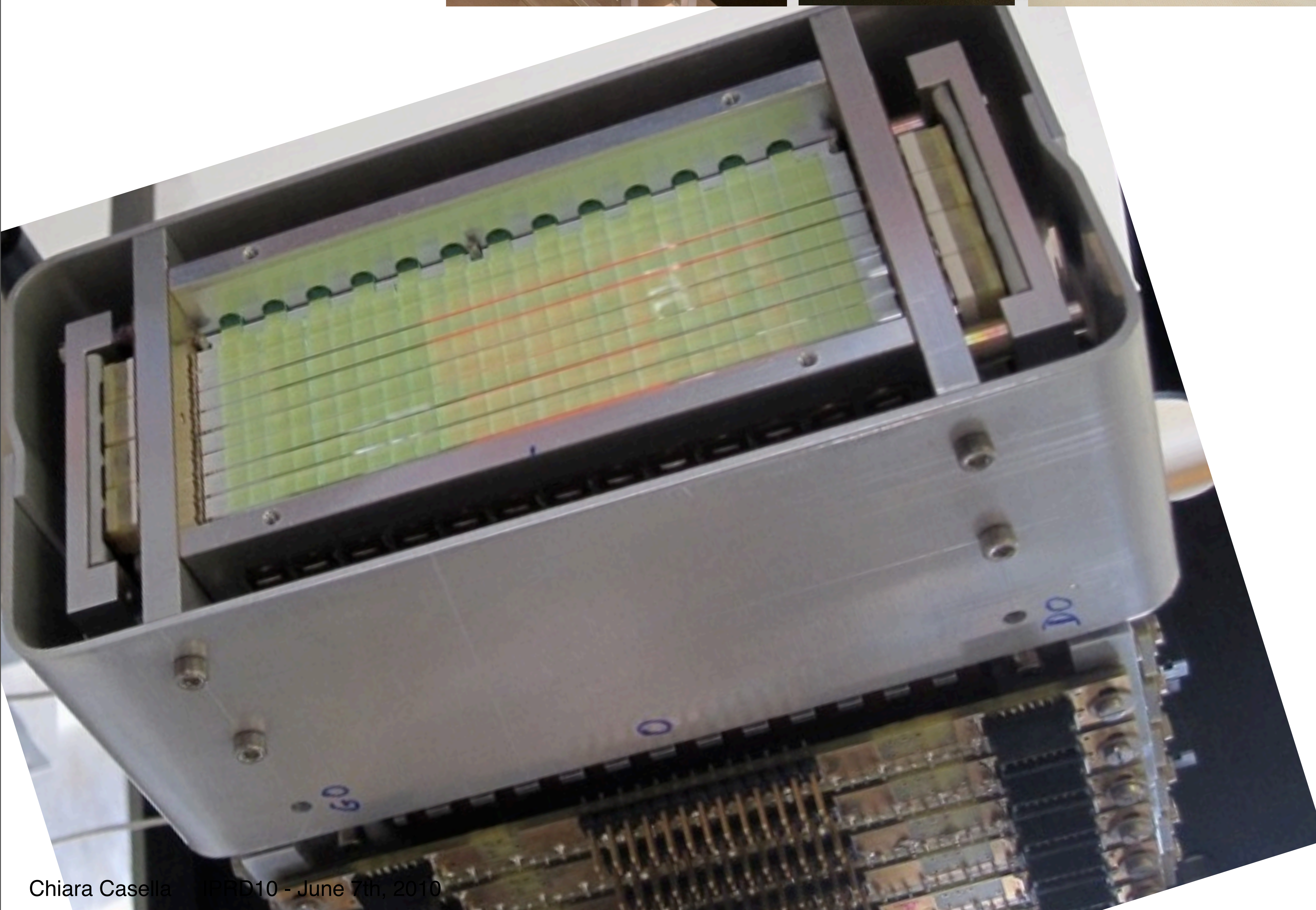
- 1.2 x 3.2 mm² active area
- 70 µm x 70 µm pixel
- 1200 pixels
- Gain ~ 4 x 10^5
- custom made units

AX-PET MODULE





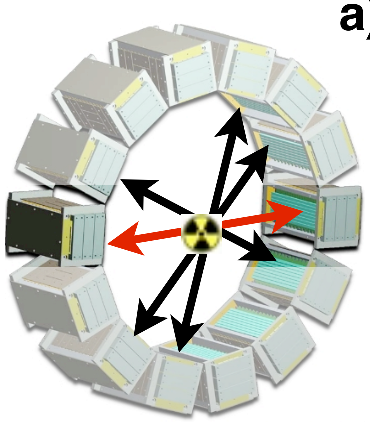




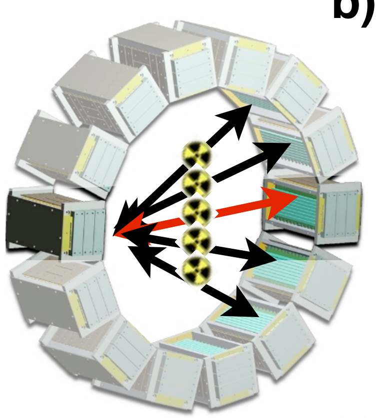
BARE ASSEMBLED MODULE, incuding CONNECTIVITY CARDS

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 mods coincidence + rotating source

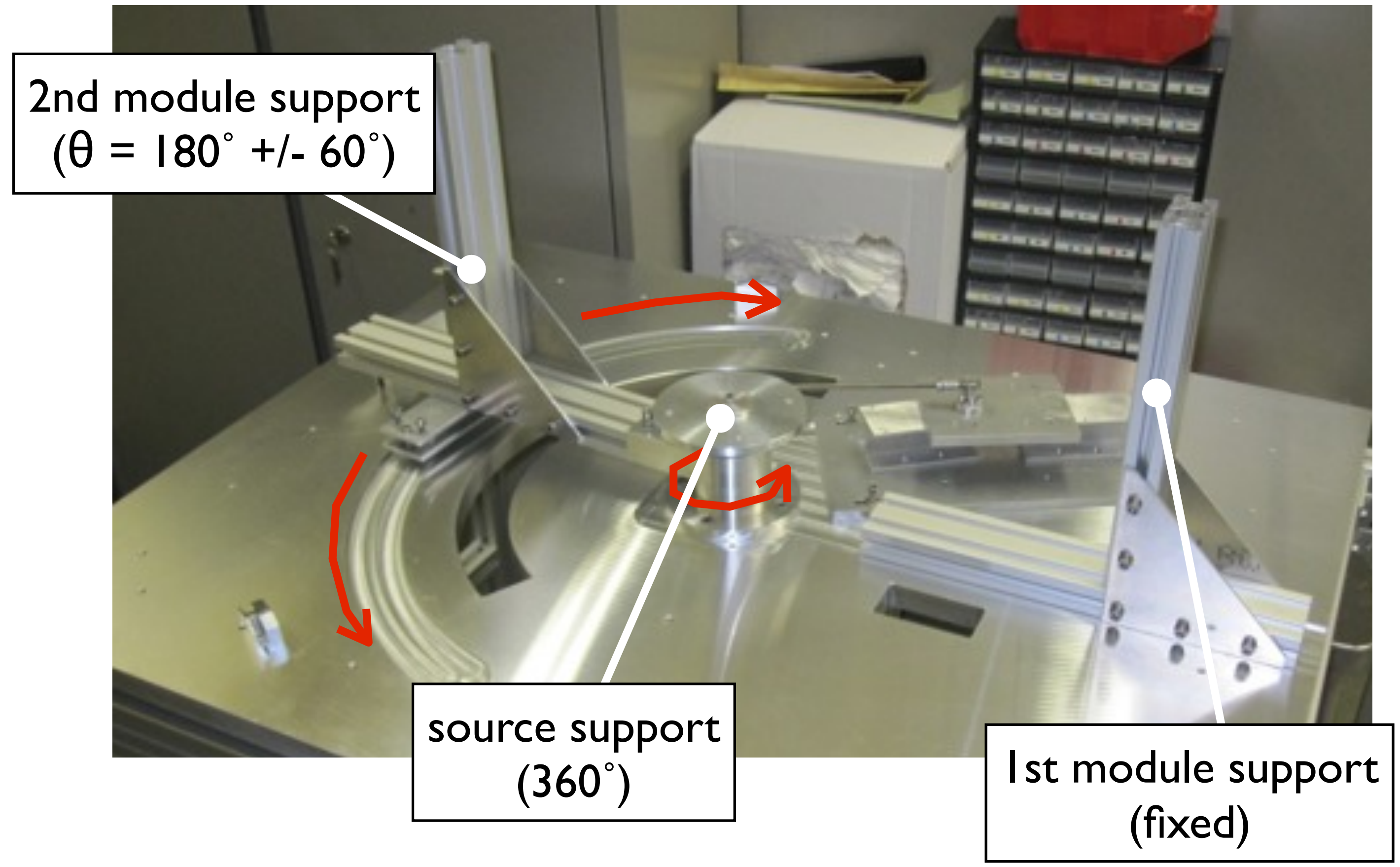


a) small FOV coverage:
- 2 modules fixed, back to back position (180˚)
- rotating source in the center of FOV



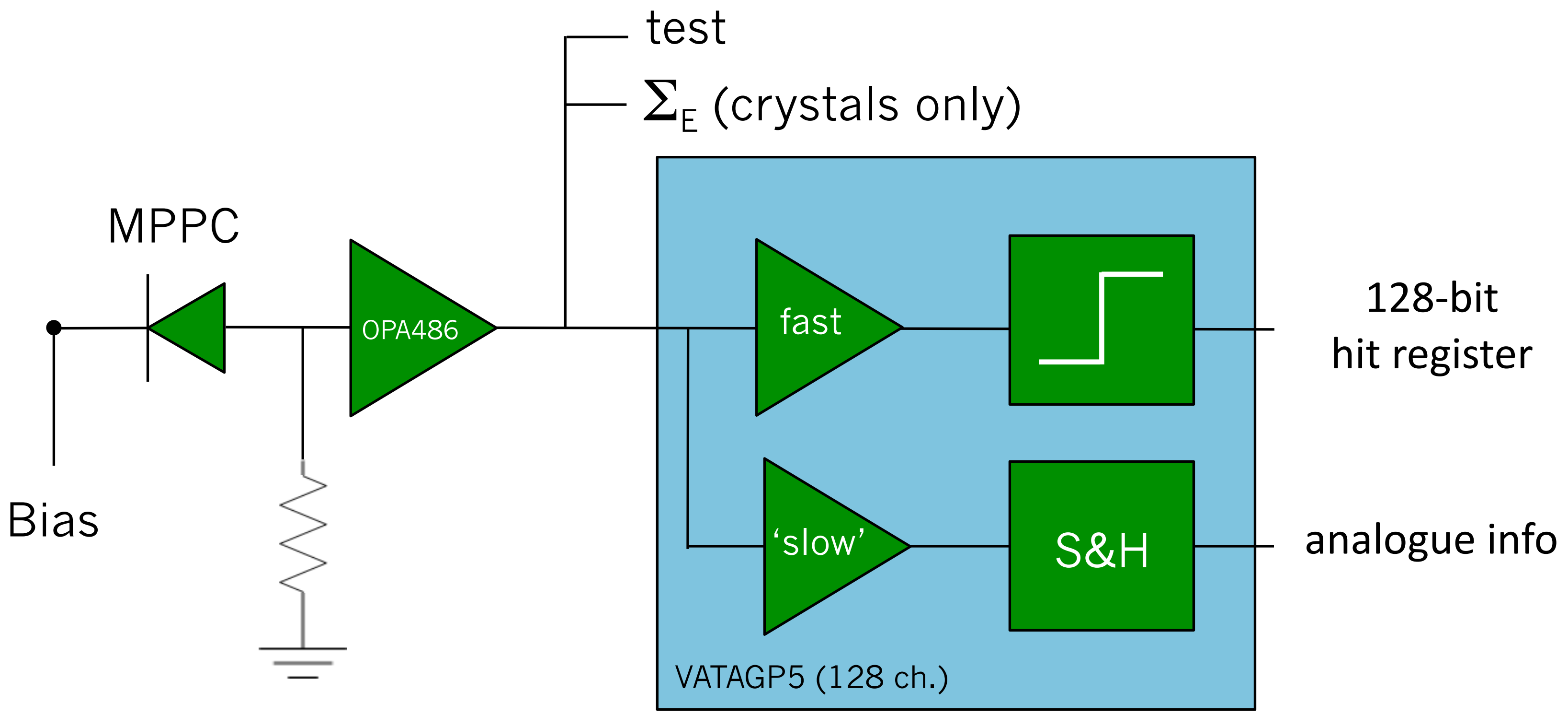
b) extended FOV coverage:
- allow coincidences btw 2 modules not at 180˚
- 1st mod. fixed
- 2nd mod. rotating (θ=180˚+/- 60˚)
- rotating source

"gantry" system / mechanics for the demonstrator

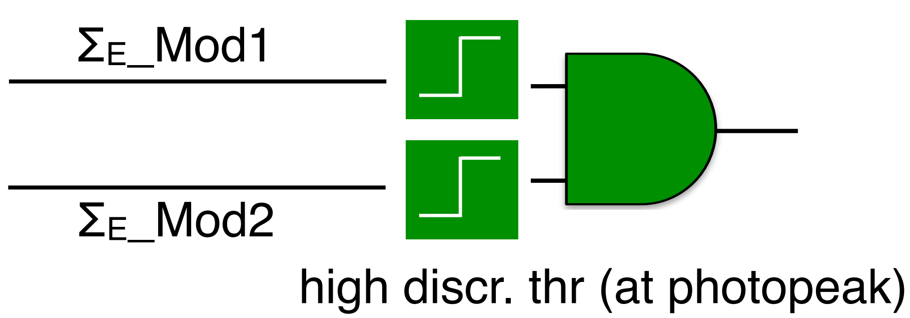


- **dedicated simulations, 2 mods** + validation of the simulation from the data
- final performance of the full scanner : assessed with **dedicated simulations, full scanner**

Demonstrator READOUT and TRIGGER

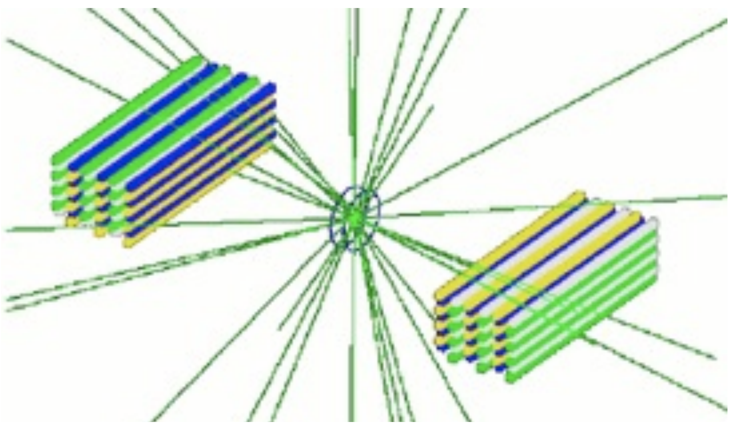


- **Custom designed DAQ system - Individual analogue readout of MPPC output**
- **Amplifiers** : OPA486 (Lyso) / OPA487 (WLS) - **Fast energy sum of all the crystals module**
- **VATA GP5 chip** : 128-ch charge sensitive integrating [AXPET : x4 VATA GP5 chips]
  - Fast (~40ns) / Slow (~250ns) branches
  - Sequential or <u>Sparse readout mode</u>
  - **Sparse** = the analogue signals of the flagged - i.e. above thr - channels only is multiplexed into the output
- **EXTERNAL TRIGGER** (NIM logic) :
  Coincidence of the two 511 keV annihilation photons (one per module), with high energy discrimination thr



AXPET (2 modules, coinc.) is fully modeled by **dedicated Monte Carlo simulations**

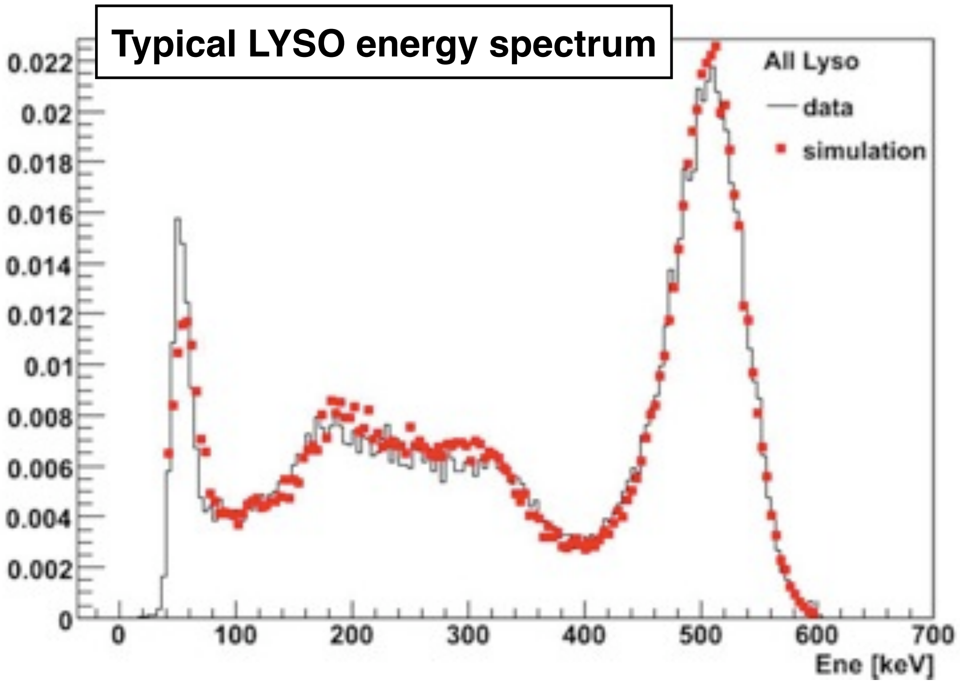
GATE simulation package (G4 application for tomographic emission, including time-dependent phenomena e.g. detector movement)

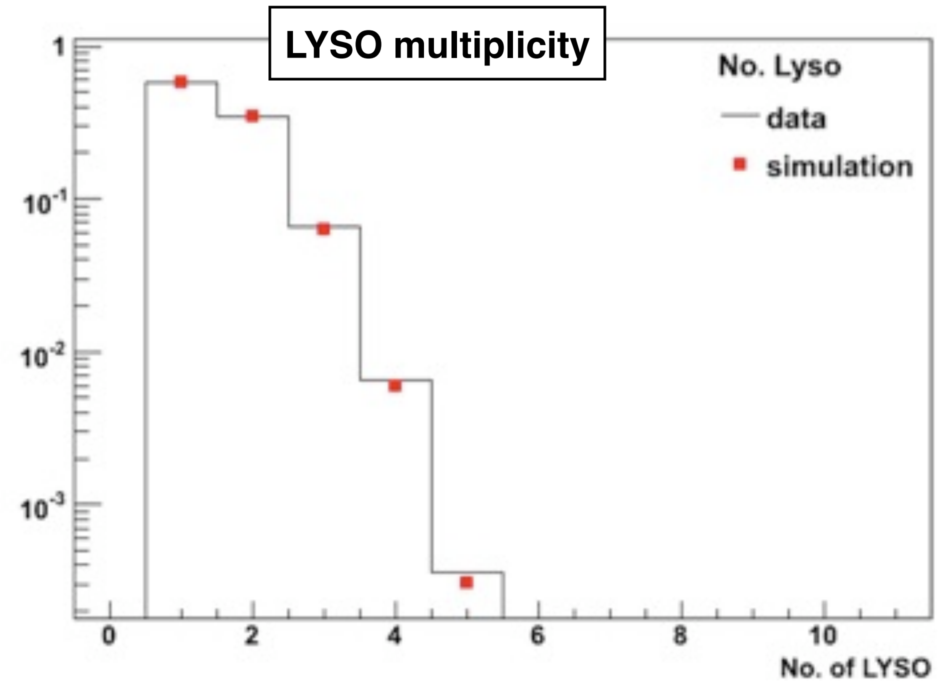


AXPET challenges for realistic simulations :
- non conventional PET design
- WLS parameterization in the digitizer(*)
- Sorter for the coincidences

(*) = implied major change in the simulation source code

Excellent agreement data / simulations :





One AXPET Module illuminated by a collimated 511 keV gamma beam : Data and Simulations

AX-PET STORY: RECENT MILESTONES

- Module 1 : assembled - **July 2009**
- Module 2 : assembled - **Sept 2009**

- Single module characterization in a dedicated test setup (**Aug '09 - Nov '09**)
  - with ^{22}Na point-like sources
  - at CERN
- Two modules in coincidence - dedicated test setup (**Nov '09 - March '10**)
  - with ^{22}Na point-like sources
  - at CERN
- Transition to the new gantry setup (**Mar - Apr 2010**)
  - at CERN, with point-like sources on rotating table
- Two modules in coincidence with phantoms filled with 18F-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute
  - **20th - 30th April 2010**

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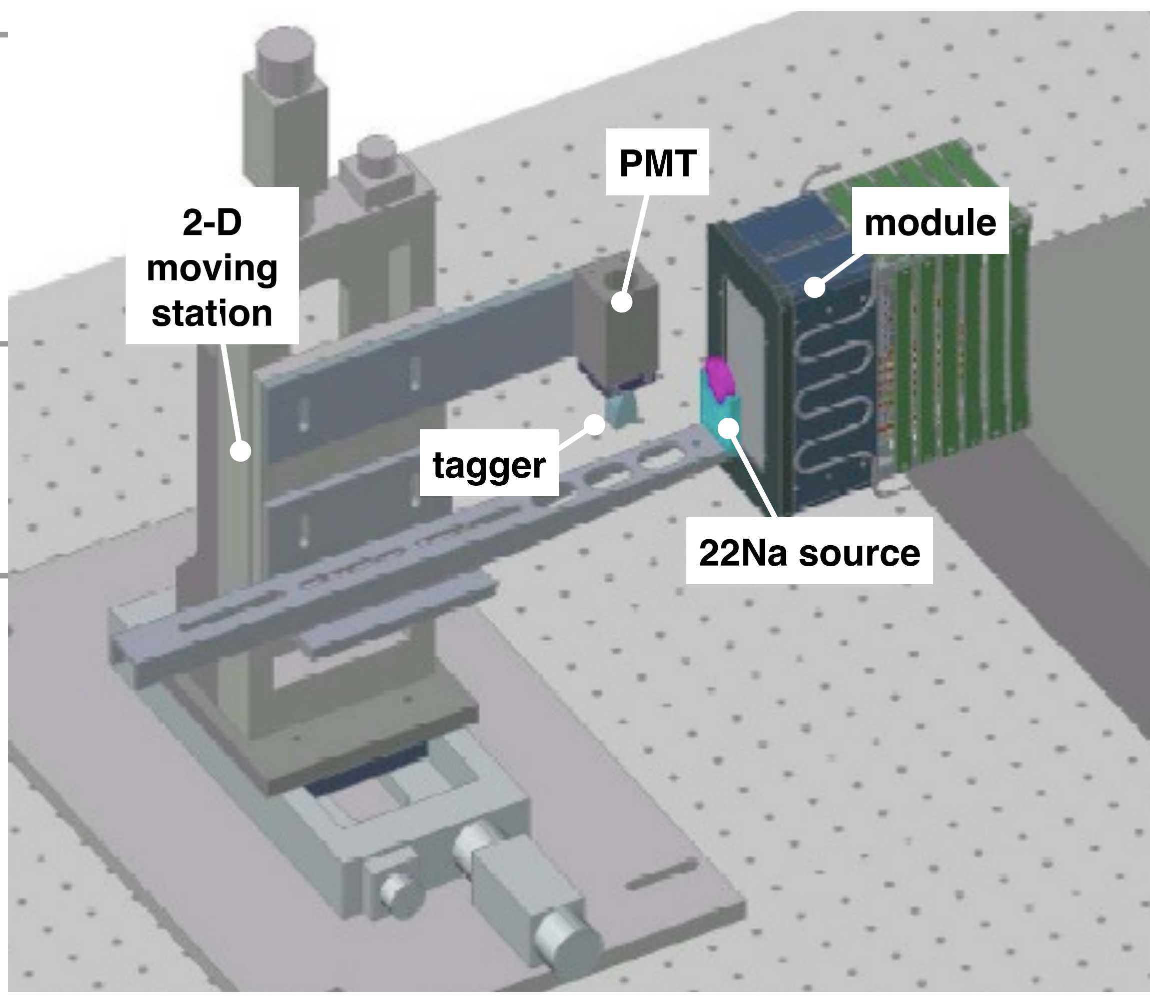

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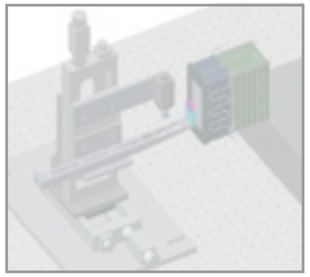

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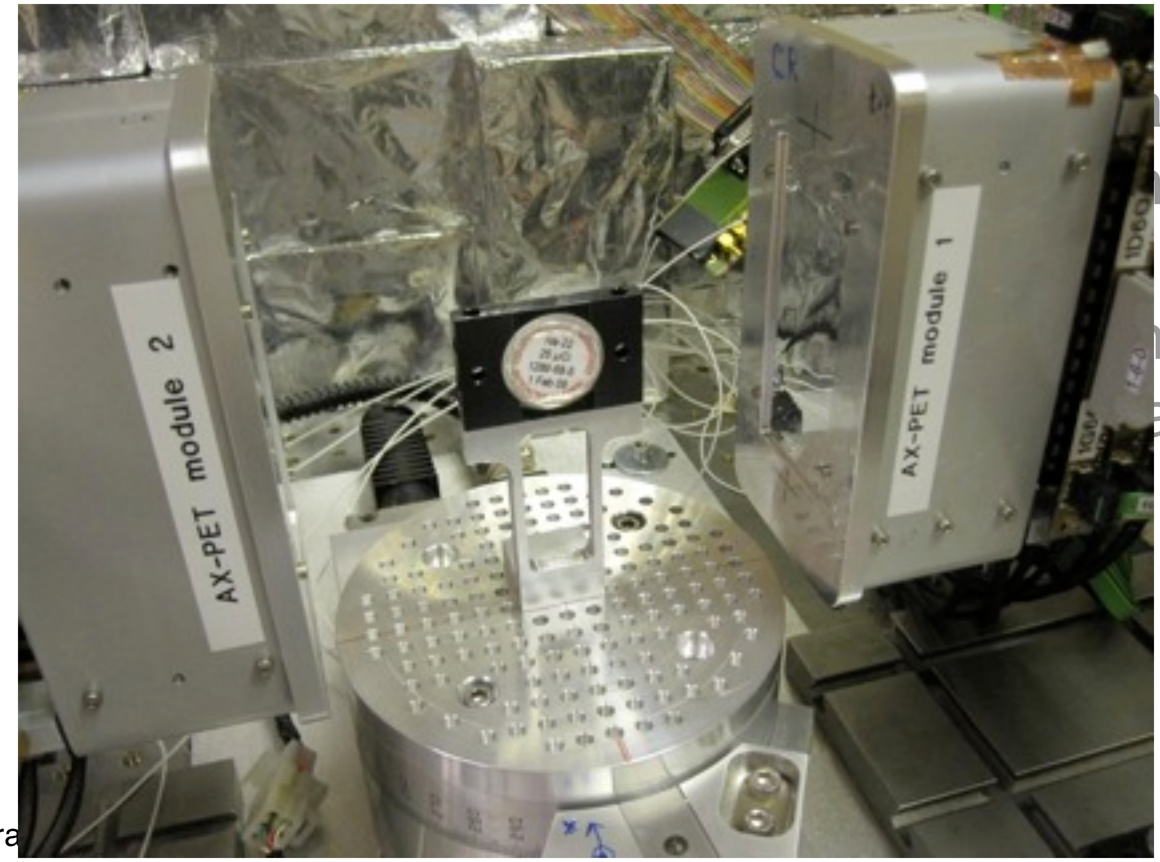

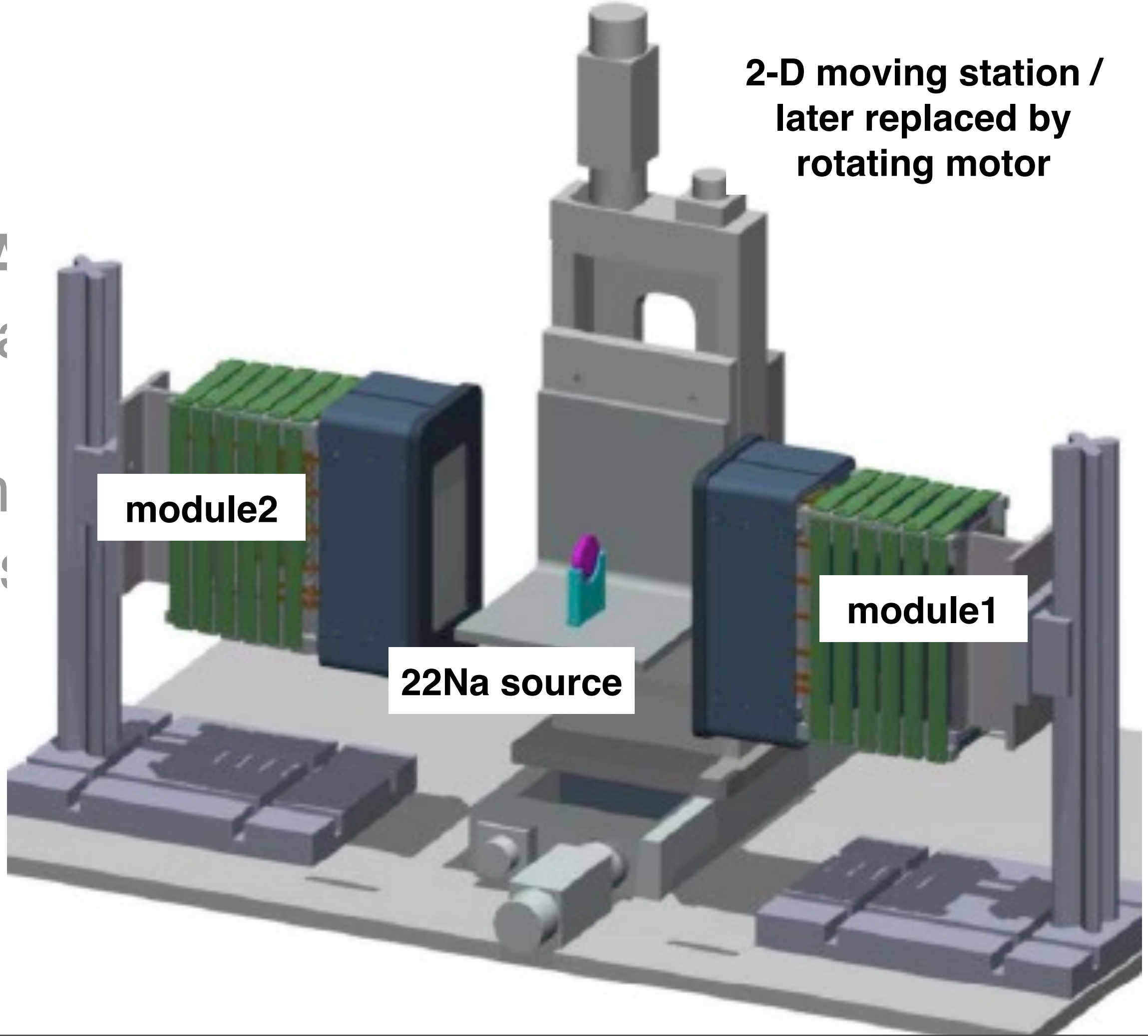

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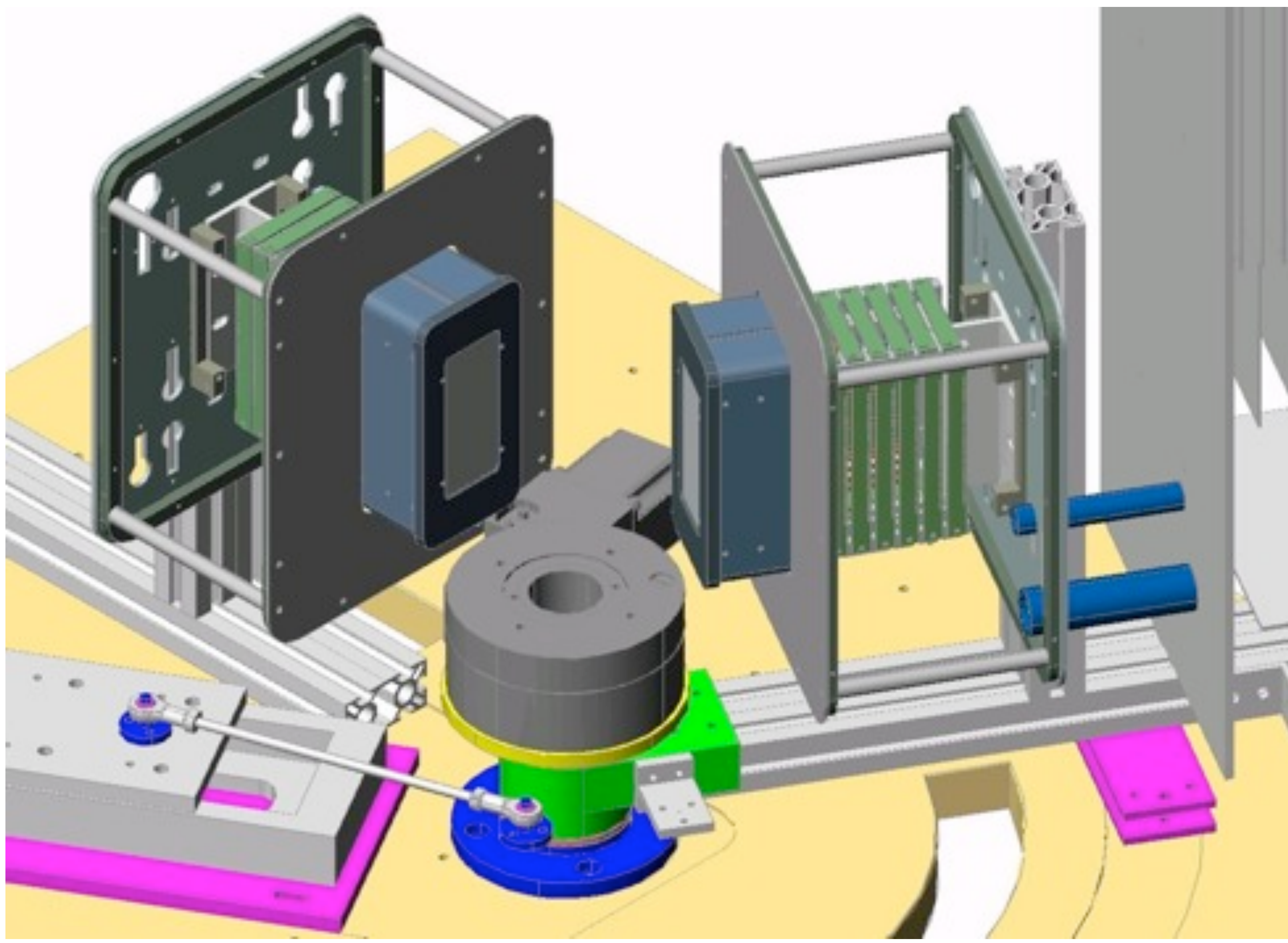

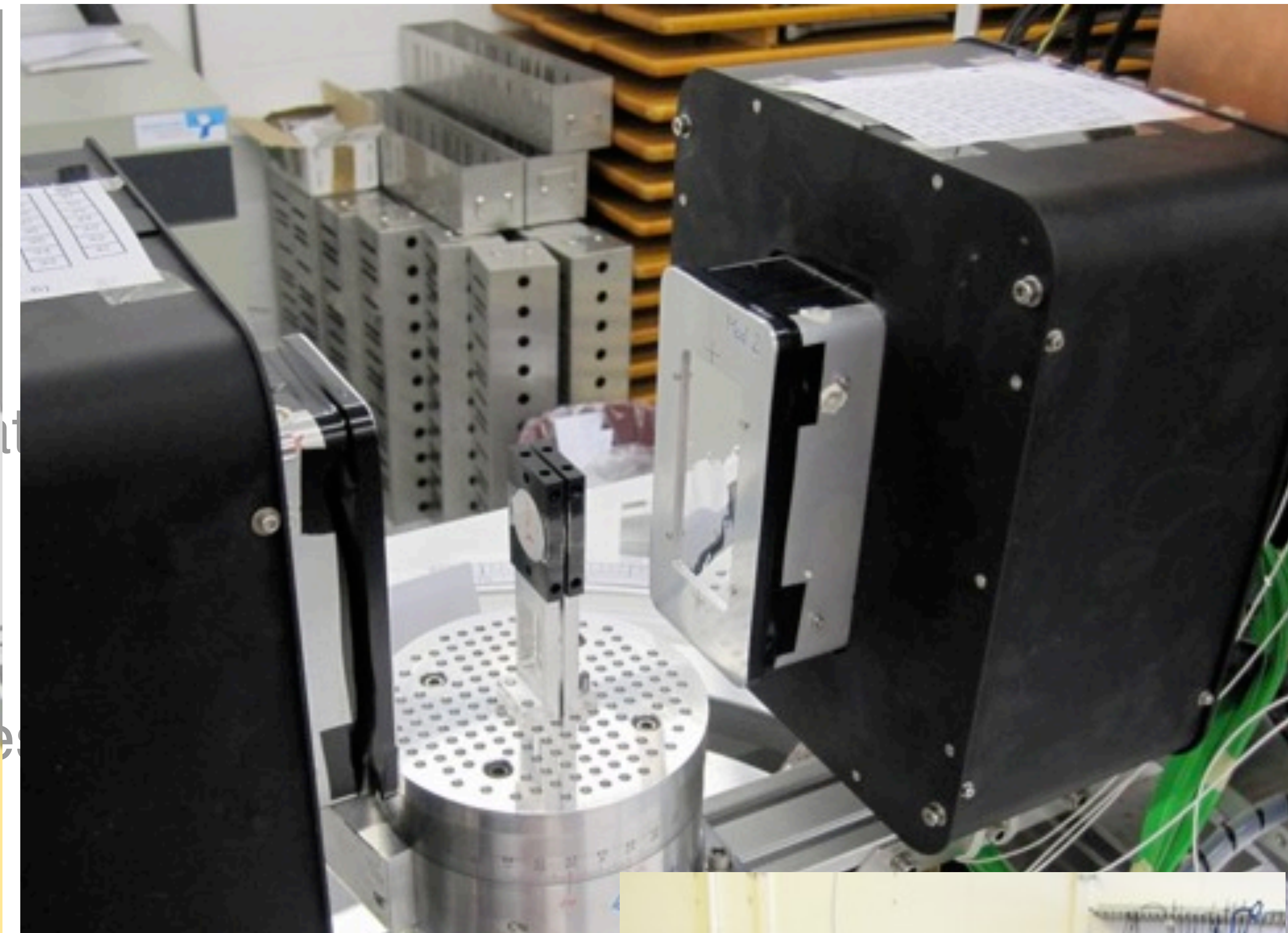

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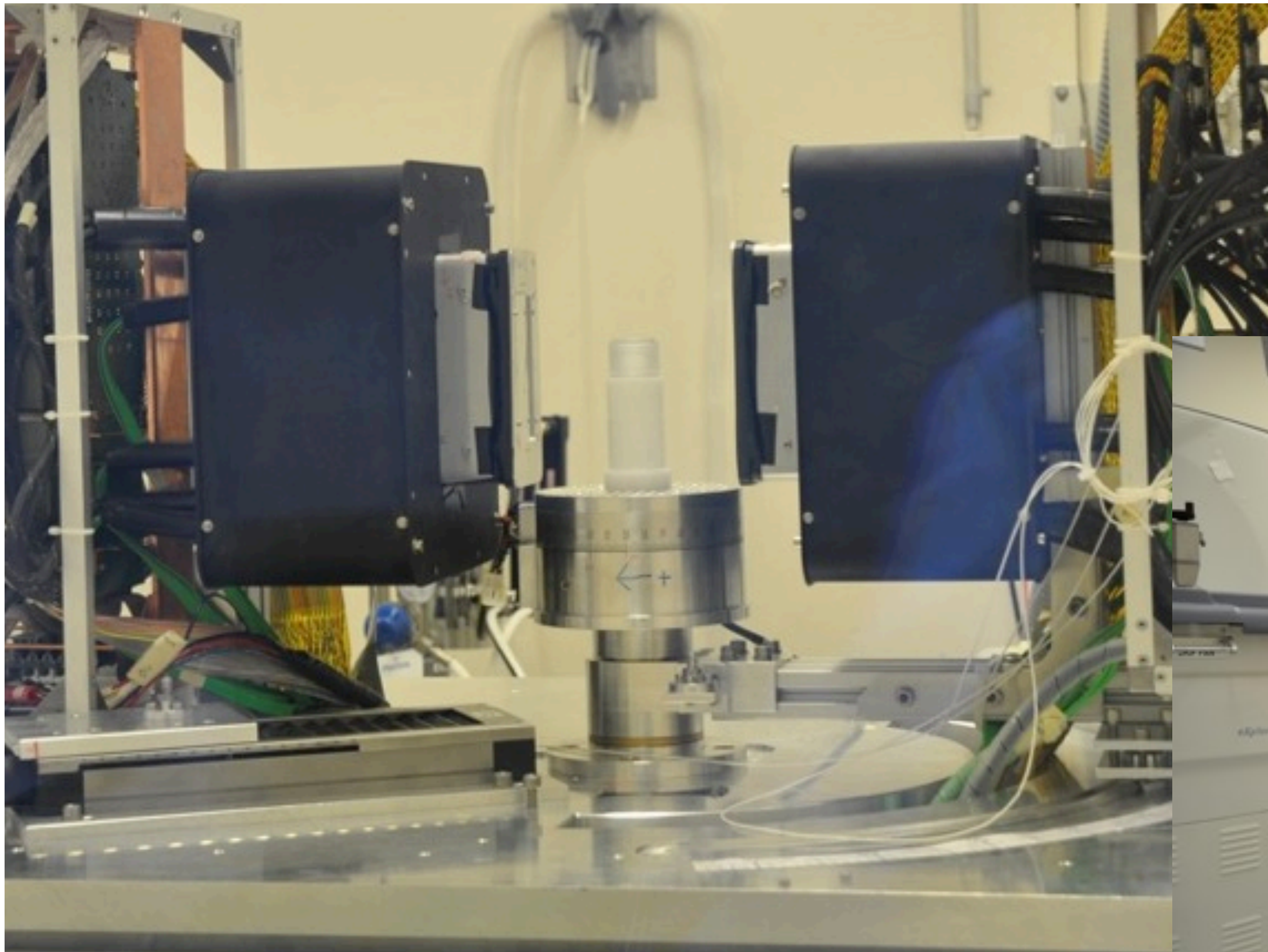

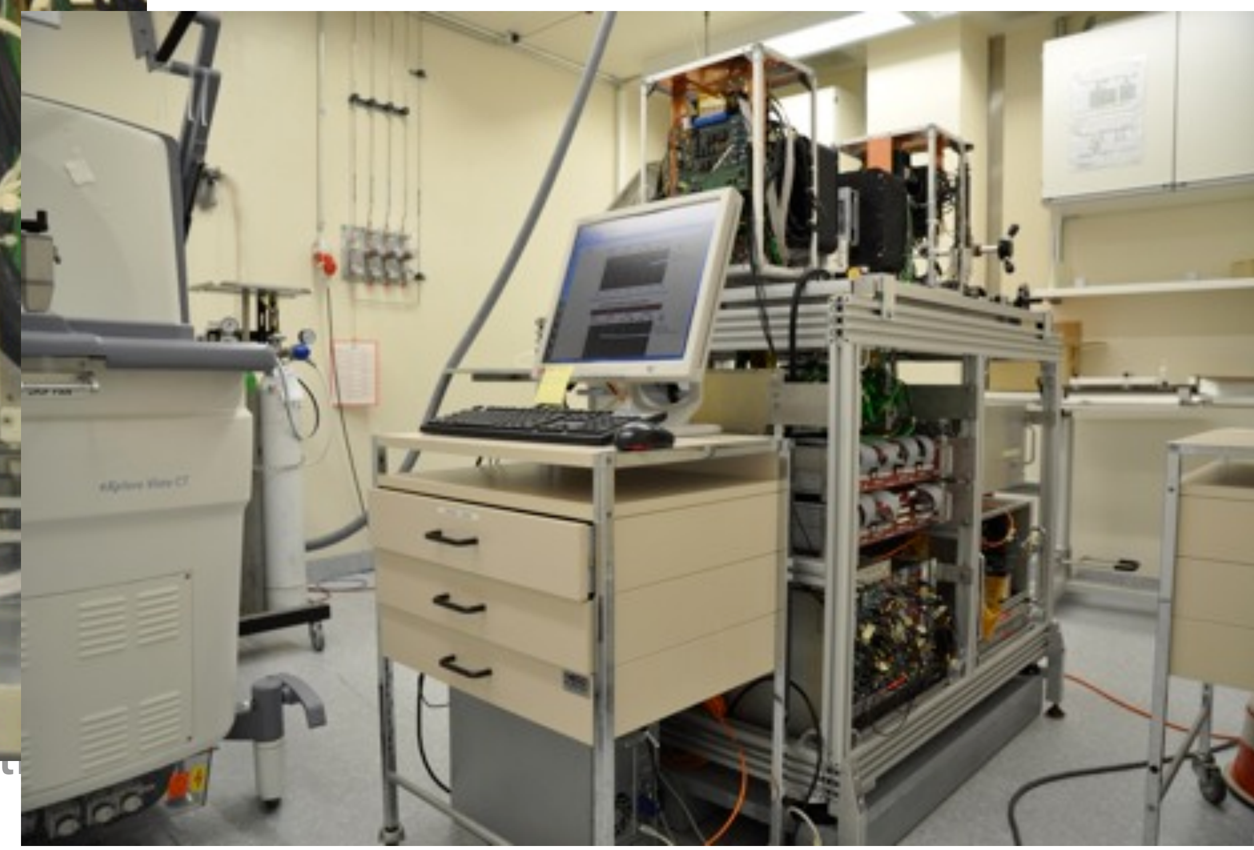

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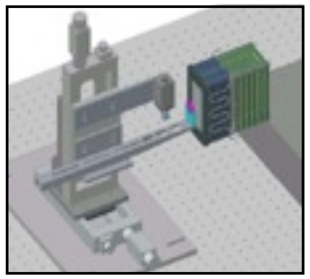

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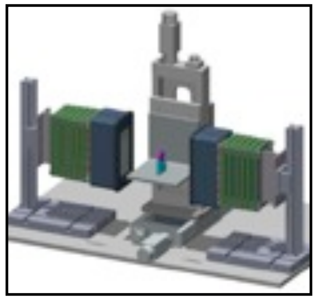

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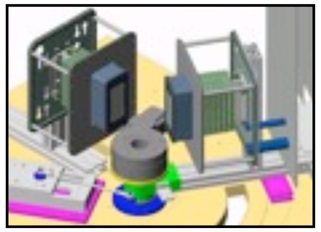

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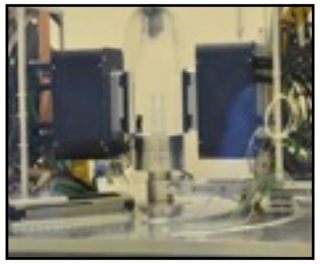

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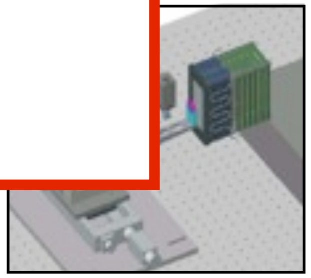
DETECTOR PERFORMANCE:
- energy resolution
- spatial (axial) resolution
- timing performance
- occupancy / multiplicities



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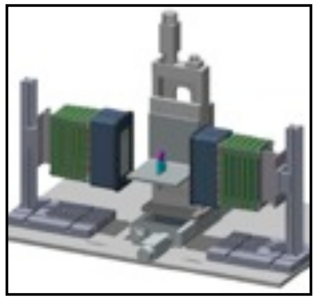

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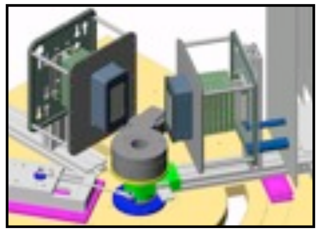
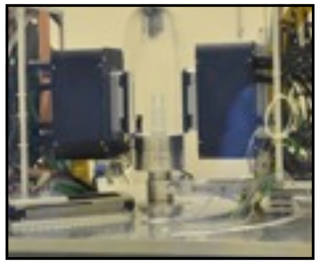
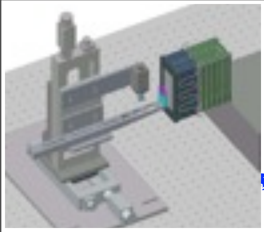
  - **20th - 30th April 2010**

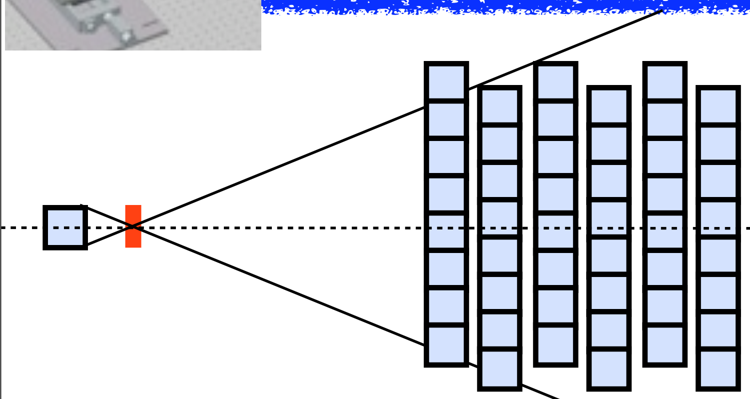




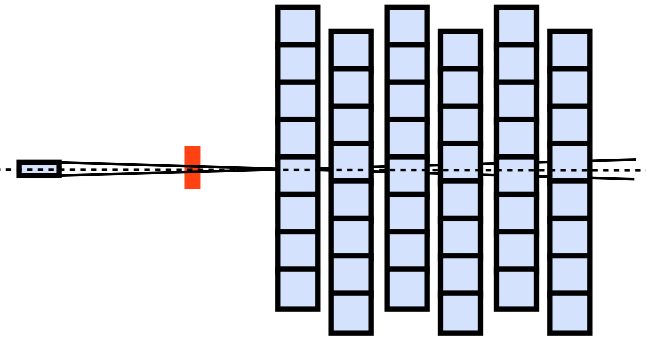
- image reconstruction
- very first results

Single module characterization

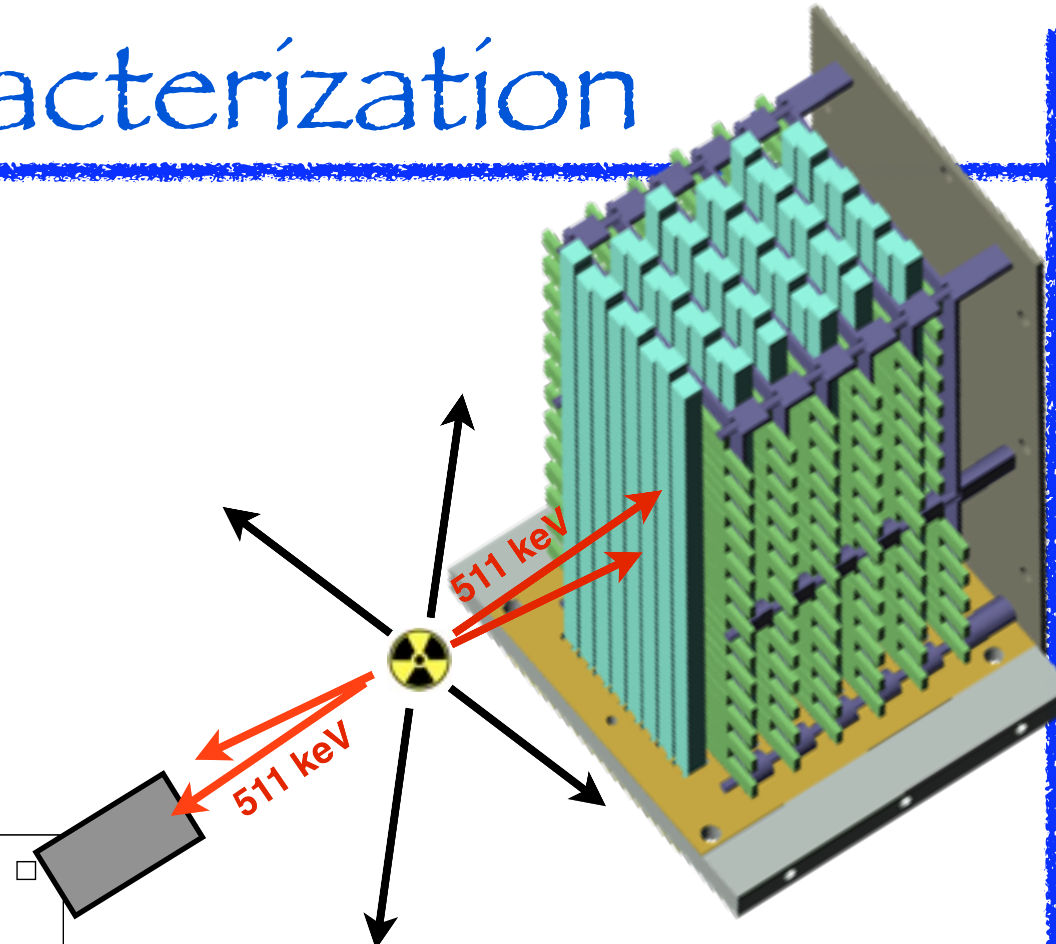


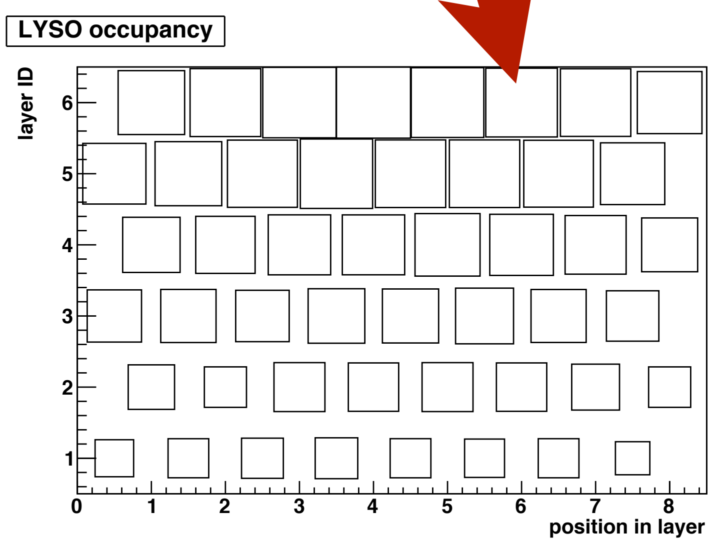


for energy calibration, energy resolution

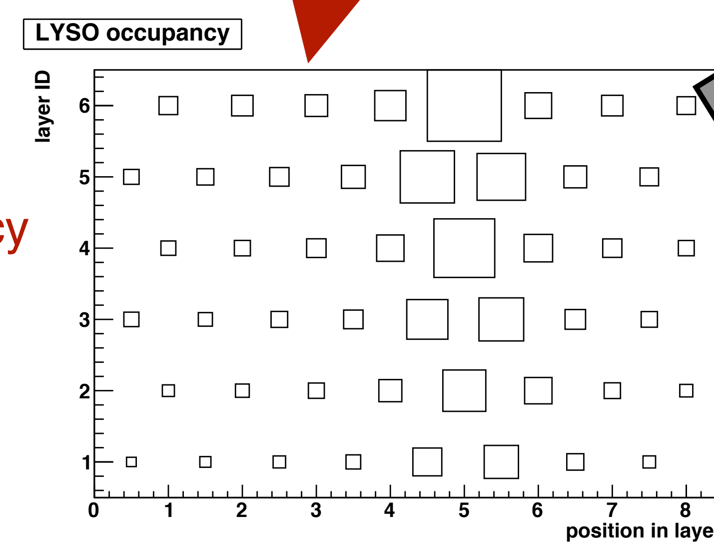


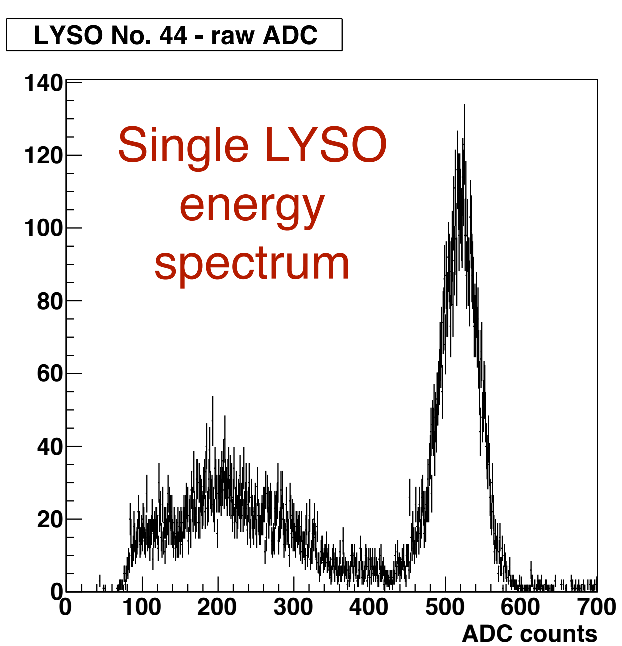
collimated beam spot, spatial resolution

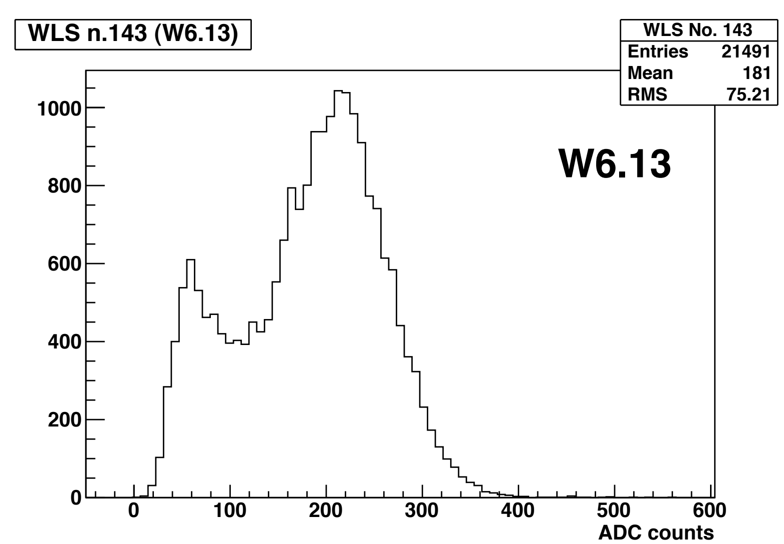




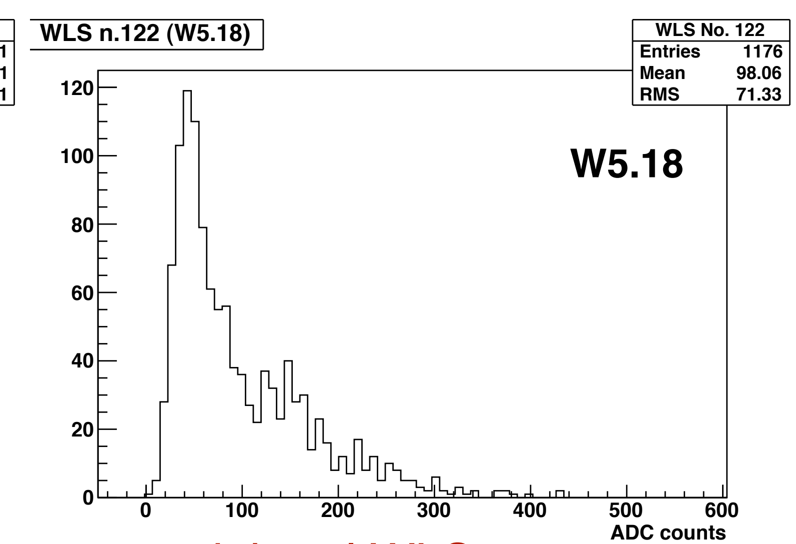
LYSO occupancy



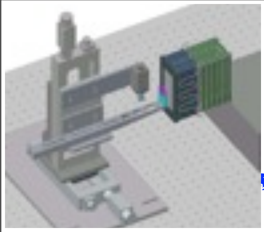




central WLS spectrum

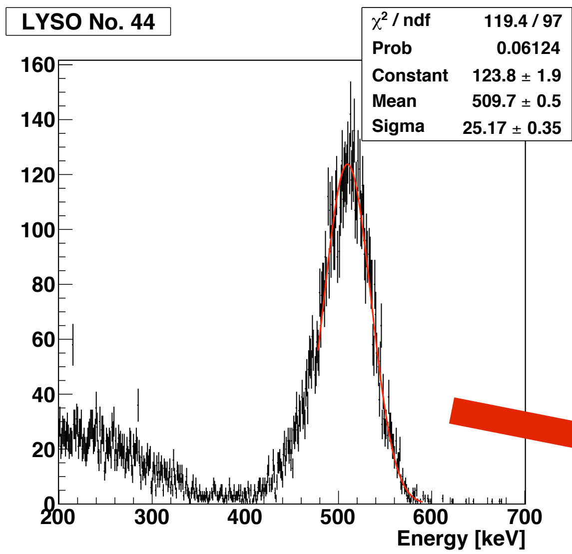


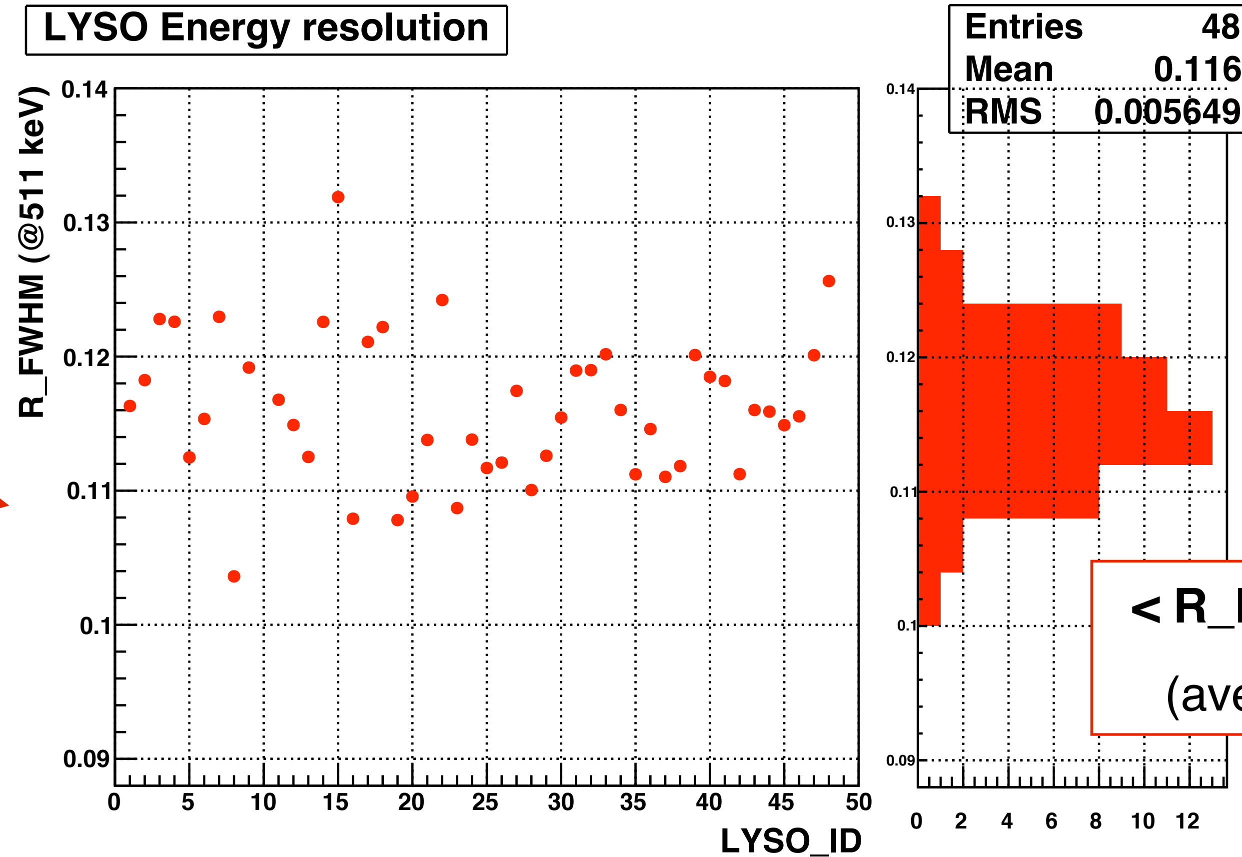
peripheral WLS spectrum



ENERGY RESOLUTION

After ENERGY CALIBRATION (i.e. from raw ADC counts to keV units) :



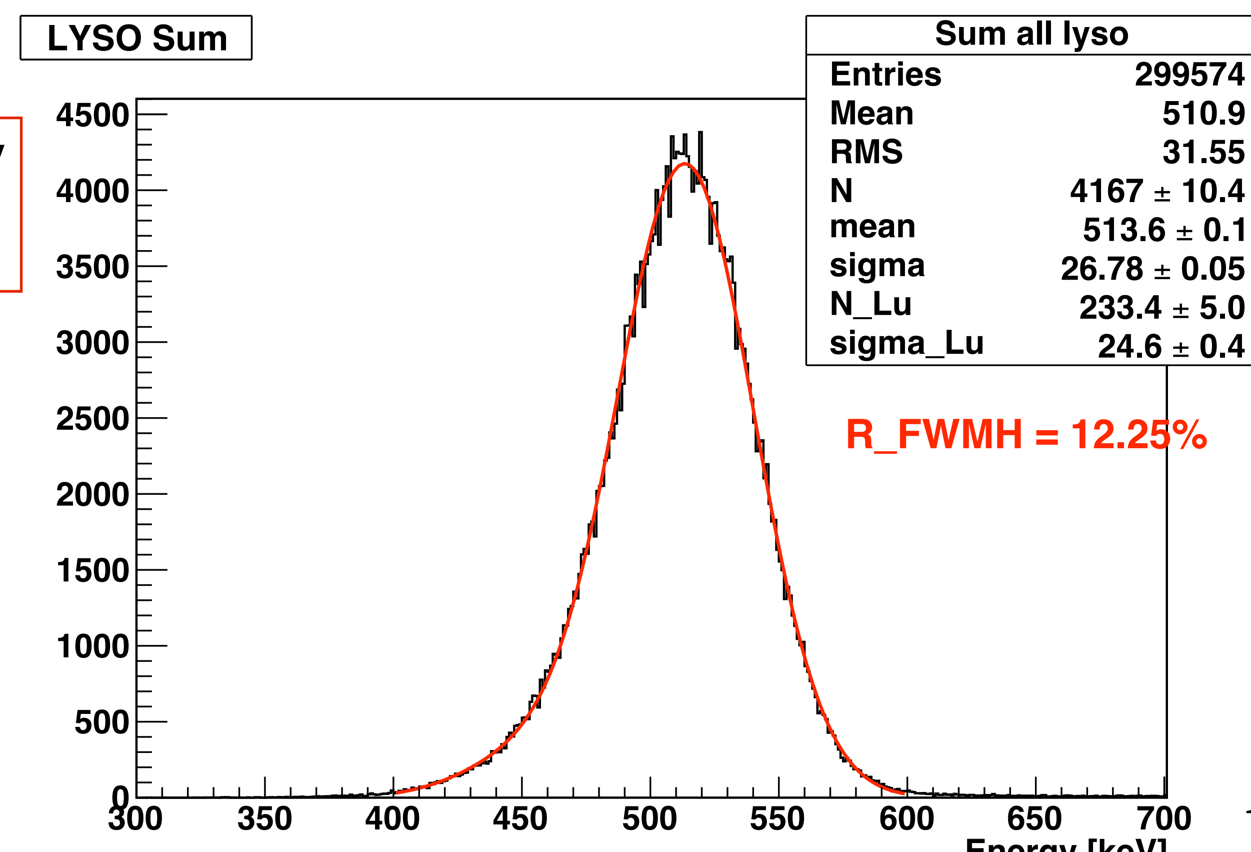


< R_FWHM > ~ 11.6% @511 keV

(averaged on 48 LYSO crystals)

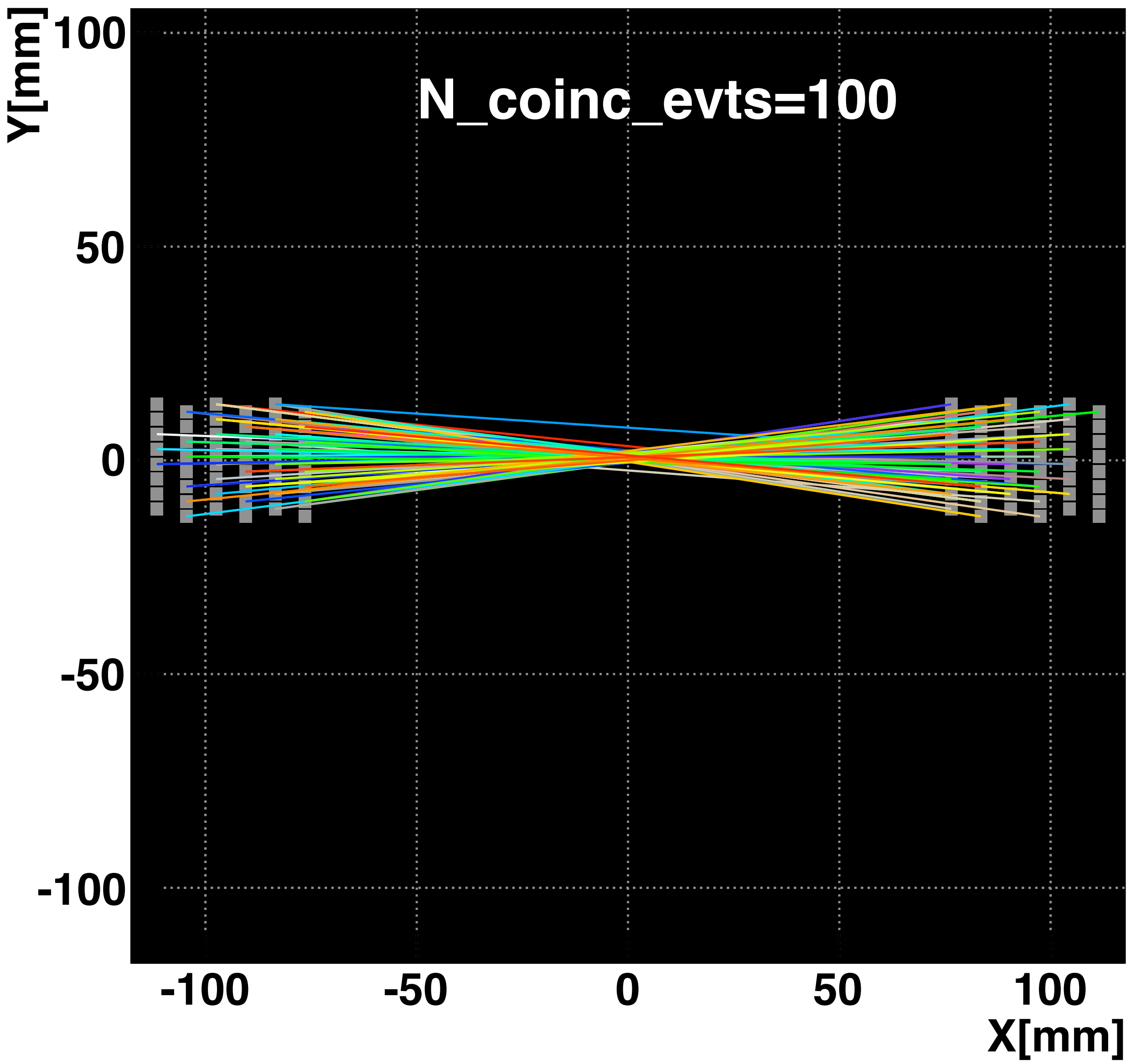
R_FWHM_Sum ~ 12.25% at 511 keV

(on the summed distribution)

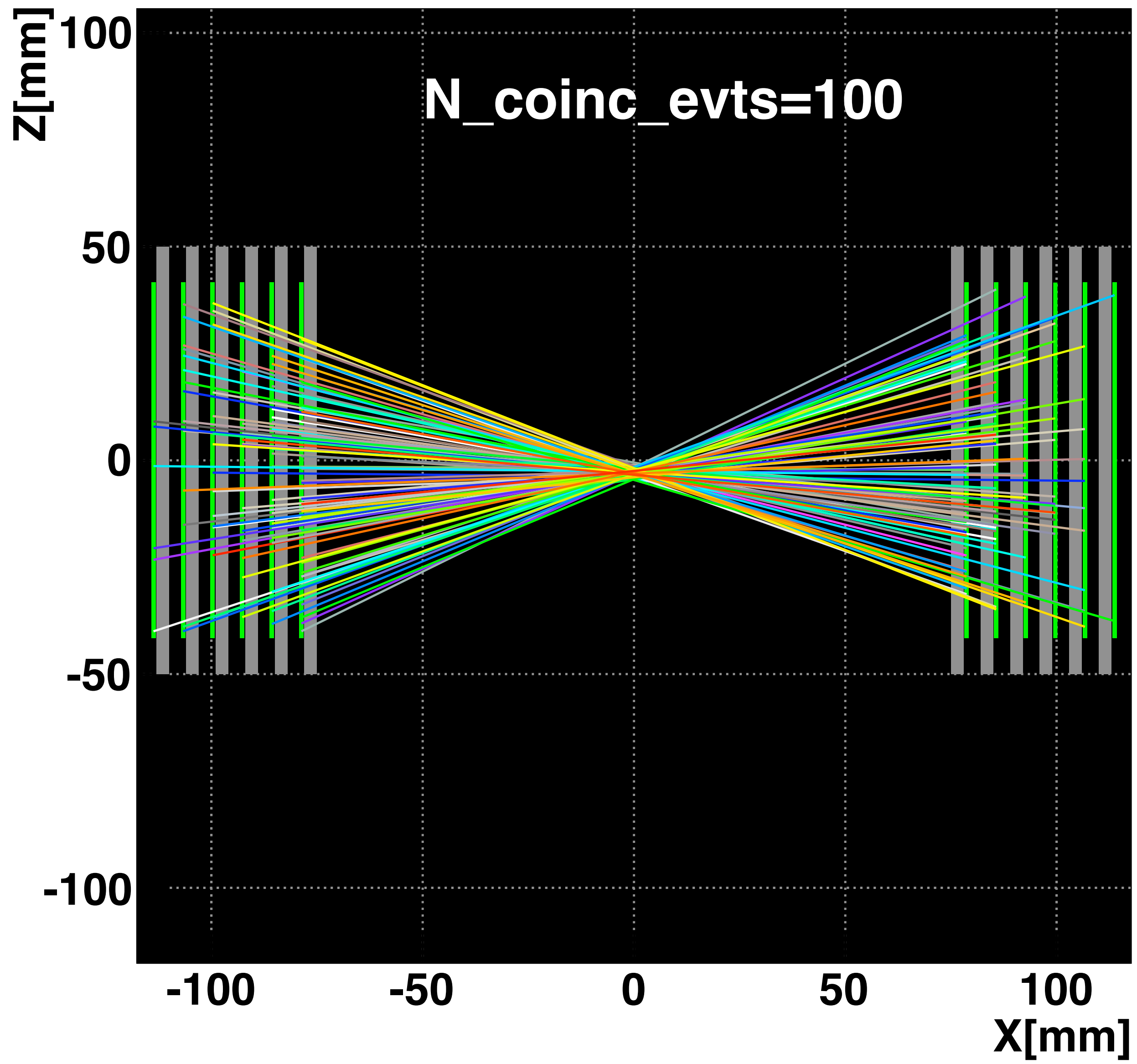


TWO MODULES COINCIDENCE

TOP View - d(Mod1,Mod2) = 150 mm



SIDE View - d(Mod1,Mod2) = 150 mm

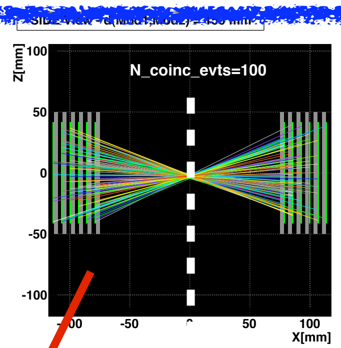


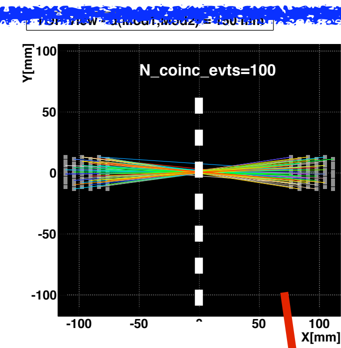
on scale!
[mm]

/home/daq/axpet/log/run02730.log INFO: Temperature is 20.89 in Mod1 21.05 in Mod2
/home/daq/axpet/log/run02730.log INFO: **
/home/daq/axpet/log/run02730.log INFO: Run Number: ********** 02730 **********
/home/daq/axpet/log/run02730.log INFO: **
/home/daq/axpet/log/run02730.log INFO: Run Start Time: Mon Nov 23 12:01:20 2009

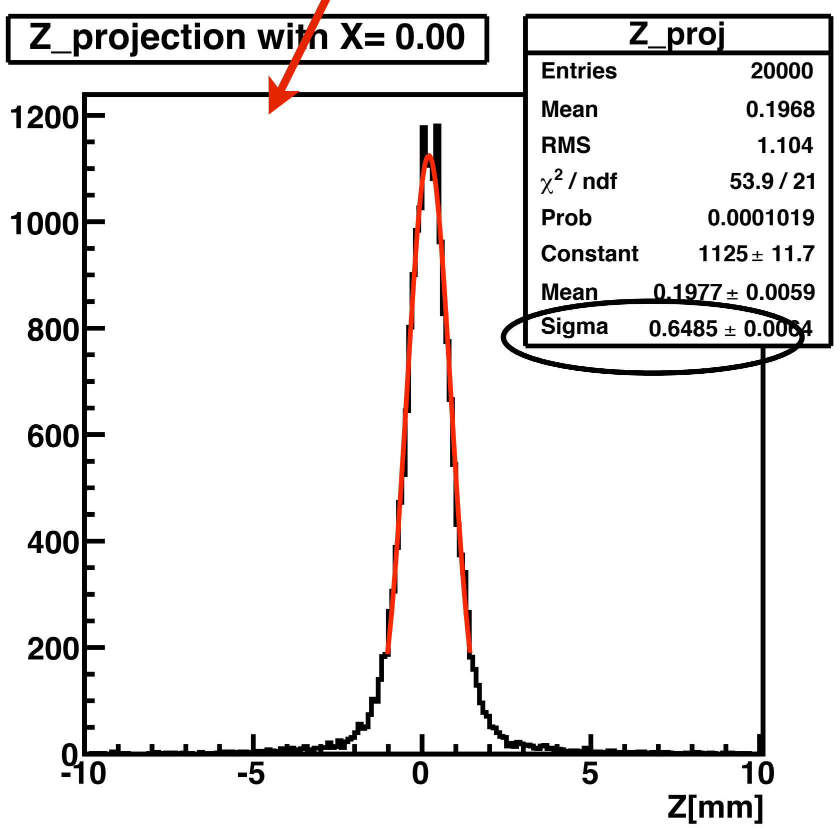
/home/daq/axpet/log/run02730.log INFO: Run Type: SPARSE readout
/home/daq/axpet/log/run02730.log INFO: Comment: Test_Mod1_AND_Mod2 Temp. 20.89 M1 - 21.05 M2

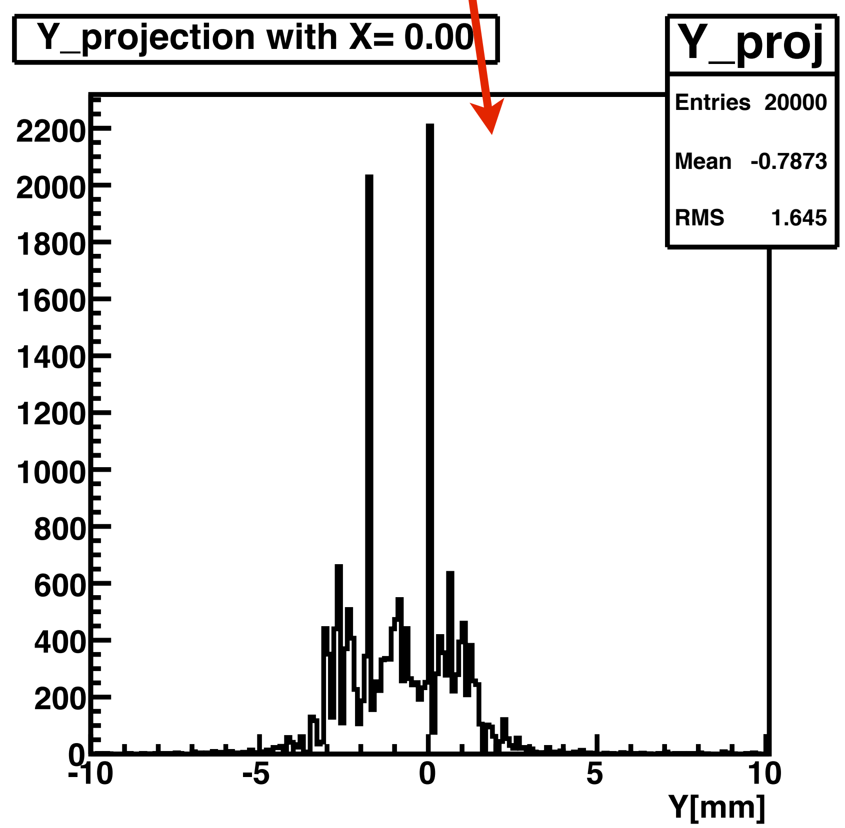
AXIAL RESOLUTION

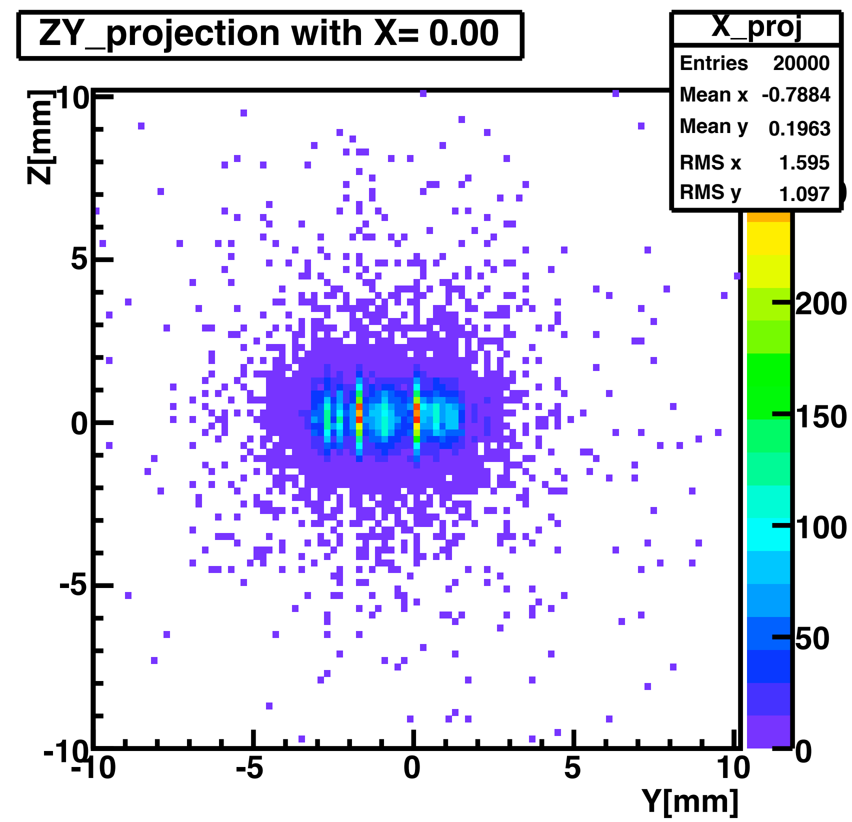




Intersection of LOR with central plane -- no tomographic reconstruction !!!





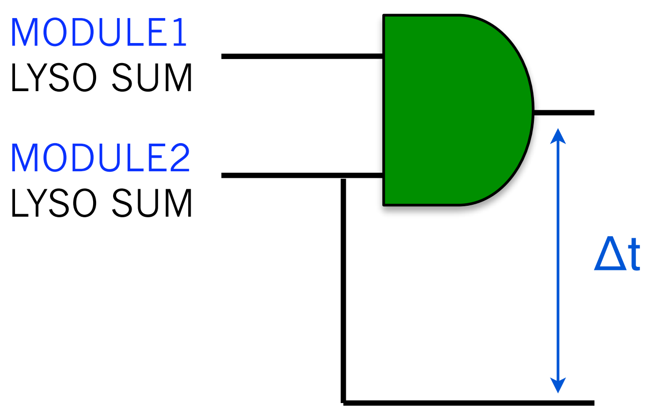


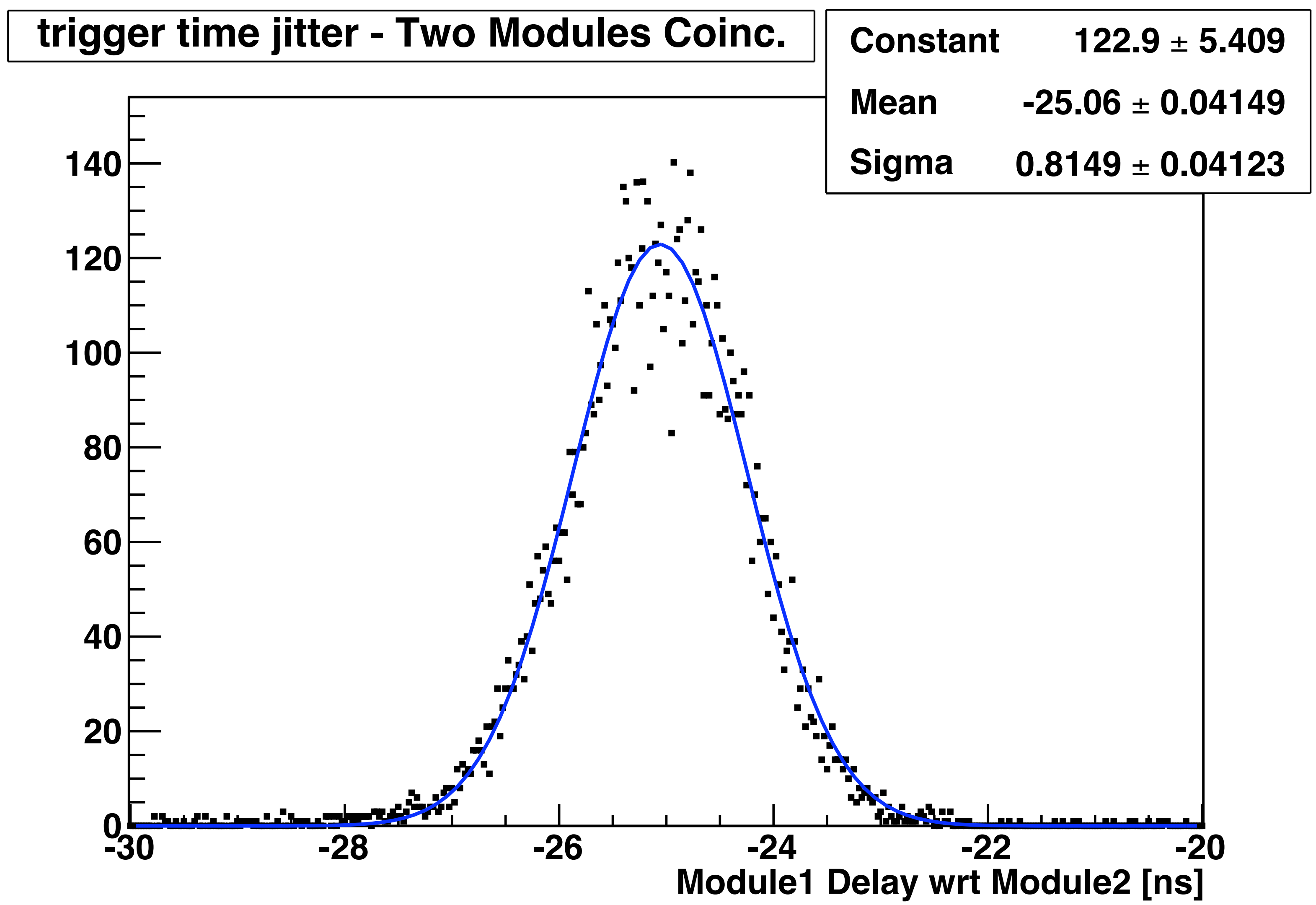
- $(R\_FWHM)_z \sim 1.5$ mm
  - intrinsic resolution
  - positron range
  - non collinearity
  - (source dimensions ; ø=250μm)

=> **$(R\_intrinsic\_FWHM)_z \sim 1.35$ mm**

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

- measure delay of coincidence wrt Mod2
- measurement from the scope [Lecroy Waverunner LT584 L 1GHz]





Measured time resolution : **FWHM ~ 1.9 ns**

MEASUREMENTS with PHANTOMS

- **First measurements with extended objects filled with radio-tracers**
- **Apr 26th-30th 2010**
- at **ETH Zurich - Radiopharmaceutical Institute (Animal PET Lab)**
- ^{18}F - FDG ($t_{1/2}$ ~ 110 mins)
- Phantoms used : micro-Derenzo, with and without inserts (L= 1.5 cm; ø = 2 cm; ø_rods = [0.8,1.3] mm)
  mouse-like phantom (L = 7 cm; ø = 3 cm)
  capillaries (L = 3 cm; ø = 1.4 mm)

- acquisition method: only source rotating - 2 modules fixed (i.e. center FOV)
- Dist_2mod2 = 15 cm

- for the moment only “golden events” are used for the reconstruction
  (1 LYSO per module, unambiguous definition of the z coordinate)

RECONSTRUCTION

- Statistical iterative reconstruction method
- MLEM (Max Likelihood Expectation Maximisation)
- System matrix
  - detailed description of the geometry
  - based on Siddon algorithm

- FOV : voxel dimension : 1 x 1 x 1 mm^3

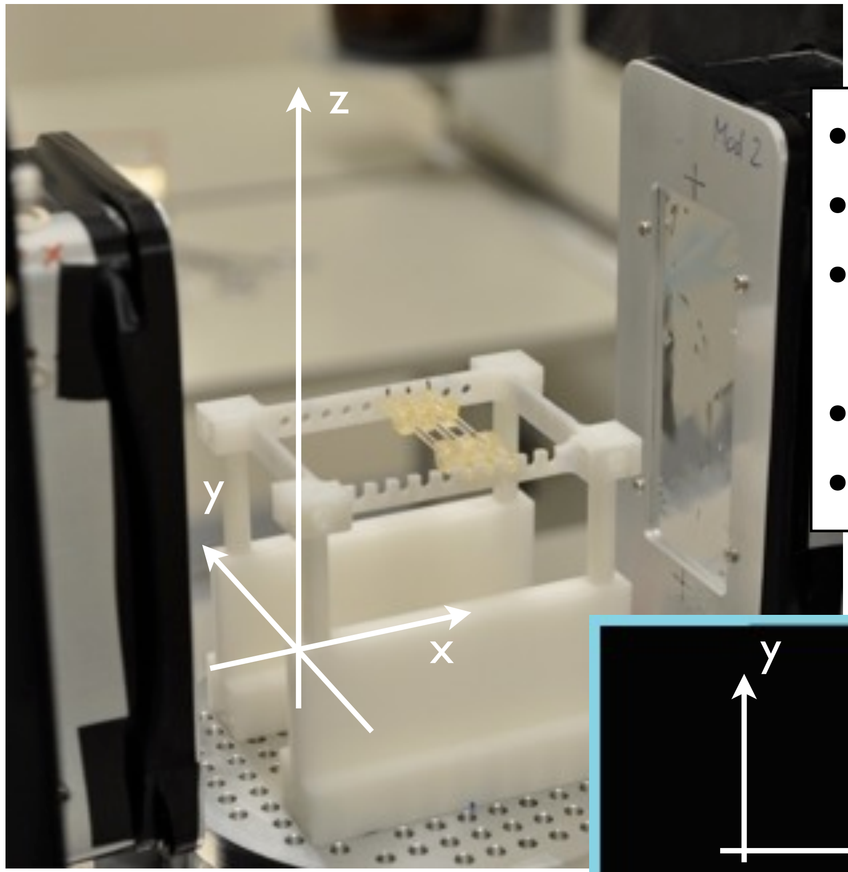
MEASUREMENTS GOALS :

- test performance
- uniformity
  - Derenzo without inserts
  - mouse-like phantom
- resolution
  - Derenzo with inserts
  - Capillaries

WORKS IN PROGRESS

PRELIMINARY RESULTS !

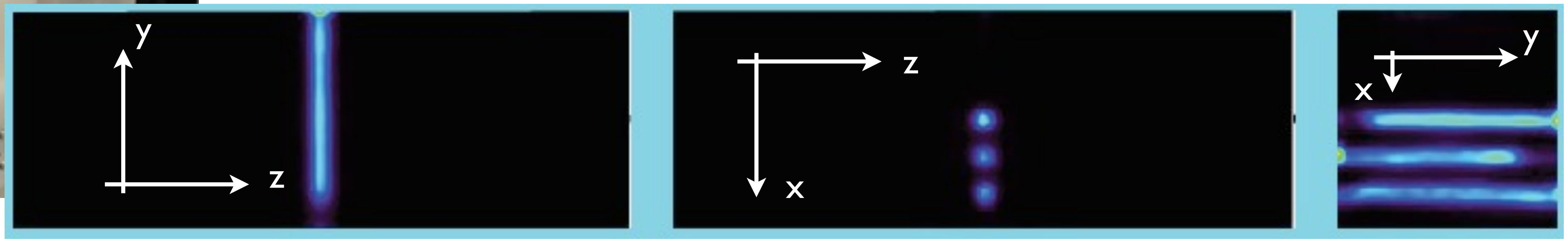
RECONSTRUCTED IMAGE : Capillaries (1)

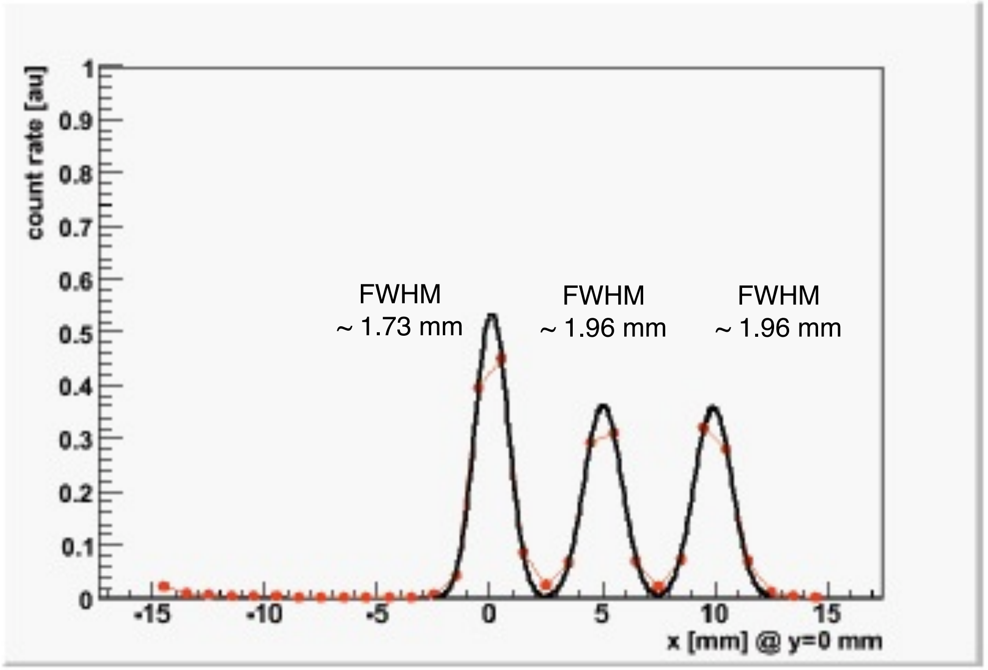


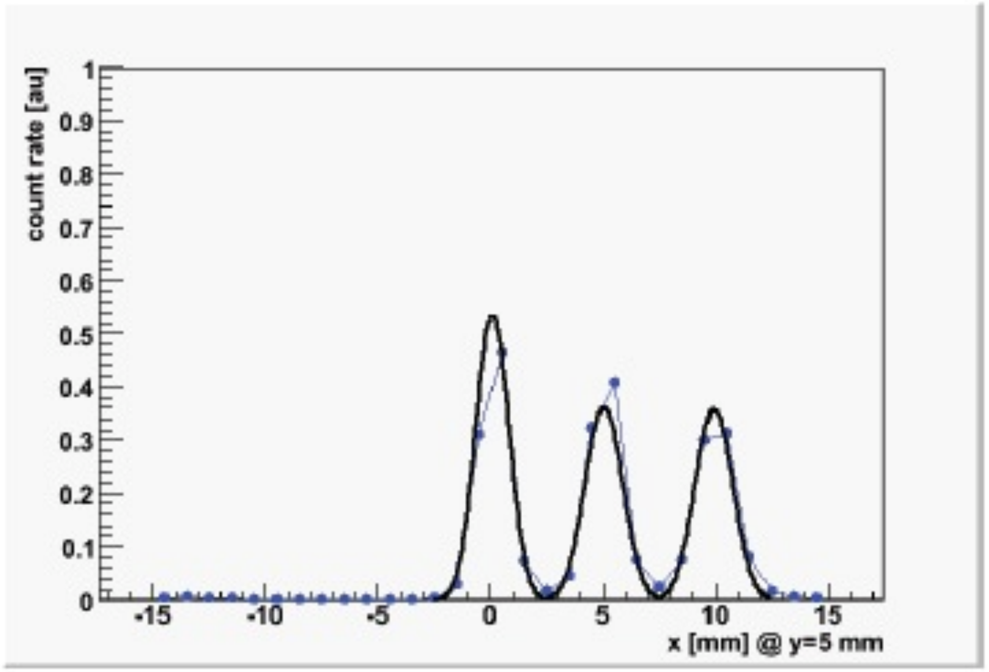
- phantom : 3 capillaries (// xy)
- capillaries (x3) : **L = 3cm** ; **Diam = 1.4 mm** ; **Pitch = 5 mm**
- 17 positions of the phantom, θ in [0˚,170˚]

- FOV : 30 x 30 x 83 vox³ = 30 x 30 x 83 mm³
- 30 iterations

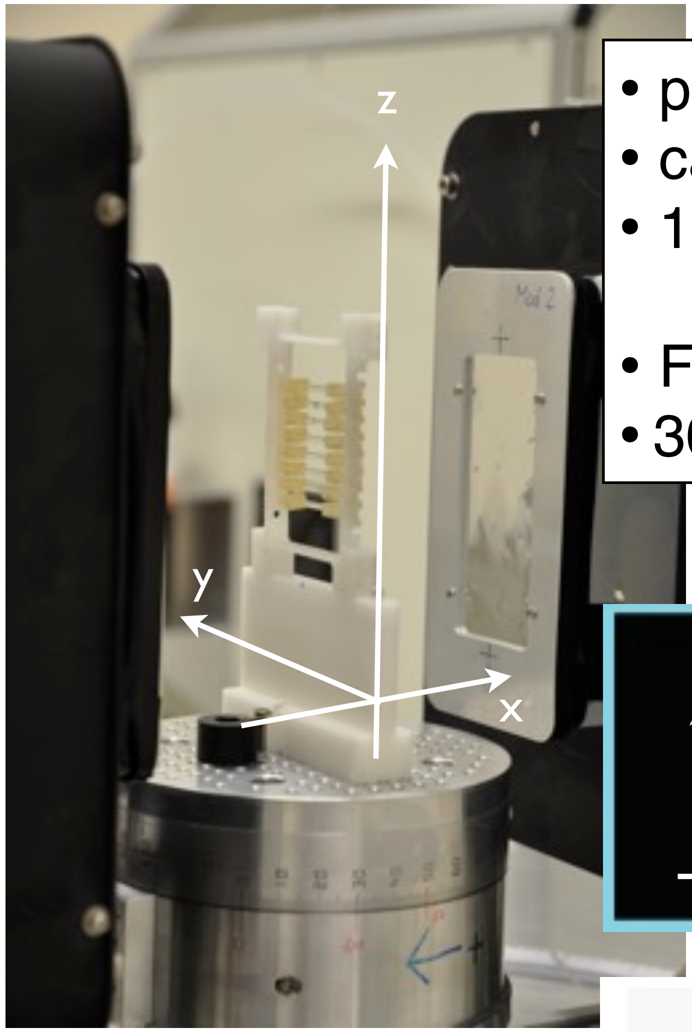
preliminar!!!







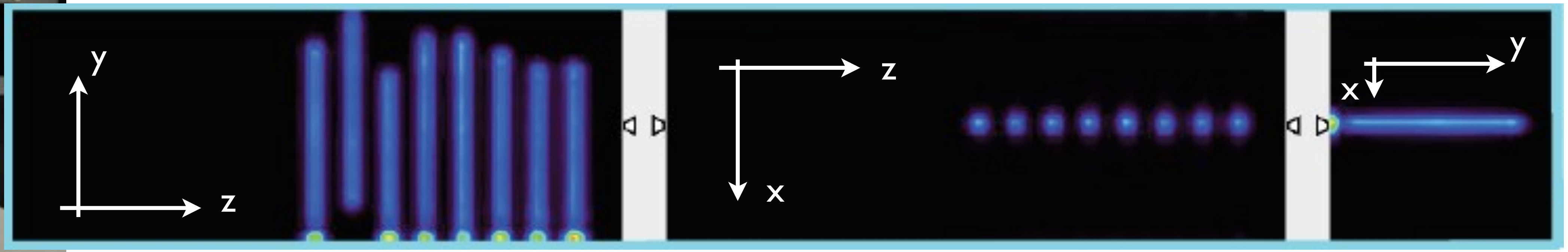
RECONSTRUCTED IMAGE : Capillaries (2)

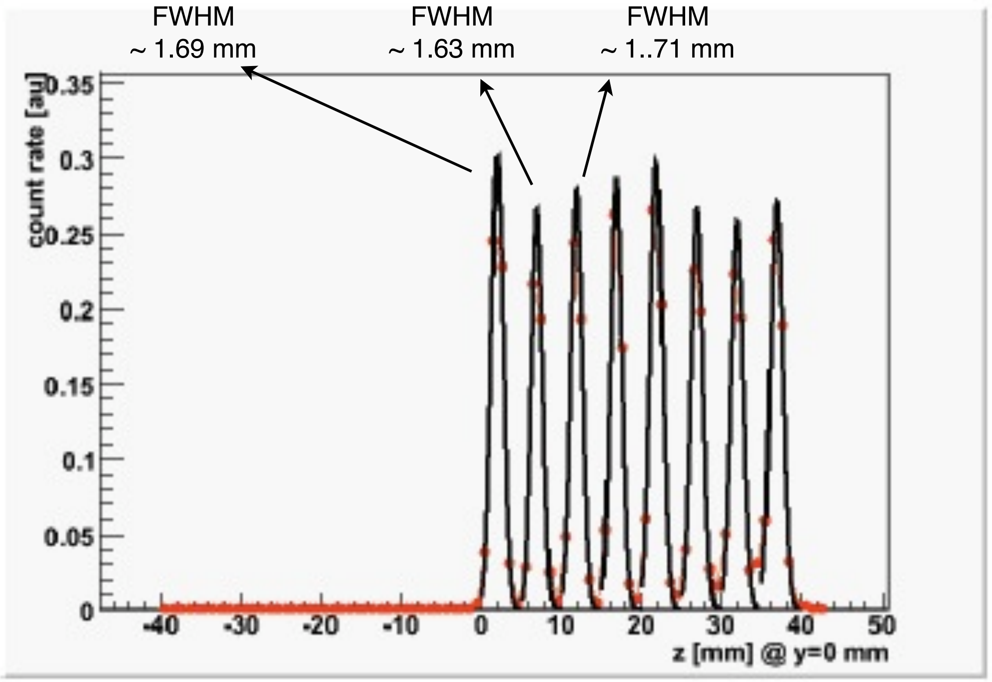


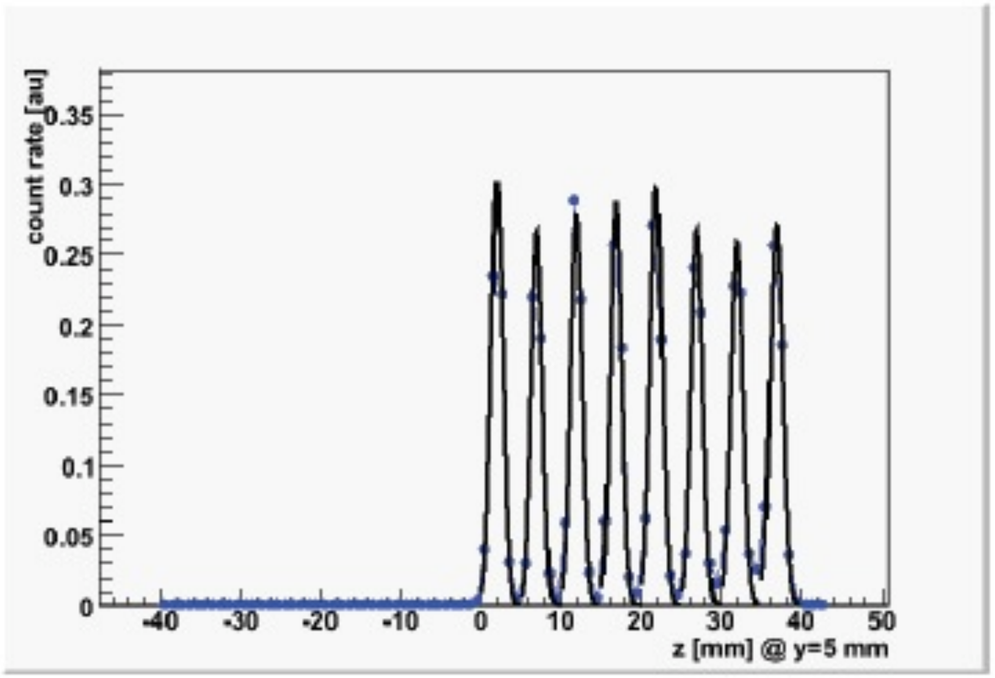
- phantom : 8 capillaries (// WLS)
- capillaries (x8) : **L = 3cm** ; **Diam = 1.4 mm** ; **Pitch = 5 mm**
- 17 positions of the phantom, θ in [0˚,170˚]

- FOV : 30 x 30 x 83 vox³ = 30 x 30 x 83 mm³
- 30 iterations

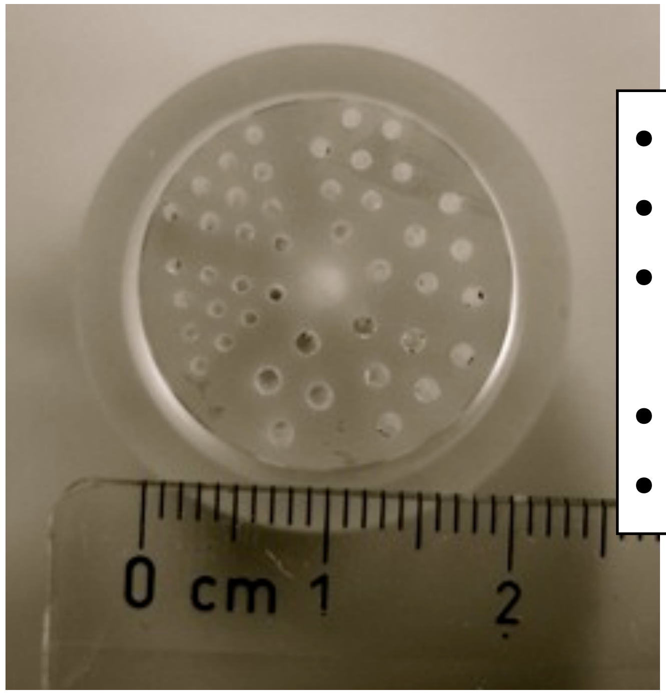
preliminar!!!







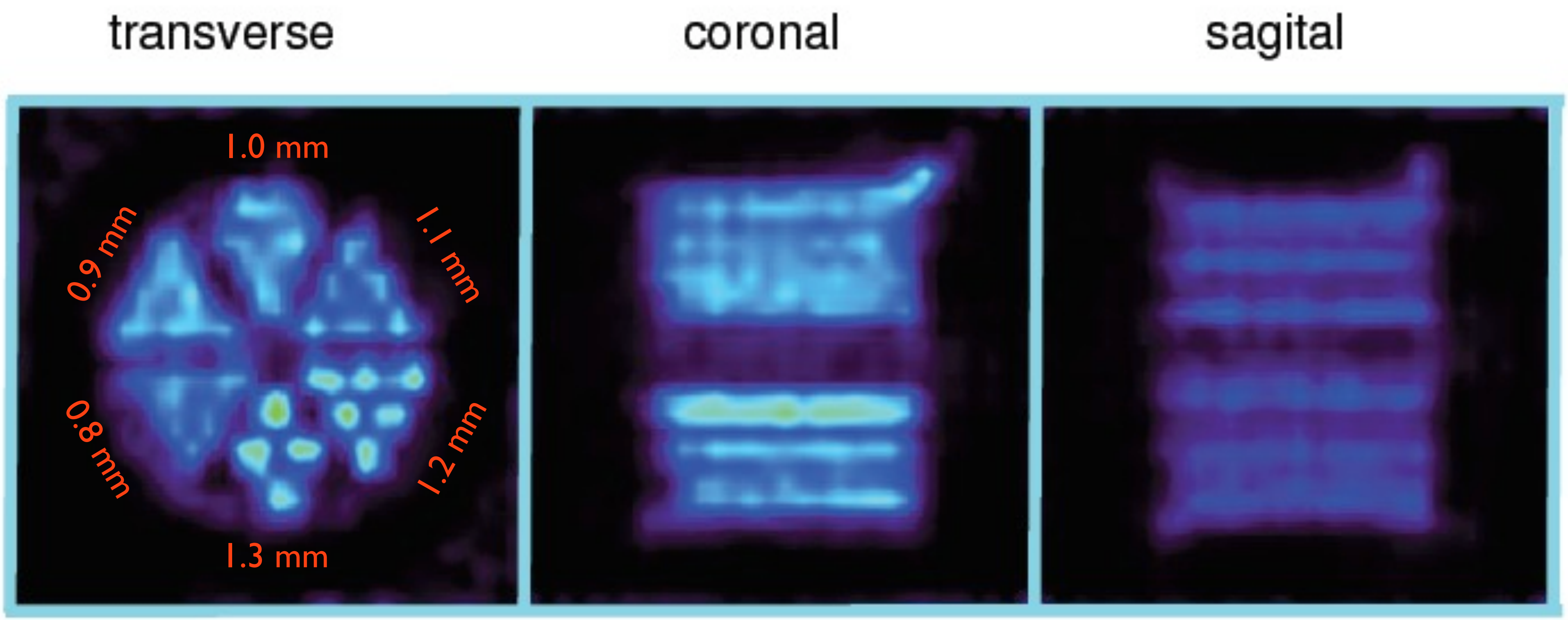
RECONSTRUCTED IMAGE : micro Derenzo



- phantom : micro Derenzo
- **L = 1.5 cm** ; **Diam = 2 cm**; **Rods_Diam = 0.8÷1.3 mm**
- 17 positions of the phantom, θ in [0˚,170˚]

- FOV : 30 x 30 x 30 vox^3 = 30 x 30 x 30 mm^3
- 200 iterations

preliminar!!!



- more statistics available (x2)
- no correction applied for the moment

CONCLUSIONS and OUTLOOK

Novelty of AX-PET

(1) as calorimeter

- "unconventional" use of WLS to collect escaping scintillation light / bare scintillators

(2) as PET

- new **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)
- **Versatile concept**, can be scaled in size and Nr. layers (small animal PET, brain PET, PEM...)
- Fully simulated detector

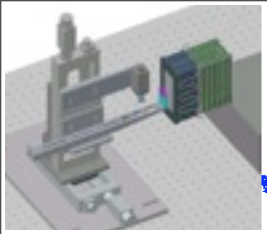
Status / Performance of AX-PET

- 2 modules (i.e. demonstrator) built and characterized (individually / in coincidence) with sources
- ASSESSED PERFORMANCE :
  - **energy resolution: R_FWHM 11.6 % (@511 keV)**
  - **time resolution : $\Delta t \sim 1.9$ ns FWHM**
  - **intrinsic spatial resolution : R_RWHM ~ 1.35 mm**
- First measurements campaign **with phantoms** filled with FDG radiotracer
- **First reconstructed images** (very preliminary, but encouraging...)

What's next?

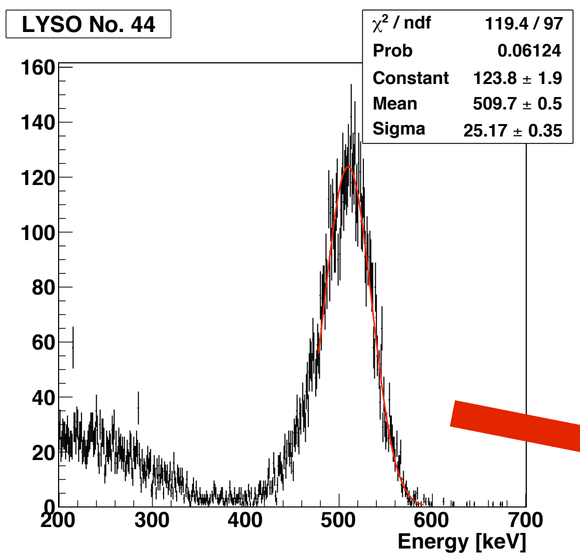
- improve the quality of the reconstruction (system matrix / statistics / corrections ...)
- potentiality of Inter Crystal Scattering (ICS)
- large FOV coverage: new phantom measurements campaign (July 2010 ?)
- ...

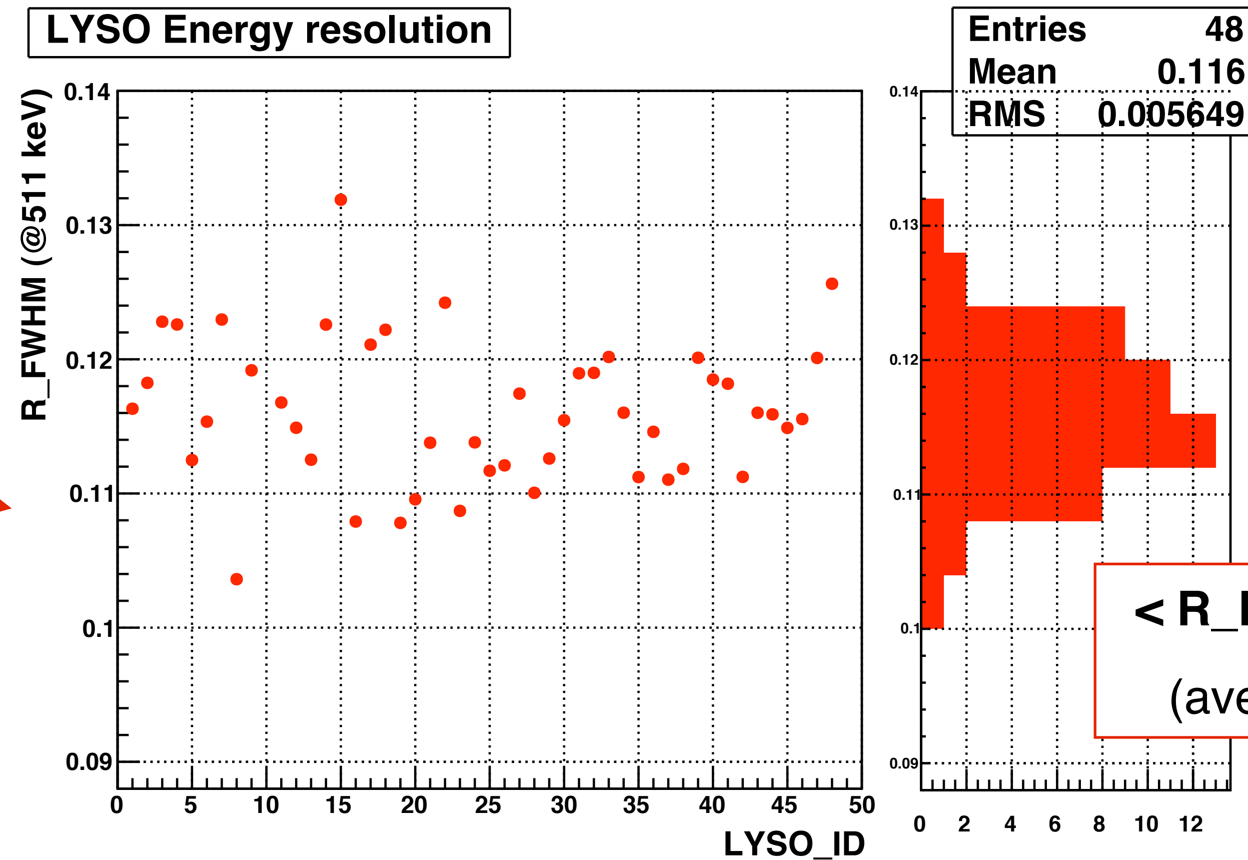
BACKUP



ENERGY RESOLUTION

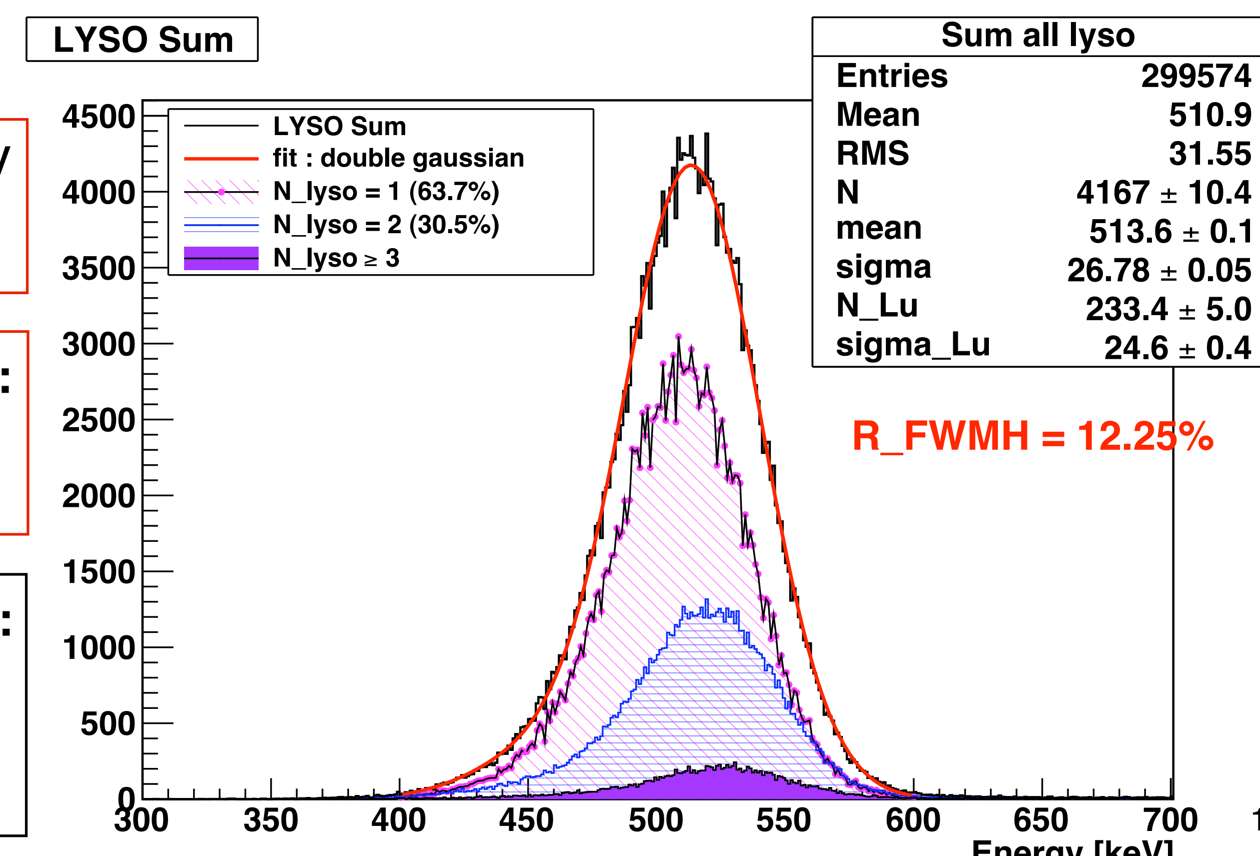
After ENERGY CALIBRATION (i.e. from raw ADC counts to keV units) :





< R_FWHM > ~ 11.6% @511 keV

(averaged on 48 LYSO crystals)



R_FWHM_Sum ~ 12.25% at 511 keV

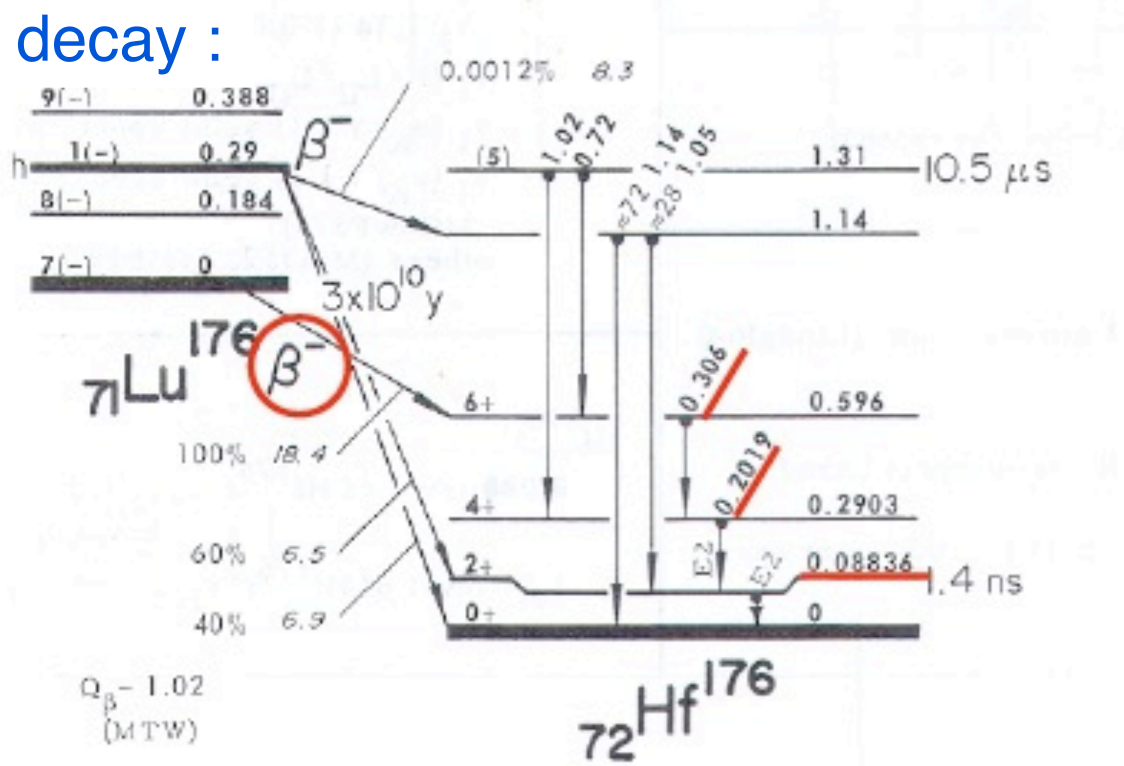
(on the summed distribution)

Typical LYSO MULTIPLICITIES (single module):
- **Prob (1LYSO) ~ 64%**
- **Prob (2LYSO) ~ 30%**

Typical LYSO MULTIPLICITIES - 2 MODS COINCIDENCES:
- **Prob (1LYSO-1LYSO "1-1") ~ 44%**
- **Prob (1LYSO-2LYSO "1-2" or "2-1") ~ 38%**
- **Prob (2LYSO-2LYSO "2-2") ~ 9%**

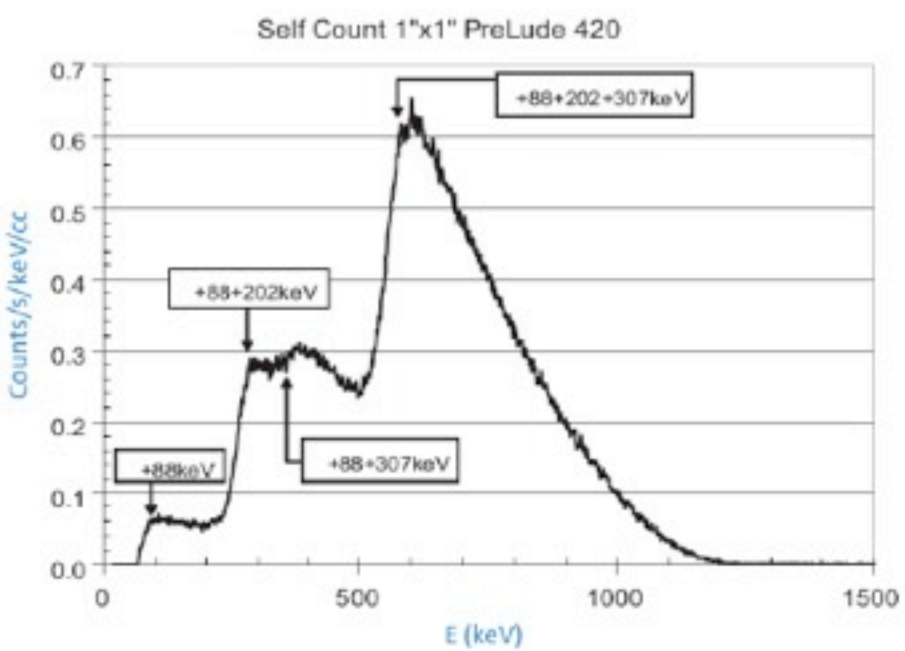
LYSO intrinsic radioactivity

Lu decay :



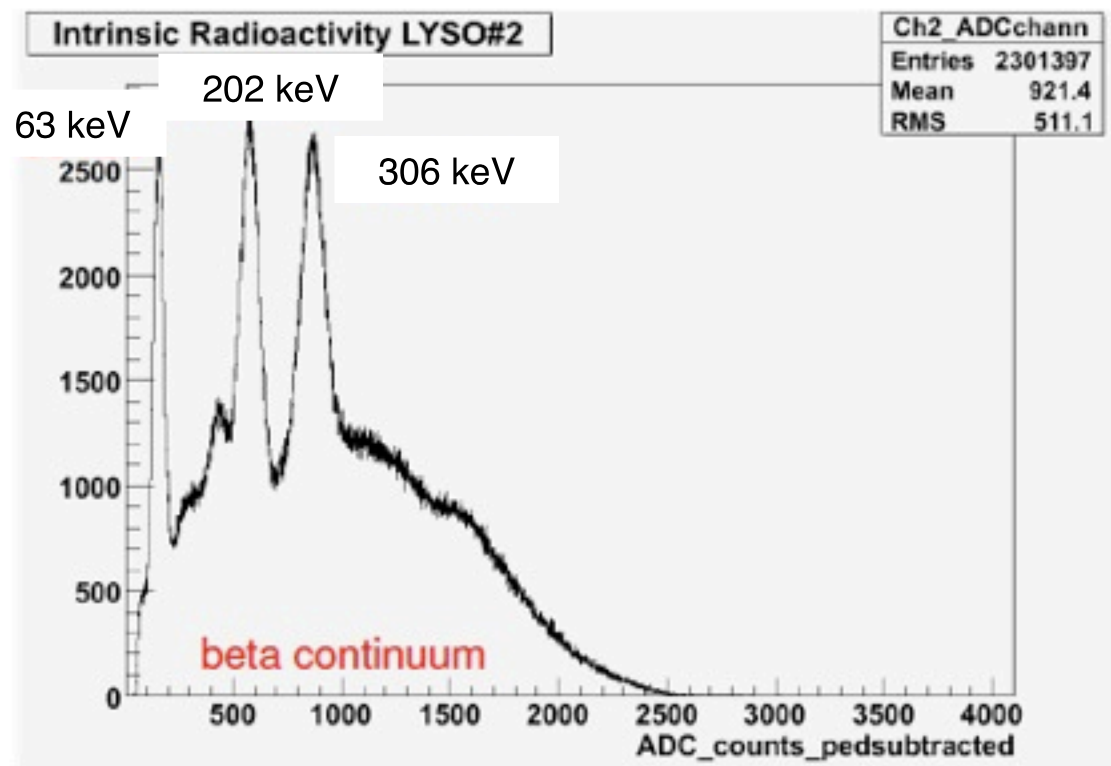
from Saint Gobain Prelude 420 spec sheet:

1) Energy spectrum measured in a 1"diameter x 1" high LYSO crystal:



in LYSO: β absorbed in the crystal + one, two or 3 γ escaping the crystal (88 keV, 202 keV, 307 keV)

- one LYSO crystal only INSIDE THE MATRIX
- self trigger (low threshold) on this crystal



- beta continuum (with shifts due to the three gammas absorption, difficult to resolve) from the intrinsic radioactivity of the crystal itself
- single gamma lines from the intrinsic radioactivity of the neighbor crystals

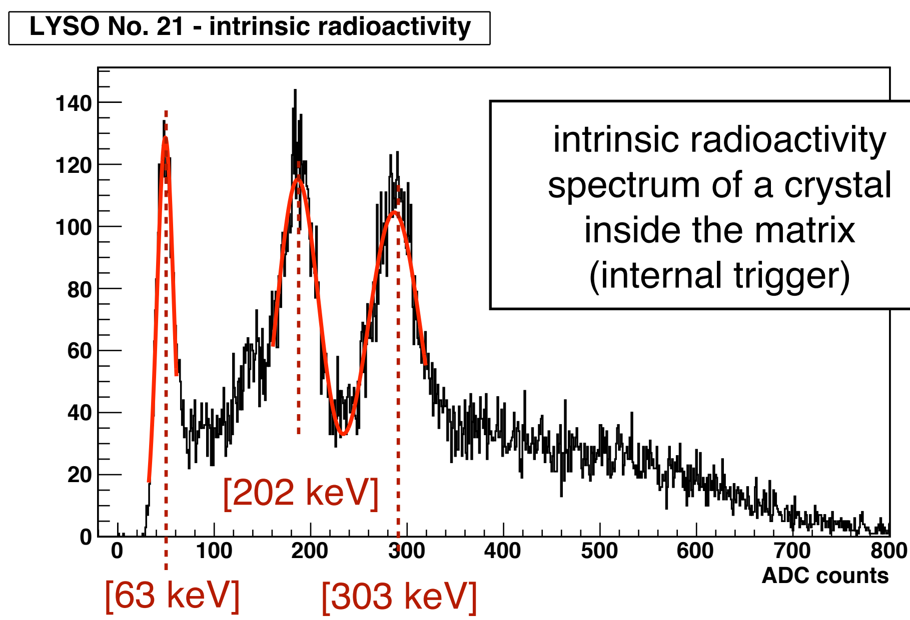
2) **A = 39 Bq/g** (ρ=7.1g/cm3) => expected **250 Bq** in 3x3x100mm3 LYSO

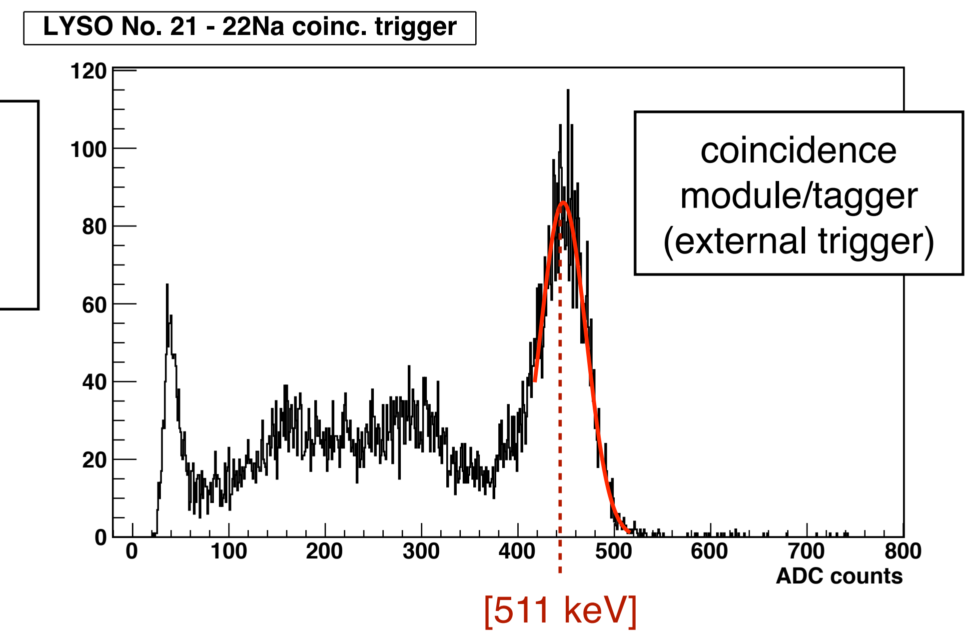
ENERGY CALIBRATION

Why energy calibration (i.e. ADC values => keV) **?**

- equalized response from all channels
- correct for the MPPC's non linearity (at 511 keV)

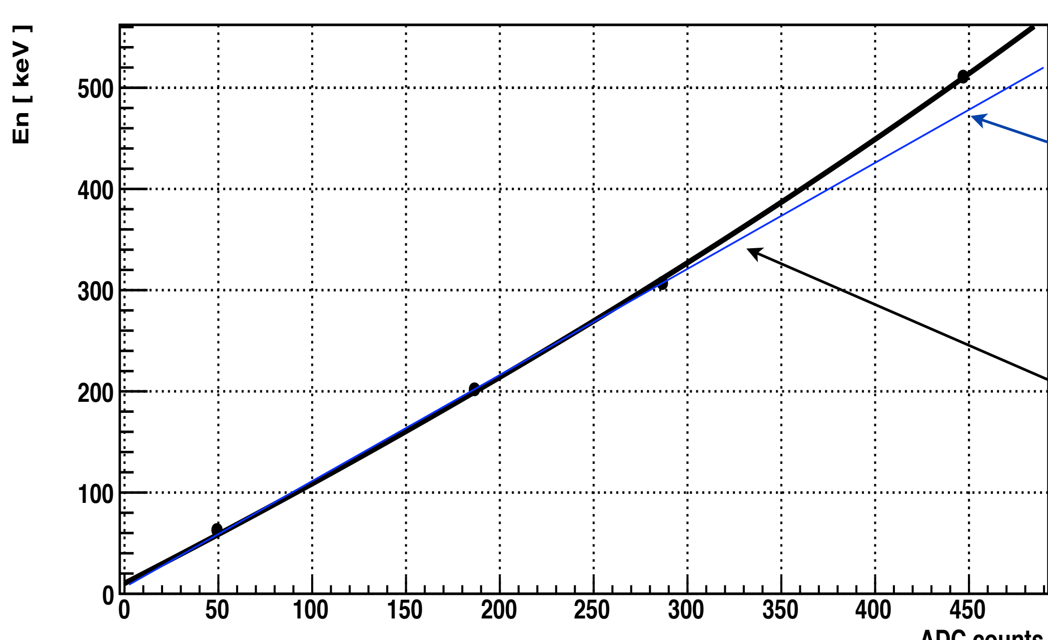
Intrinsic Lu radioactivity + Photopeak: good tool for the energy calibration





same procedure applied identically for every other channel

AX-PET : "self-calibrating" device



- deviation from linearity (~ 5% effect)

- parameterization:

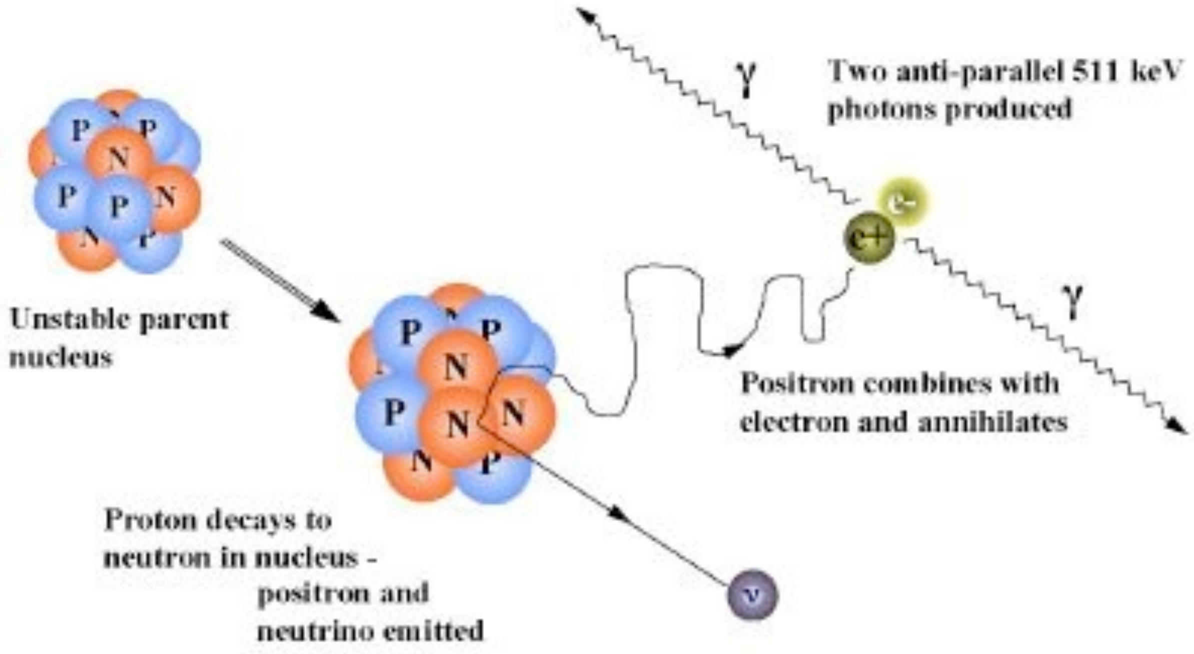
negative logarithmic fitting func.

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

Ch

PHYSICS LIMITS to spatial resolution

Fundamental limitations in the spatial resolution of PET imaging from the physics of the β+ annihilation process



1. Effective positron range

- **depends** on the energy of the emitted positron (i.e. **on isotope**)
- R_FWHM_ρ ~ 0.54 mm
- (in water, 18-F compounds, $E_{avg}\beta^+$ ~ 250 keV)
- similar range effect 18-F in water and 22-Na in lucite ($E_{avg}\beta^+$ ~ 216 keV) i.e. our point-like sources setup

Table 1.
Positron range factors for four isotopes. From ref. [69].

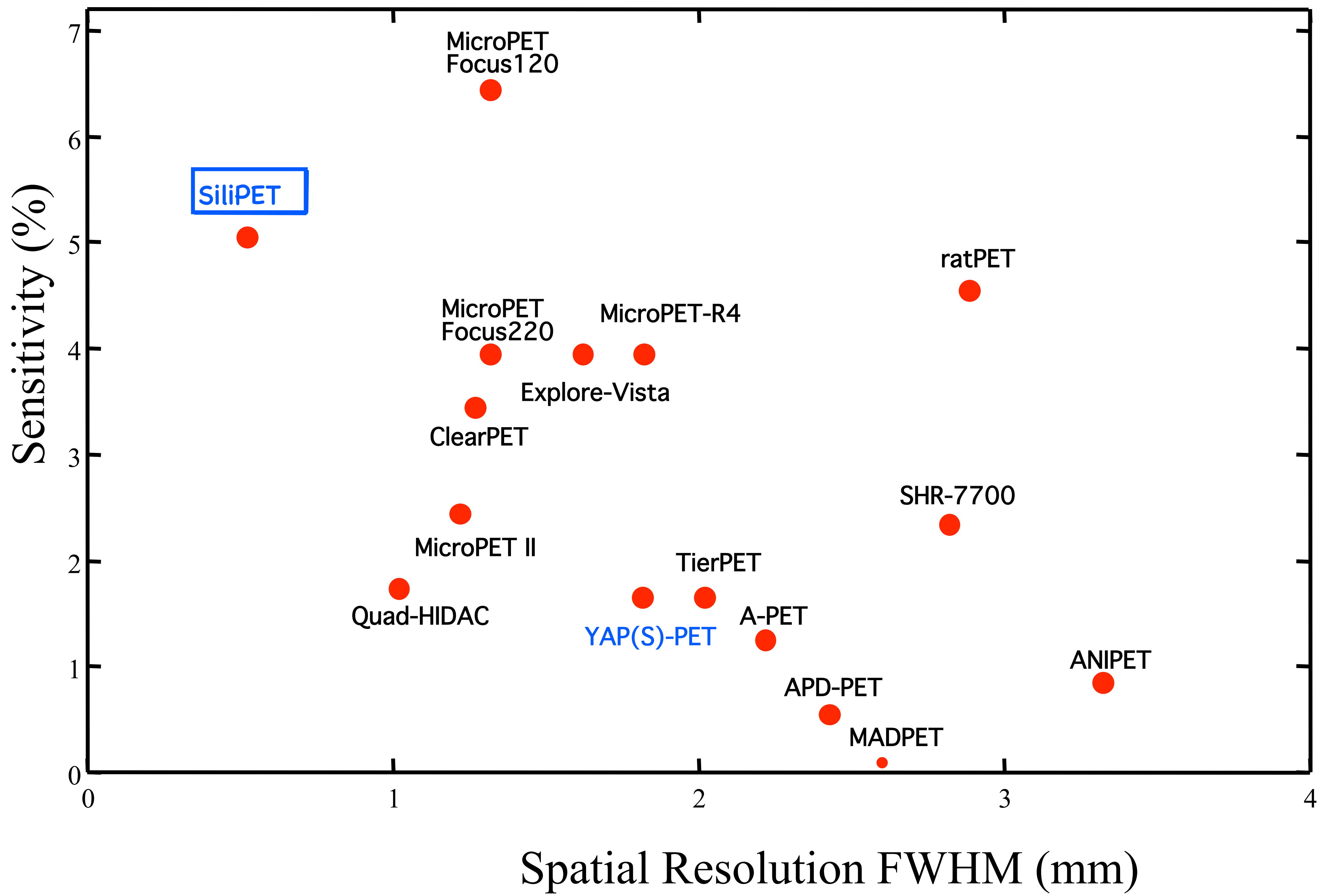
Isotope	^{18}F	^{11}C	^{68}Ga	^{82}Rb
Max β^+ energy (MeV)	0.64	0.96	1.90	3.35
fwhm (mm)	0.13	0.13	0.31	0.42
fw(0.1)m (mm)	0.38	0.39	1.6	1.9
$r = 2.35 \times$ rms (mm)	0.54	0.92	2.8	6.1

69 S. E. Derenzo, "Mathematical removal of positron range blurring in high resolution tomography," IEEE Trans Nucl Sci 1986; NS-33: 565-569.

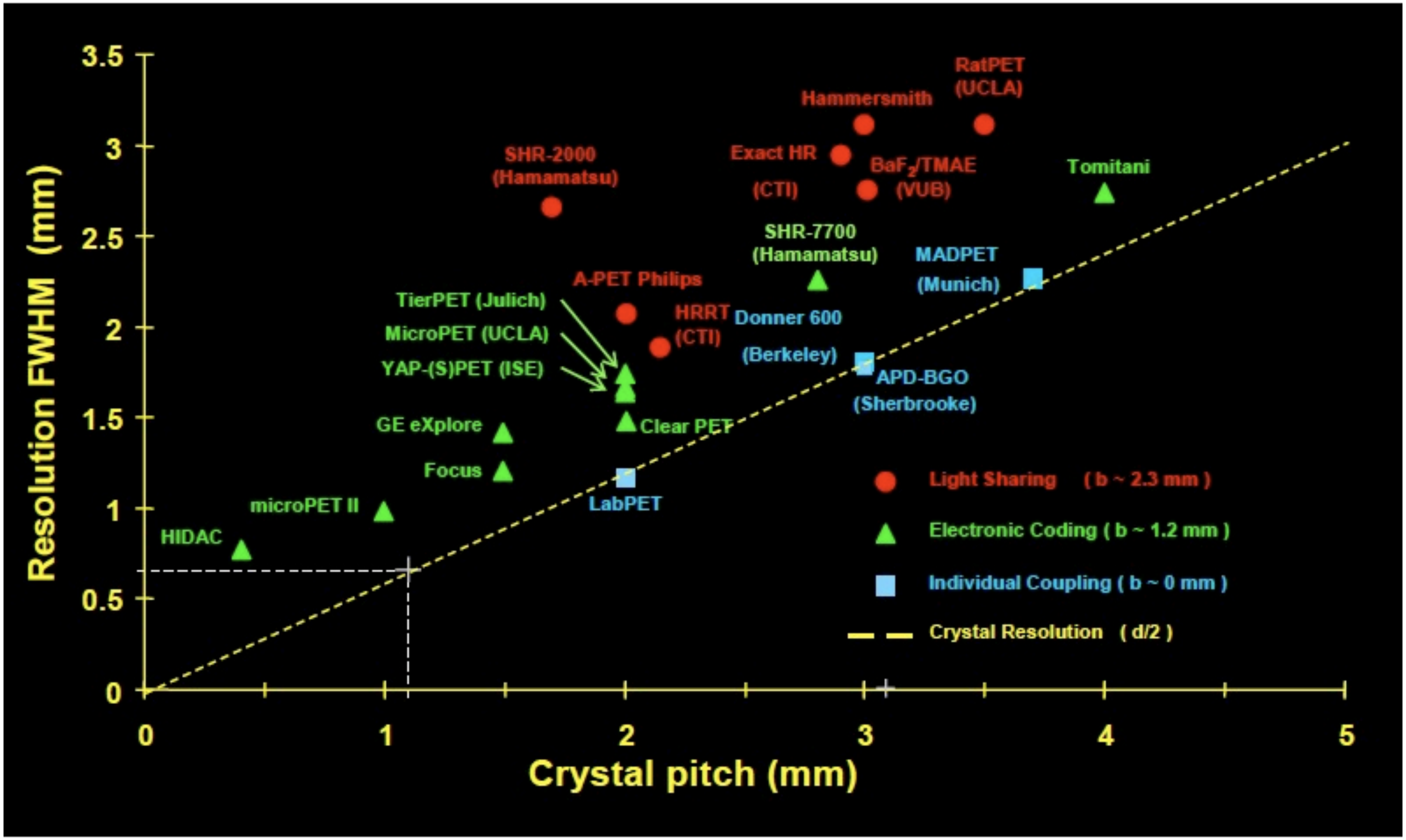
2. Non collinearity

- residual momentum of the e+e- at the annihilation => the 2 gamma rays emitted with a small deviation from 180˚
- Δθ ~ 0.5˚
- blurring of the spatial resolution proportional to the distance among modules : **R_FWHM_180 ~ 0.0022 x D [mm]**
- D = 15 cm => R_FWHM_180 ~ 0.33 mm

Small animal PET comparison :



Intrinsic resolution of commercial scanners

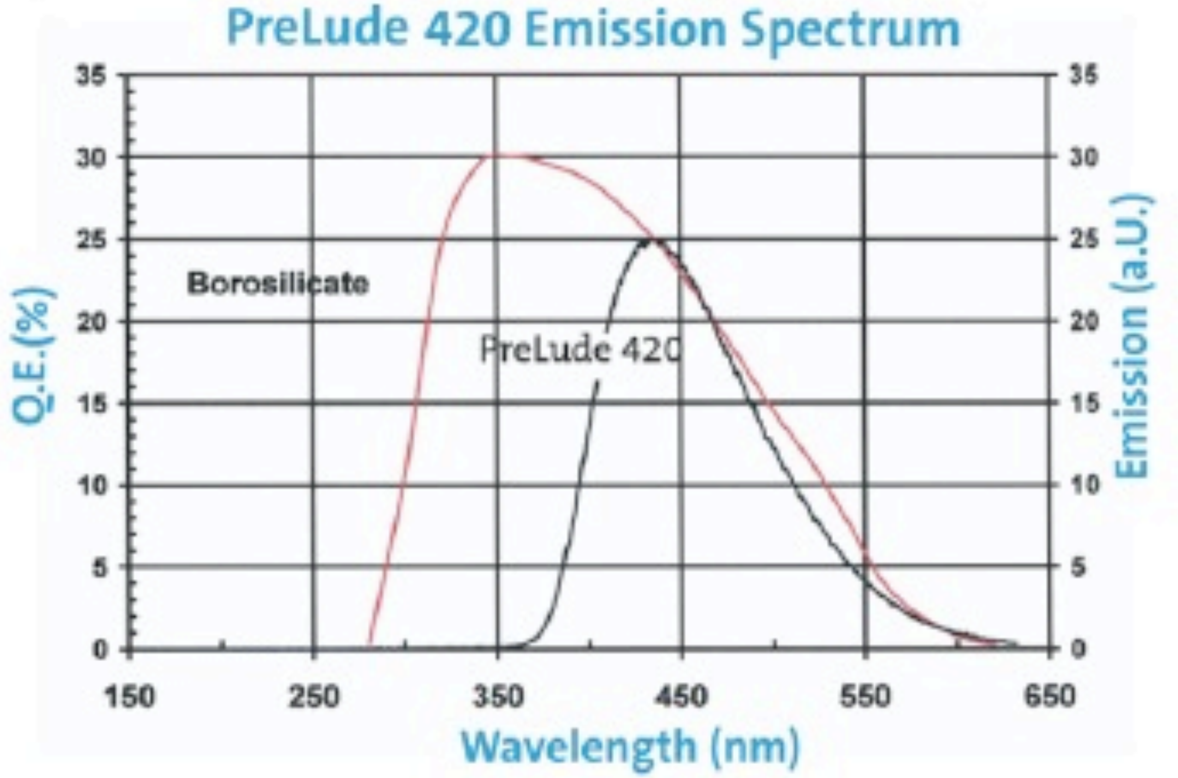


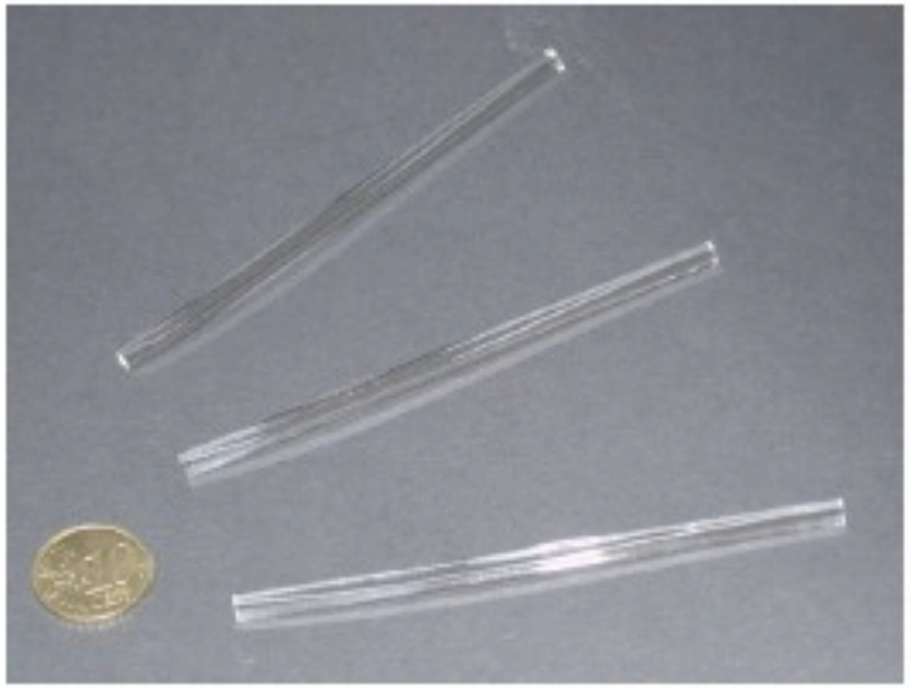
AX-PET components

The **scintillator crystals** are Ce doped LYSO ($Lu_{1.8}Y_{.2}SiO_5$:Ce) single crystals, fabricated by Saint Gobain and commercialized under the trade name PreLude 420.

The main characteristics are:

Density [g/cm3]	7.1
Attenuation length for 511 keV [cm]	1.2
Wavelength of maximum emission [nm]	420
Refractive index at W.L. of max. emission	1.81
Light yield [photons/keV]	32
Average temperature coefficient [%/K]	-0.28
Decay time [ns]	41
Intrinsic energy resolution [%, FWHM]	~8
Natural radioactivity [Bq/cm³]	~300
Effective optical absorption length [mm]	~ 420





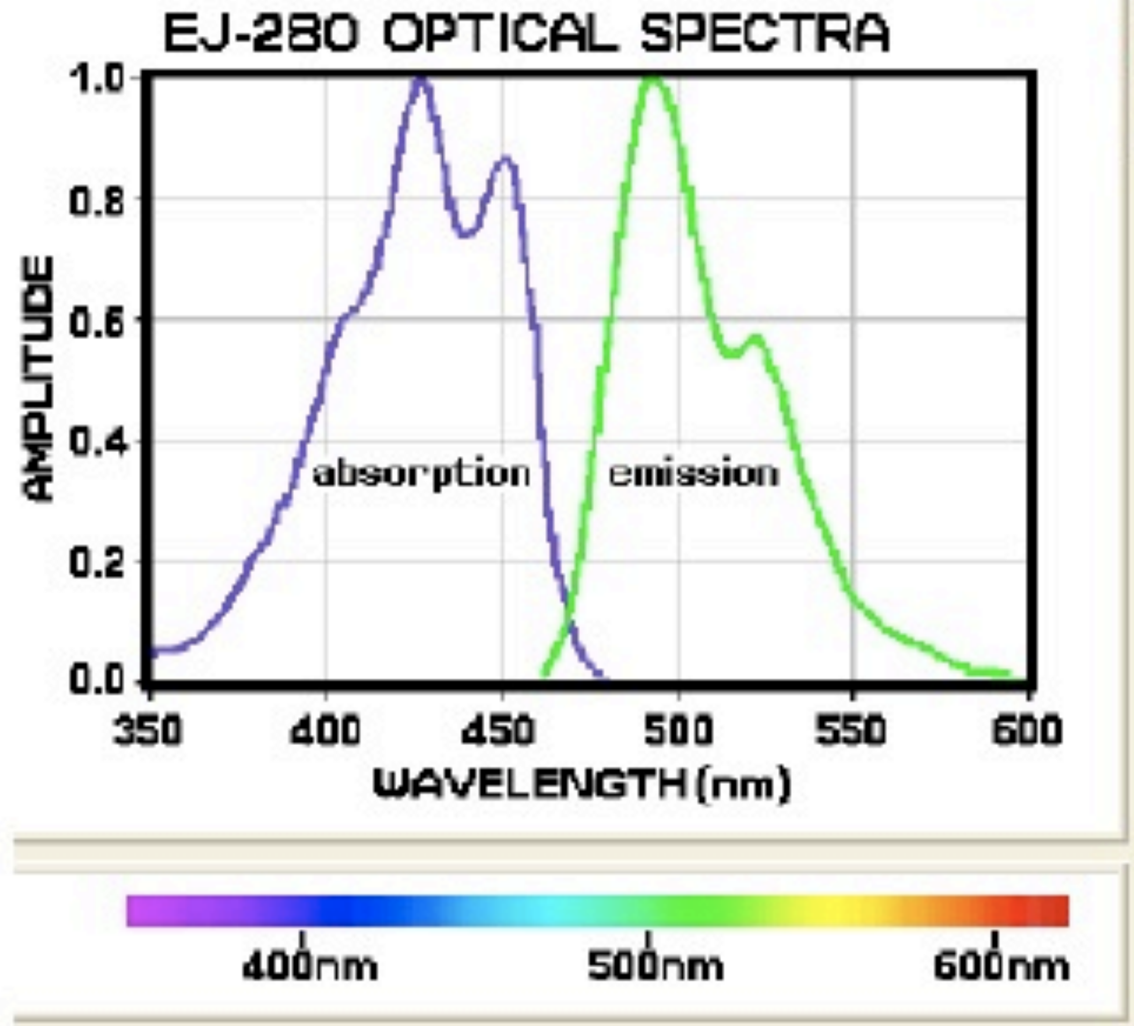
Dimensions: 3 x 3 x 100 mm³

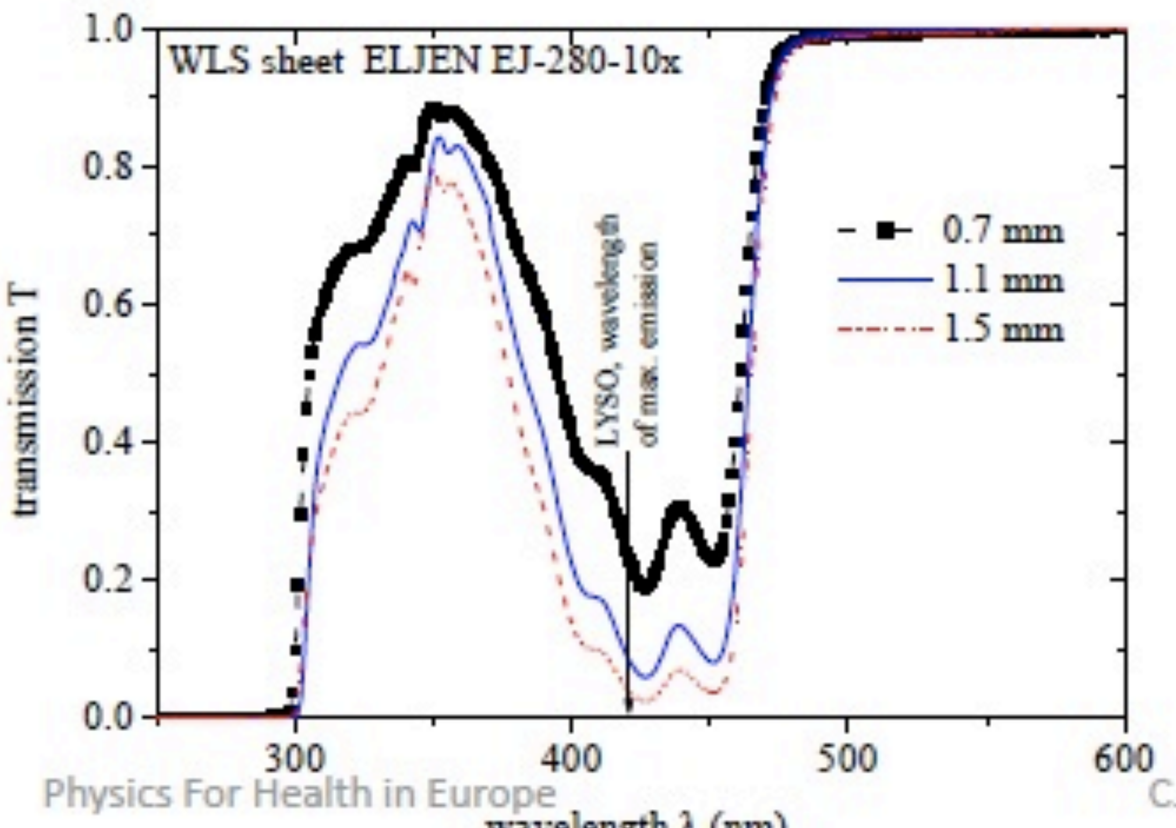
One end is read out, the other end is mirror-coated (evaporated Al-film).

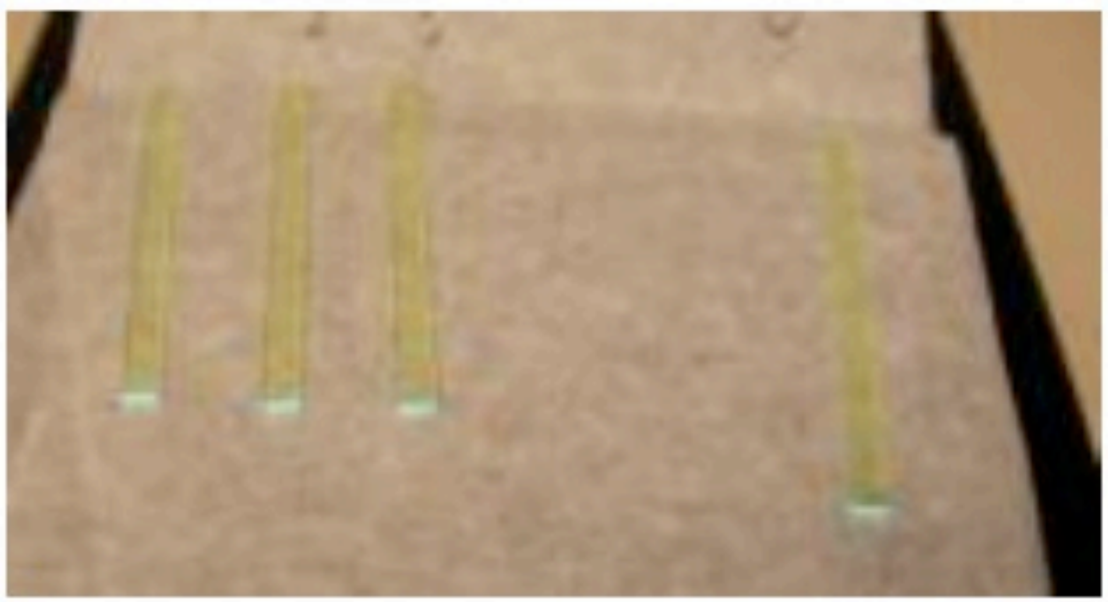
The **WLS strips** are of type EJ-280-10x from Eljen Technologies

- Shift light from blue to green
- Density: 1.023 g/cm3
- Absorption length for blue light: 0.4mm (10 x standard concentration)
- Index of reflection: 1.58
- Decay time: 8.5ns
- Size: 0.9×3×40mm³

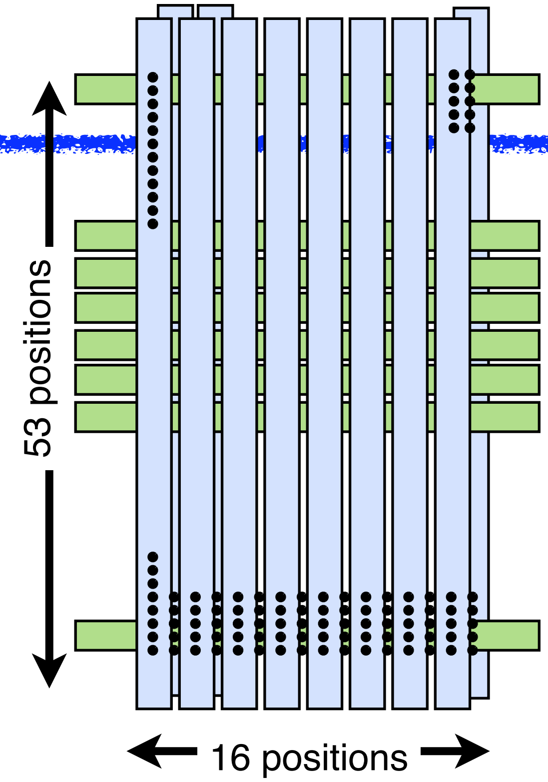
One end is read out, the other end is mirror-coated (evaporated Al-film).







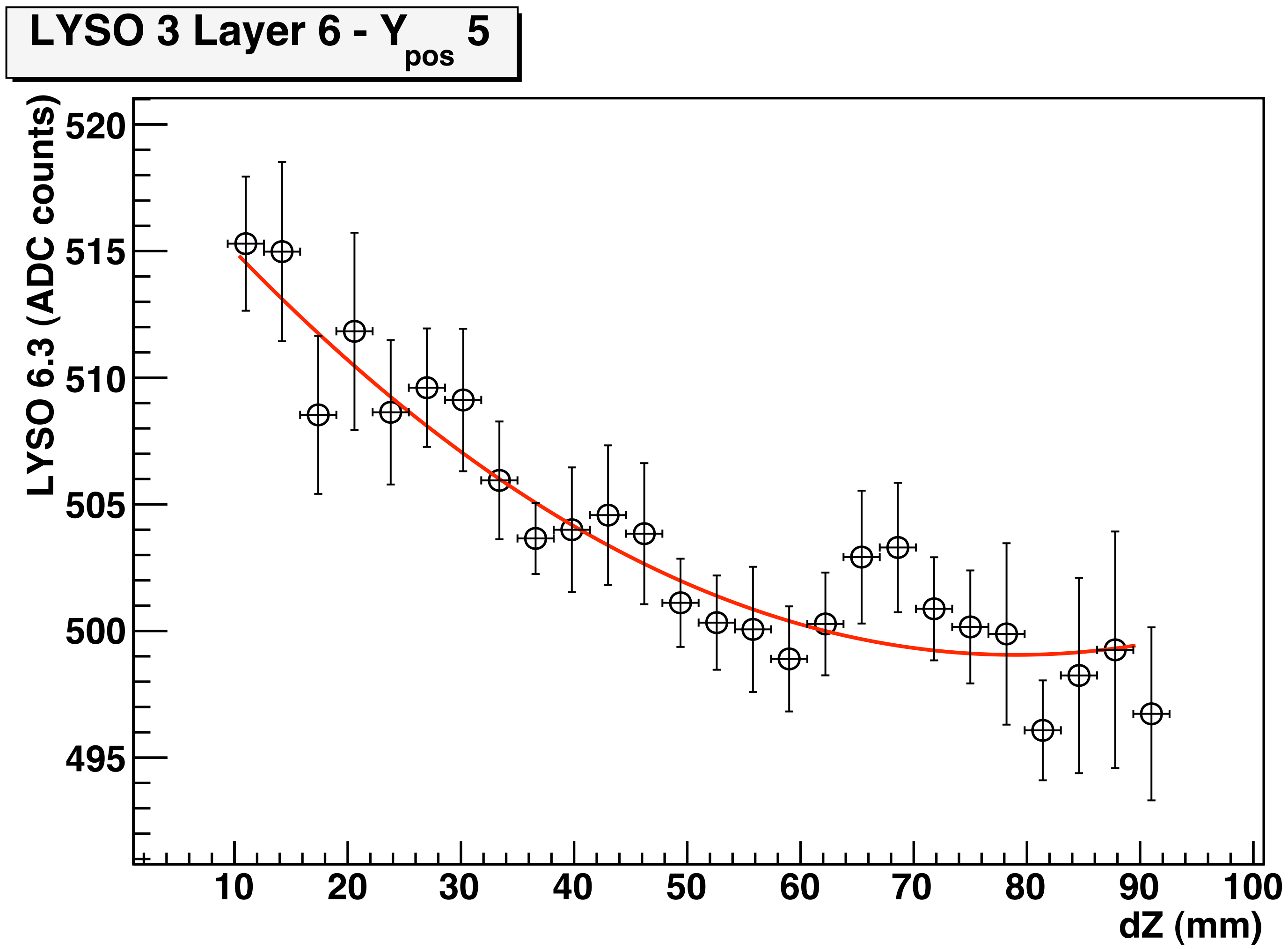
ATTENUATION LENGTH



Extended pieces of detector (L_lyso = 100 mm ; L_wls = 40 mm)
- large FOV coverage
- dependence of the detector response on the position of the interaction point ($\lambda_{attenuation}$)

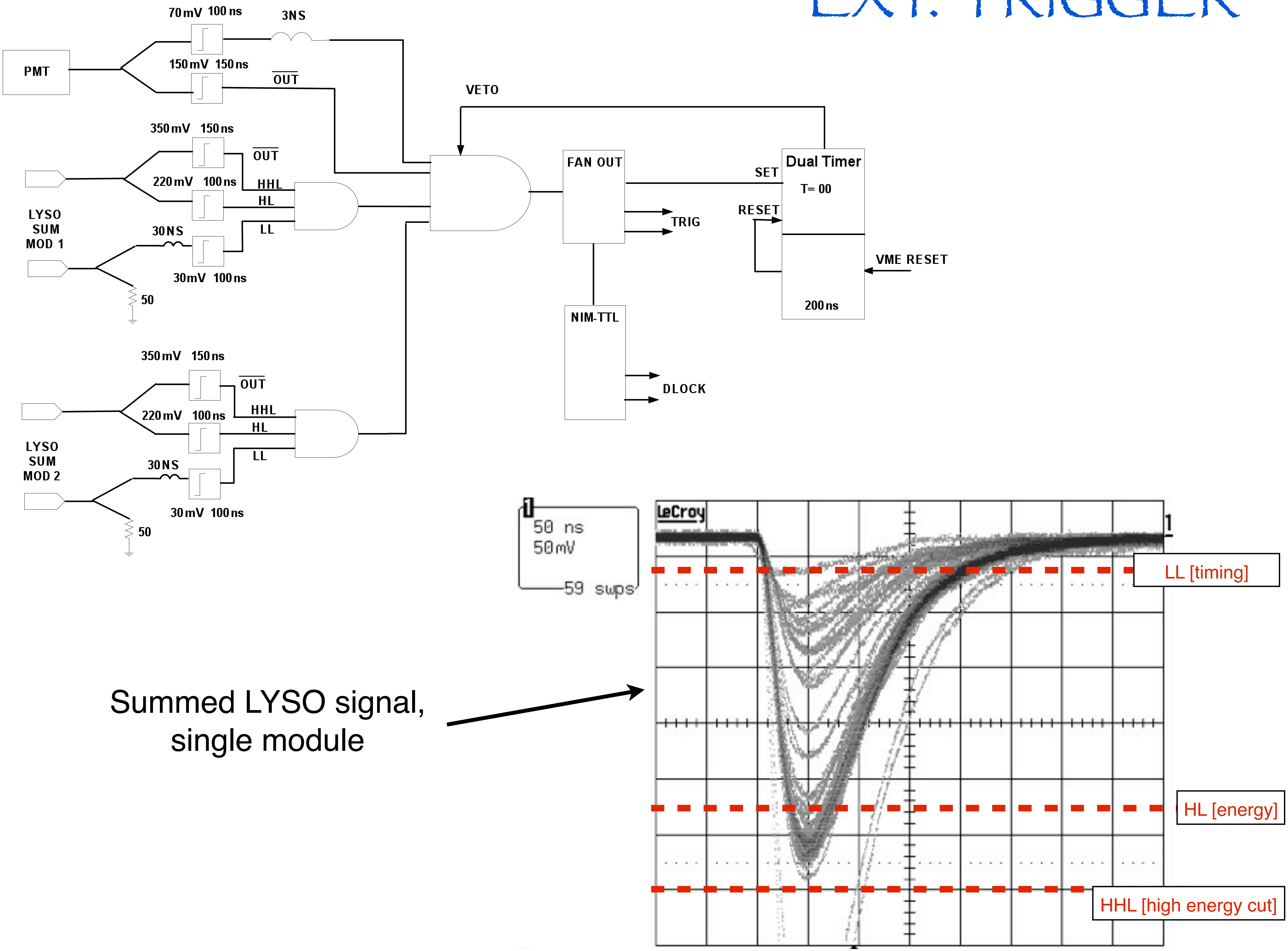
To achieve a good uniformity of the detector response :
- measure $\lambda_{attenuation}$ (**FULL SCAN** measurements)
- correct offline (on a channel by channel basis)

FULL SCAN MODULE :
- 53(z) x 16(y) positions
- 848 runs
- few days acquisition



one LYSO example

EXT. TRIGGER



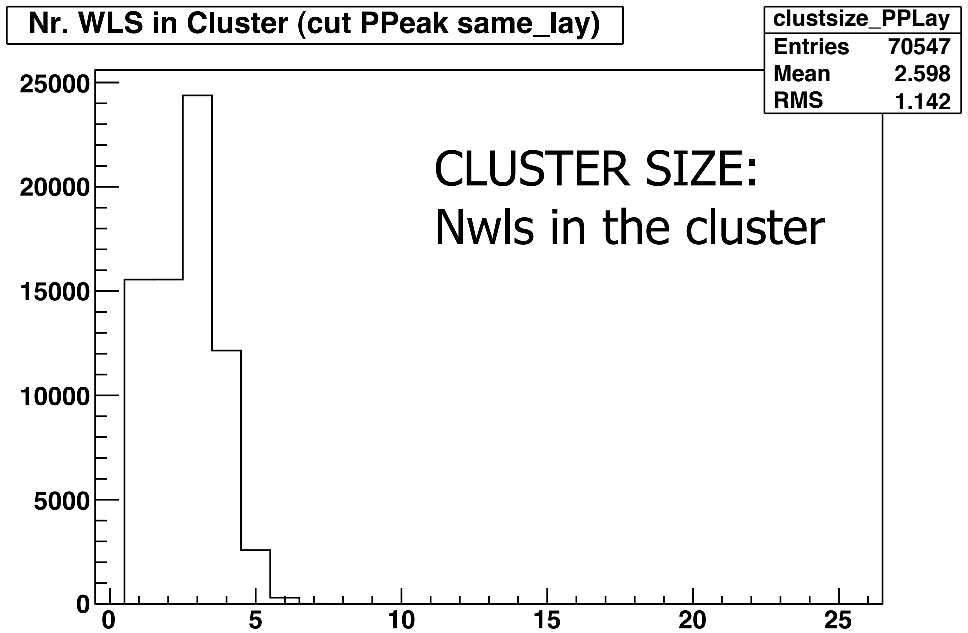
Summed LYSO signal, single module

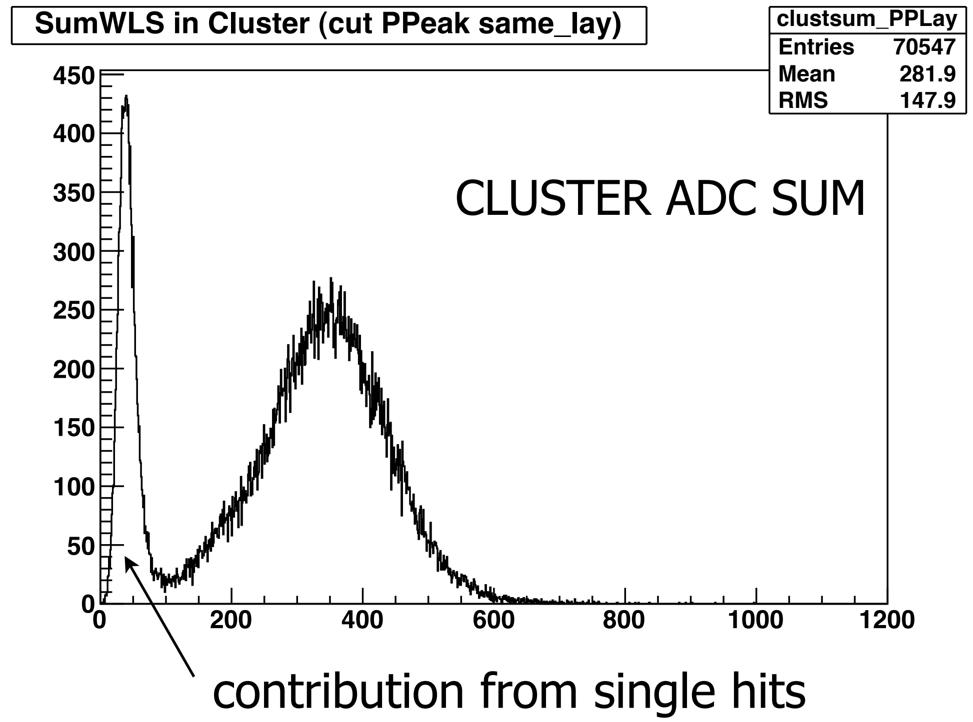
SPATIAL RESOLUTION : Cluster (group of adj. WLS)

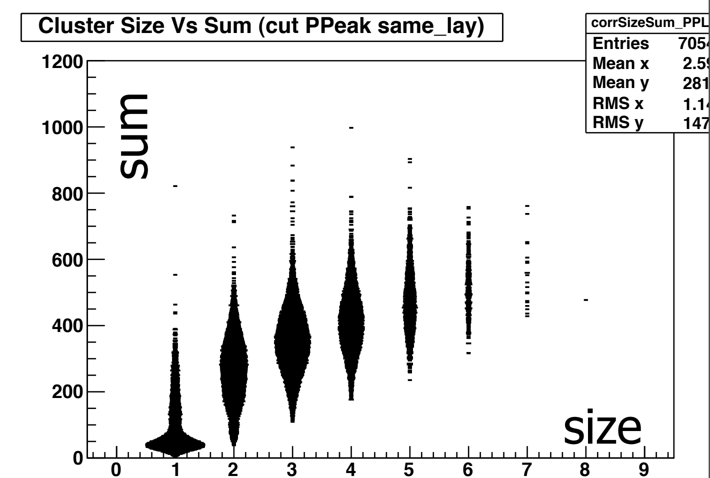
Selection0 : Photopeak events

Module 2, single file

Selection1 : Photopeak events / WLS on the same layer of LYSO

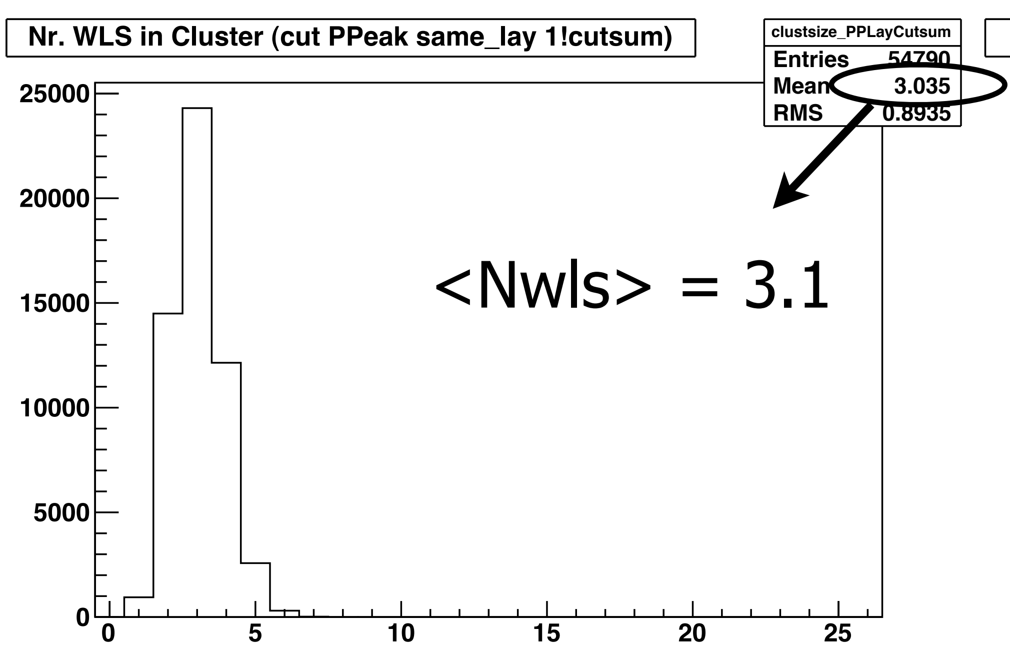


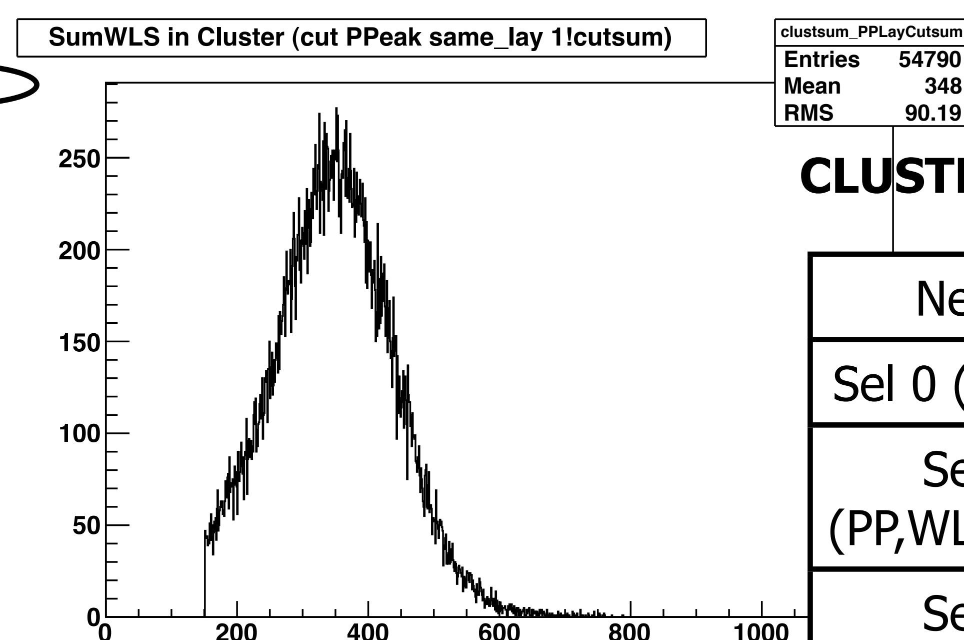




Correlation btw Cluster Size and Cluster Sum

Selection2: As before PLUS one and only one cluster in the relevant ADC region [150,800] for the cluster ADC sum





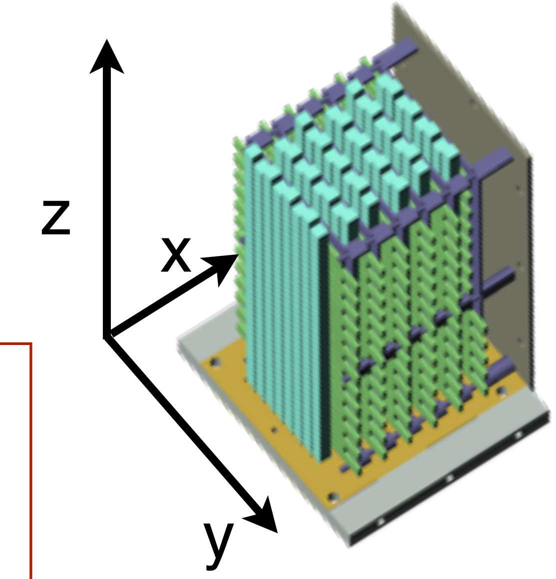
CLUSTER DETECTION EFFICIENCY:

		TOTAL	RELATIVE
Nevts	99896	1	-
Sel 0 (ppeak)	57273	0.573	0.573
Sel 1 (PP,WLSlayer)	56572	0.566	0.988
Sel 2 (PP,Lay,Sum)	54790	0.548	0.968

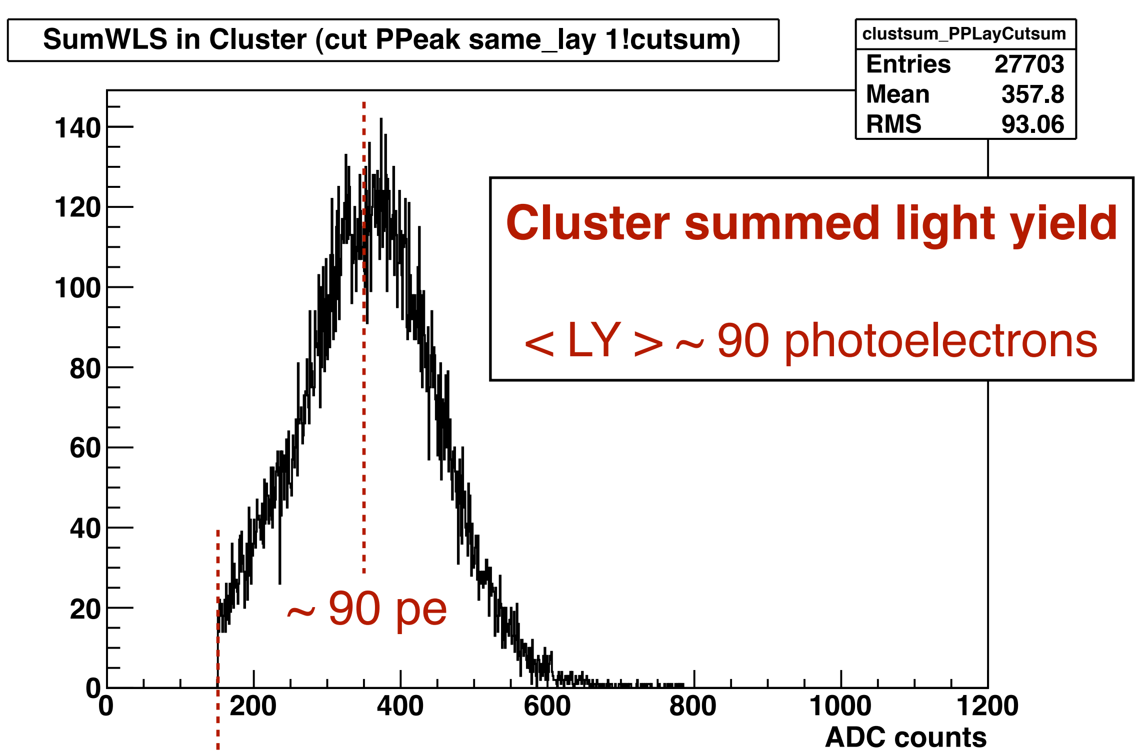
run01700_calib1684.root

- $<\sigma_z>$: derived from center of gravity method from all the WLS participating to the event (i.e. CLUSTER of WLS)

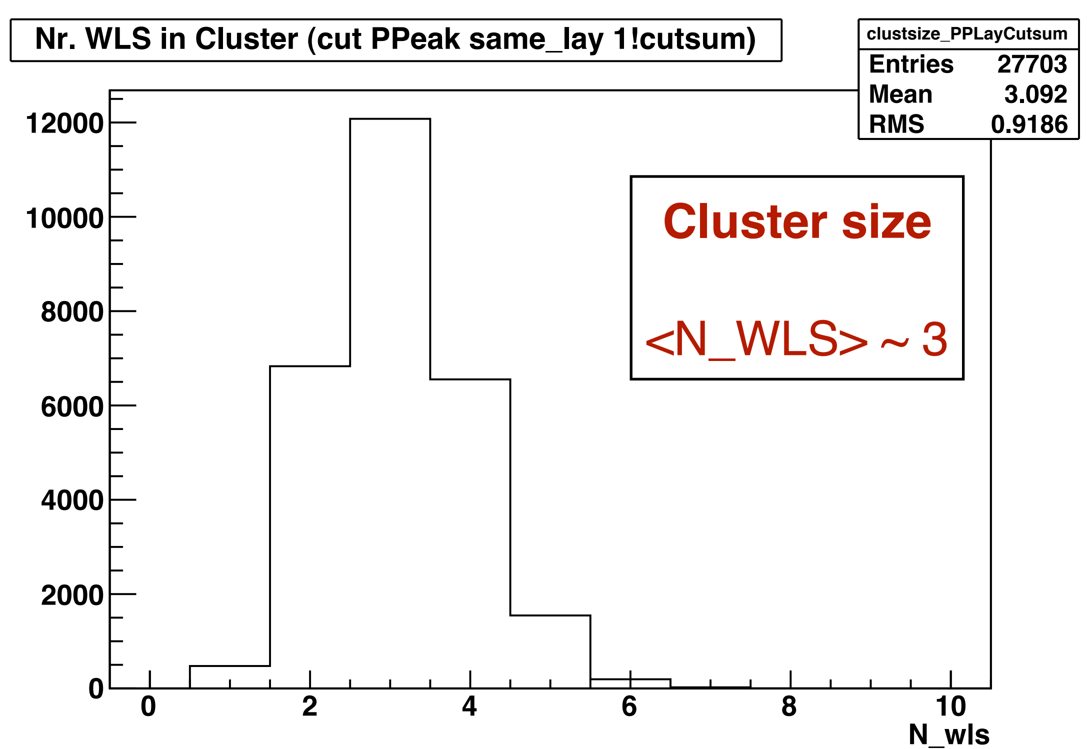
$$z_{reco} = \sum_i \frac{z_i \times LY_i}{LY_i}$$



1. Event selection : only photopeak events (1! LYSO, E_{LYSO} in [350,650] keV)
2. Cluster of WLS : group of adjacent WLS on the same layer of the (single) LYSO



Cut at low light yields to suppress isolated single hits

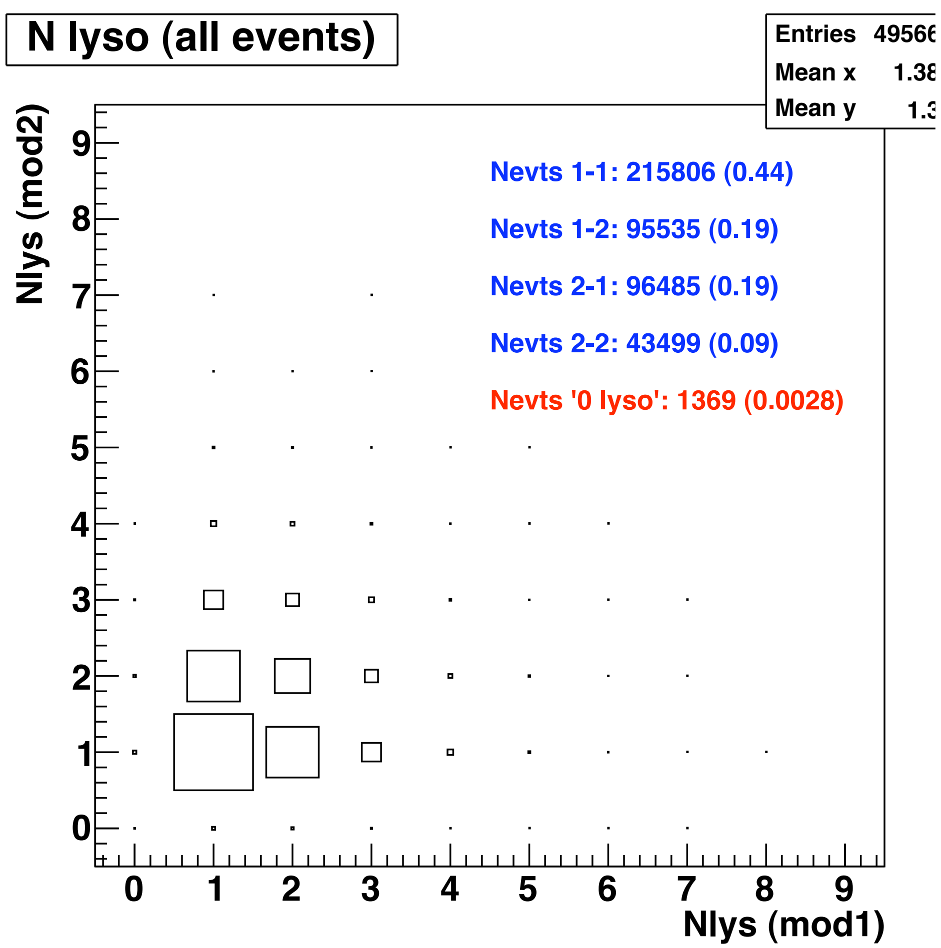


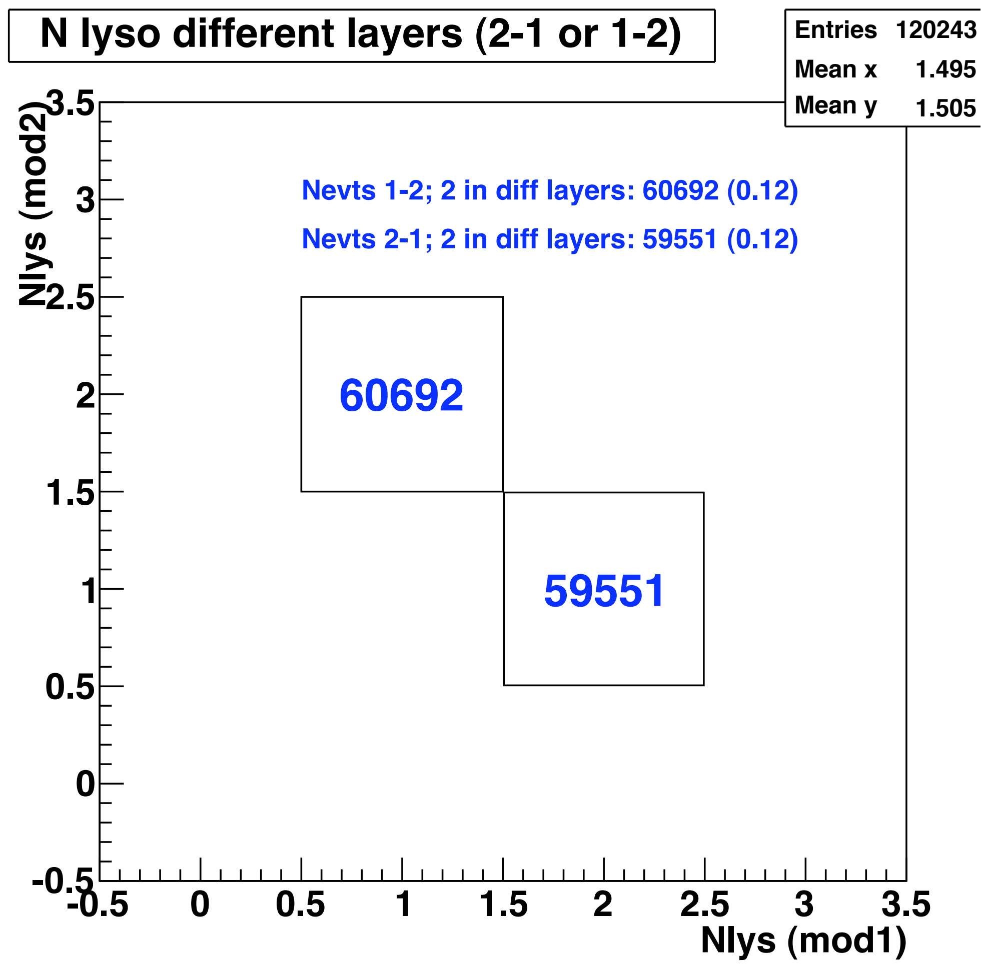
MULTIPLICITIES and EFFICIENCIES

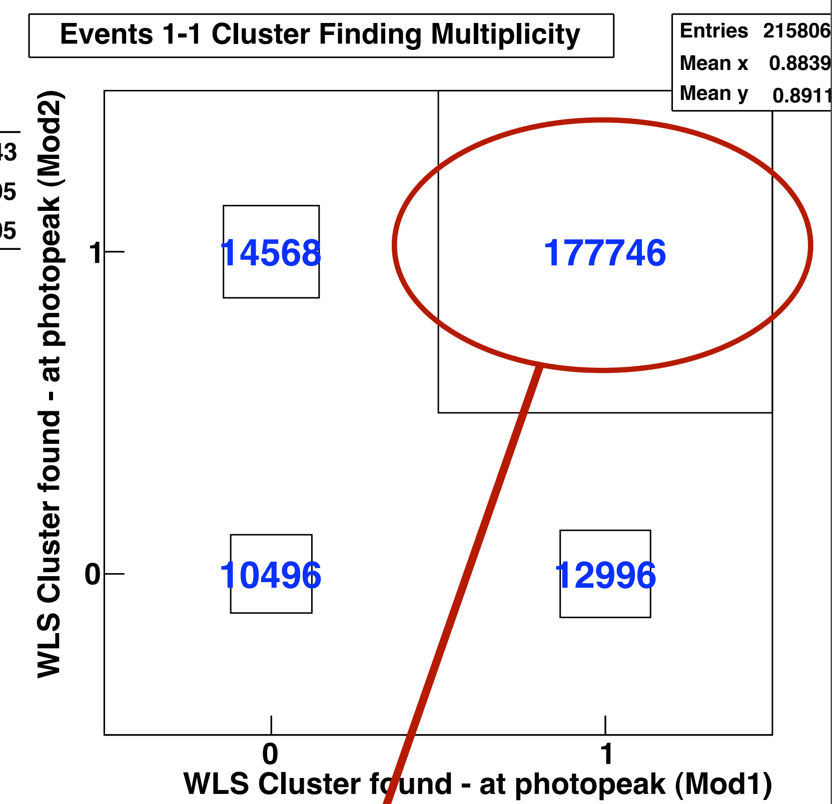
2 mods coincidences

golden evts efficiency

LYSO multiplicities







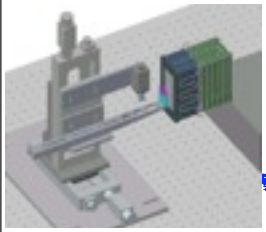
- **Photoelectric events** on both modules **~ 44%**

- Events “1-2” or “2-1” ~ 38%
- **2 hits on two different layers ~ 24%** (ICS candidates)

N_evts : 495665
N_1-1 : 215806 (0.44)
N_1-1 good cluster : 177746 (0.36) (0.82)

Cluster finding efficiency (normalized on N1lyso): 0.824

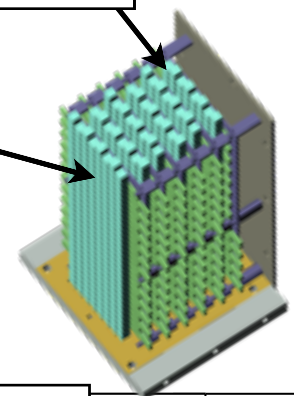
Cluster finding efficiency (normalized on Nevts) : 0.359

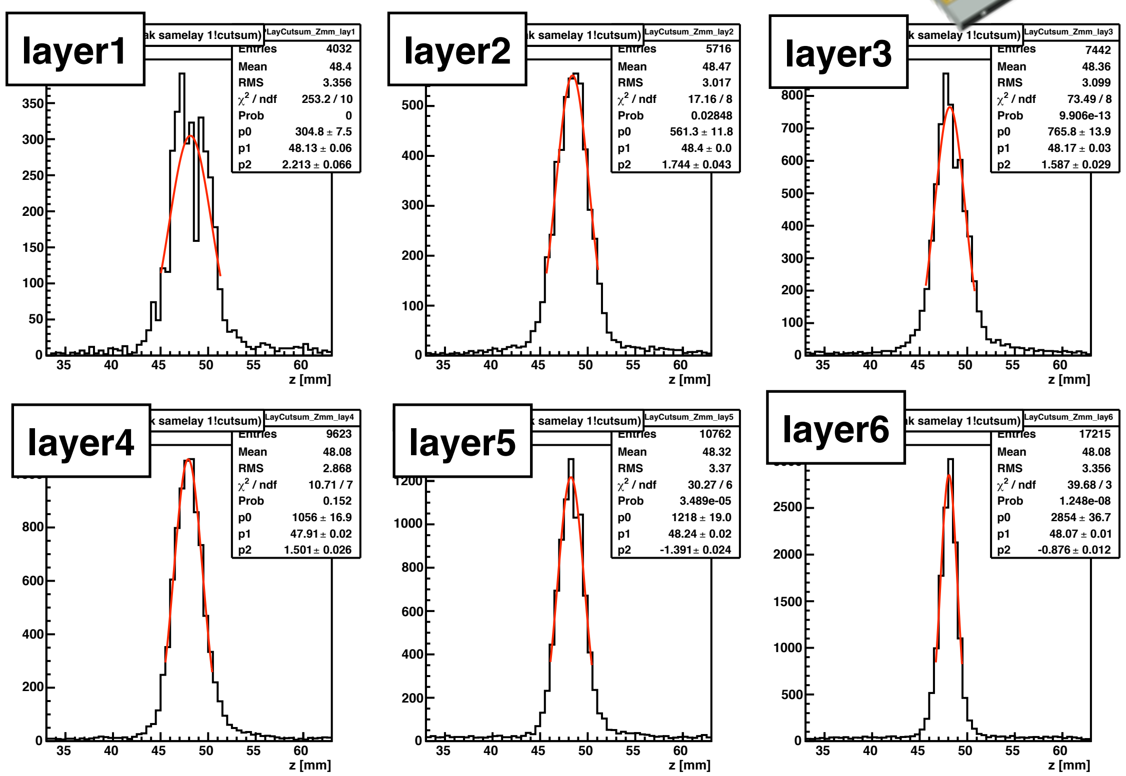


AXIAL RESOLUTION

Reconstructed z coordinate on each layer :

$$z_{reco} = \sum_i \frac{z_i \times LY_i}{LY_i}$$





=> spatial resolution : fitted σ_i [i=1,6]

It includes:

- intrinsic spatial resolution
- beam spot size on each layer

$$\sigma_i^2 = \sigma_{i\_beam}^2 + \sigma_{Z-res}^2$$

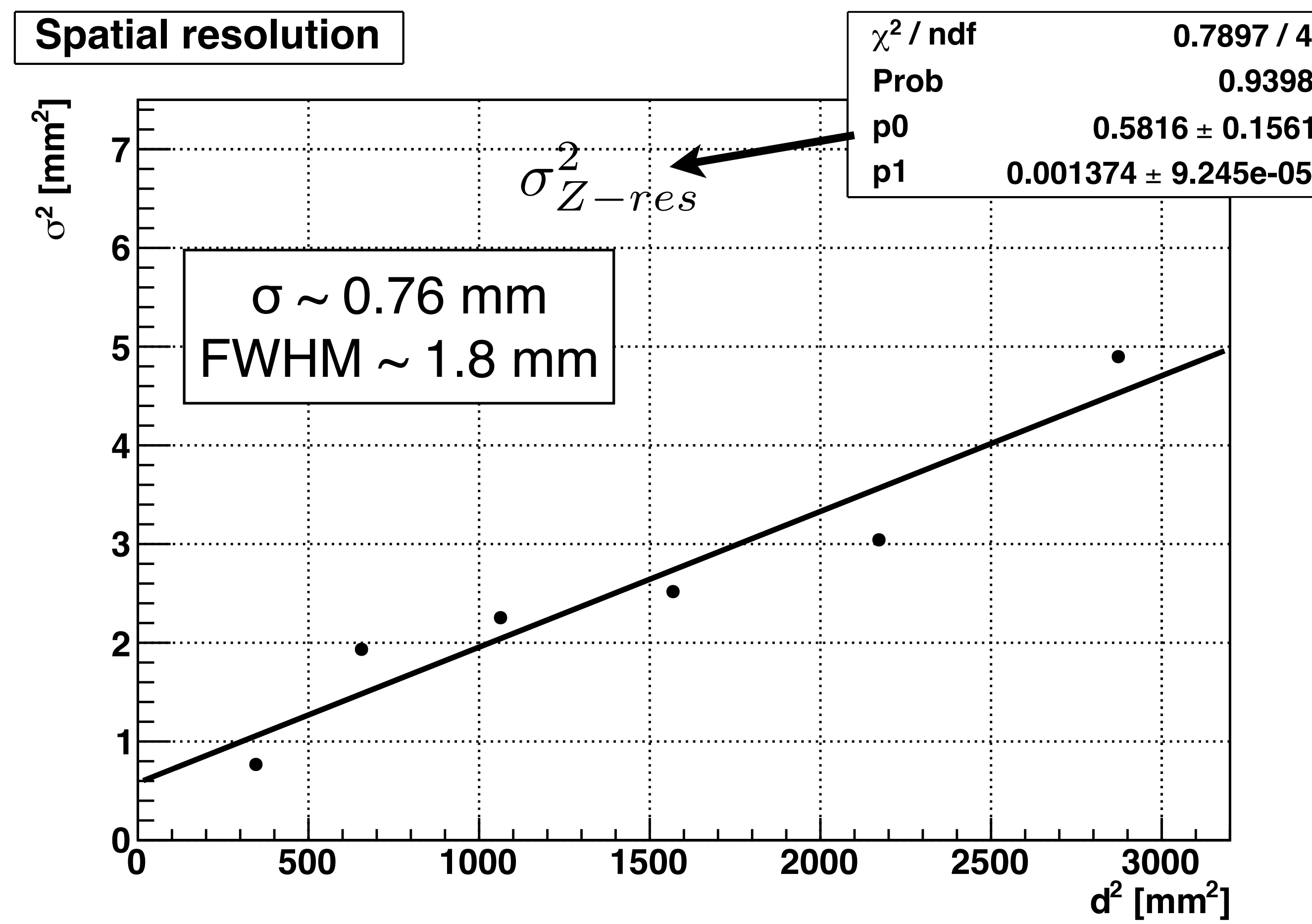
How to derive the intrinsic spatial resolution?

1. make hypothesis :

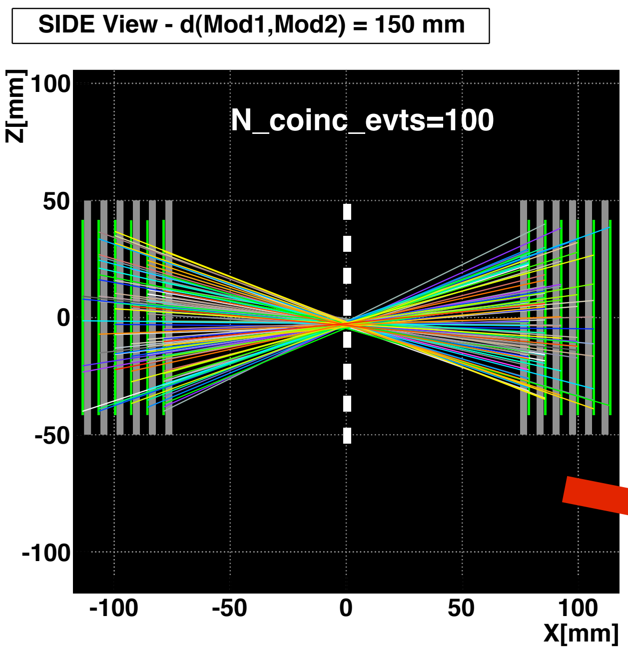
$$\sigma_{i\_beam} \propto d_i$$

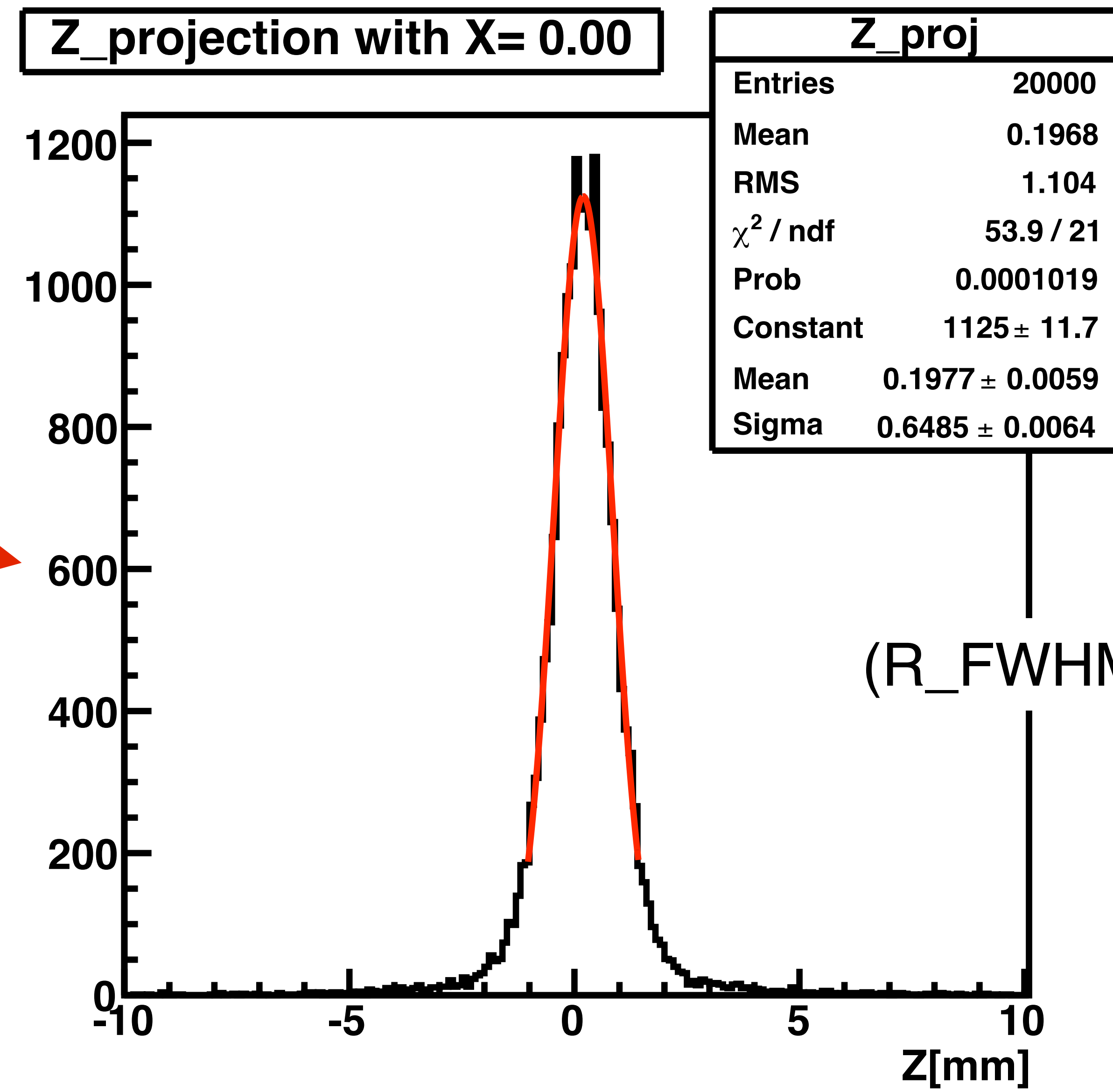
$$\sigma_i^2 = \sigma_{Z-res}^2 + \alpha d_i^2 \qquad \alpha = \frac{\sigma_{beam}^2}{d^2}$$

2. extrapolate at zero distance



AXIAL RESOLUTION



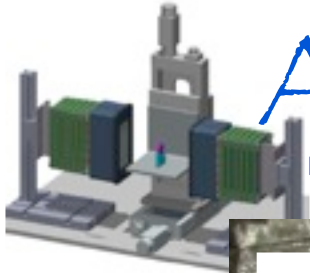


$(R\_FWHM)_Z \sim 1.5$ mm

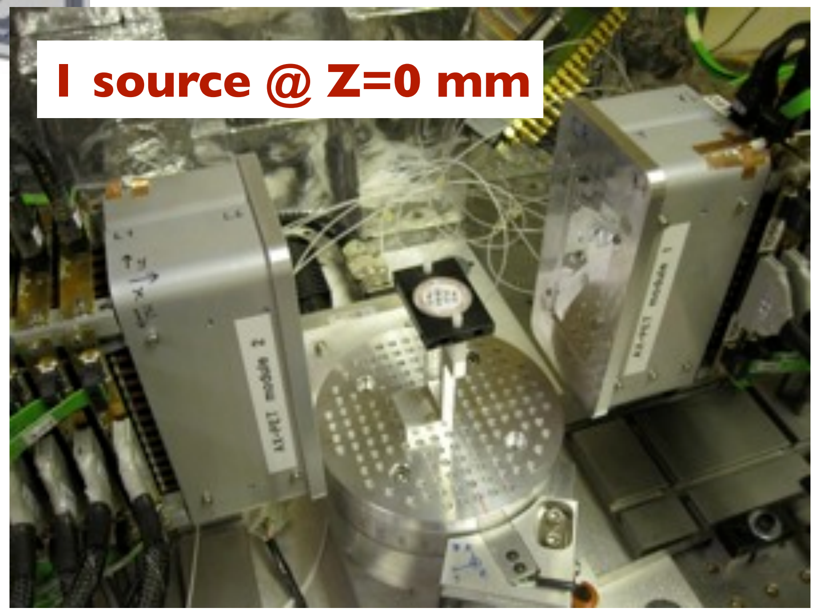
$$R_{intr} = \sqrt{R^2_{meas} - R^2_{\rho} - R^2_{180}} \approx \mathbf{1.35\ mm}$$

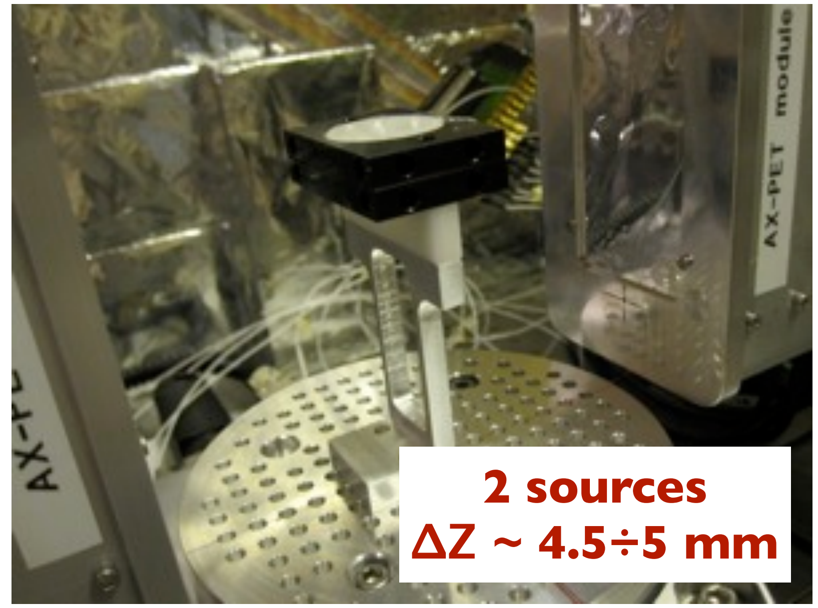
R^2_{ρ}: $(0.54\ \text{mm})^2$

R^2_{180}: $[0.0022 \times \text{Diam} = 0.33\ \text{mm}]^2$



AXIAL RESOL. - two sources separation

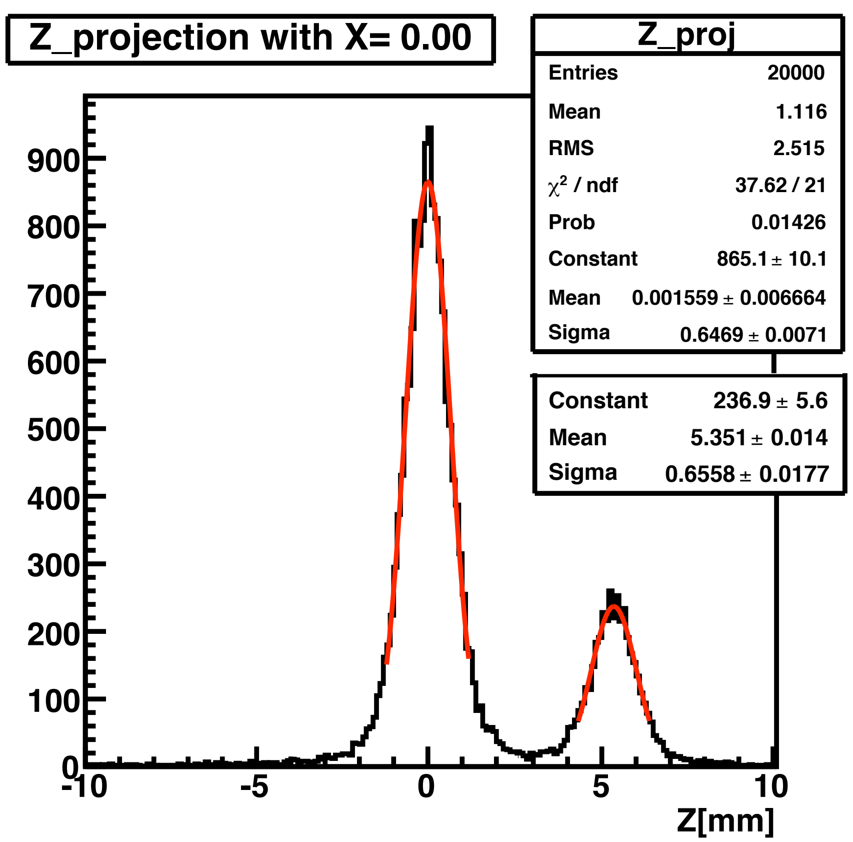


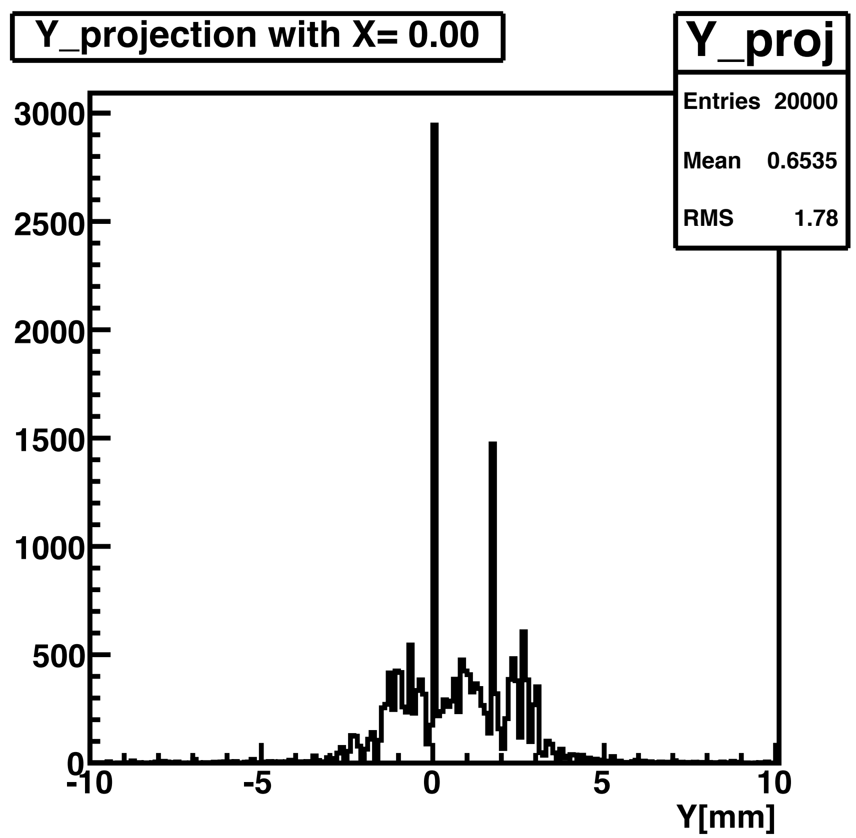


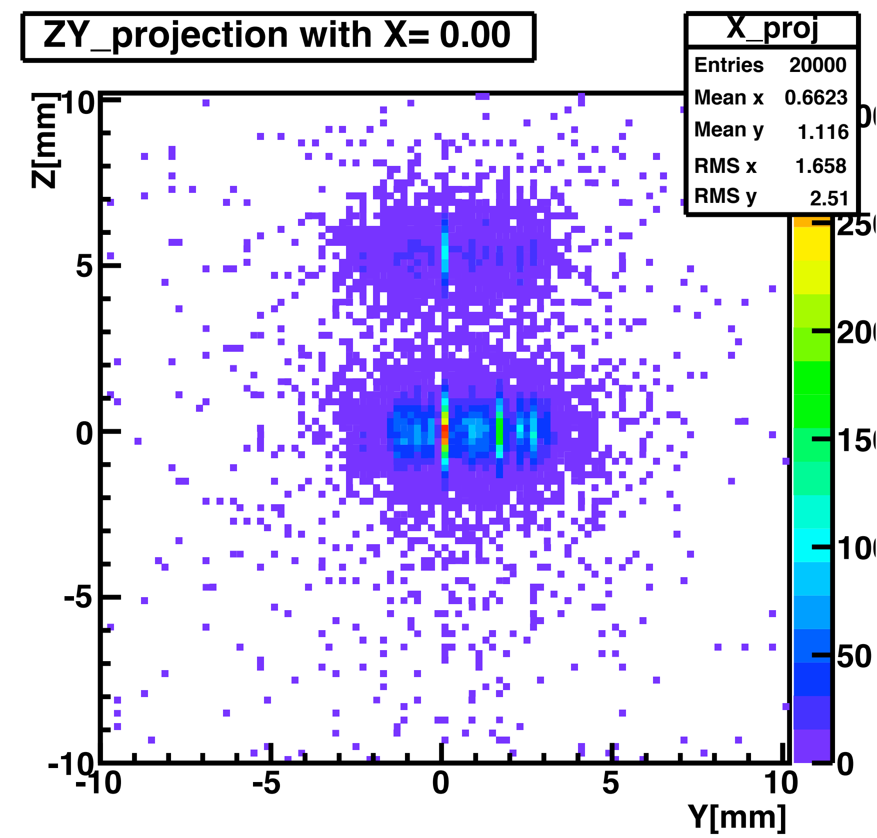
two sources :

1) A ~ 600 MBq ; in (0,0,0)

2) A ~ 100 kBq ; in (0,0,ΔZ)







History and Publications

1. Ter-Pogossian et al, **1978** : pioneering original concept of NaI crystals axial arrangement

2004

- Proposed 5 years ago to use HPD (Hybrid Photon Detector) for the readout of long crystals in axial configuration. Pulse height ration was used to derive axial coordinate
- Best achievable axial resolution was 6mm for 100mm crystal → Not sufficient
- HPD were based on custom made in-house developments

2007

- New proposal:
  - Use interleaving WLS strips for the reconstruction of the axial coordinate
  - G-APD for crystal and WLS readout

- Publication:
  - J. Séguinot et al., Novel Geometrical Concept of a High Performance Brain PET Scanner- Principle,Design and Performance, Il Nuovo Cimento C, Volume 29 Issue 04 (2005) p429.
  - A. Braem et al., Scintillator Studies for the HPDPET Concept, Nucl. Instr. Meth. A 571 (2007) 419.
  - A. Braem et al., High precision Axial Coordinate Readout for an Axial 3-D PETDetector Module using a Wave Length Shifter Strip Matrix, Nucl. Instr. Meth. A580 (2007) p1513.
  - A. Braem et al., Wave Length Shifter Strips and G-APD Arrays for the Read-Out of the z-Coordinate in Axial PET Modules, Nucl. Instr. Meth. A 586, (2008),p300-308.
  - A. Braem et al., Wave Length Shifter Strips and G-APD Arrays for the Read-Outof the z-Coordinate in Axial PET Modules (short version of Nim Paper), Conference Record IEEE Meeting 2007, Honolulu.

Erlend Bolle, NDIP'08, Aix-Les-Bains, June 2008

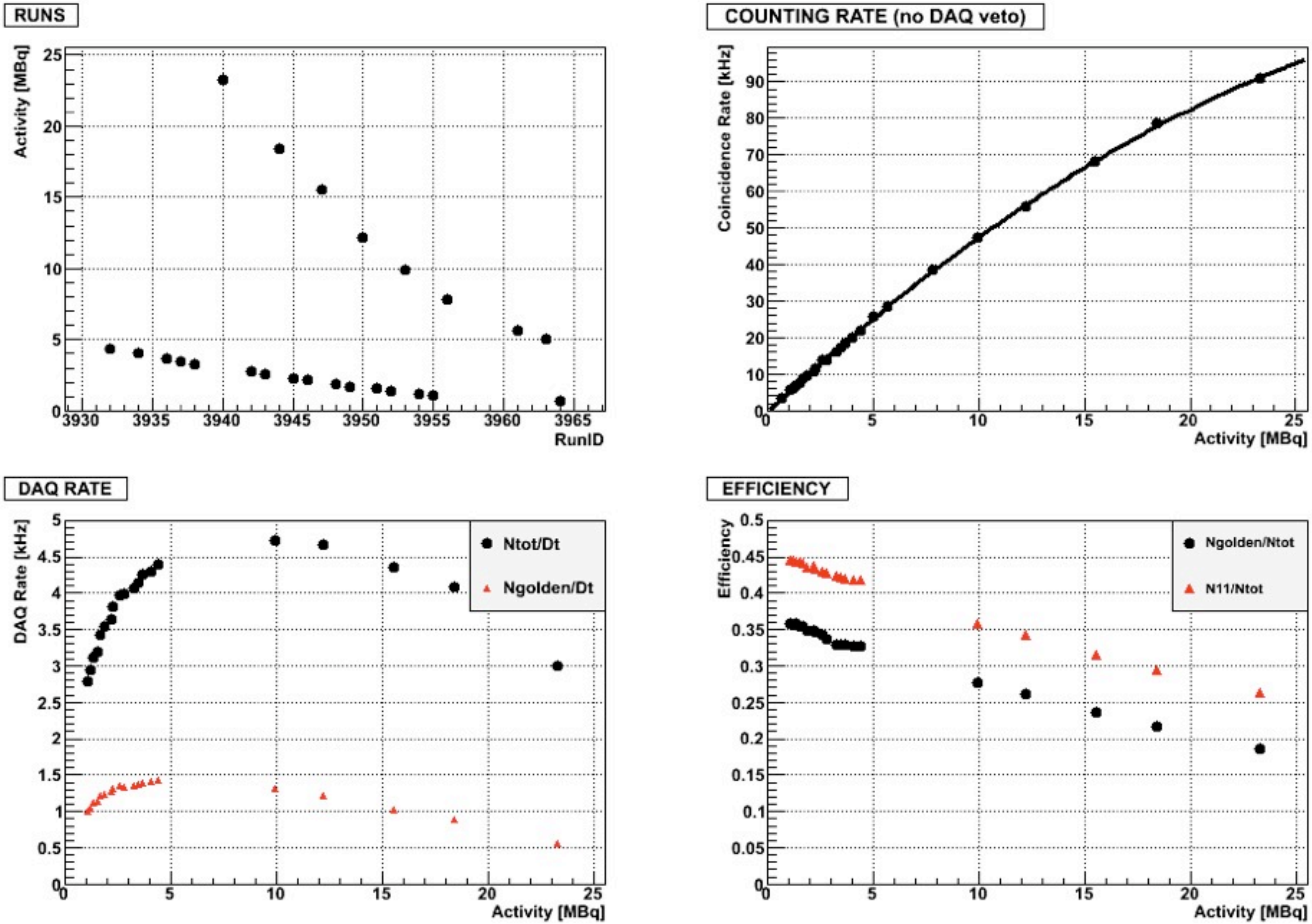
2009 :

- module constructions / performance assessment / single module characterization / 2 mods coincidence (with sources) **[PAPER IN PREPARATION]**
- software progress : simulations / reconstruction **[PAPER IN PREPARATION]**

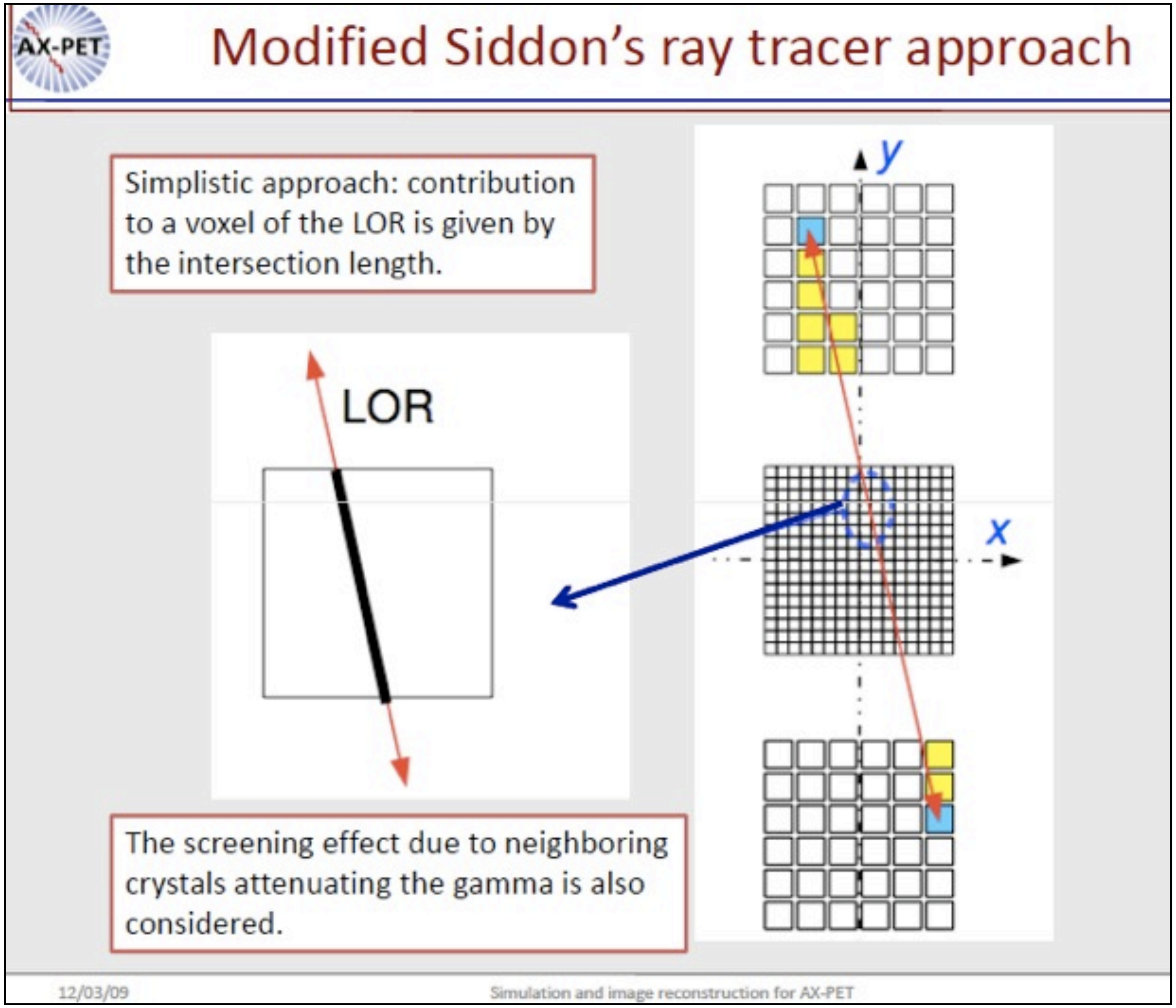
2010 :

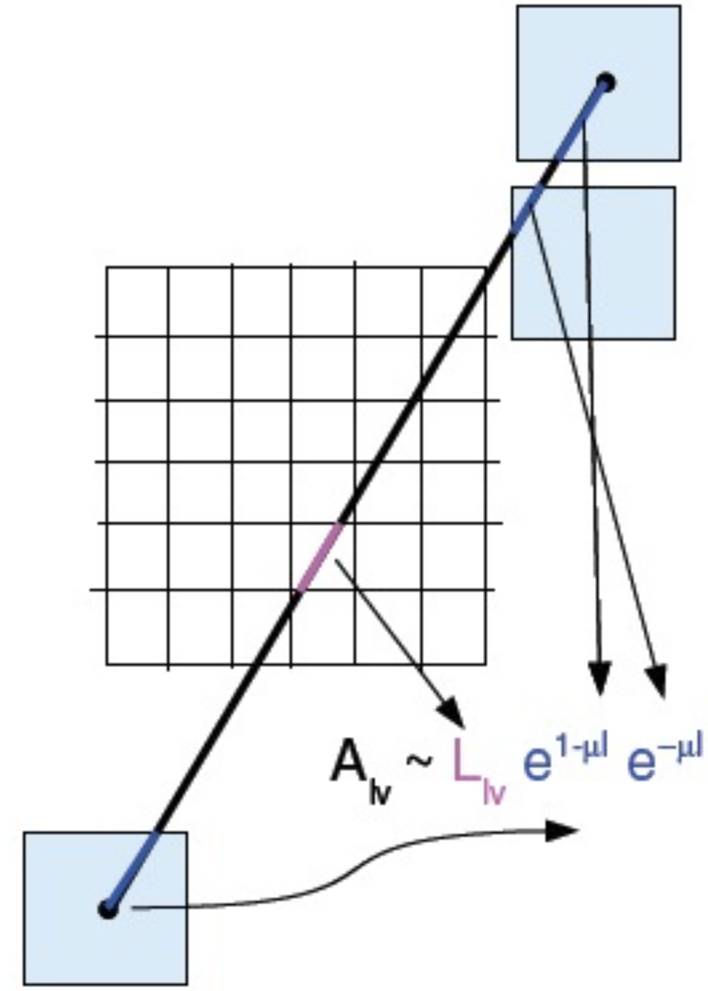
- measurements with phantoms

Measurements with phantoms - DAQ limits



strong dead-time effect in the DAQ

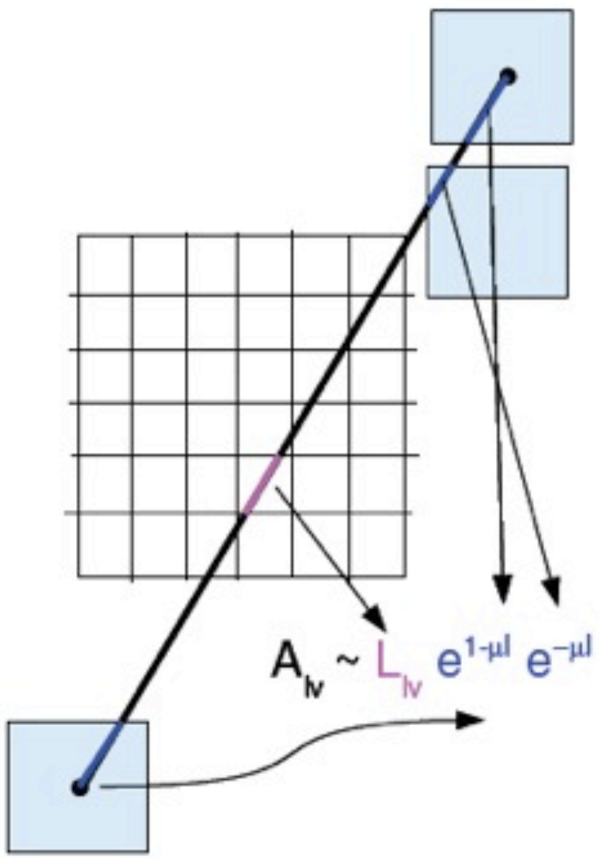


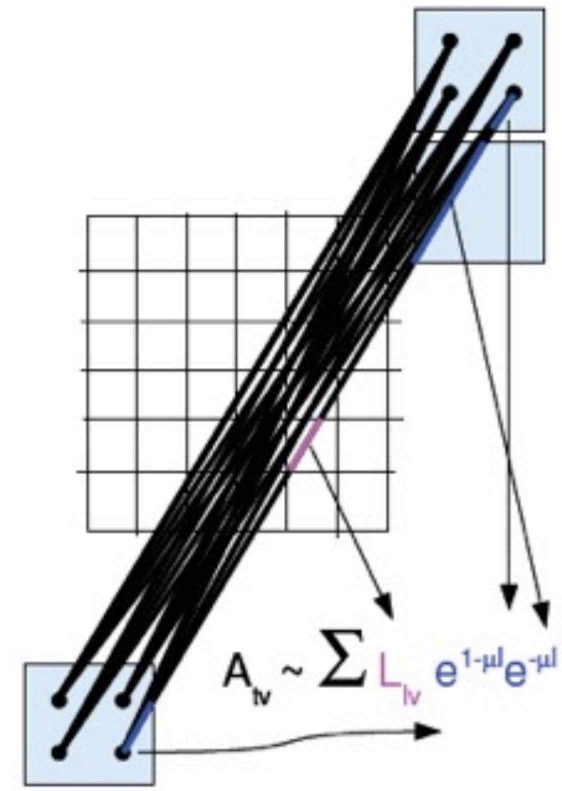


Outline of SM computation without subsampling

- LYSO crystals are discretized in detector elements
- Lines of Response, LORs, joining centers are considered.
- Siddon algorithm. Intersection lengths between LOR and voxel are used to aproximate the probability of a decay that takes place at that particular voxel gives a signal in that LOR.
- Crystal penetration effects were considered.
- **Ignores effects due to the finite size of the crystals**

Subsampling: Improving the quality of the system matrix





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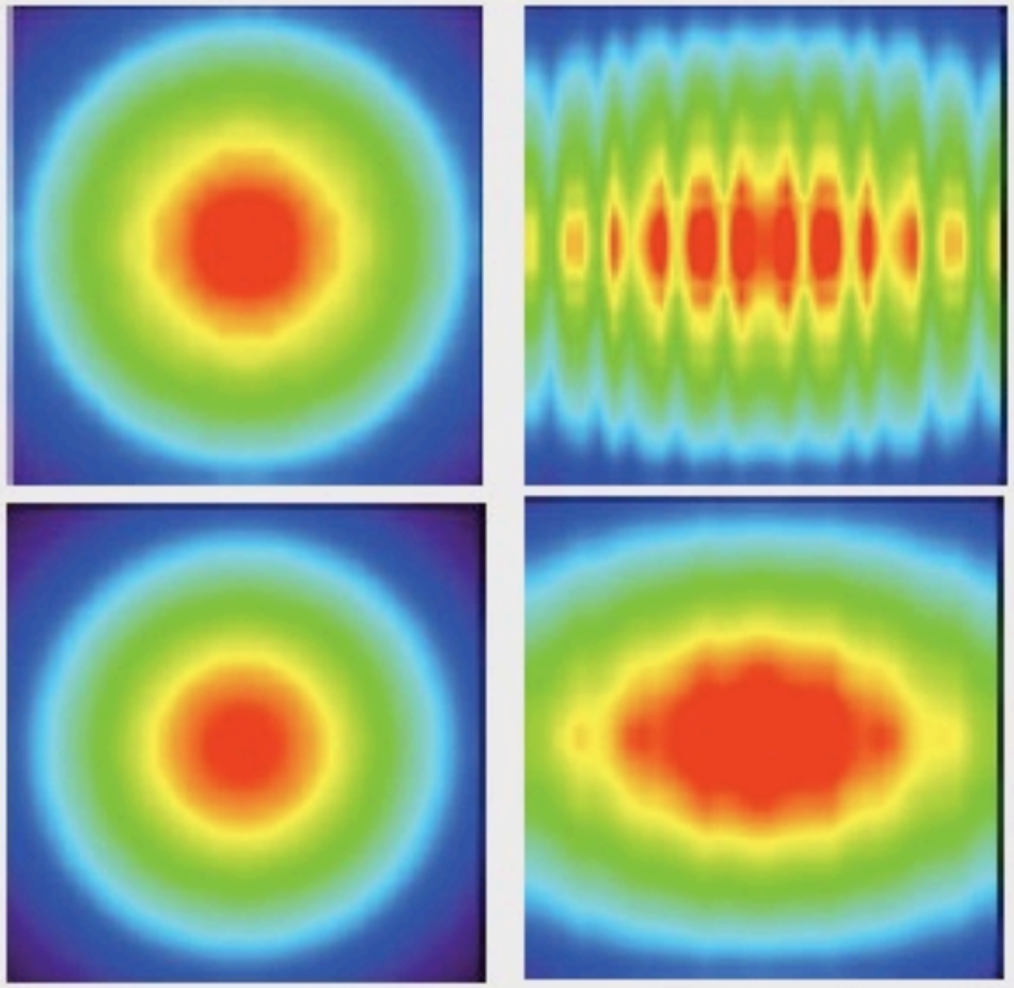
- LYSO crystals are discretized in detector elements
- Lines of Response, LORs, joining centers are considered.
- Siddon algorithm. Intersection lengths between LOR and voxel are used to aproximate the probability of a decay that takes place at that particular voxel gives a signal in that LOR.
- Crystal penetration effects were considered.
- **Ignores effects due to the finite size of the crystals**

Outline of SM computation with subsampling

- LYSO crystals are discretized in detector elements
- Instead of LORs each pair of detector elements define a Tube of Response, TOR.
- Each TOR is composed of several LORs defined by a grid of sampling points inside the detector element. All possible combinations
- Individual LOR contributions are computed as before,ie. Siddon algorithm.
- Crystal penetration effects are properly considered. **Each LOR has its own factor.** No factorization.
- Effects due to the finite size of the crystals are partialy considered.

Sensitivity Matrix

Transaxial slide sample — Axial slide sample



Without subsampling

LORs:	$2.80\ 10^{7}$
Elements:	$7.57\ 10^{11}$
non-zero elem.:	$7.5\ 10^{8}$
Size:	5.7 G
sampling:	1x1x1

With subsampling

LORs:	$2.80\ 10^{7}$
Elements:	$7.57\ 10^{11}$
non-zero elem.:	$4.45\ 10^{9}$
Size:	34 G (not optimized)
sampling:	2x2x2

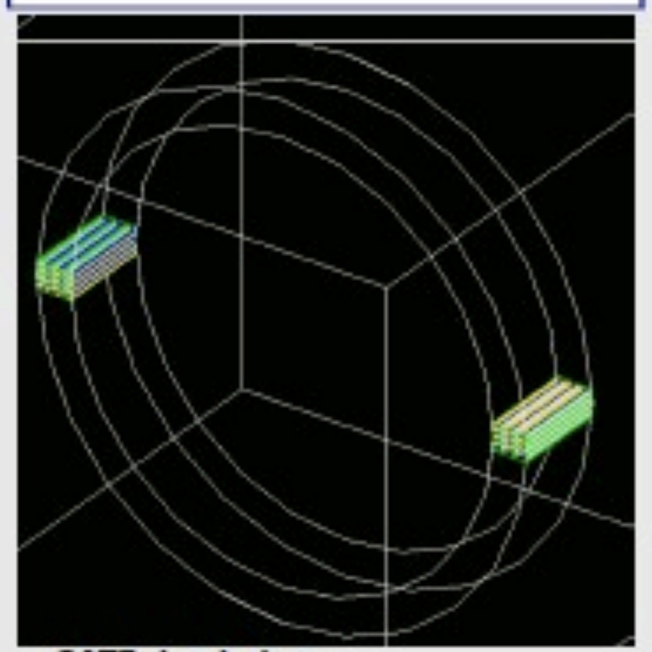
FOV

Volume(vox):	30x30x30 vox
Volume(mm^3) :	30x30x30 mm^3
voxel dimensions:	1x1x1 mm^3
voxels:	27000

GATE simulation of the full module

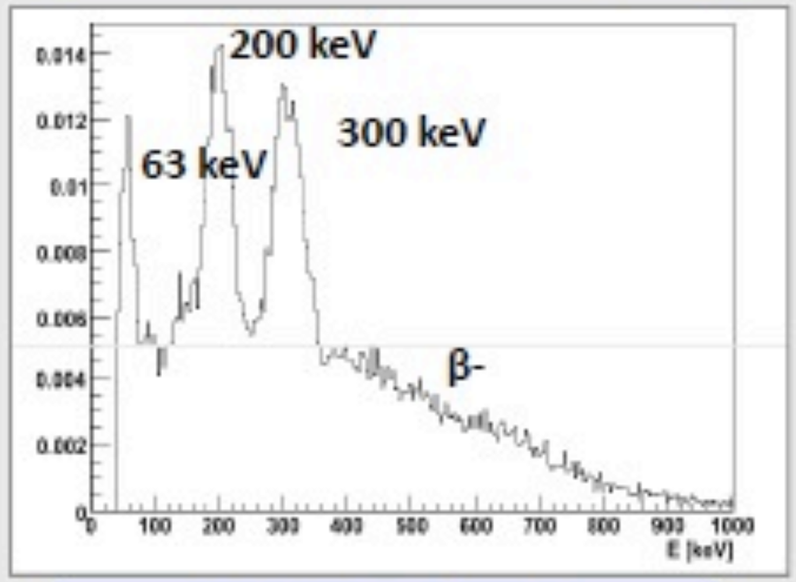
The AX-PET scanner is modeled by means of GATE. In order to correctly reproduce the achievable spatial resolution, the source code is modified to include the z coordinate parameterization according to WLS response.

Geometry modeled

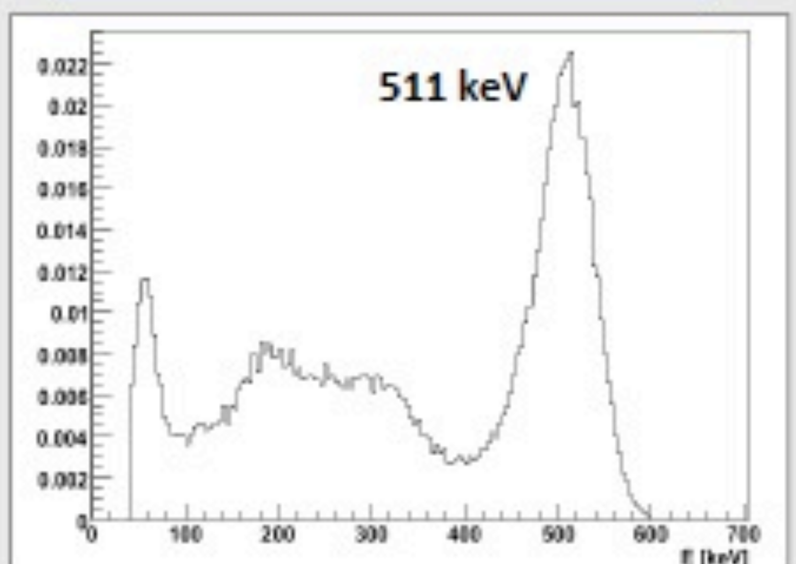


GATE simulation

Intrinsic radioactivity



Gamma source

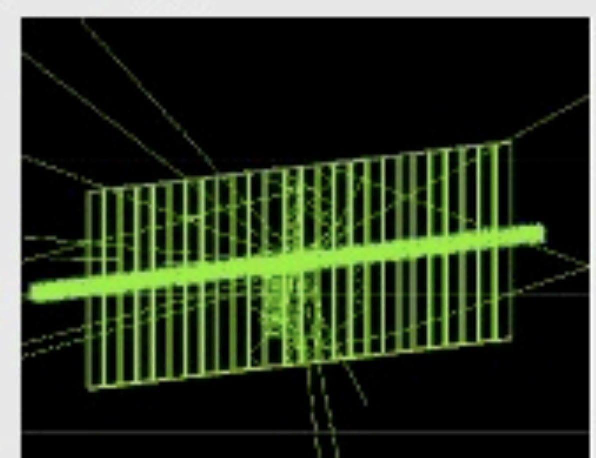


Digitizer

- energy and time blurring;
- threshold at crystal level;
- coincidence unit;
- dead time in the acquisition;
- rotation of the scanner.

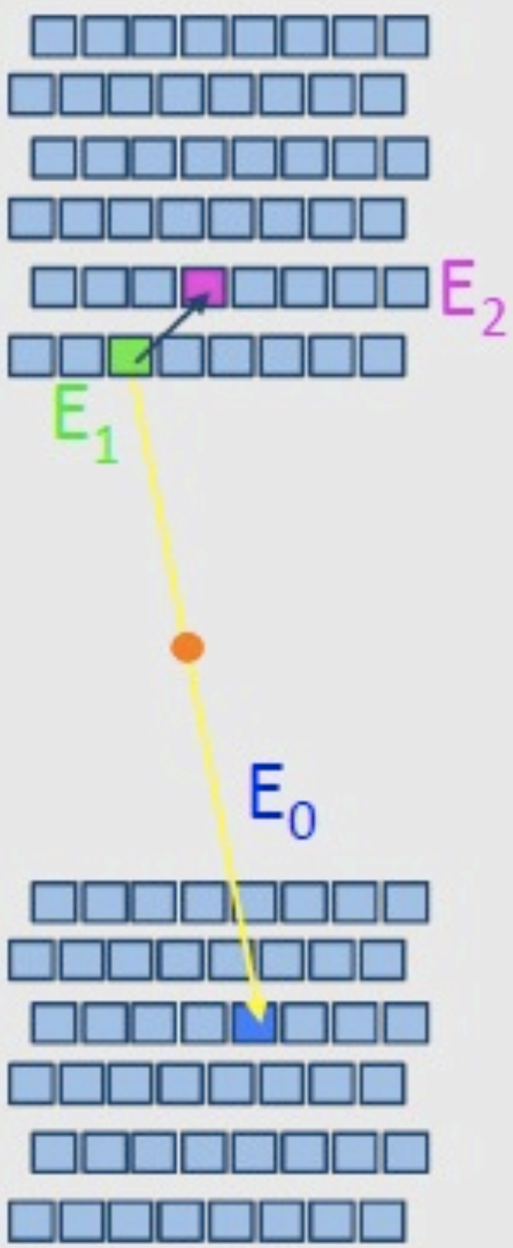
WLS parameterization

$$N_{pe,i,n} = N_{pe,i,n-1} + A(x_n, E_n) \cdot e^{\frac{(z_n - z_i)^2}{2\sigma^2(x_n)}}$$



Geant4 simulation

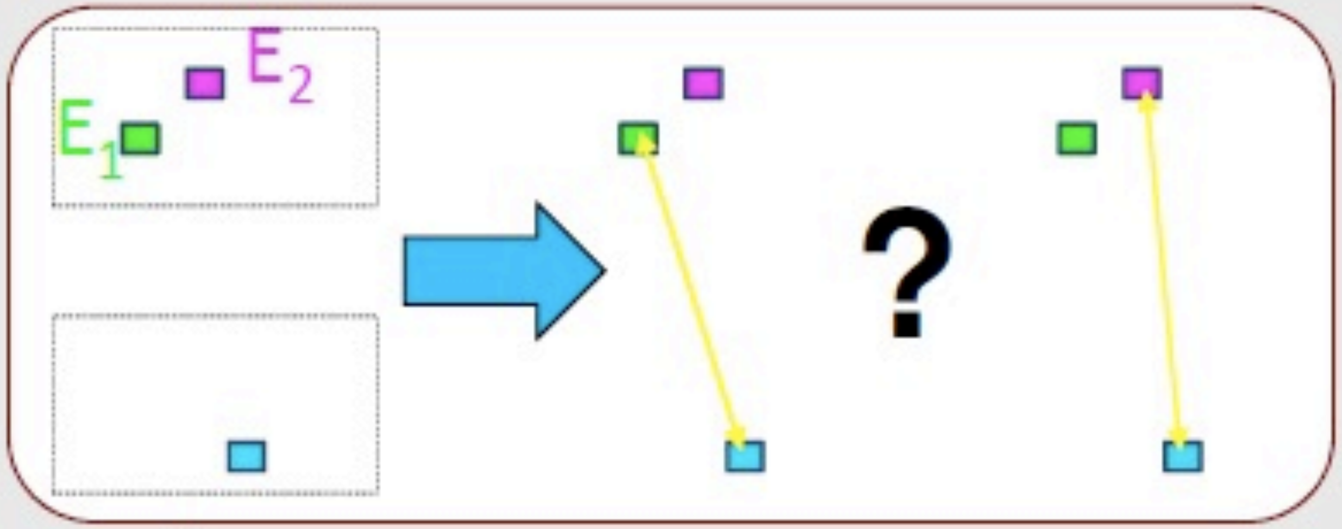
Investigate Inter-crystal scattering



Multiple events are accepted if E1+E2≈511 keV.

The use of ICS events implies:

- higher sensitivity;
- need of proper techniques to include ICS in the reconstruction algorithm to avoid spoiling the spatial resolution.



Different approaches:

- identify and reconstruct ICS and feed the image reconstruction algorithm with the "good" LOR;
- keep all LORs and adapt the system model.

ICS identification and reconstruction

Different identification algorithms are tested and their efficiency in ICS reconstruction is estimated on simulations.

- Klein-Nishina based on geometry or energy;
- Maximum Energy;
- Compton Kinematics (CK);
- Neural Network.

Simulation is performed by using 12% energy resolution at 511 keV, with point-like source in the centre of the FOV, back-to-back gamma emission, 2 modules at 85 mm distance.

Max. E	Compton K.	Klein-Nishina	Neural Networks
61%	65%-66%	61%-63%	75%