The AX-PET Demonstrator : Performance and first results

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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, only 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

The AX–PET camera modules – Design, Construction and Characterization

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[e] *Ohio State University, Columbus, Ohio 43210, USA*
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PET: Positron Emission Tomography

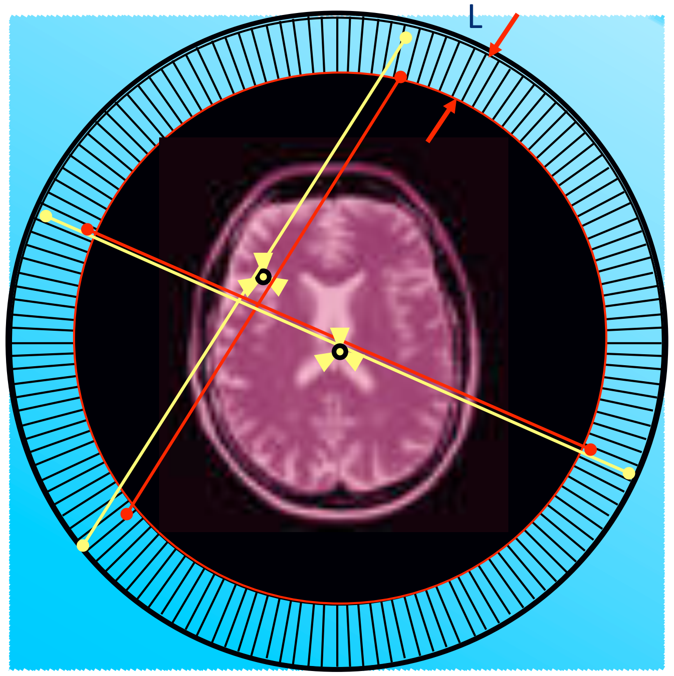
$$p \rightarrow n + e^+ + \nu_e$$
$$e^+e^- \rightarrow \gamma\gamma$$
$$(E_\gamma = 511\ keV)$$

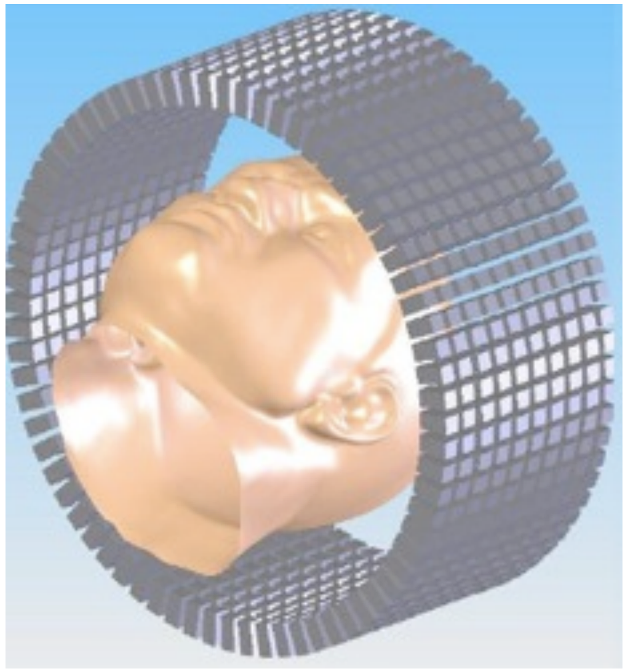
IDEAL PET SCANNER REQUIREMENTS :

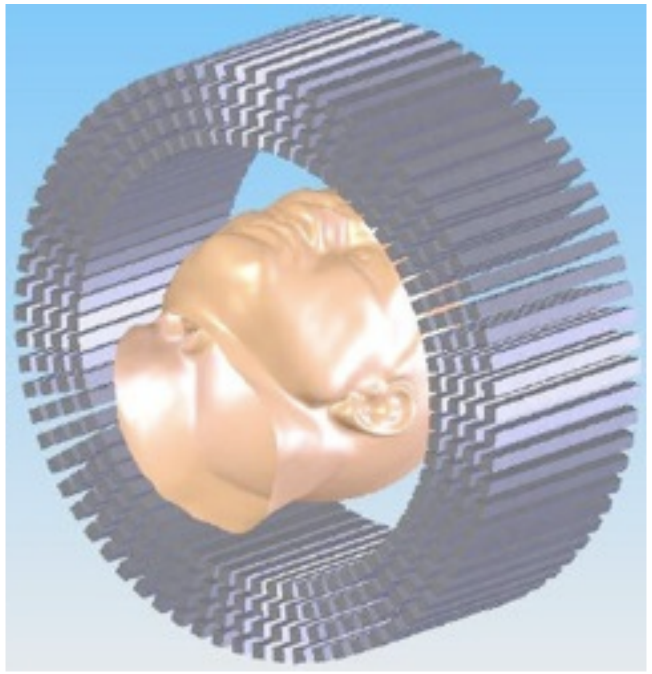
- 2π full coverage
- maximum spatial resolution (up to the limits imposed by the physics of the β+ annihilation)
- maximum sensitivity
- good energy resolution
- good time performance
- ...

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

conventional PET (radial arrangement)





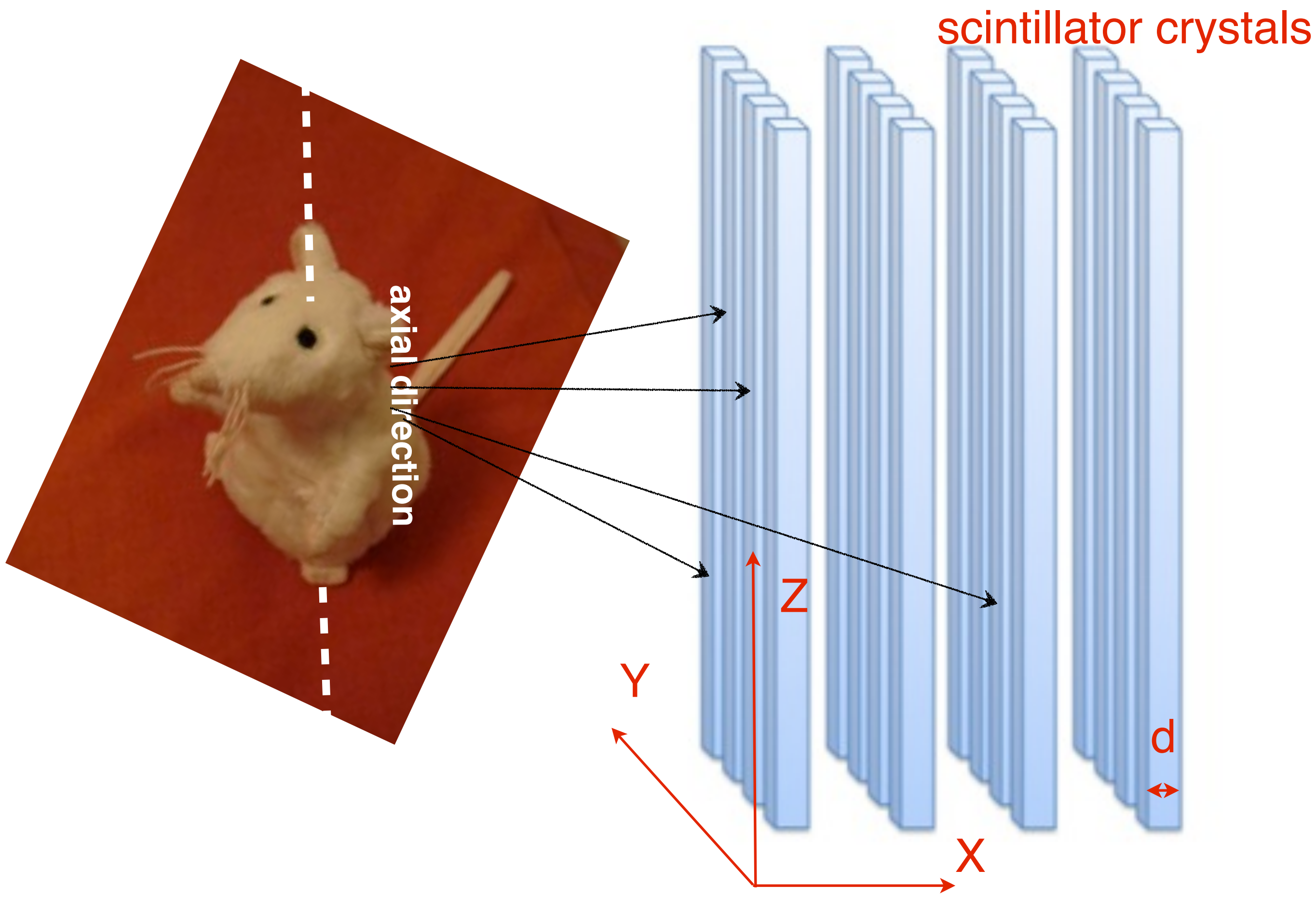


parallax err.

to be completed!

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)
- To increase sensitivity => Add additional layers

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

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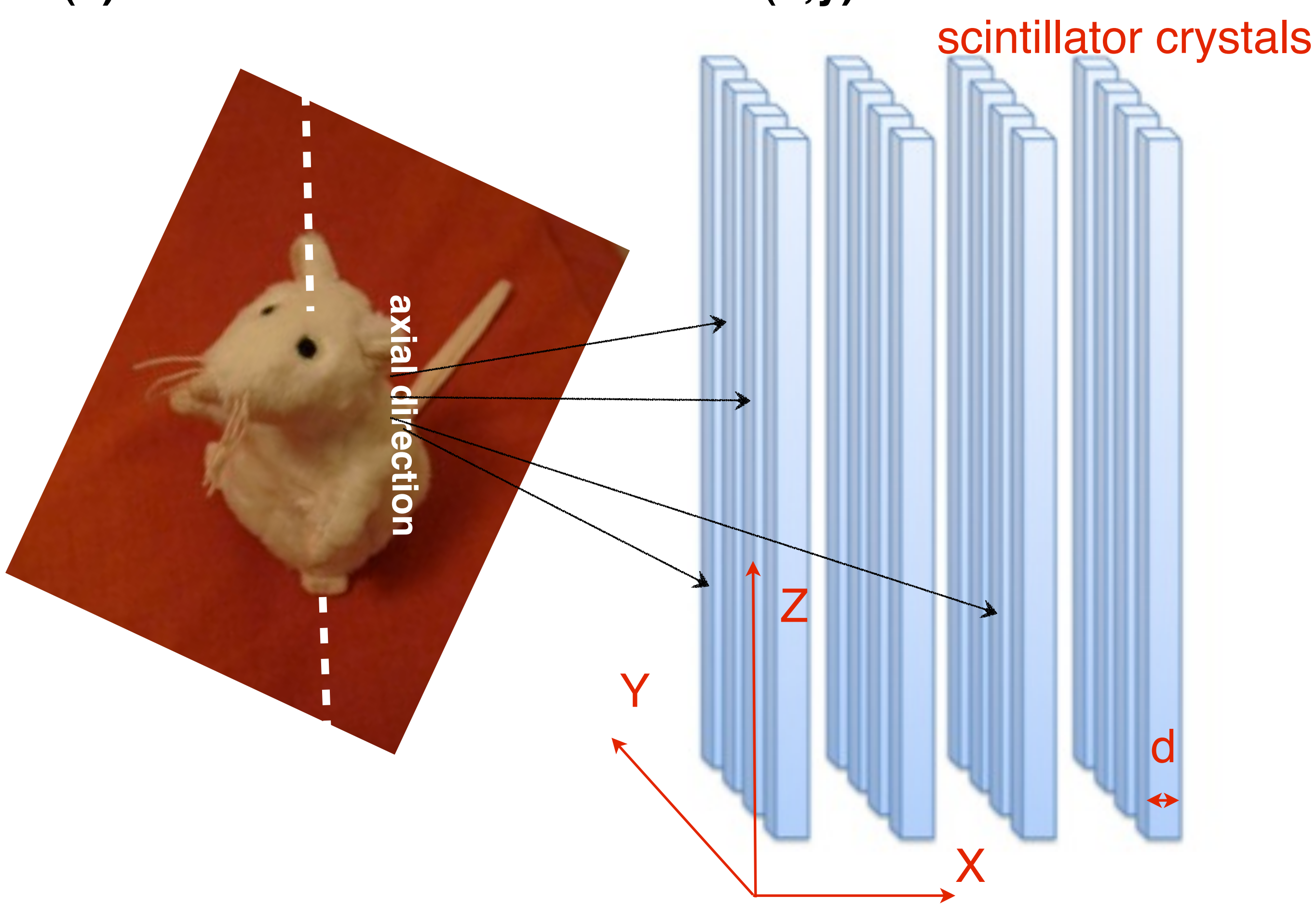

- Transaxial coordinate: from position of the hit crystal
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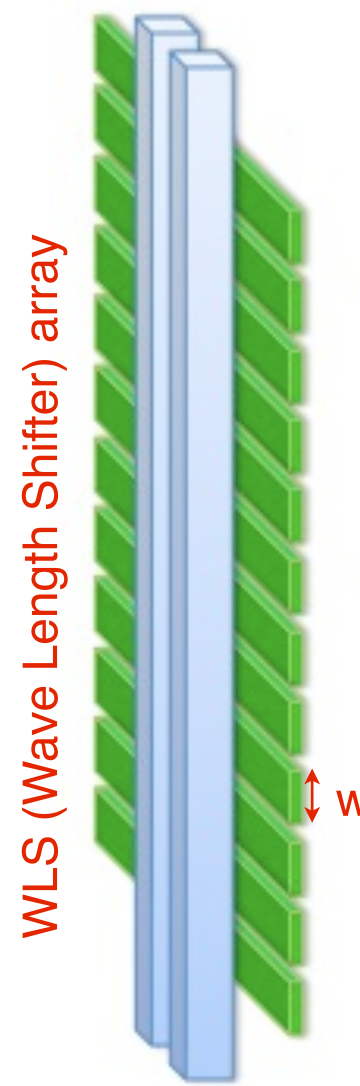
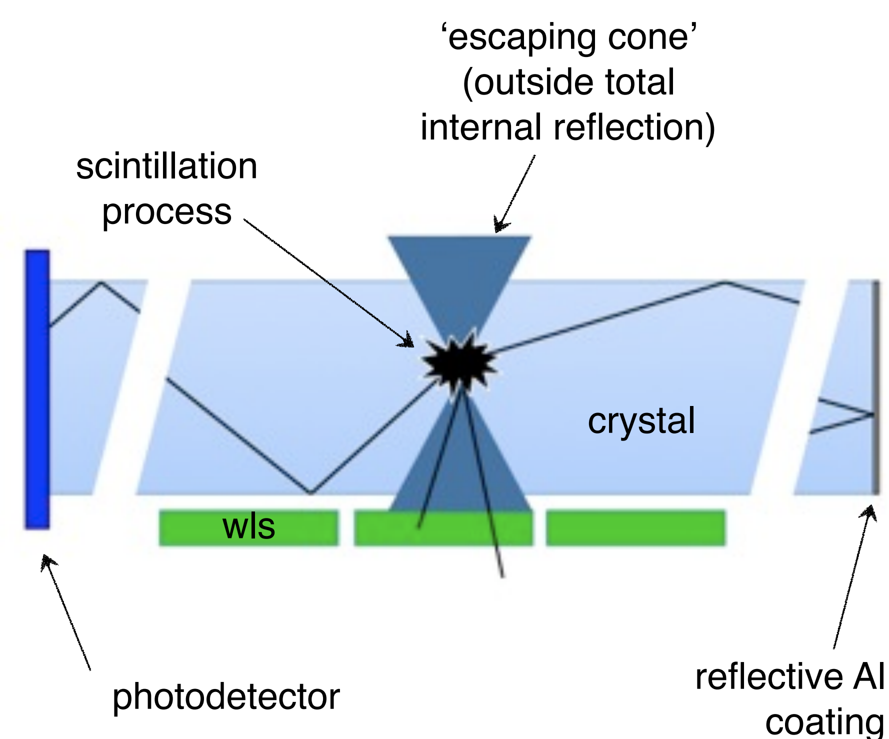
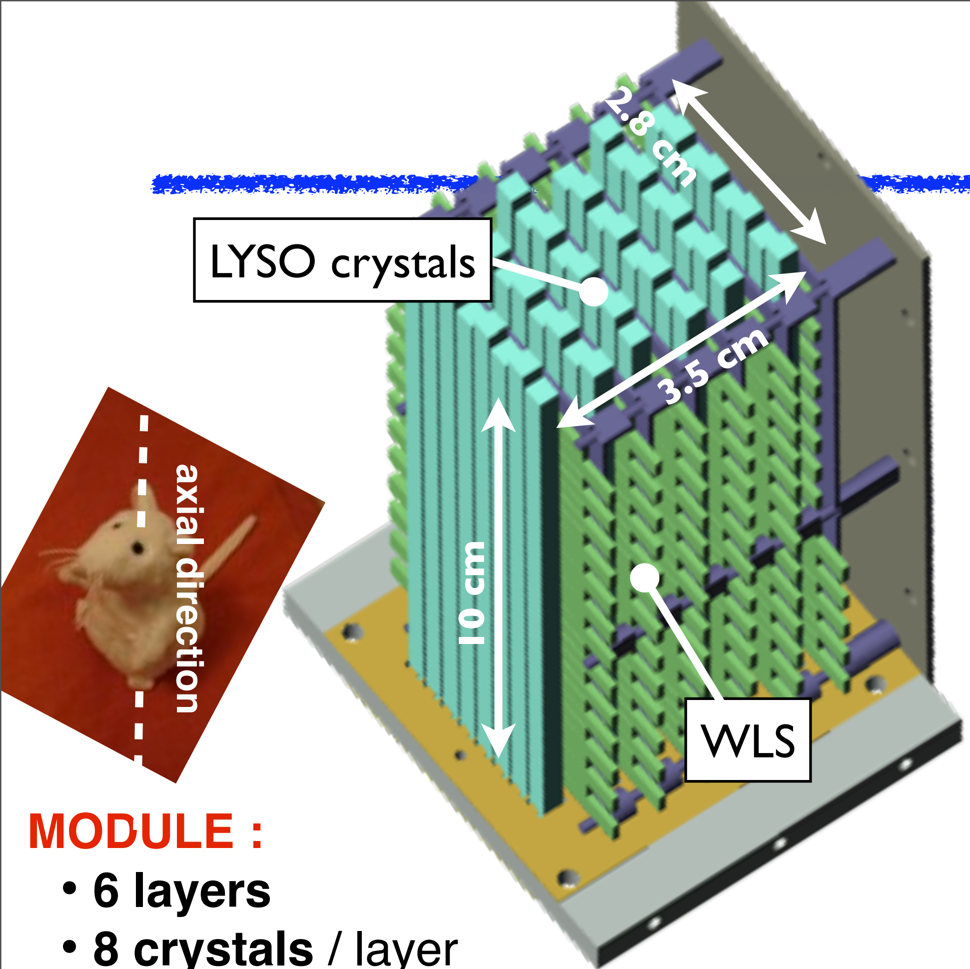
(2) AXIAL COORDINATE (z)





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

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 ($\rho = 7.1$ g/cm^3)
  - λ @511 keV ~ 1.2 cm
  - quick decay time ($\tau = 41$ ns)
  - high light yield (32000 γ / MeV)
- **3 x 3 x 100 mm^3**

- WAVE LENGTH SHIFTING STRIPS (WLS) :

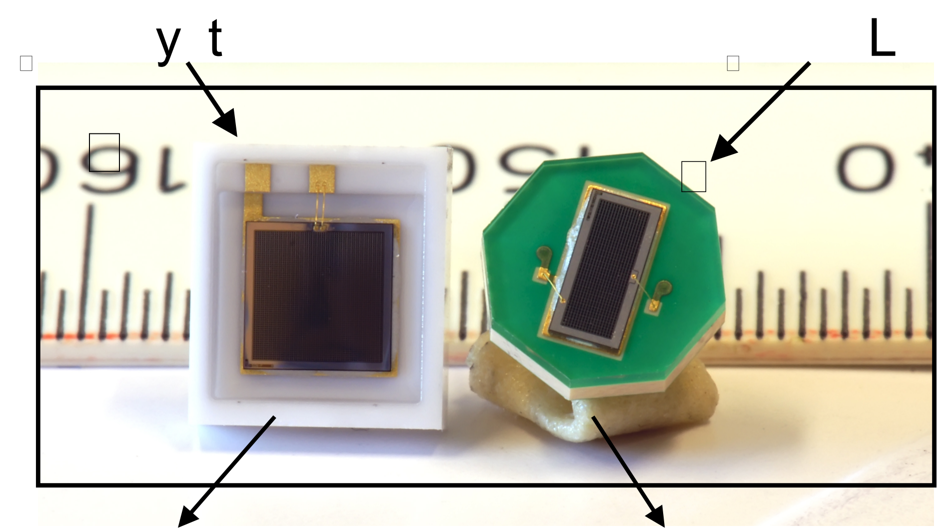
- ELJEN EJ-280-10x
- highly doped (x10 compared to standard) to optimize transmission
- **0.9 x 3 x 40 mm^3**

- 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



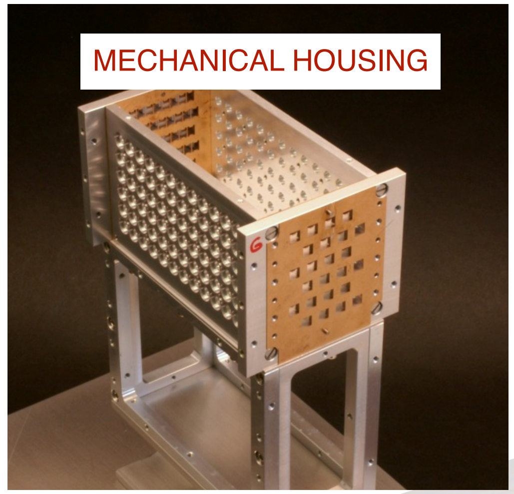
MPPC S10362-33-050C :

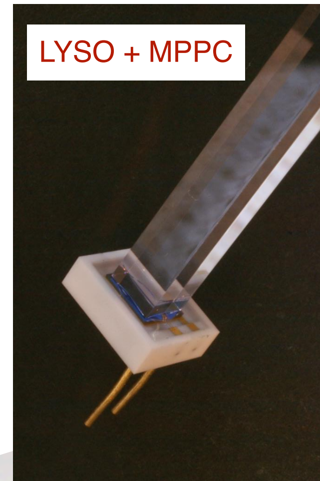
- 3x3 mm2 active area
- 50 µm x 50 µm pixel
- 3600 pixels
- Gain ~

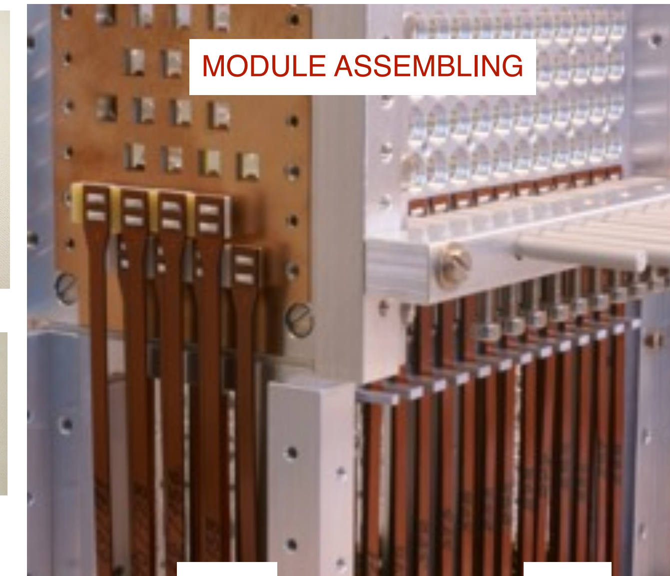
MPPC 3.22×1.19 Octagon-SMD :

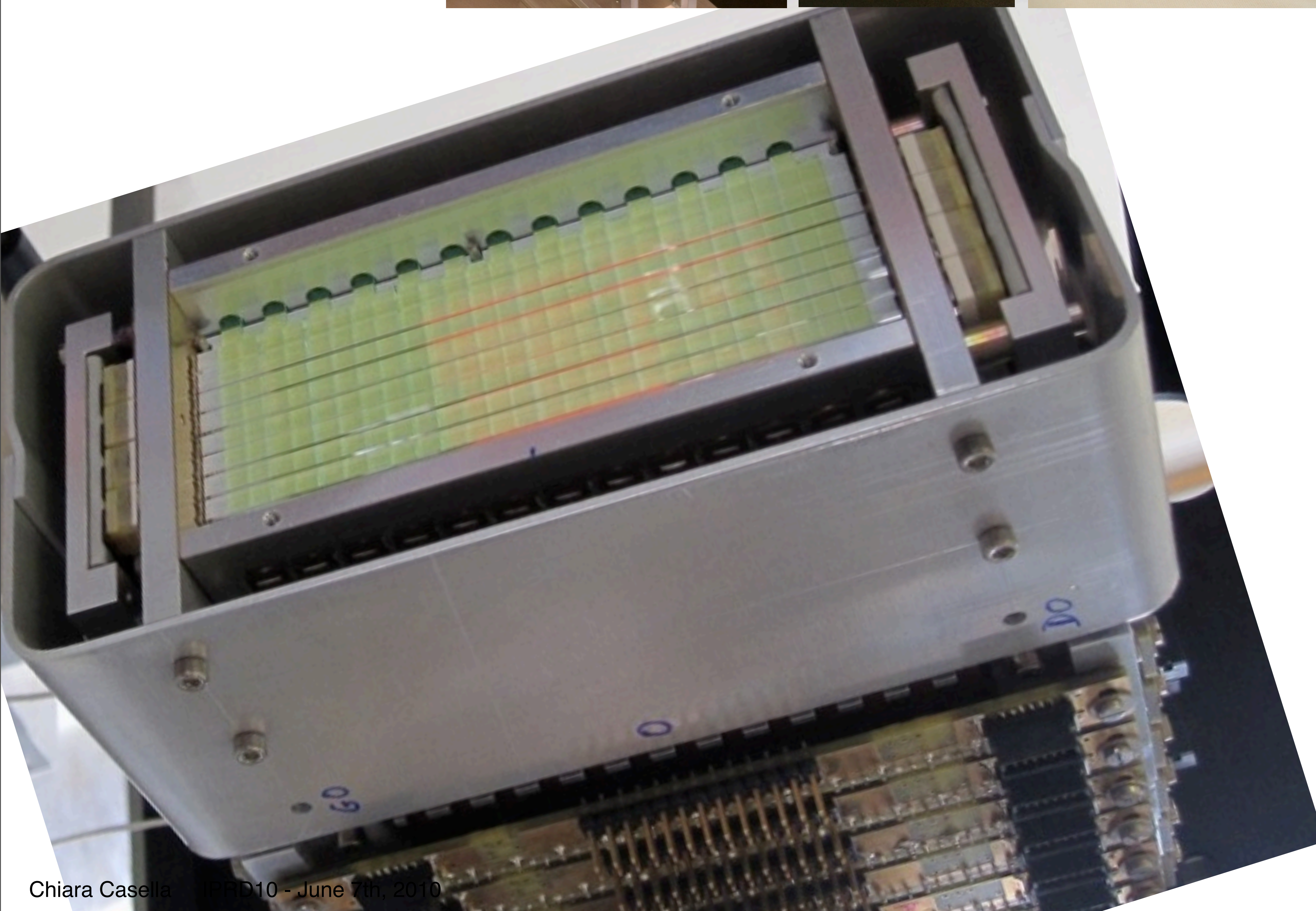
- 1.2 x 3.2 mm2 active area
- 70 µm x 70 µm pixel
- 1200 pixels
- Gain ~
- custom made units

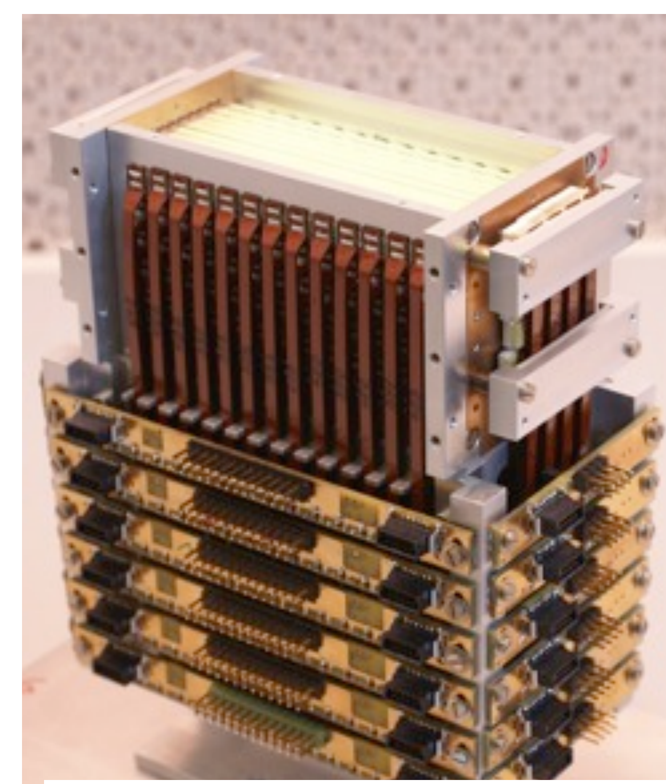
AX-PET MODULE









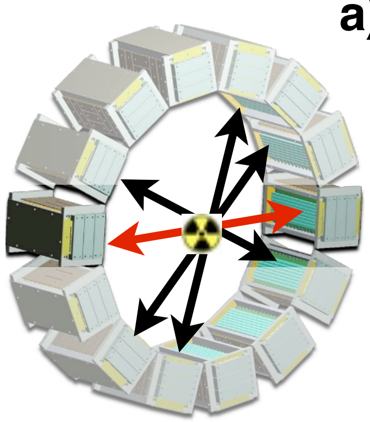


BARE ASSEMBLED MODULE, incuding CONNECTIVITY CARDS

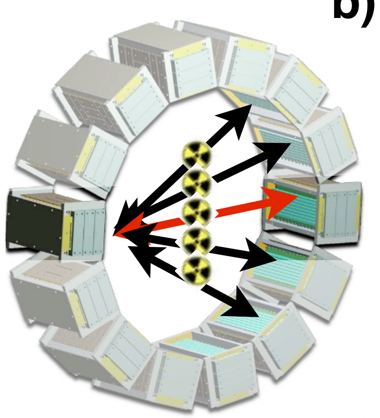
AX-PET DEMONSTRATOR

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

- not a full scanner , **2 modules only**!!!
- **to mimic the full scanner:** 2 mods coincidence + rotating source

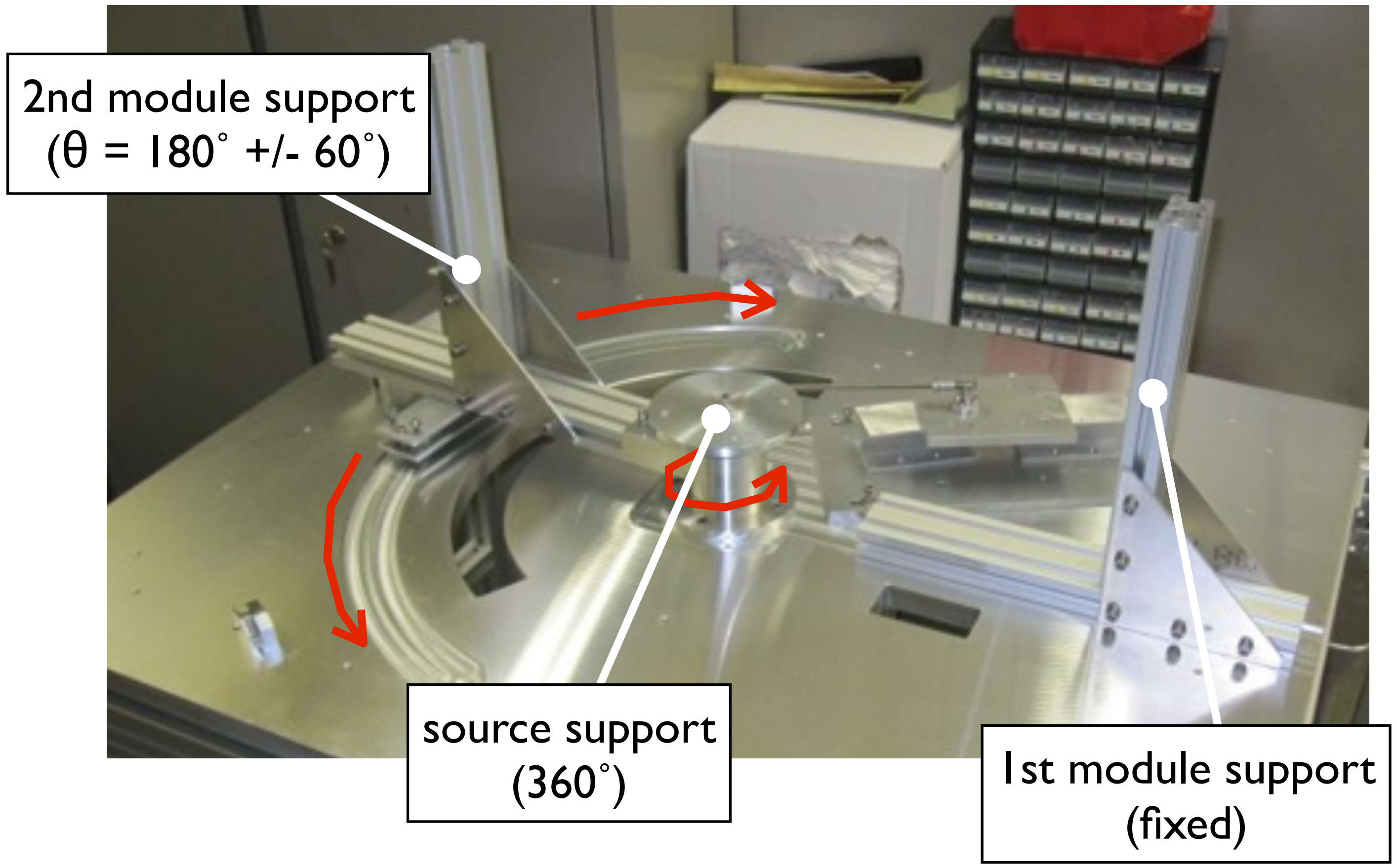


a) small FOV coverage:
- 2 modules fixed, back to back position (180˚)
- rotating source in the center of FOV



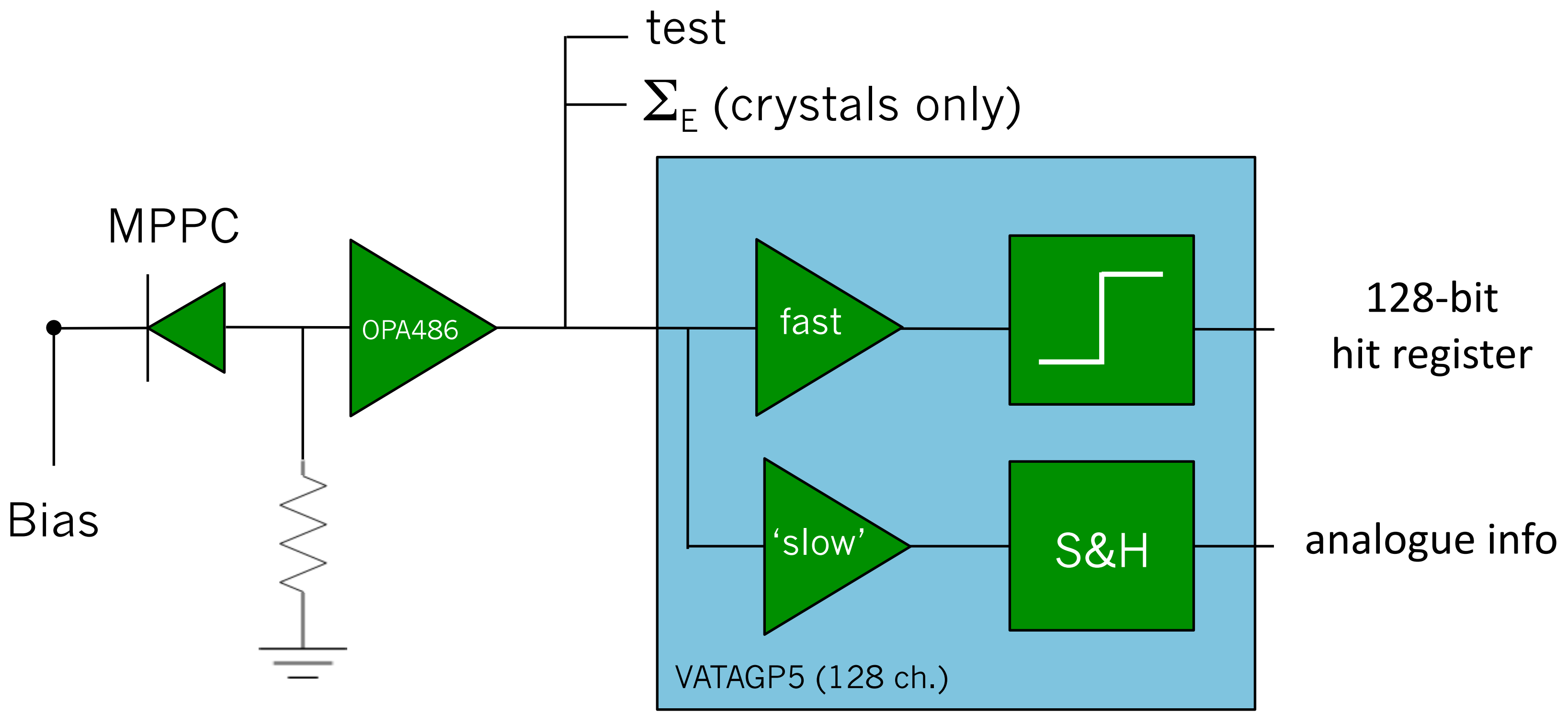
b) extended FOV coverage:
- allow coincidences btw 2 modules not at 180˚
- 1st mod. fixed
- 2nd mod. rotating (θ=180˚+/- 60˚)
- rotating source

"gantry" system /
mechanics for the demonstrator

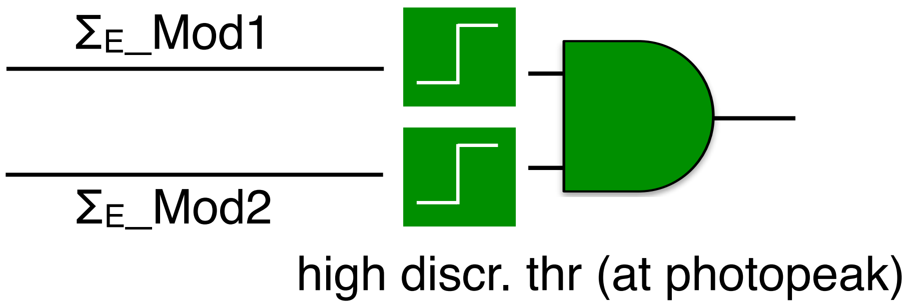


- **dedicated simulations, 2 mods** + validation of the simulation from the data
- final performance of the full scanner : assessed with **dedicated simulations, full scanner**

Demonstrator READOUT and TRIGGER

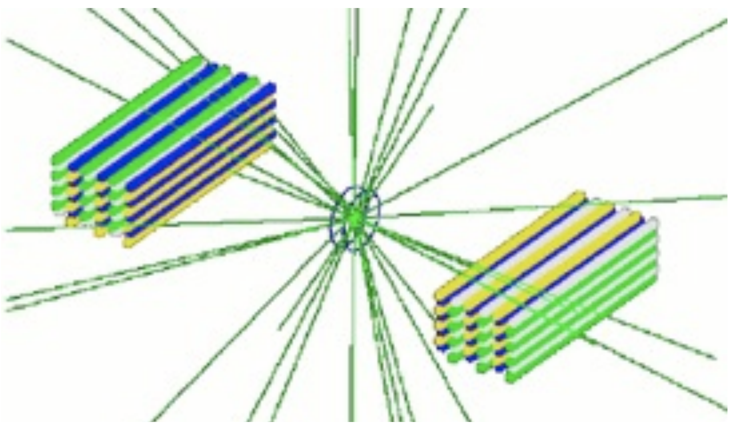


- **Custom designed DAQ system - Individual analogue readout of MPPC output**
- **Amplifiers** : OPA486 (Lyso) / OPA487 (WLS) - **Fast energy sum of all the crystals module**
- **VATA GP5 chip** : 128-ch charge sensitive integrating [AXPET : x4 VATA GP5 chips]
  - Fast (~40ns) / Slow (~250ns) branches
  - Sequential or Sparse readout mode
  - **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**

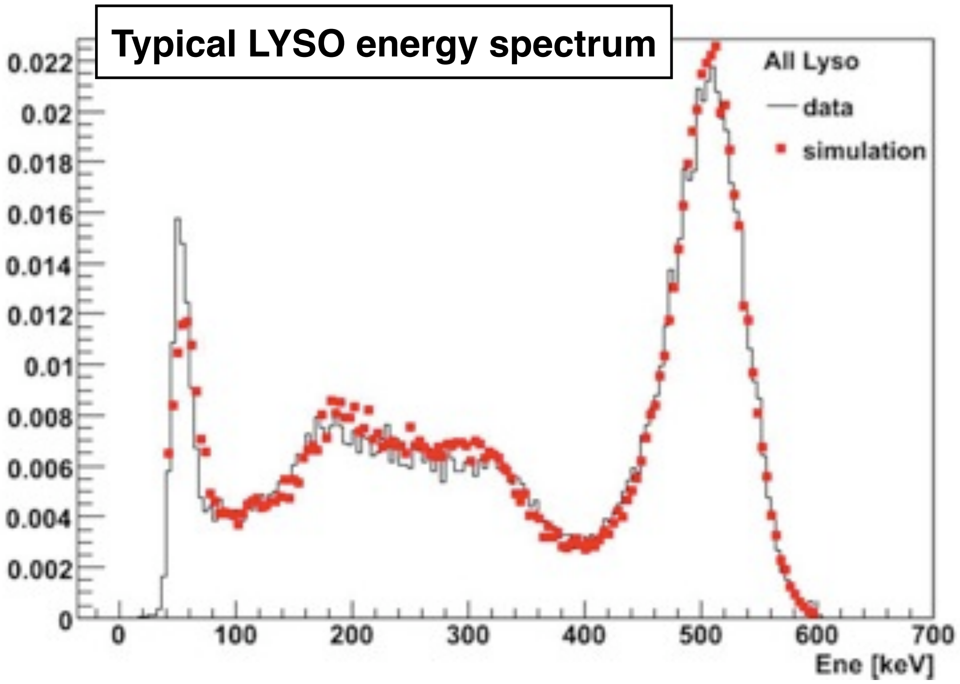
GATE simulation package (G4 application for tomographic emission, including time-dependent phenomena e.g. detector movement)

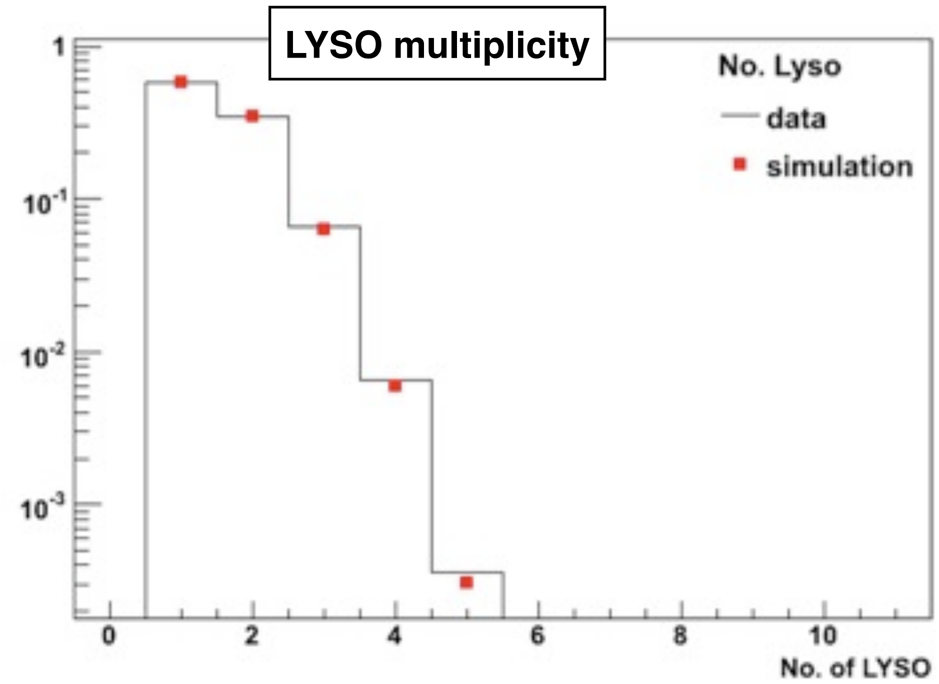


AXPET challenges for realistic simulations :
- non conventional PET design
- WLS parameterization in the digitizer(*)
- Sorter for the coincidences

(*) = 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
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- 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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- T ... Apr 2010)
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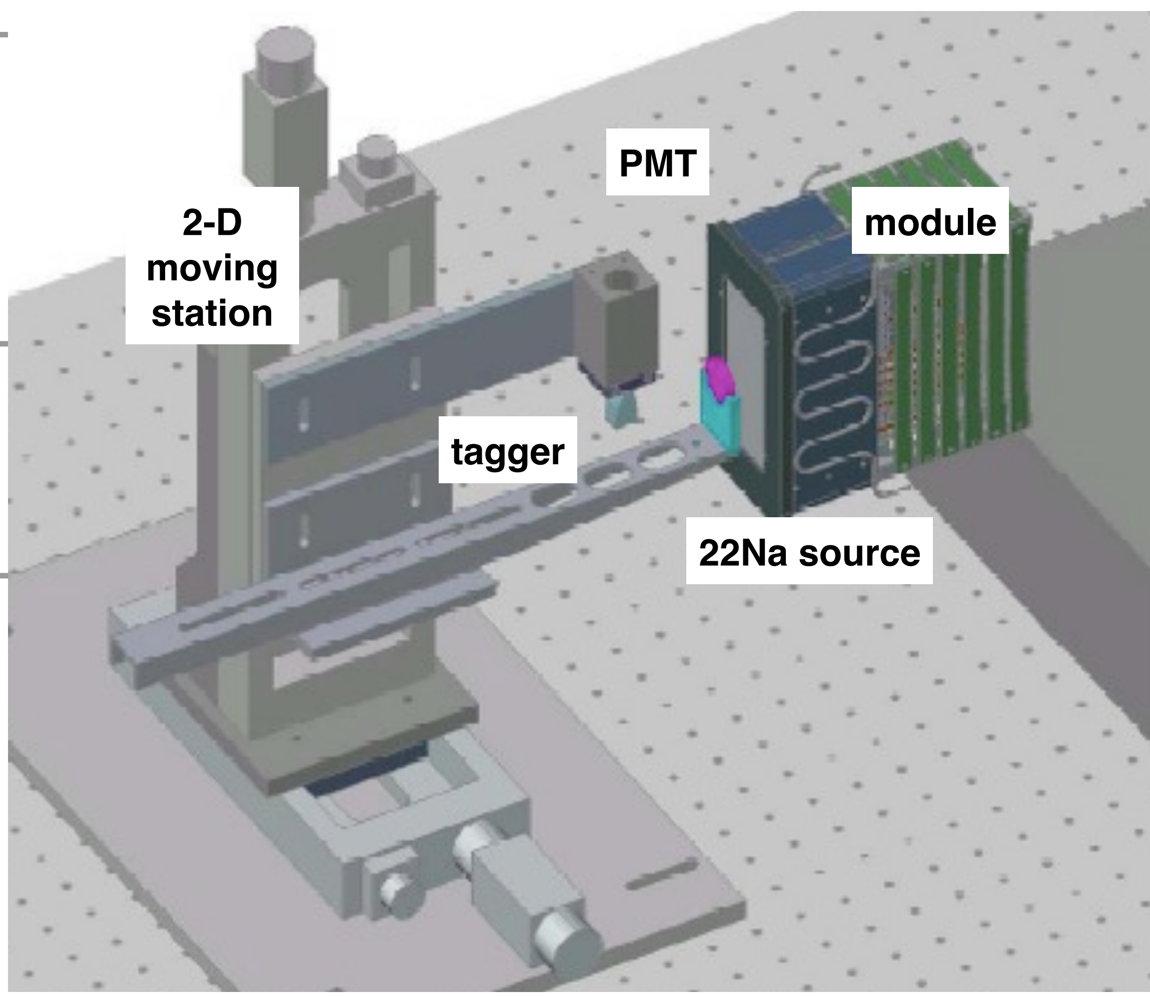

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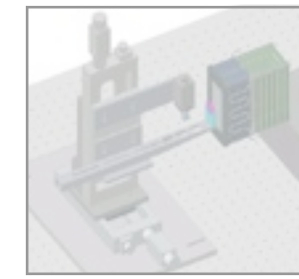

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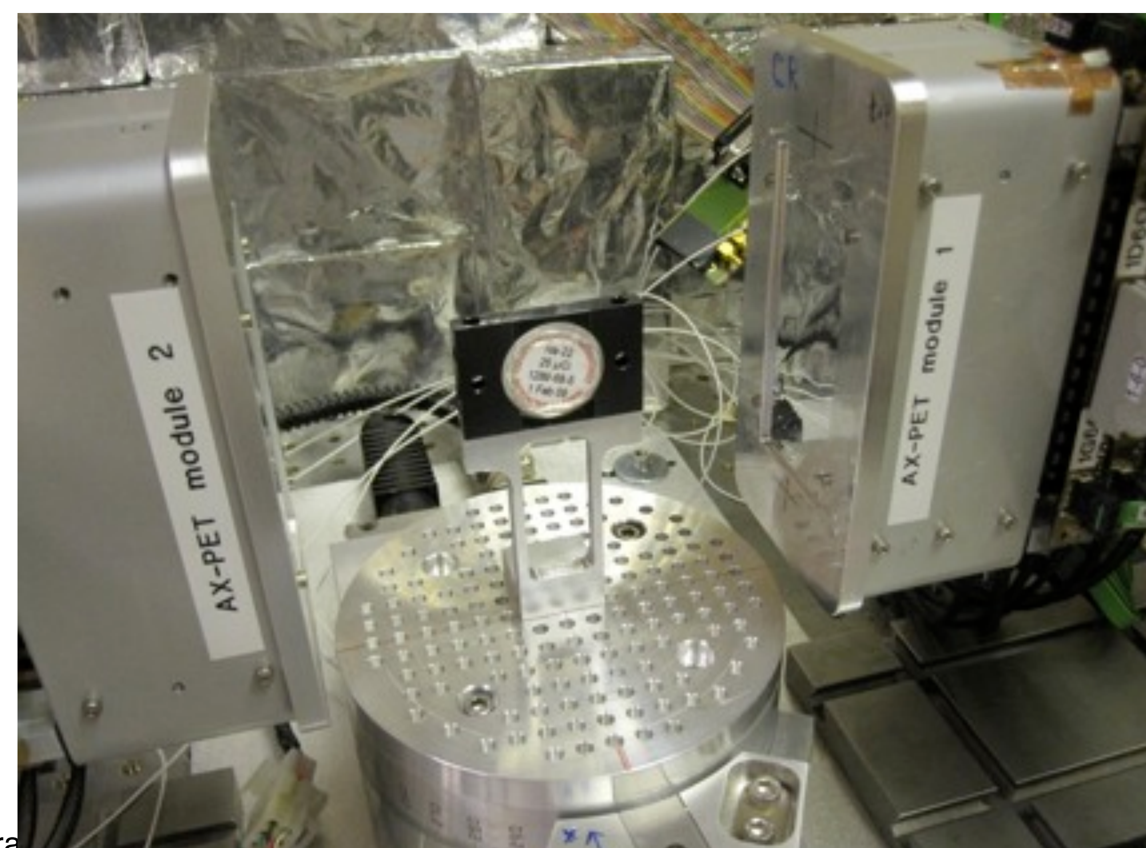

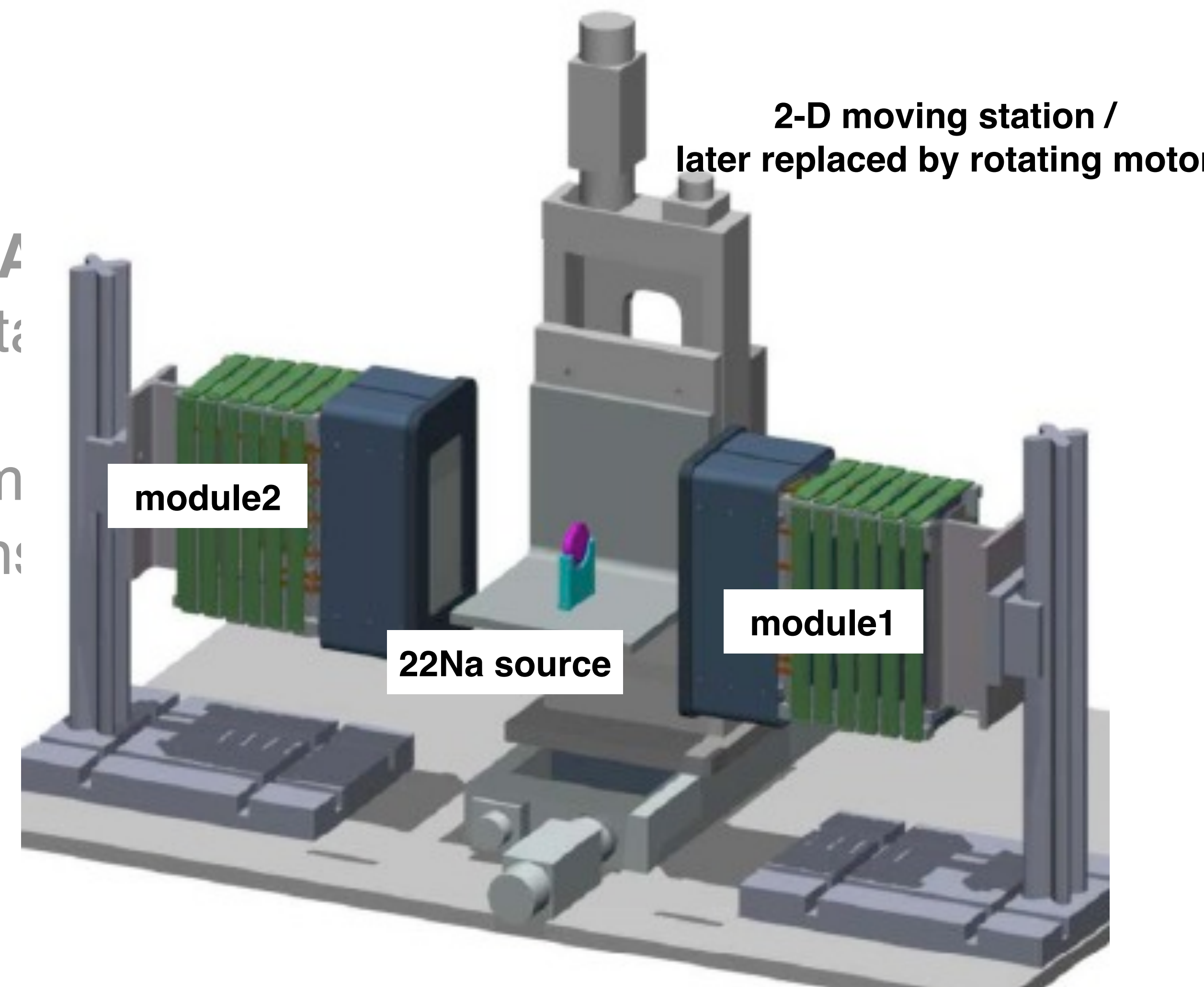

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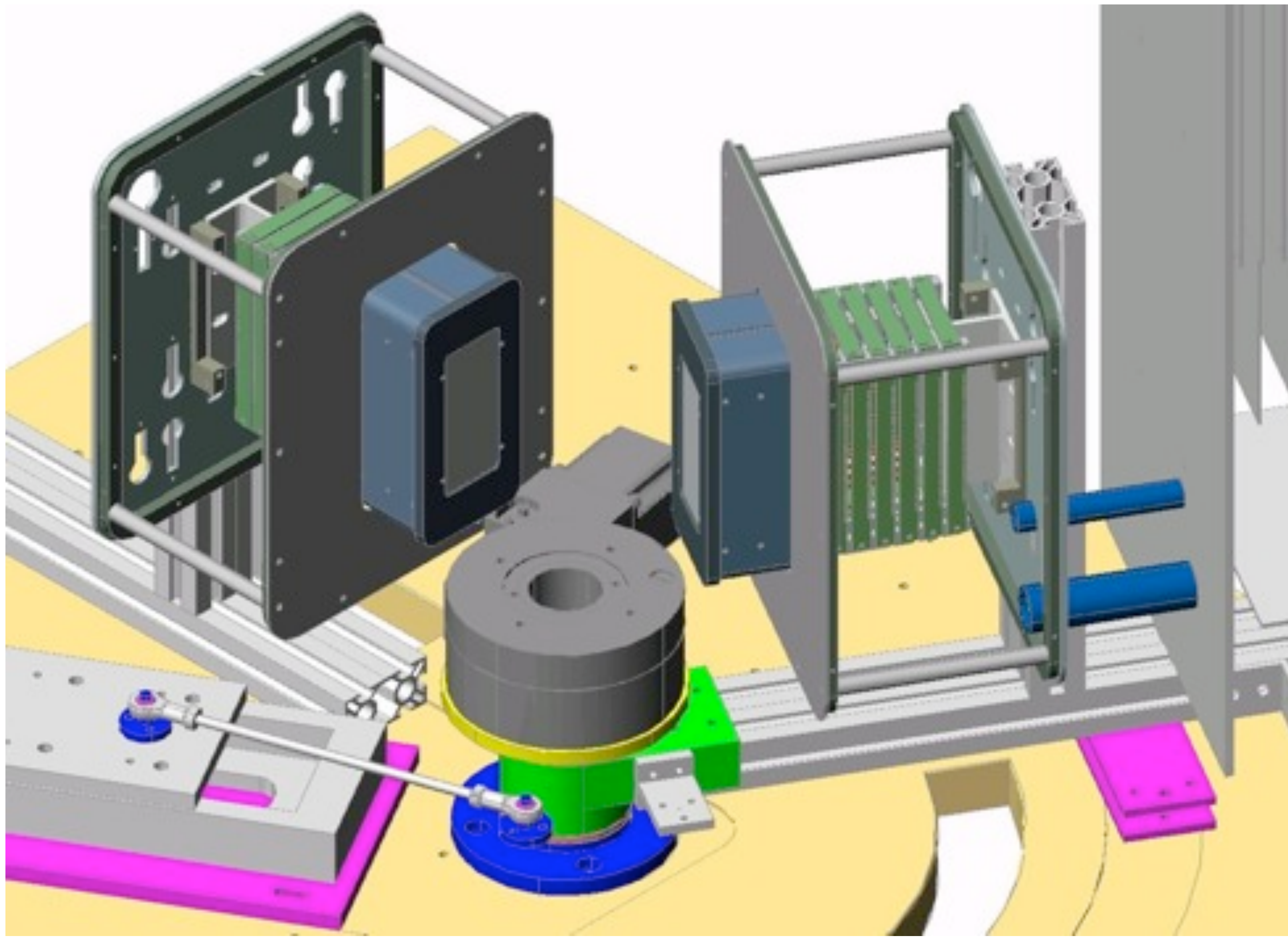

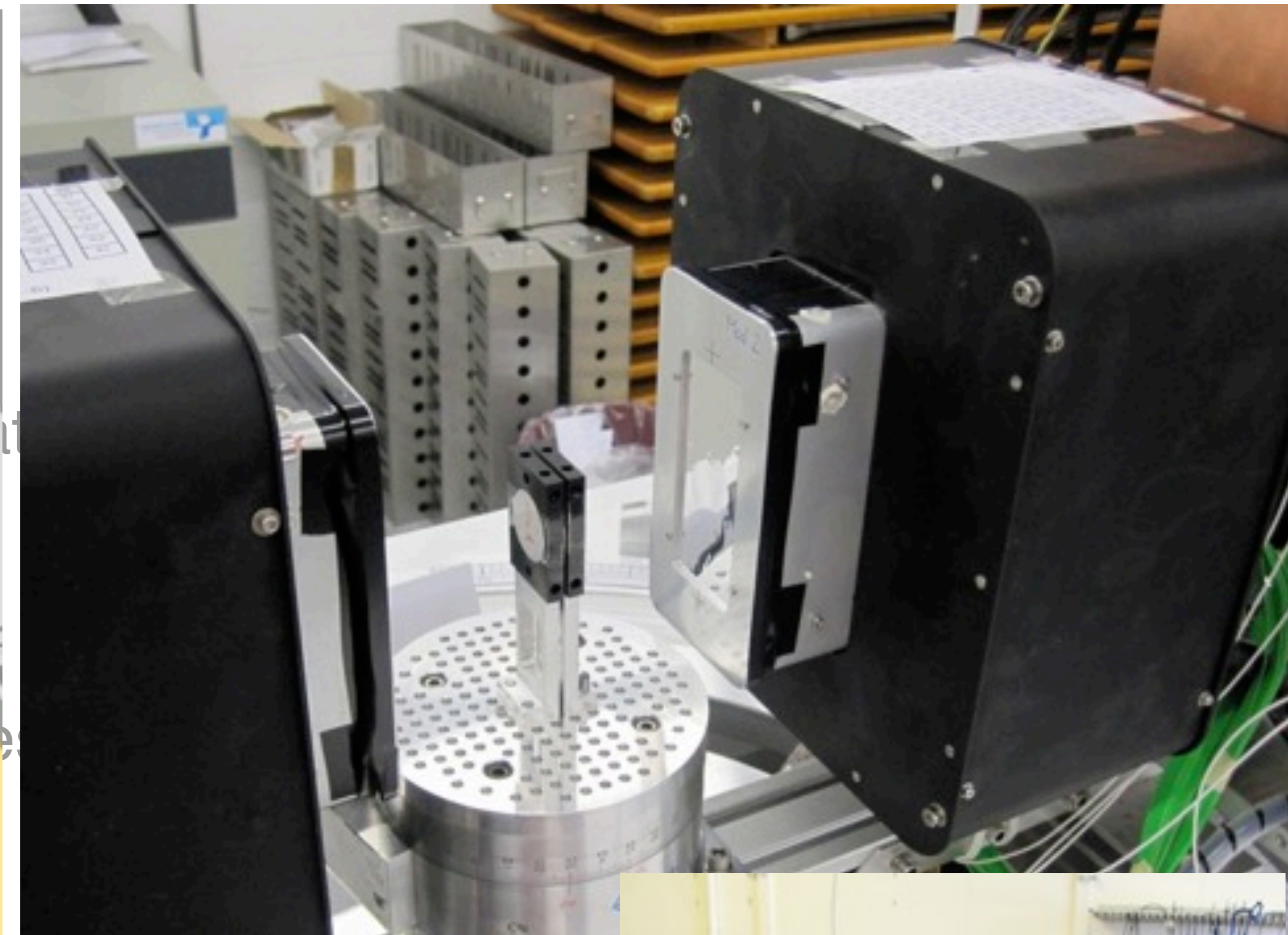

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- Two modules in coincidence with phantoms filled with 18F-radiot
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  - **20th - 30th April 2010**

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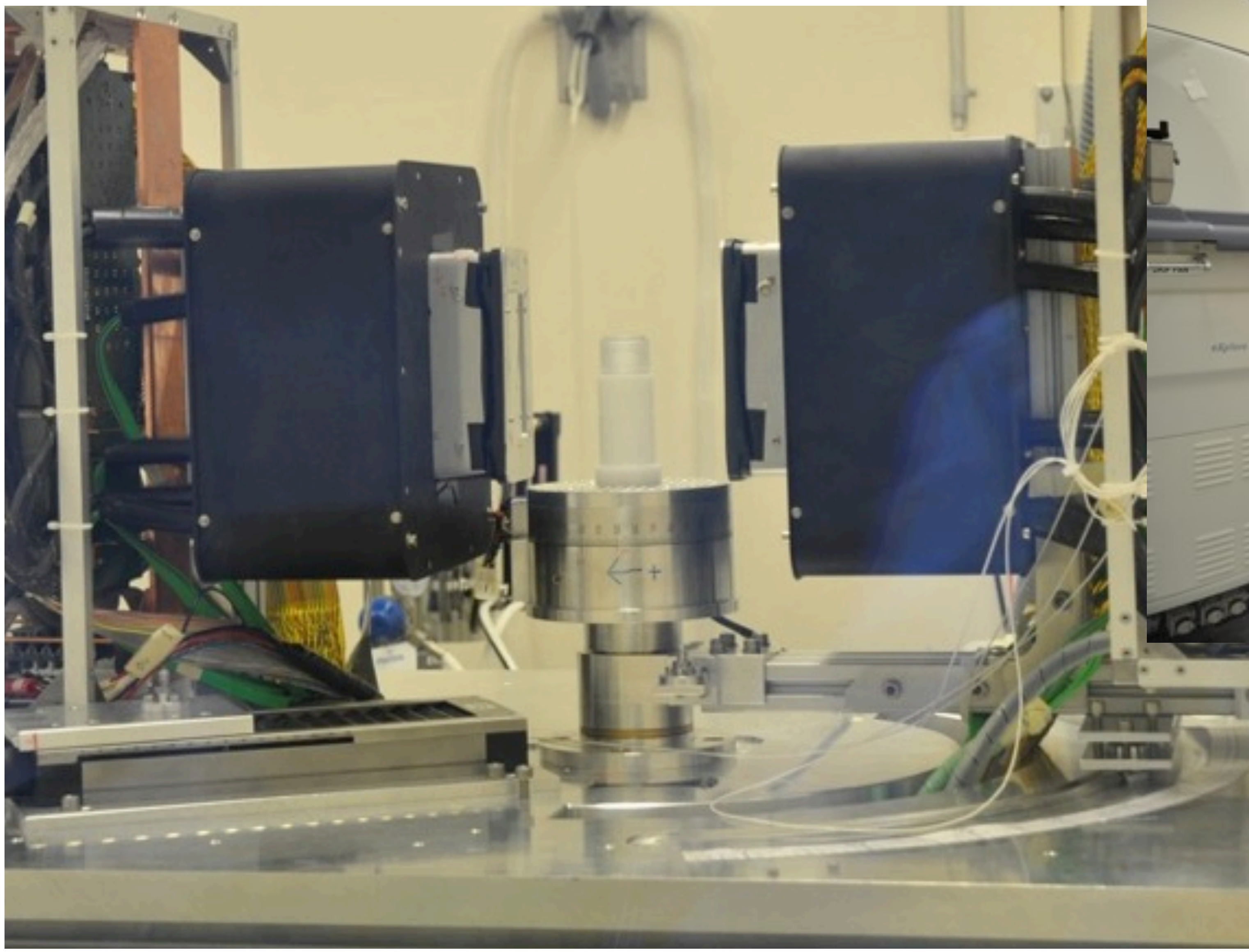

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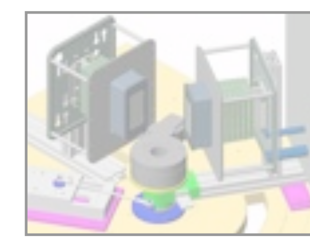

- Two modules in coincidence with phantoms filled with 18F-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute (Animal PET Lab)
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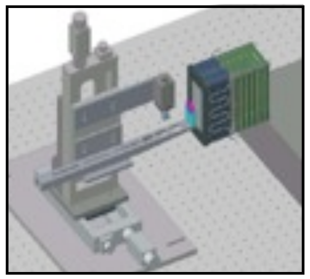

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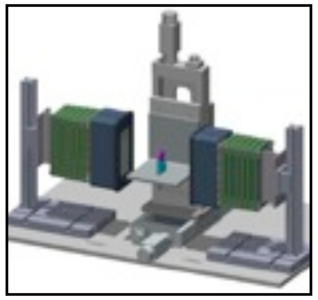

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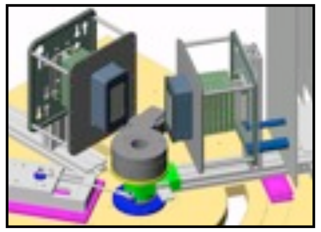

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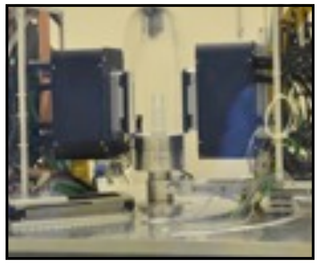

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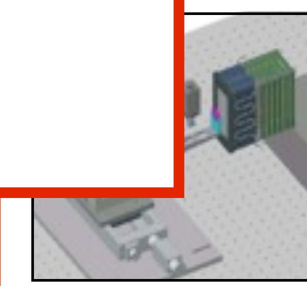
DETECTOR PERFORMANCE:
- energy resolution
- spatial (axial) resolution
- timing performance
- occupancy / multiplicities



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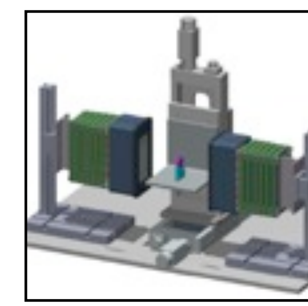

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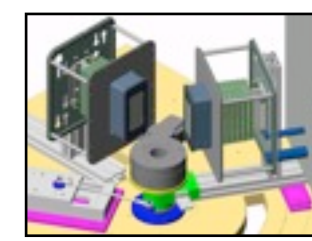

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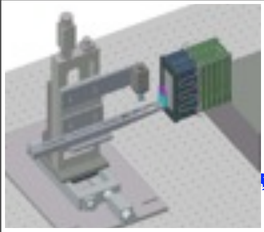
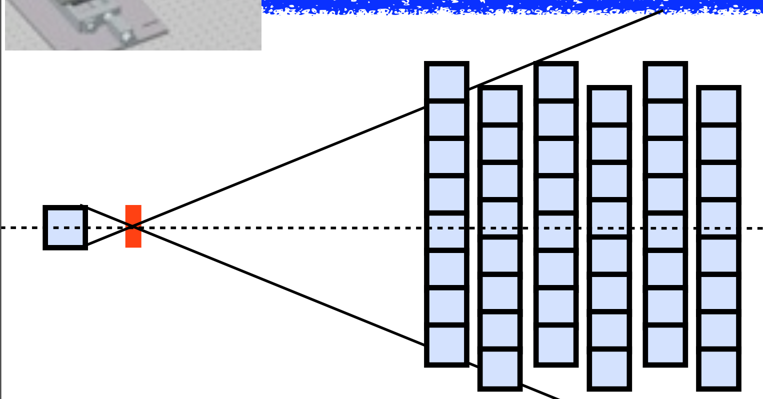
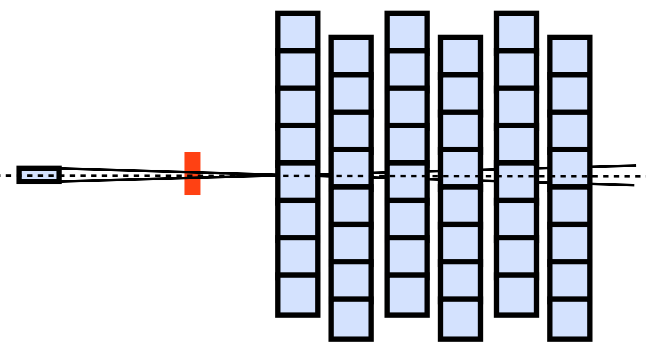
- image reconstruction
- very first results

Single module characterization

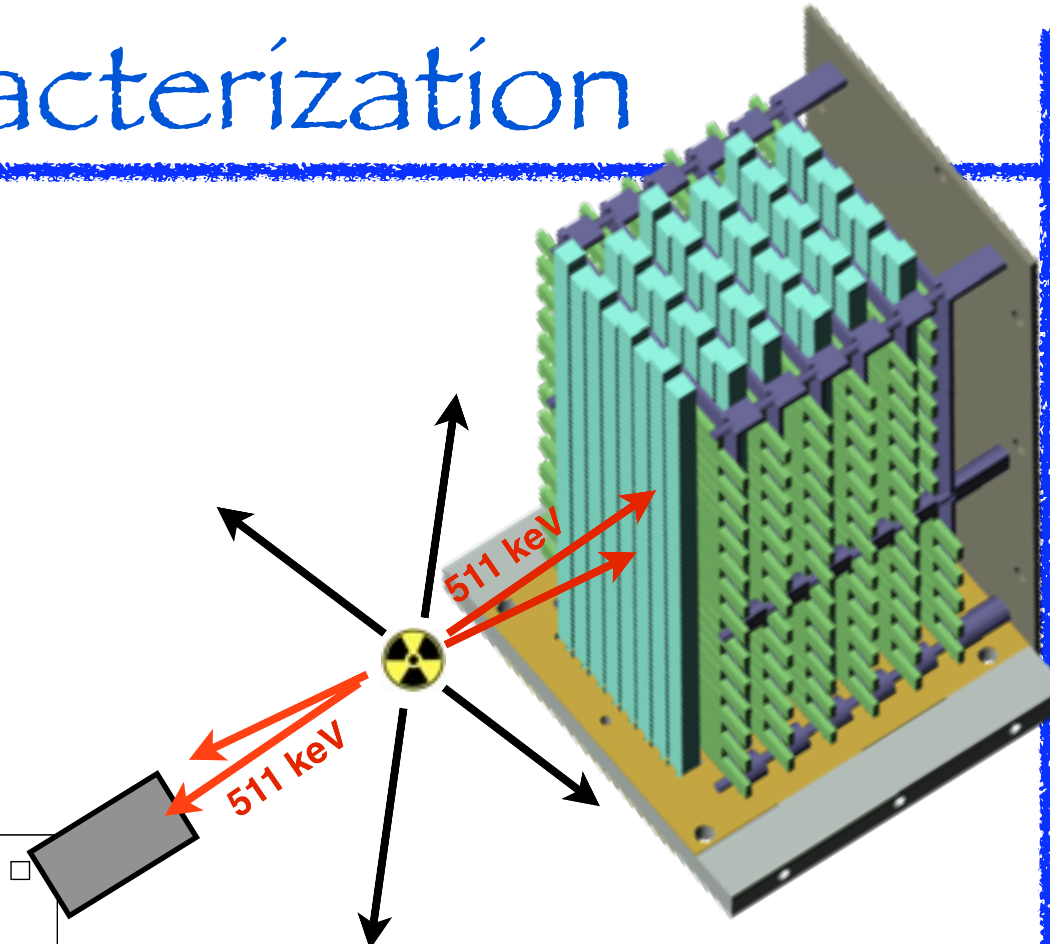


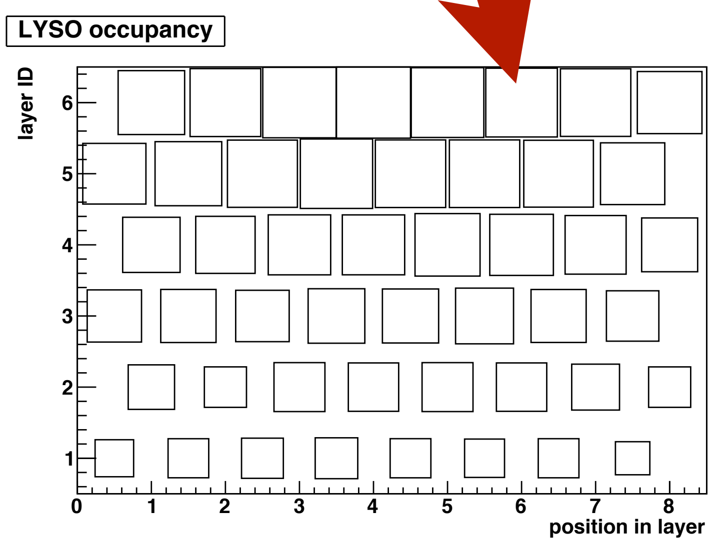


for energy calibration, energy resolution

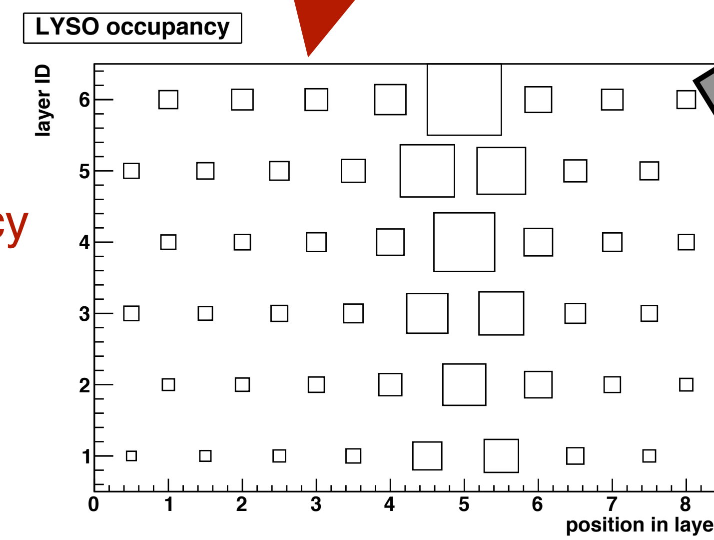


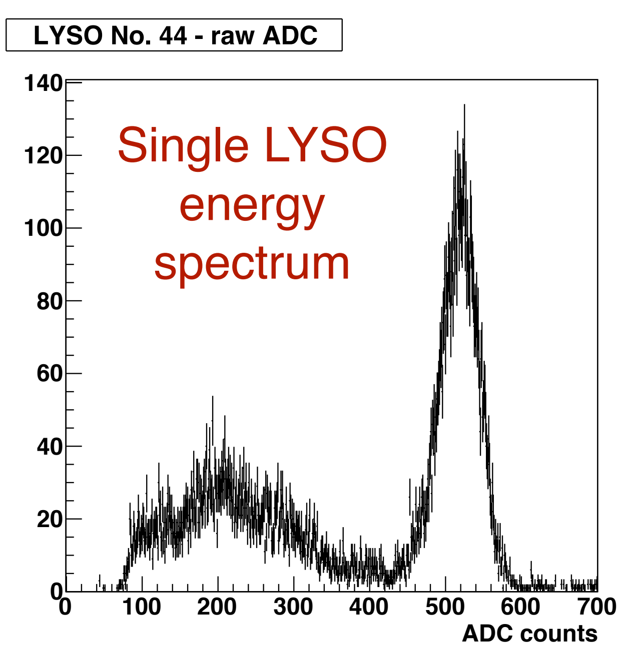
collimated beam spot, spatial resolution



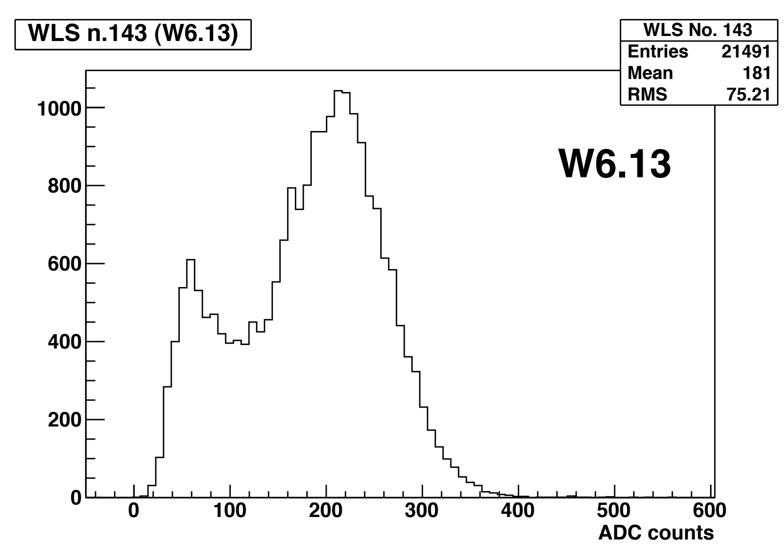


LYSO occupancy

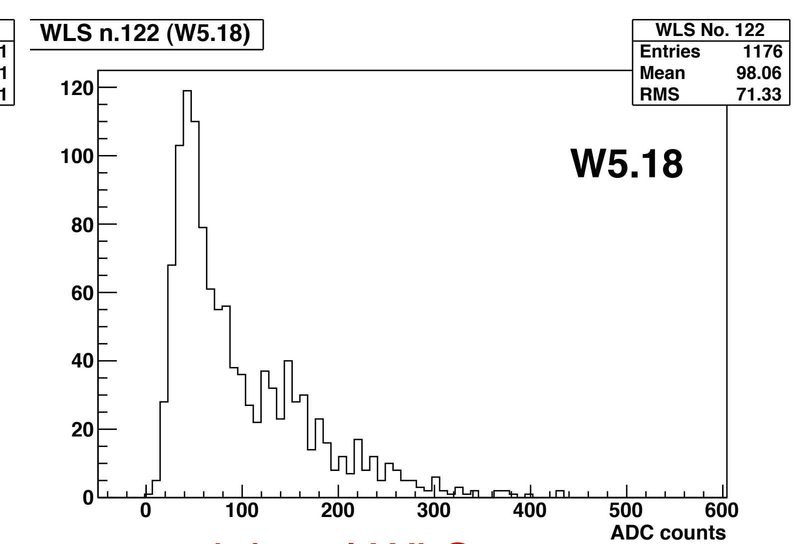




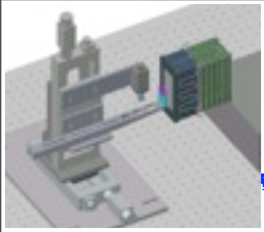
Single LYSO energy spectrum



central WLS spectrum

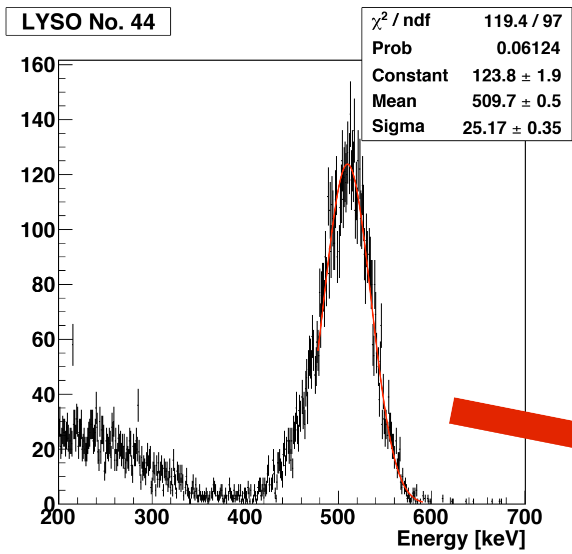


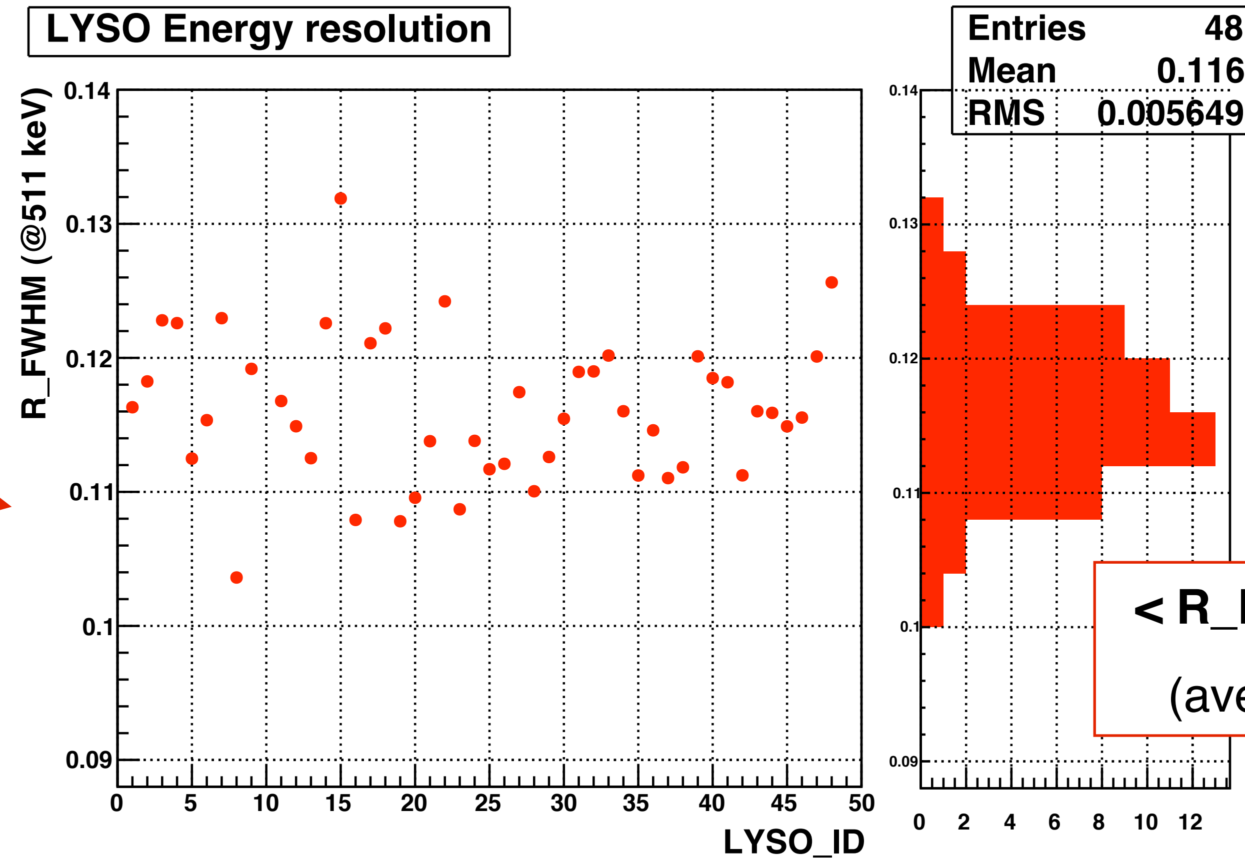
peripheral WLS spectrum



ENERGY RESOLUTION

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



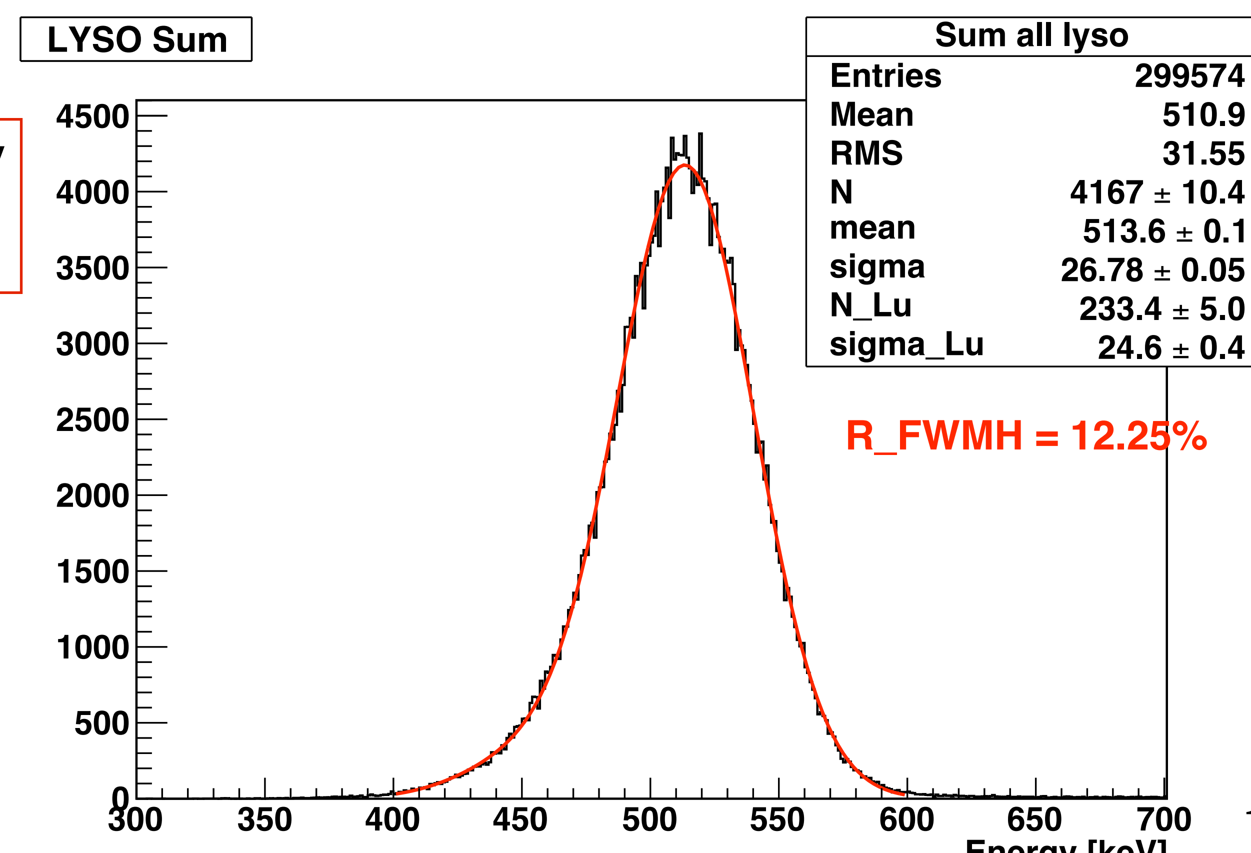


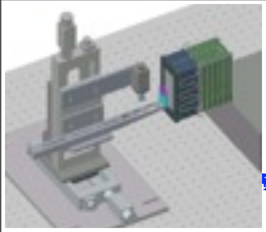
< R_FWHM > ~ 11.6% @511 keV

(averaged on 48 LYSO crystals)

R_FWHM_Sum ~ 12.25% at 511 keV

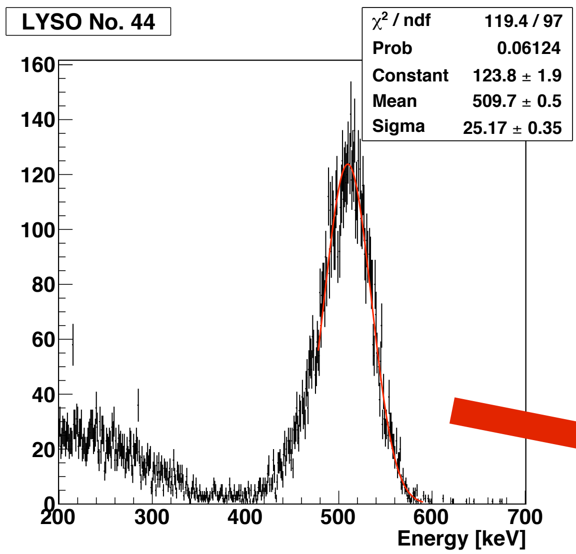
(on the summed distribution)

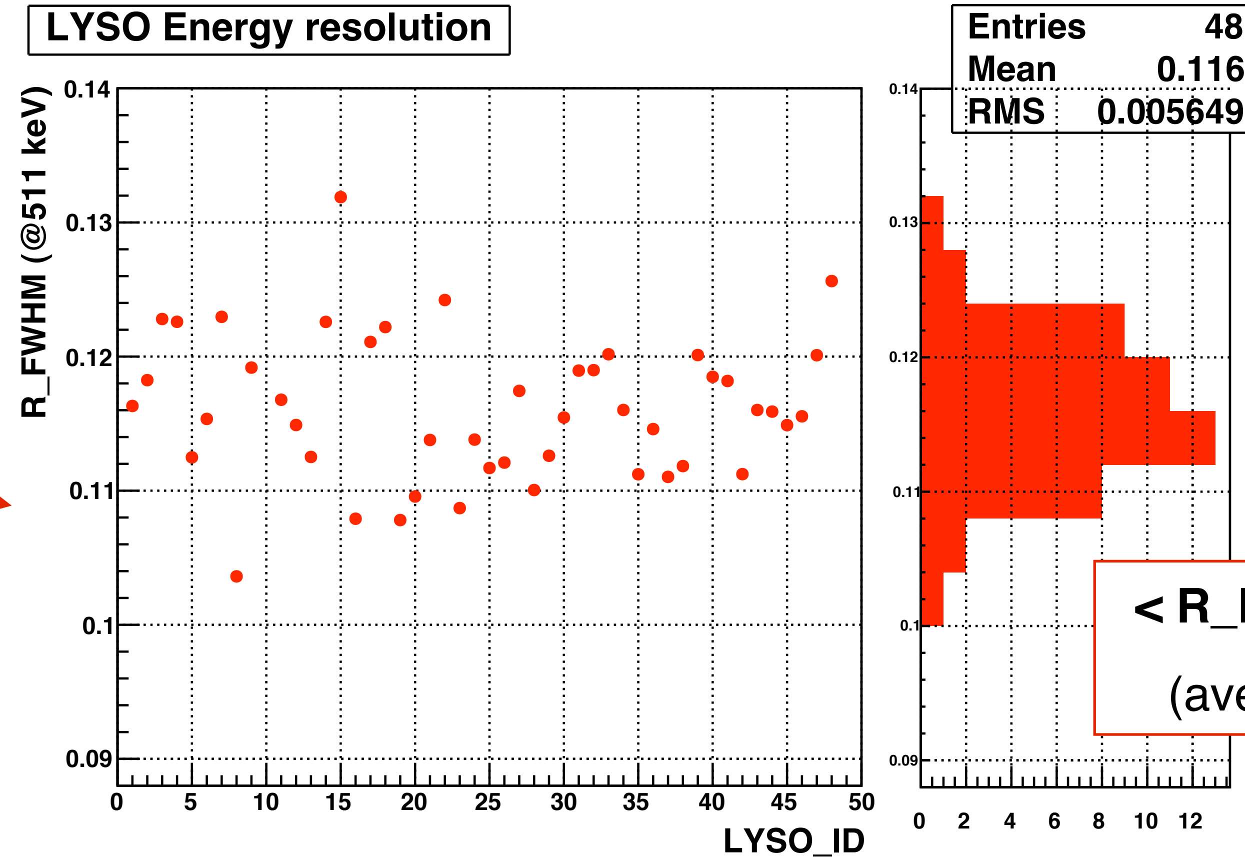




ENERGY RESOLUTION

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



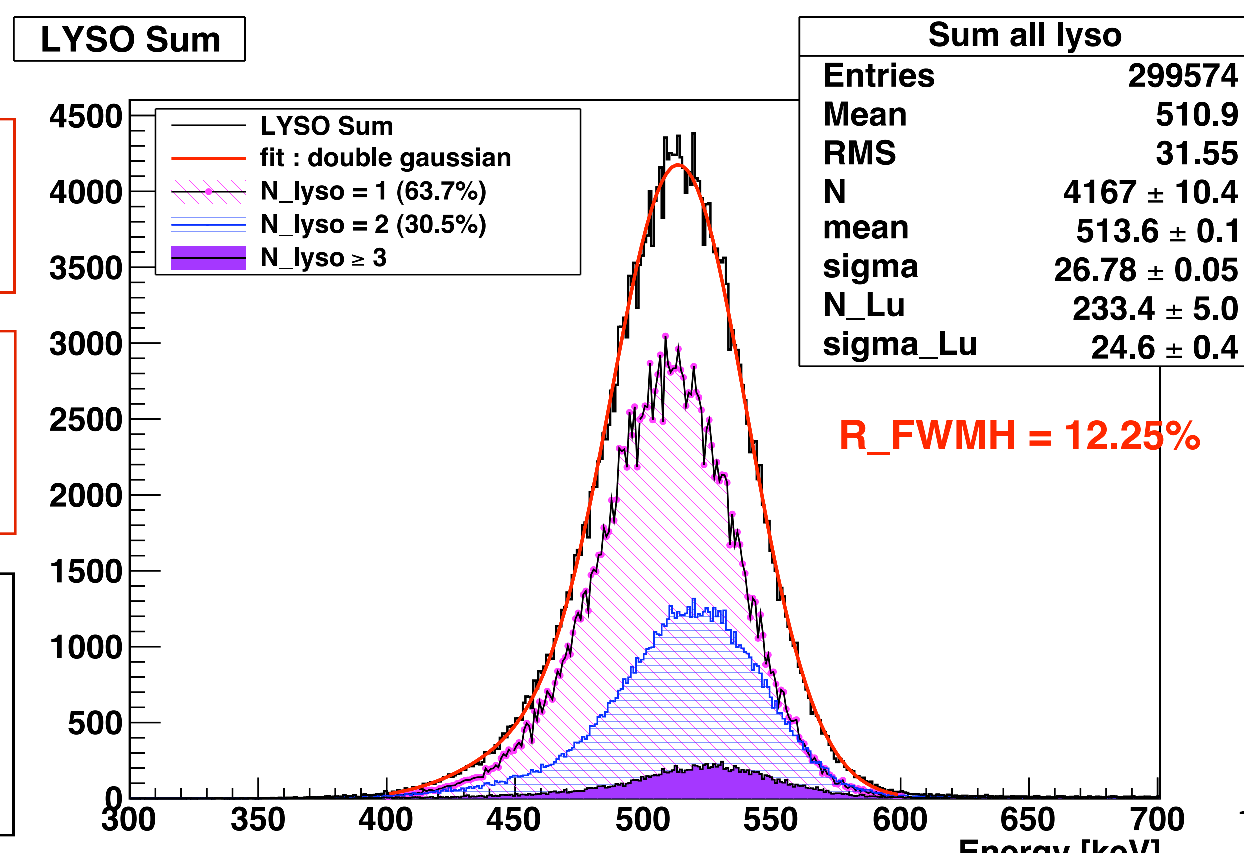


< R_FWHM > ~ 11.6% @511 keV

(averaged on 48 LYSO crystals)

R_FWHM_Sum ~ 12.25% at 511 keV

(on the summed distribution)

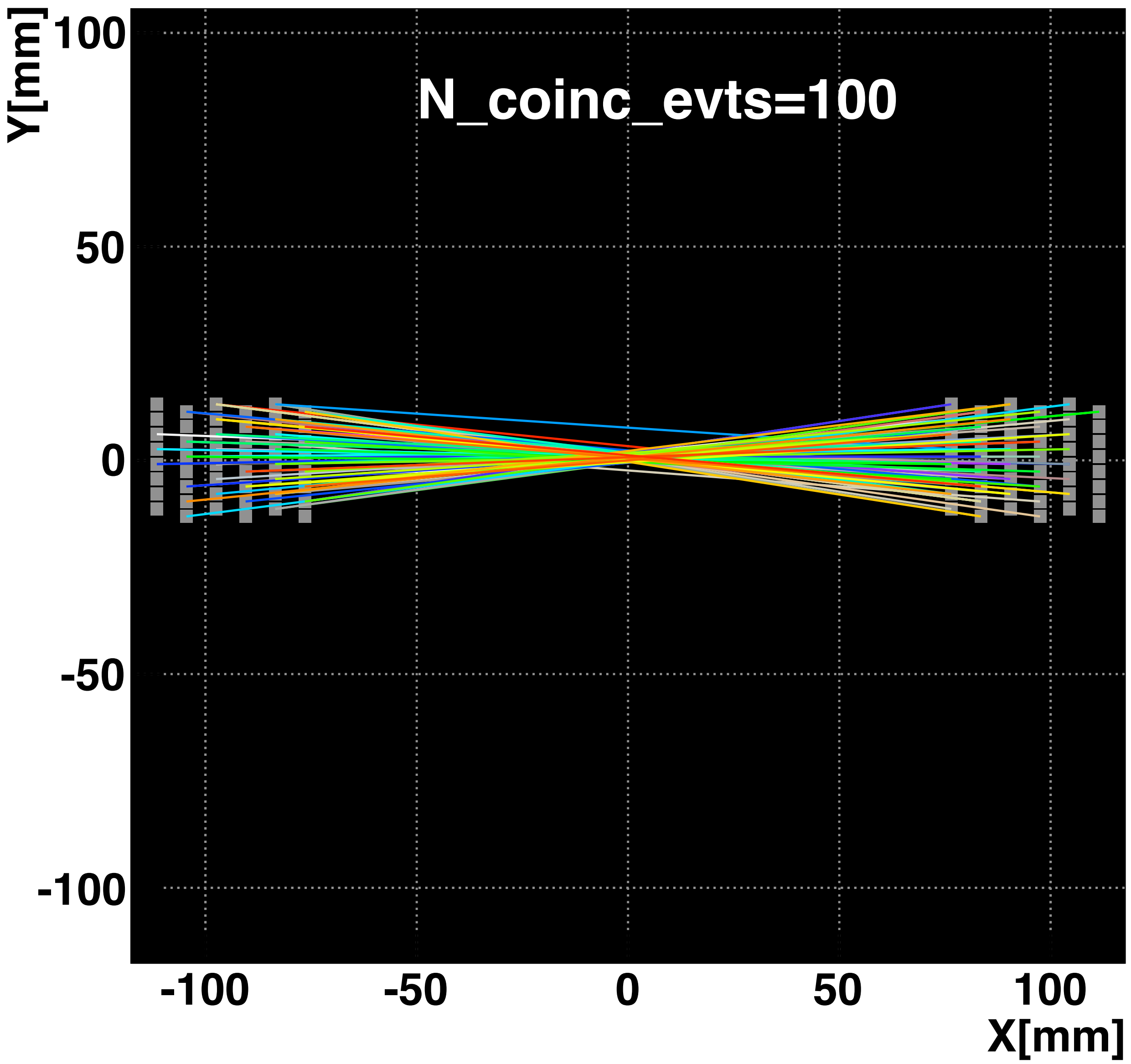


Typical LYSO MULTIPLICITIES (single module):
- **Prob (1LYSO) ~ 64%**
- **Prob (2LYSO) ~ 30%**

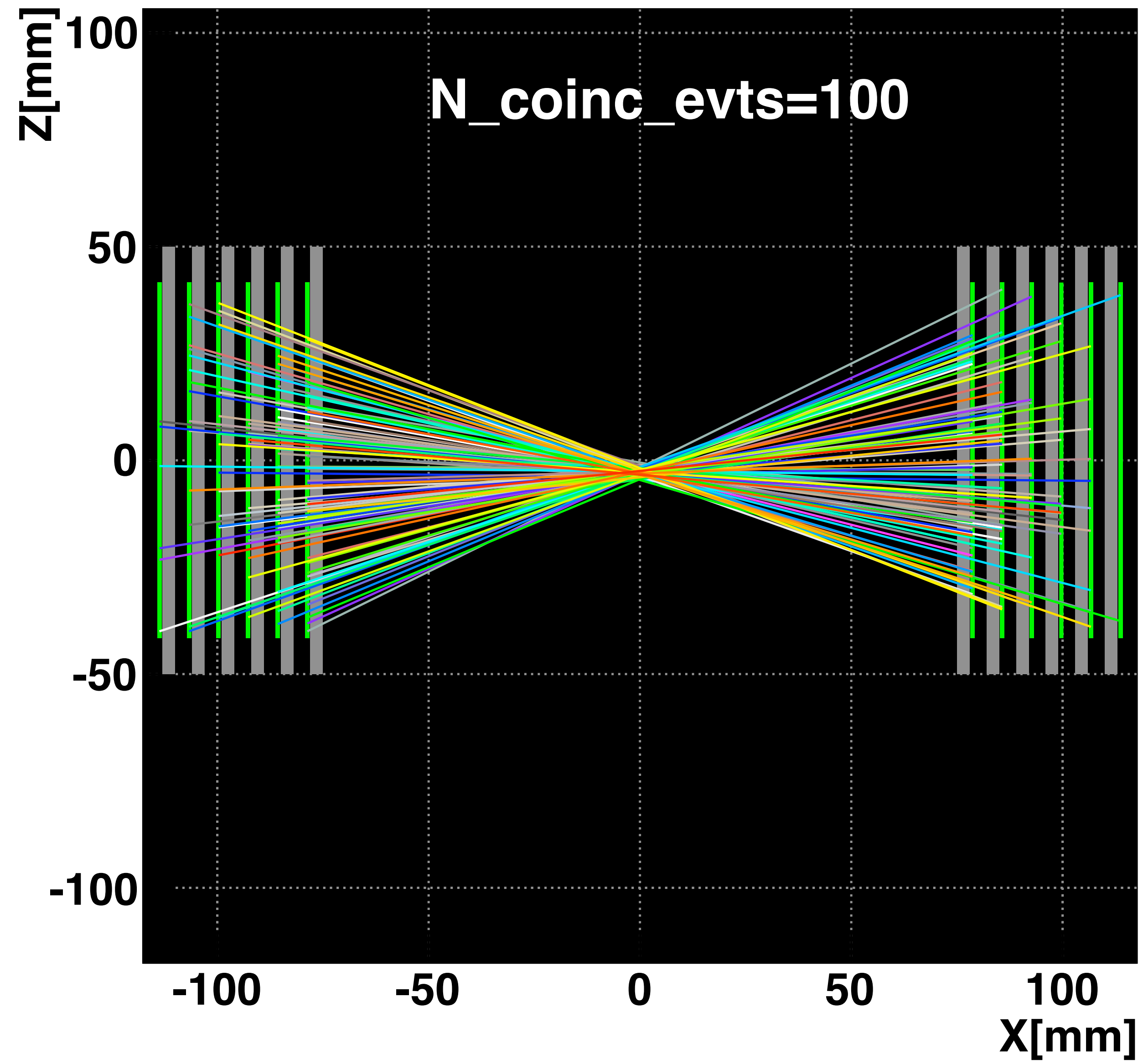
Typical LYSO MULTIPLICITIES - 2 MODS COINCIDENCES:
- **Prob (1LYSO-1LYSO "1-1") ~ 44%**
- **Prob (1LYSO-2LYSO "1-2" or "2-1") ~ 38%**
- **Prob (2LYSO-2LYSO "2-2") ~ 9%**

TWO MODULES COINCIDENCE

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



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

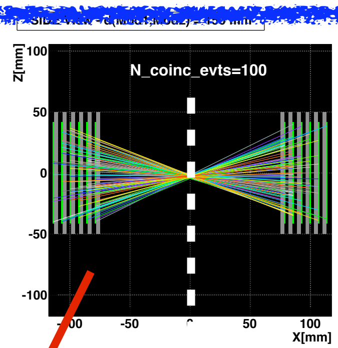


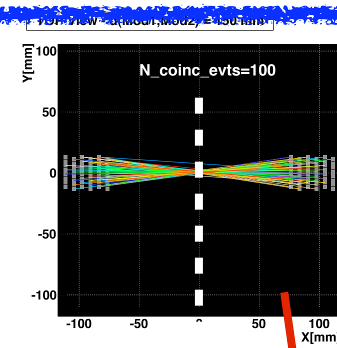
on scale!
[mm]

/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

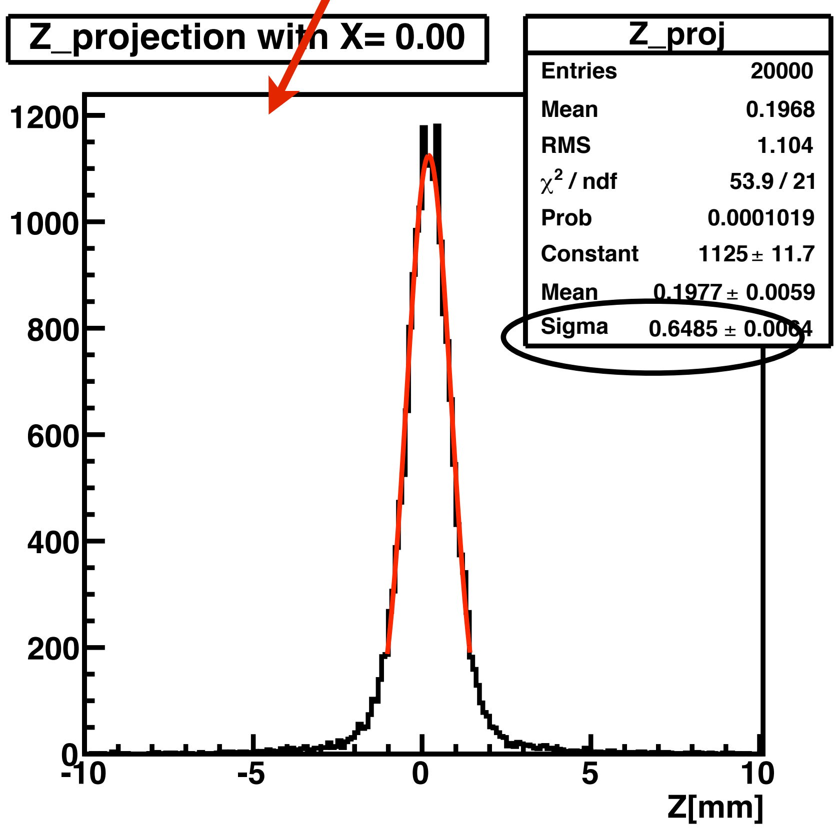
/home/daq/axpet/log/run02730.log INFO: Run Type: SPARSE readout
/home/daq/axpet/log/run02730.log INFO: Comment: Test_Mod1_AND_Mod2 Temp. 20.89 M1 - 21.05 M2

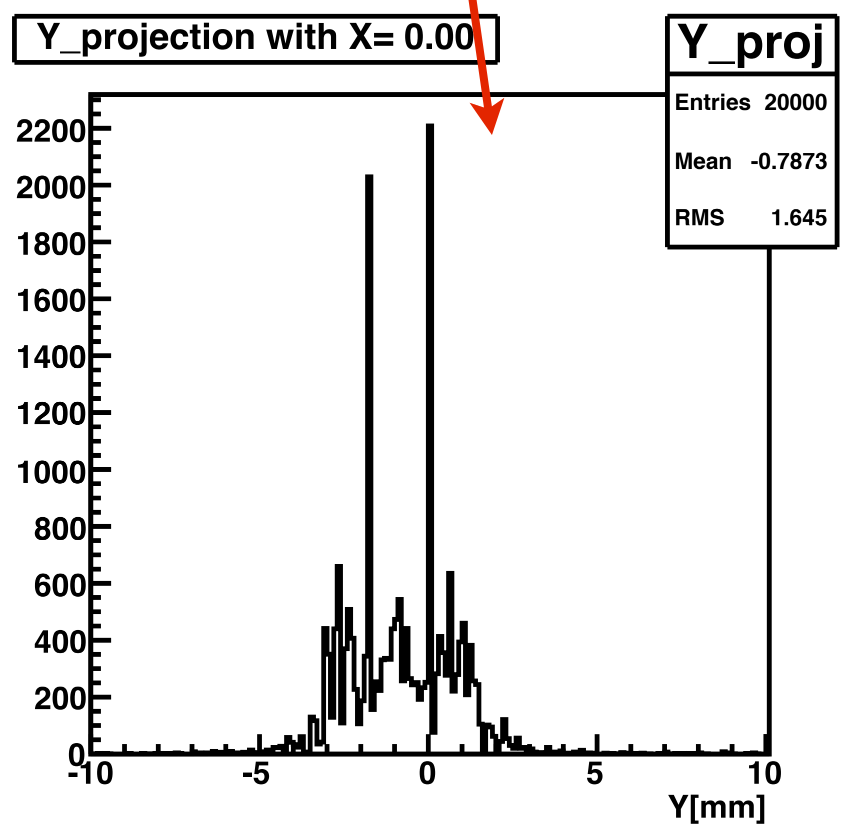
AXIAL RESOLUTION

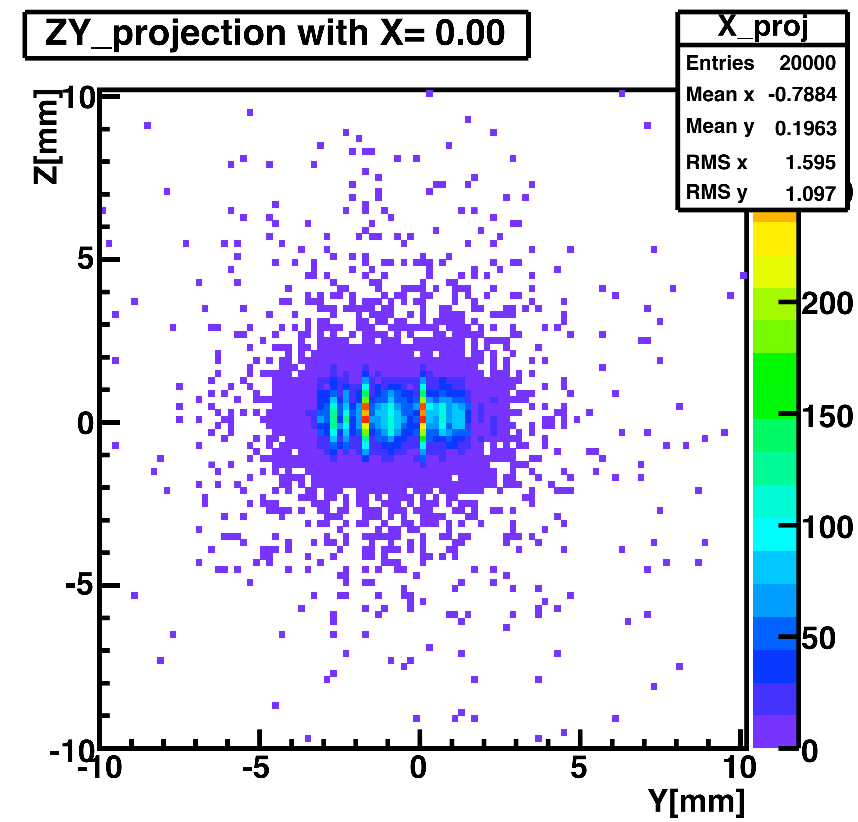




Intersection of LOR with central plane -- no tomographic reconstruction !!!







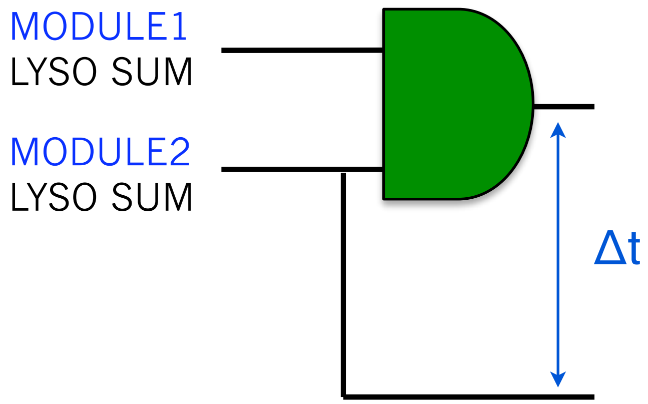
- $(R\_FWHM)_z$ ~ 1.5 mm
  - intrinsic resolution
  - positron range
  - non collinearity
  - (source dimensions ; ø=250µm)

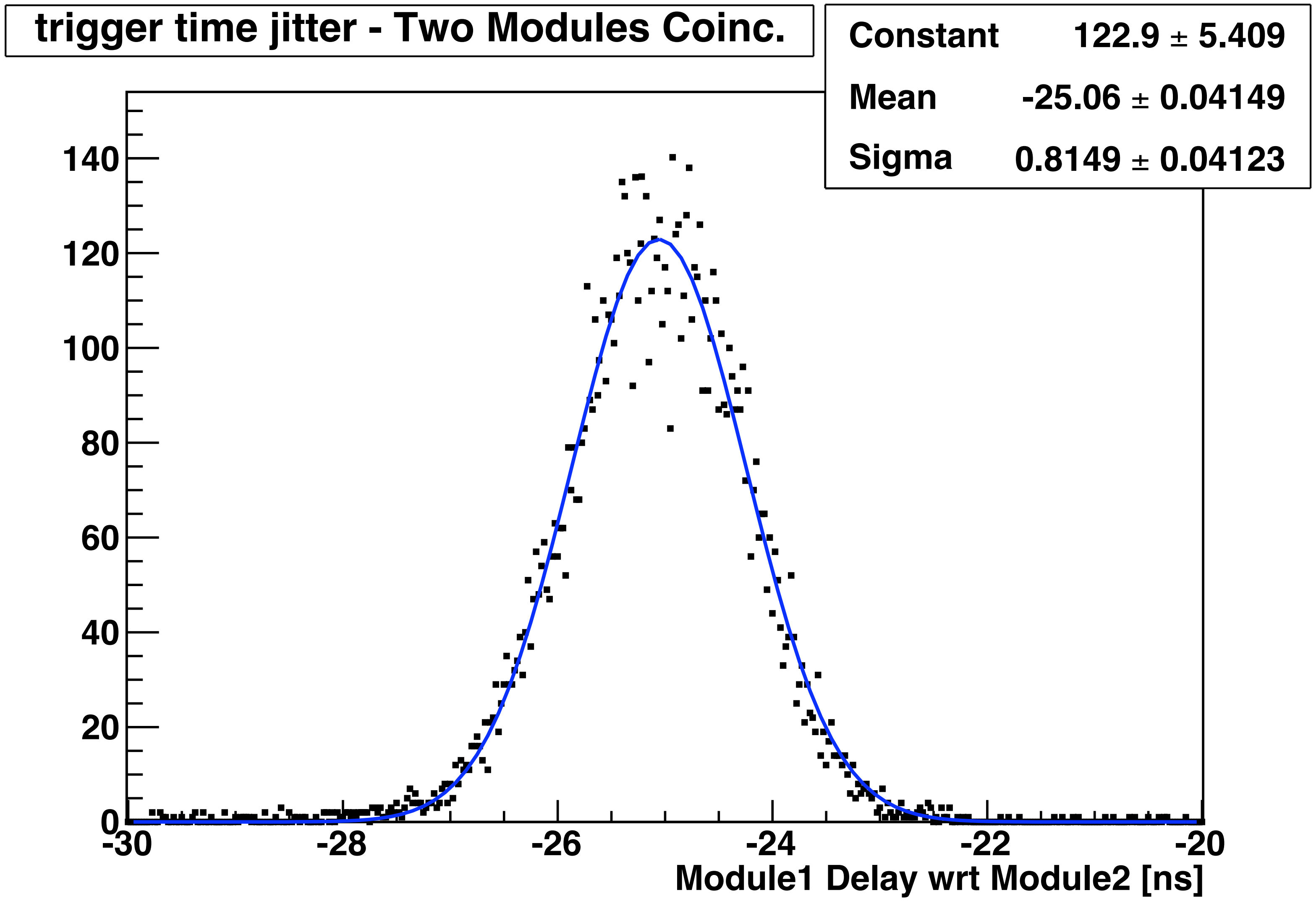
=> **$(R\_intrinsic\_FWHM)_z$ ~ 1.35 mm**

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

TIME RESOLUTION

- 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 : mini-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

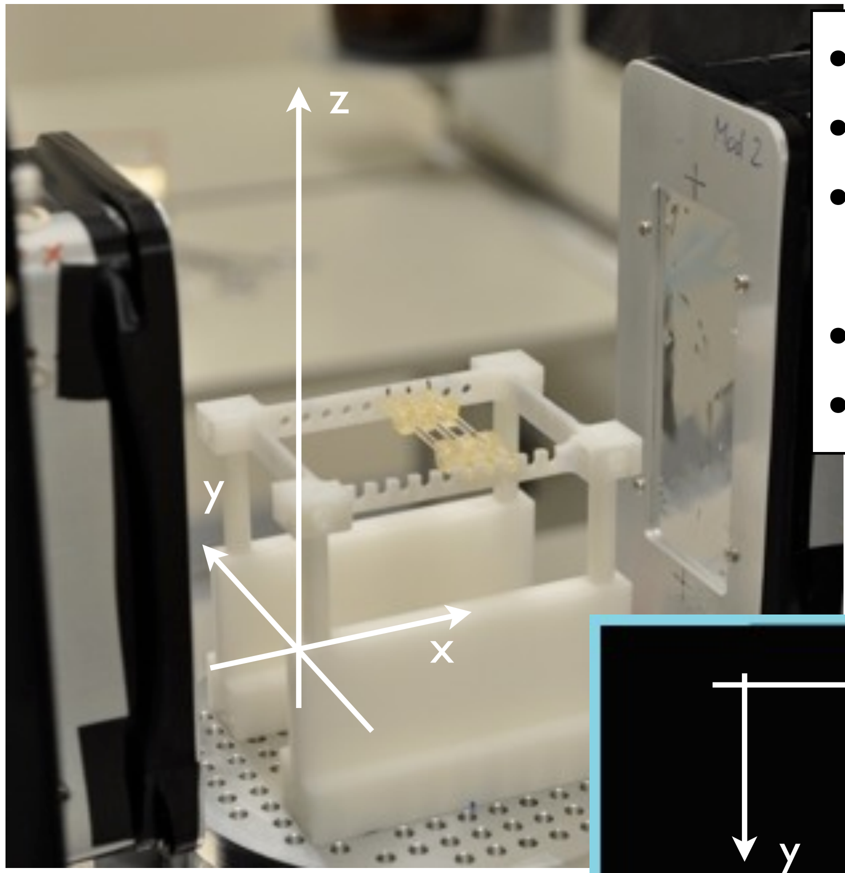
MEASUREMENTS GOALS :

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

WORKS IN PROGRESS

PRELIMINARY RESULTS !

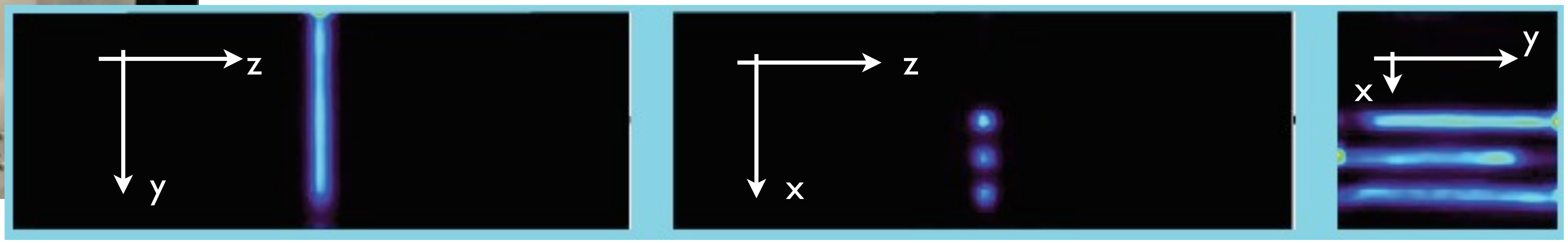
RECONSTRUCTED IMAGE : Capillaries (1)

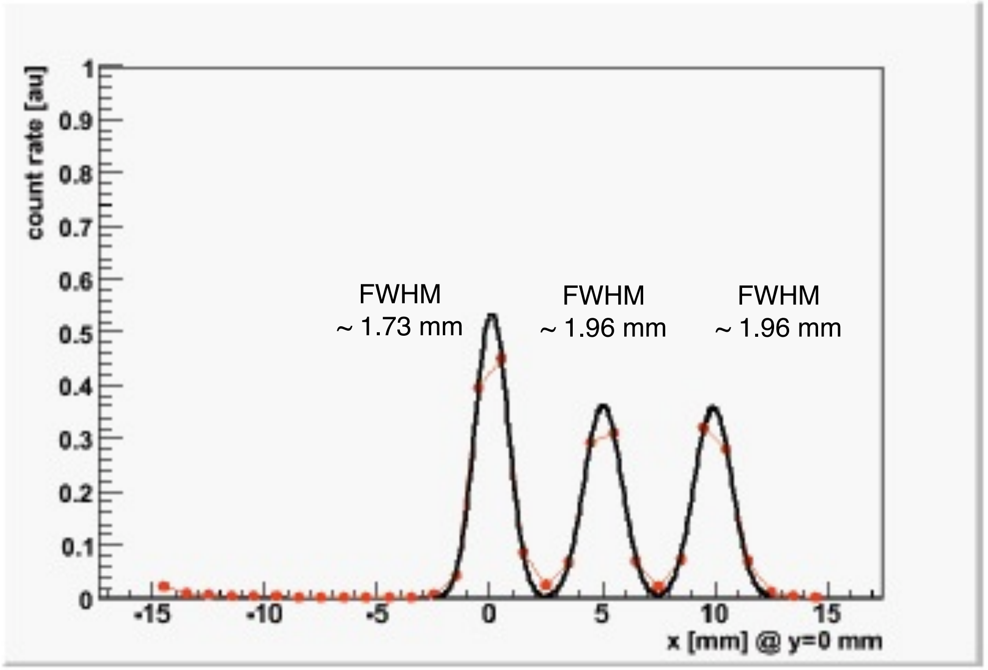


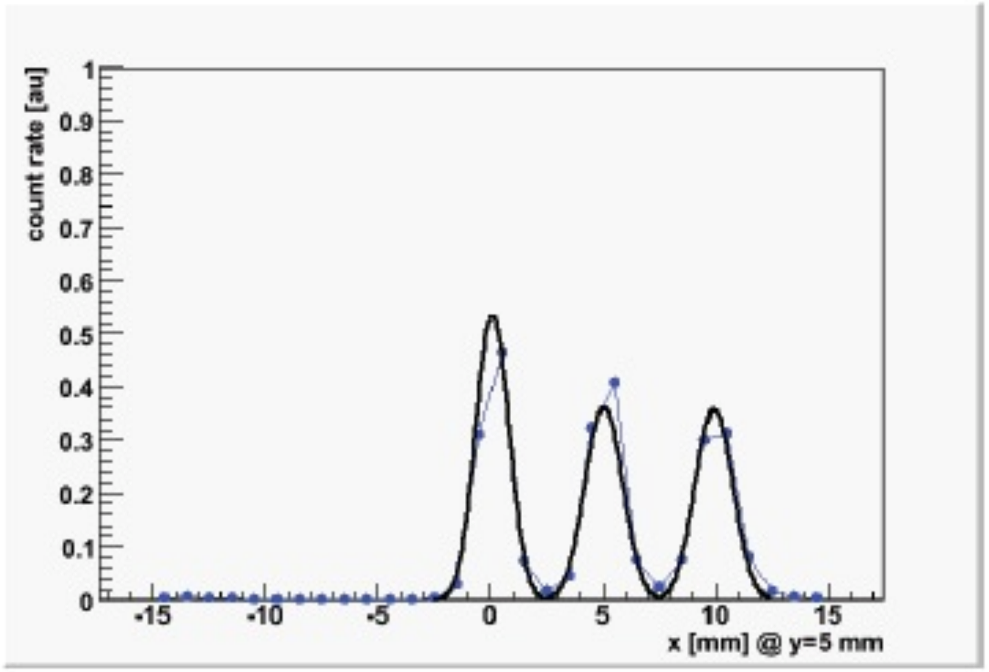
- phantom : 3 capillaries (// LYSO)
- capillaries (x3) : **L = 3cm** ; **Diam = 1.4 mm** ; **Pitch = 5 mm**
- 17 positions of the phantom, θ in [0˚,170˚]

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

preliminar!!!

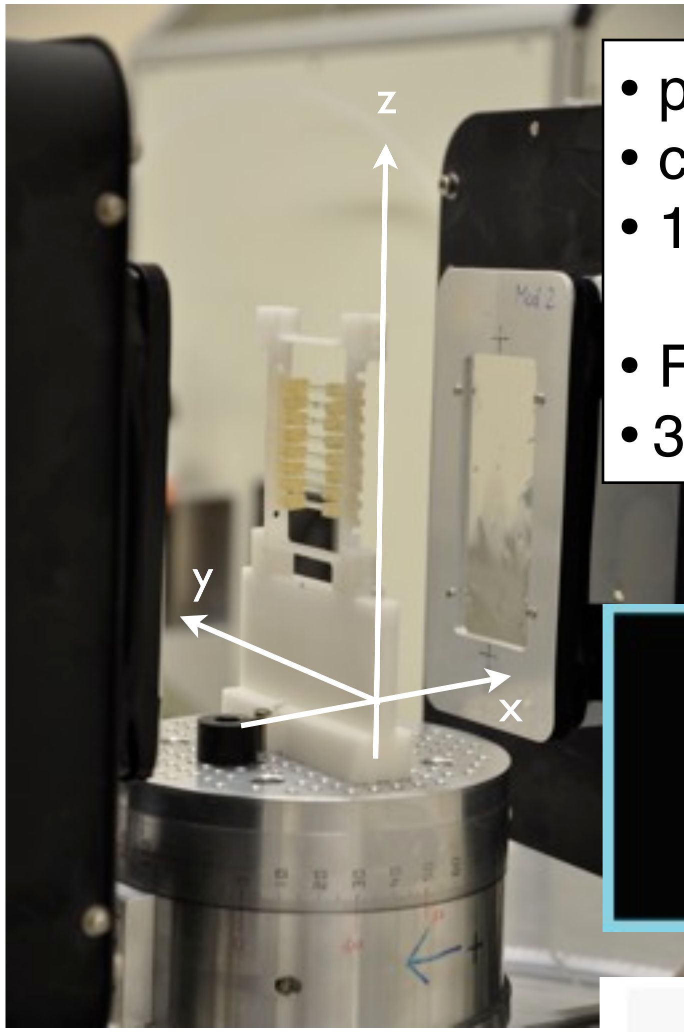






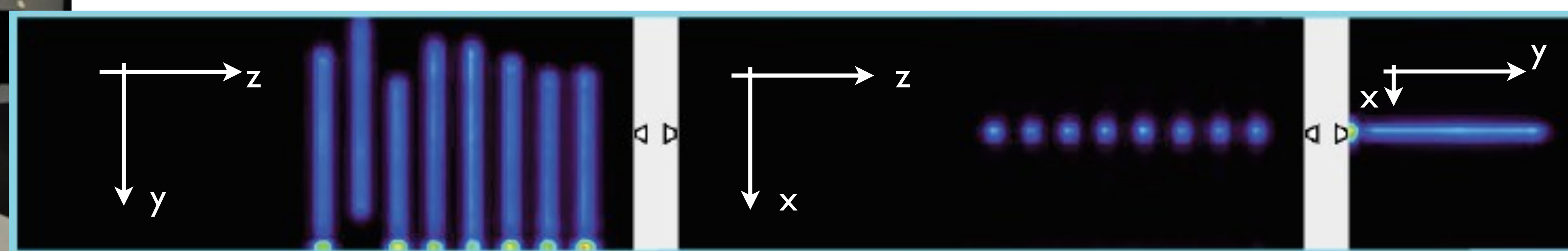
RECONSTRUCTED IMAGE : Capillaries (2)

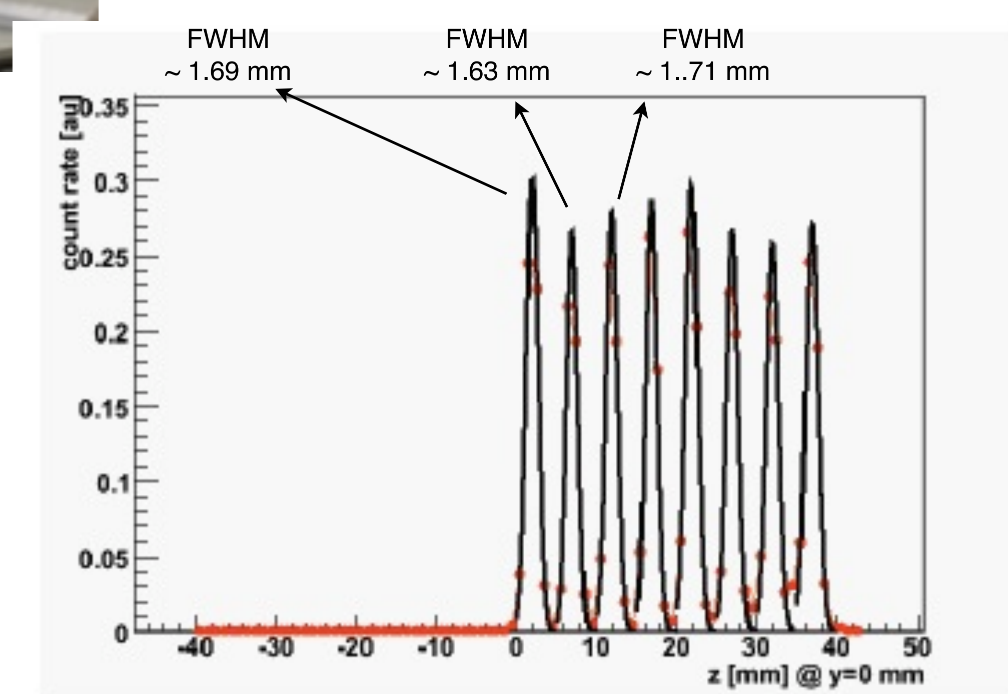
preliminar!!!

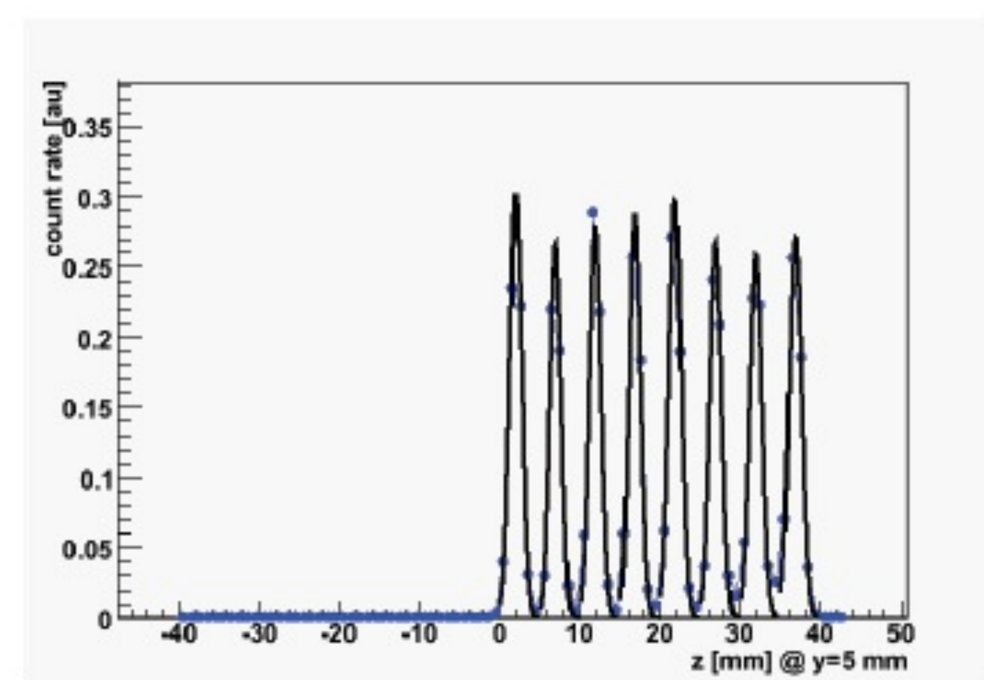


- phantom : 8 capillaries (// WLS)
- capillaries (x8) : **L = 3cm** ; **Diam = 1.4 mm** ; **Pitch = 5 mm**
- 17 positions of the phantom, θ in [0˚,170˚]

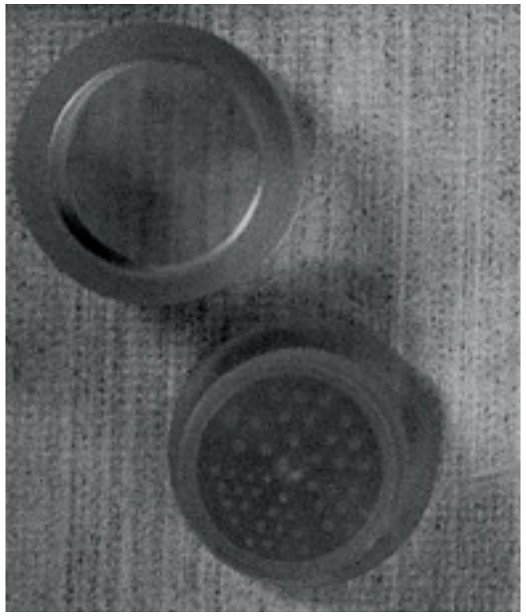
- FOV : 30 x 30 x 83 vox^3 = 30 x 30 x 83 mm^3
- 30 iterations







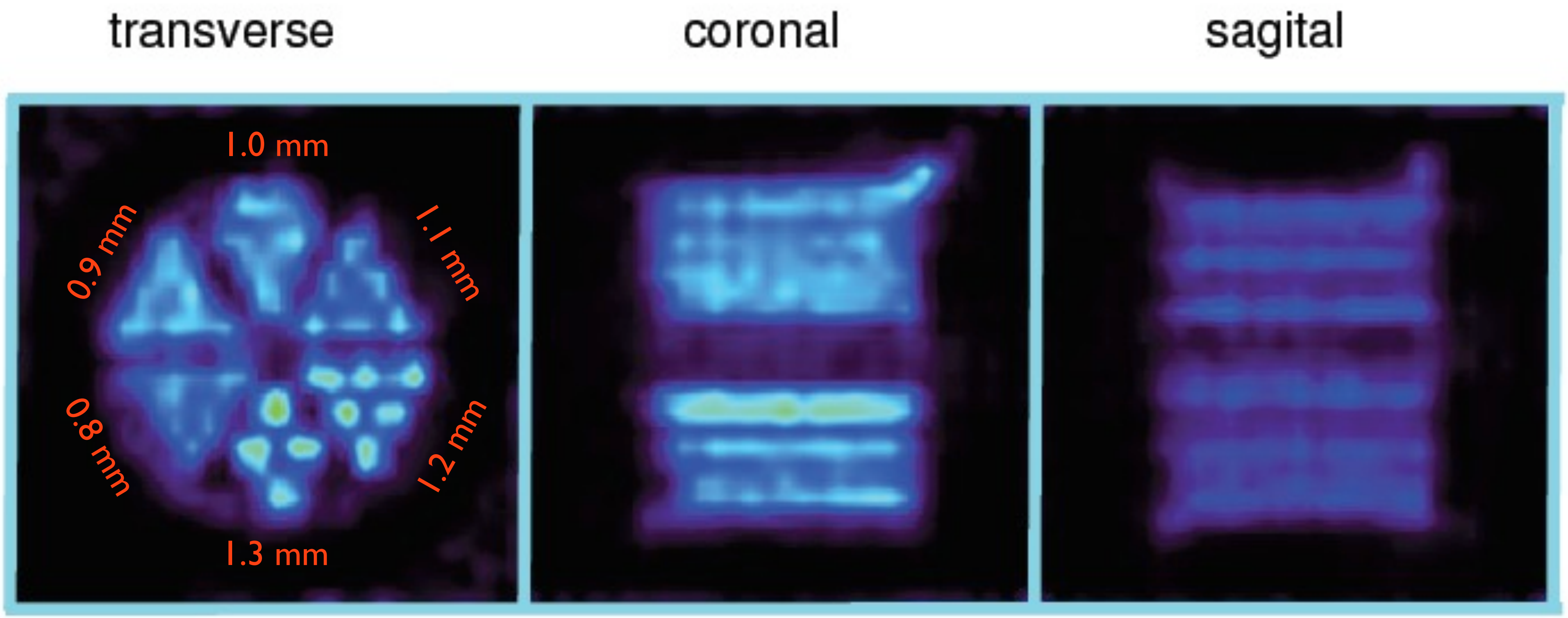
RECONSTRUCTED IMAGE : mini-Derenzo



- phantom : micro Derenzo
- L= 1.5 cm; ø = 2 cm; ø_rods = [0.8,1.3] mm
- **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

very 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 / resolution now decoupled and not competing
  - 3D reconstruction of photon interaction points
  - DOI (Depth Of Interaction) measurement => Parallax-free system
  - Resolution / Sensitivity tunable with granularity and nr. layers
- versatile concept, that can be scaled in size and nr layers to match specific needs (small animal PET, brain PET, PEM...)
- possible compatibility with MRI
- possibility to reconstruct the ICS (Inter Crystal Scattering) => Enhance sensitivity and resolution

Assessed performance

(1) as detector

In dedicated test benches, single module characterization & 2 mods coincidences

- good energy resolution
  R_FWHM : 11.6 % (@511 keV)
- good **time resolution :**
  $\Delta t \sim 1.9$ ns FWHM
- good **intrinsic spatial resolution :**
  R_RWHM ~ 1.35 mm

(2) as imaging device

First measurements with extended objects, with ^{18}F-FDG (phantoms)

- first reconstructed images
- image reconstr. sw successfully tested
- very promising (still preliminary) results
- competitive performance with state of the art PET scanners

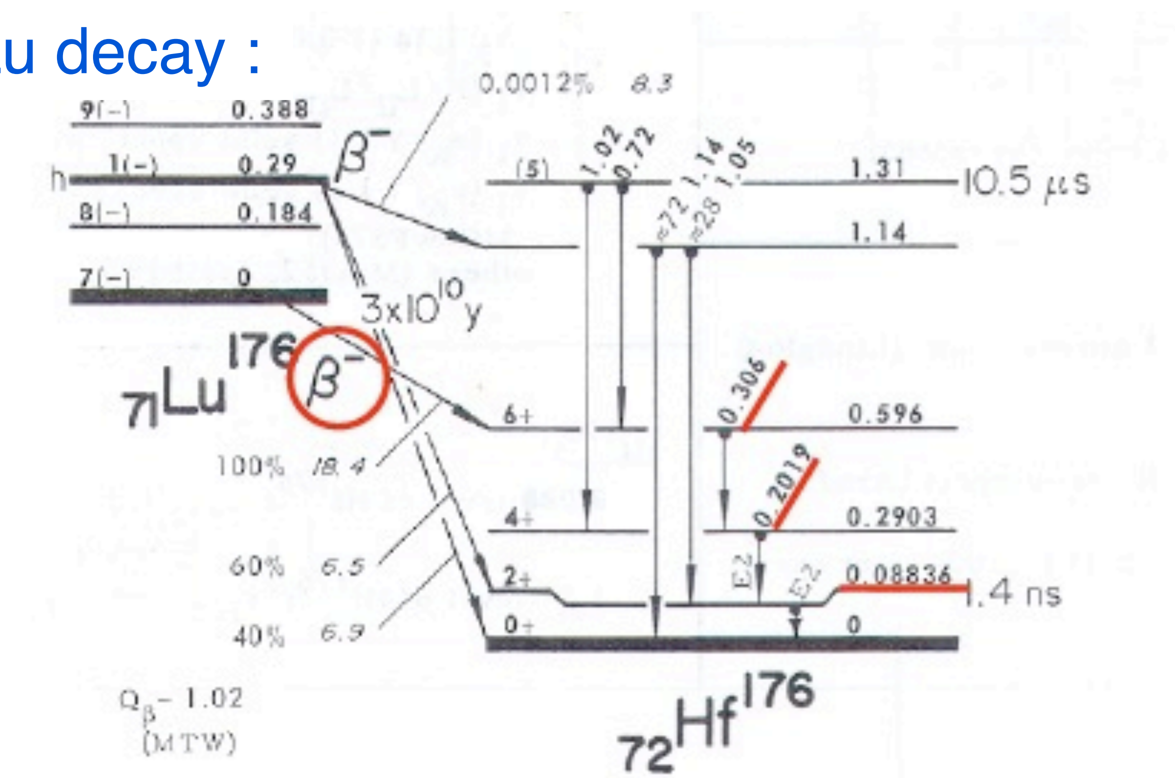
Still to do...

- 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

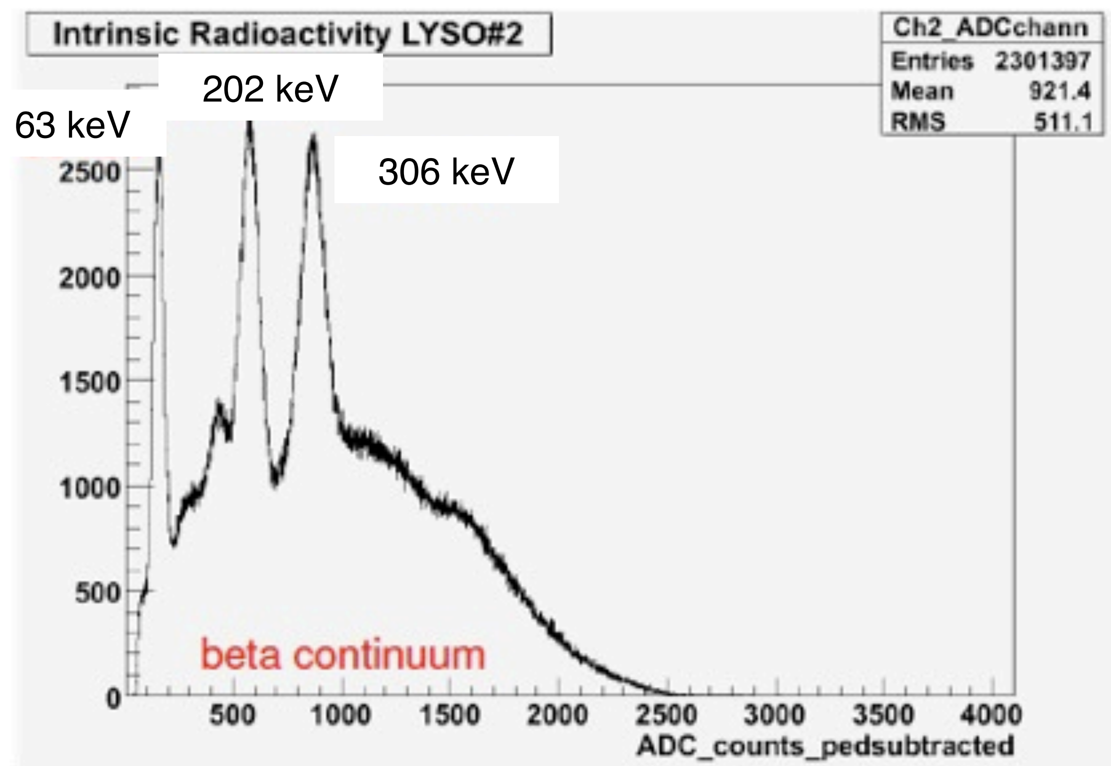
LYSO intrinsic radioactivity

Lu decay :



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

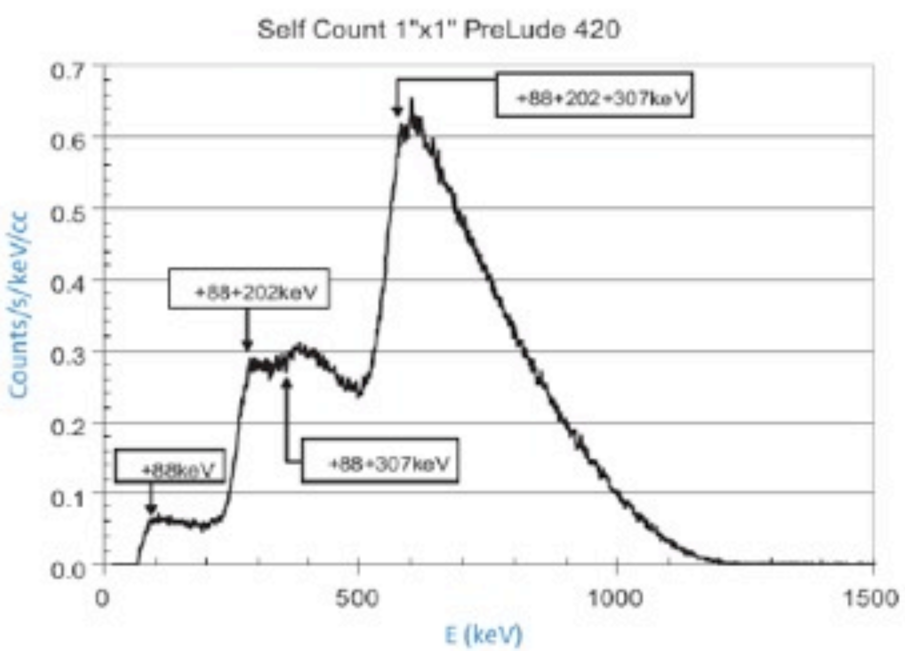
- one LYSO crystal only INSIDE THE MATRIX
- self trigger (low threshold) on this crystal



- 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

from Saint Gobain Prelude 420 spec sheet:

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

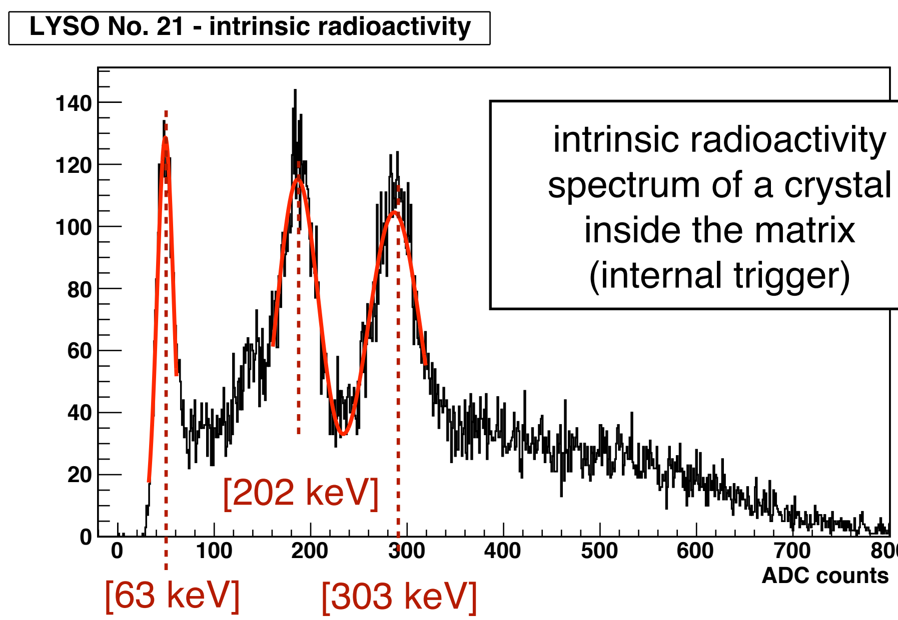


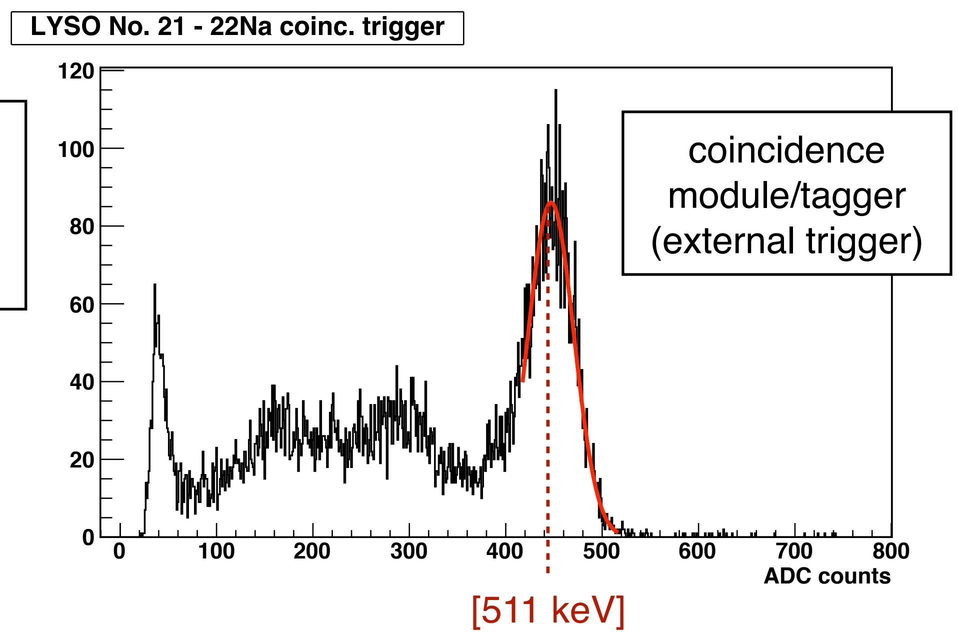
2) **A = 39 Bq/g** (ρ=7.1g/cm3) => expected **250 Bq** in 3x3x100mm3 LYSO

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)

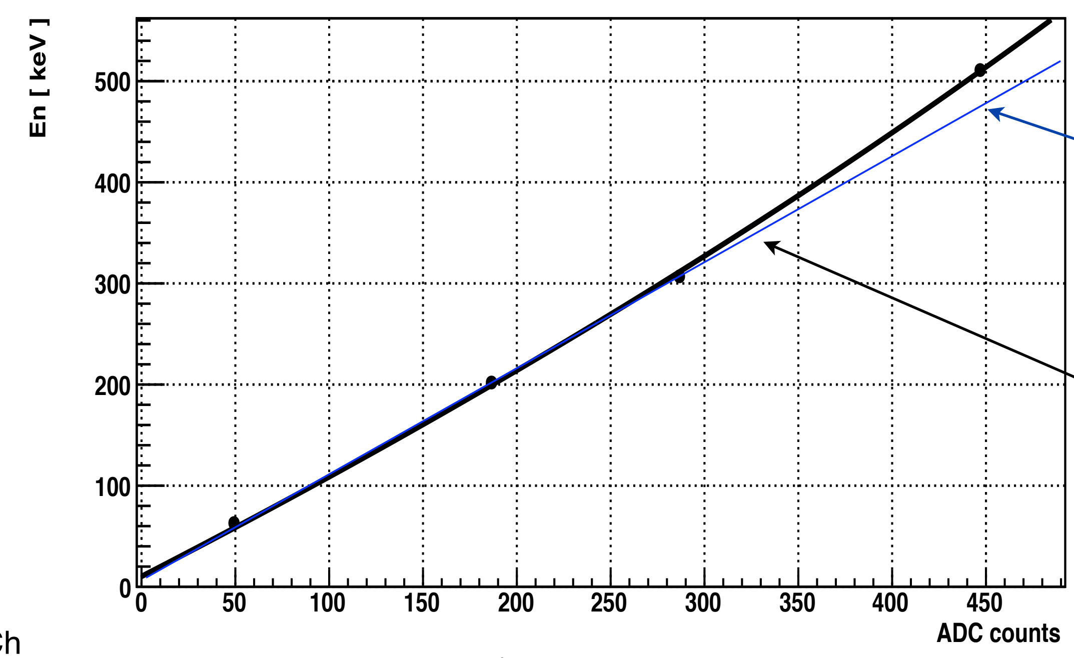
Intrinsic Lu radioactivity + Photopeak: good tool for the energy calibration





same procedure applied identically for every other channel

AX-PET :
"self-calibrating" device



- **deviation from linearity (~ 5% effect)**

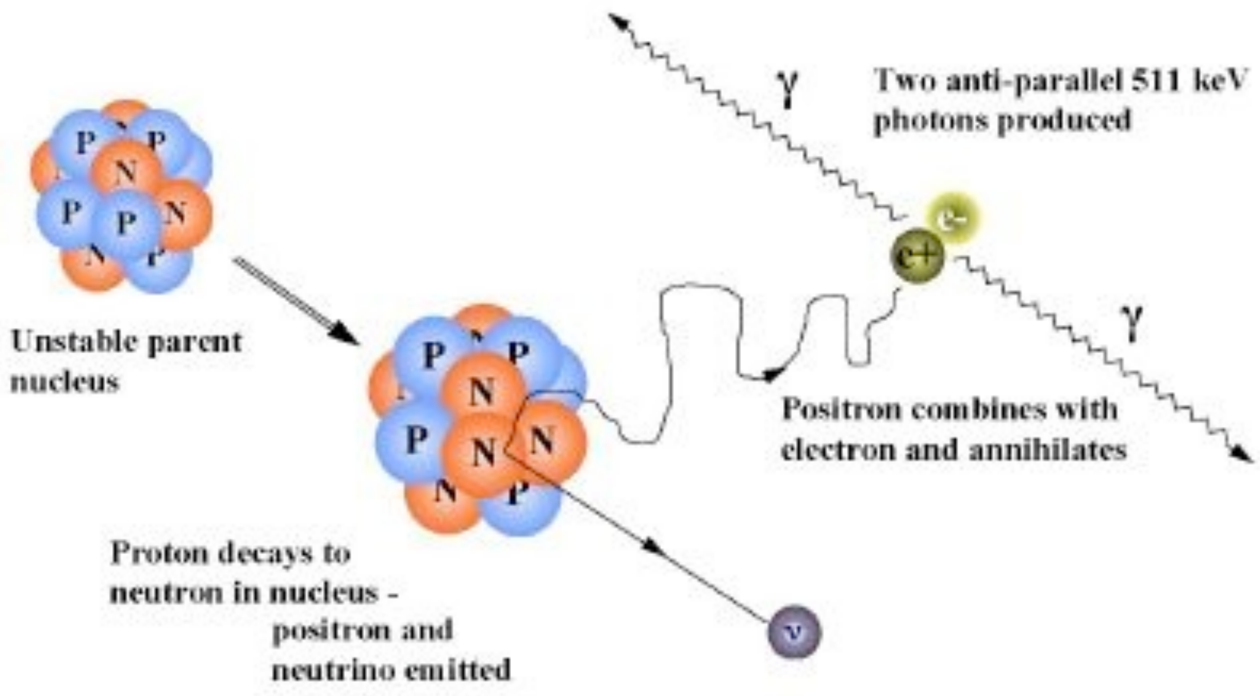
- **parameterization**:
  negative logarithmic fitting func.

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

Ch

PHYSICS LIMITS to spatial resolution

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

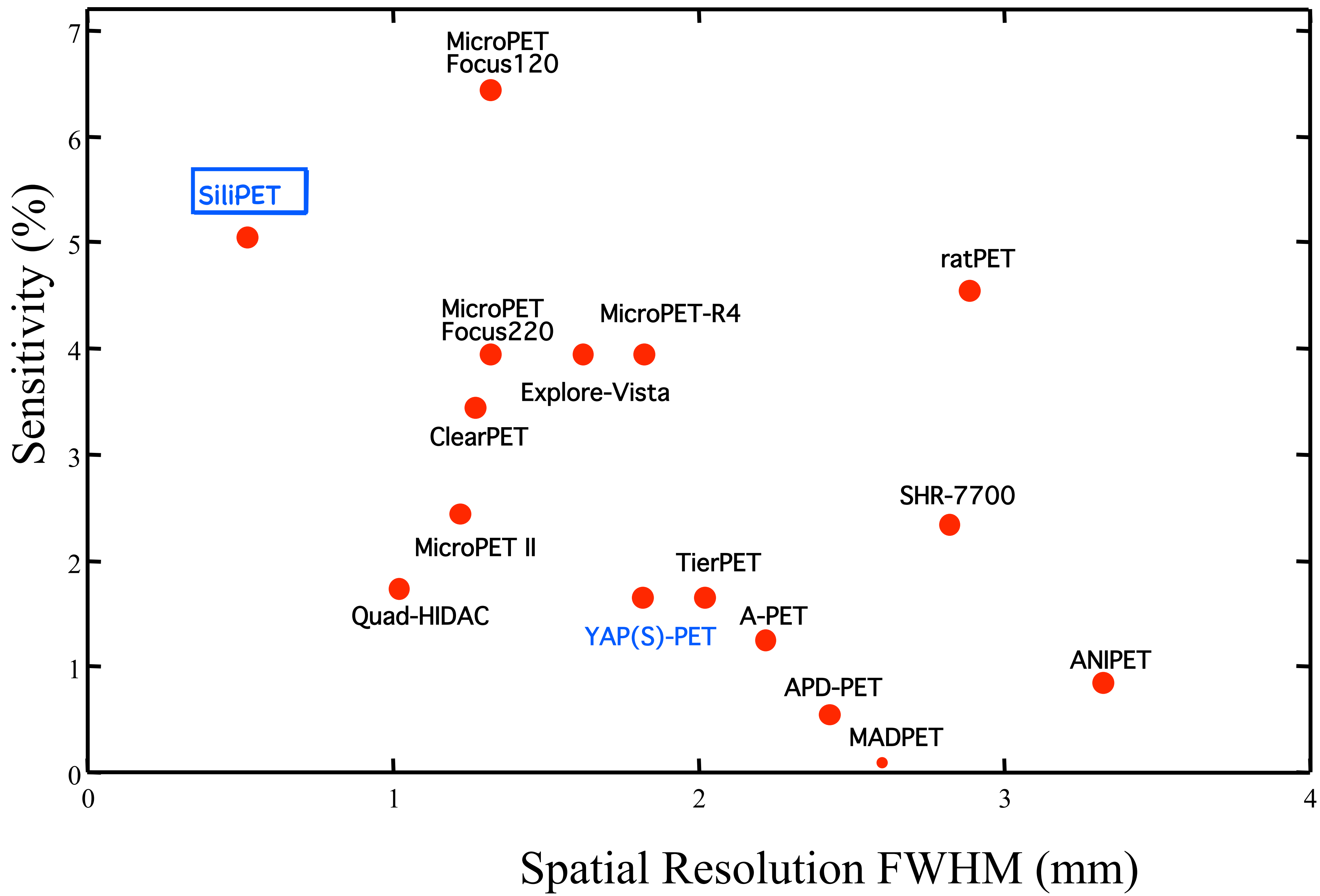


1. Effective positron range

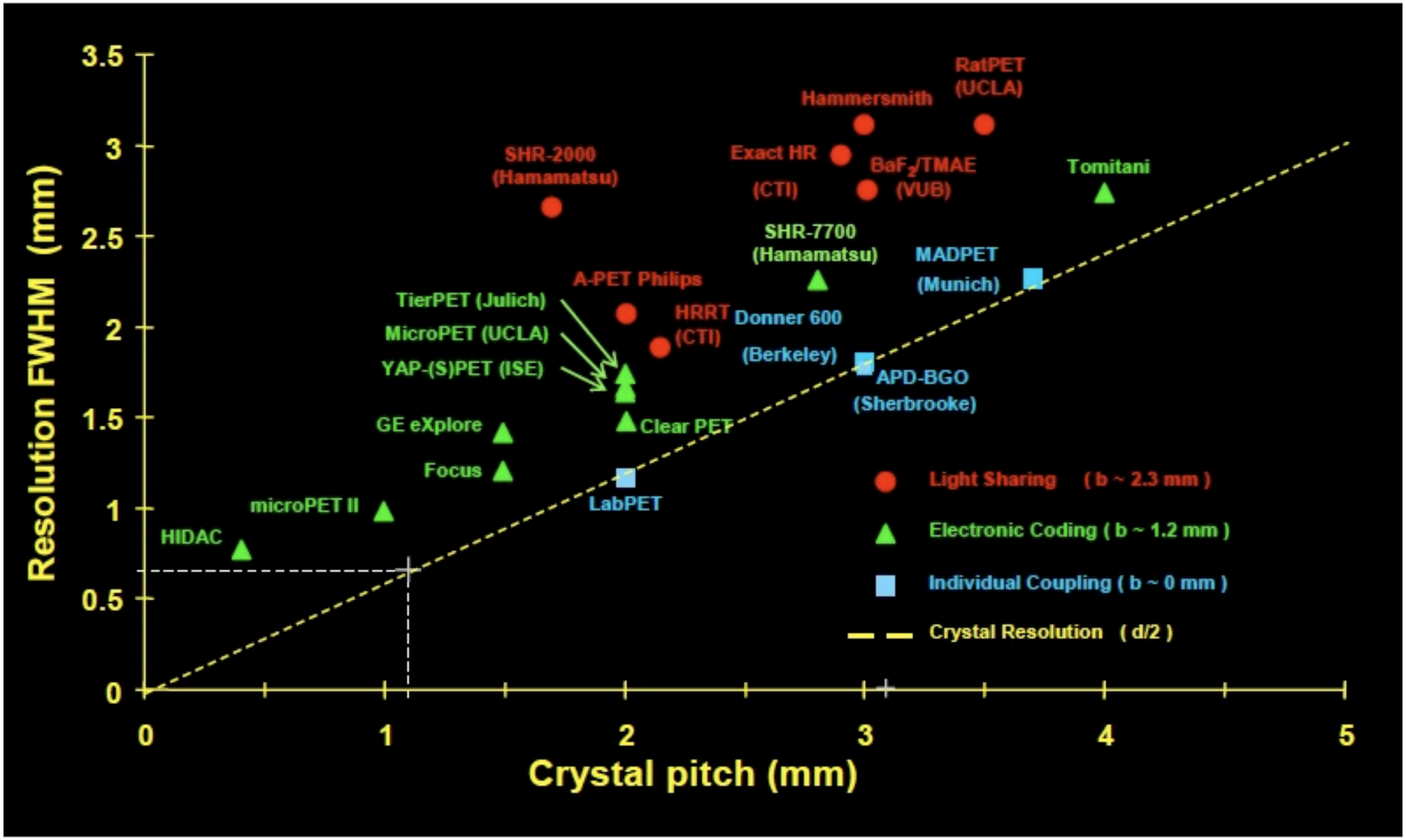
2. Non collinearity

to be completed!

Small animal PET comparison :



Intrinsic resolution of commercial scanners

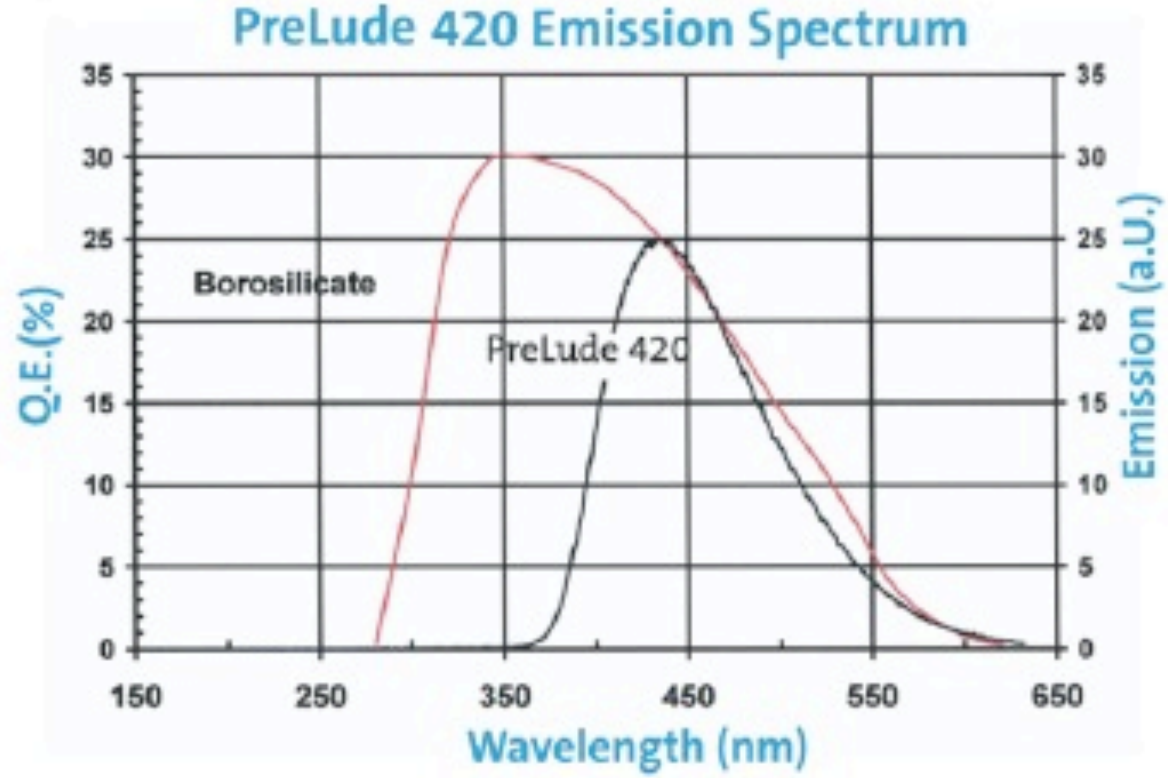


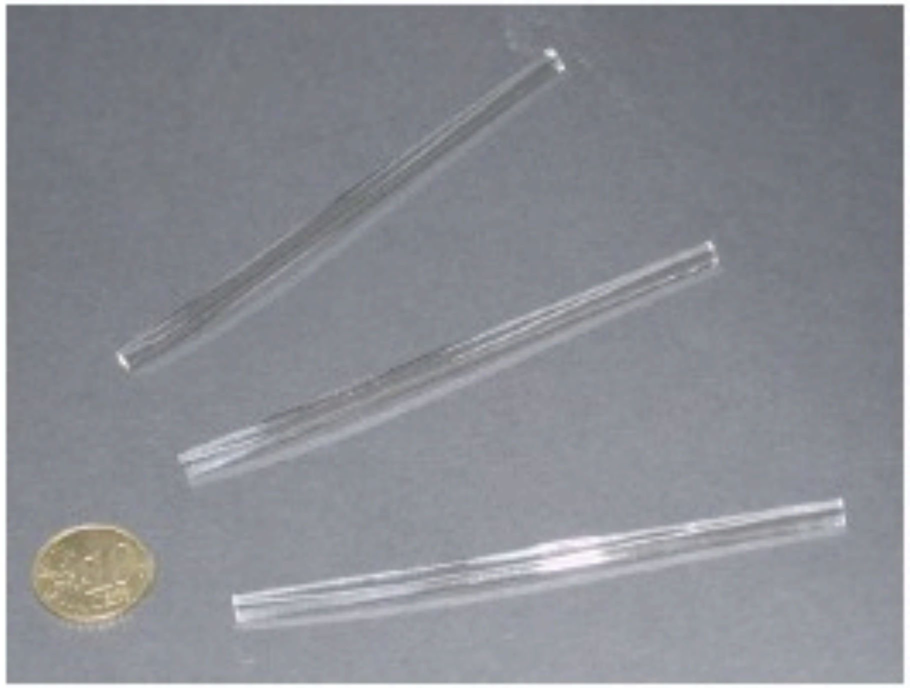
AX-PET components

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





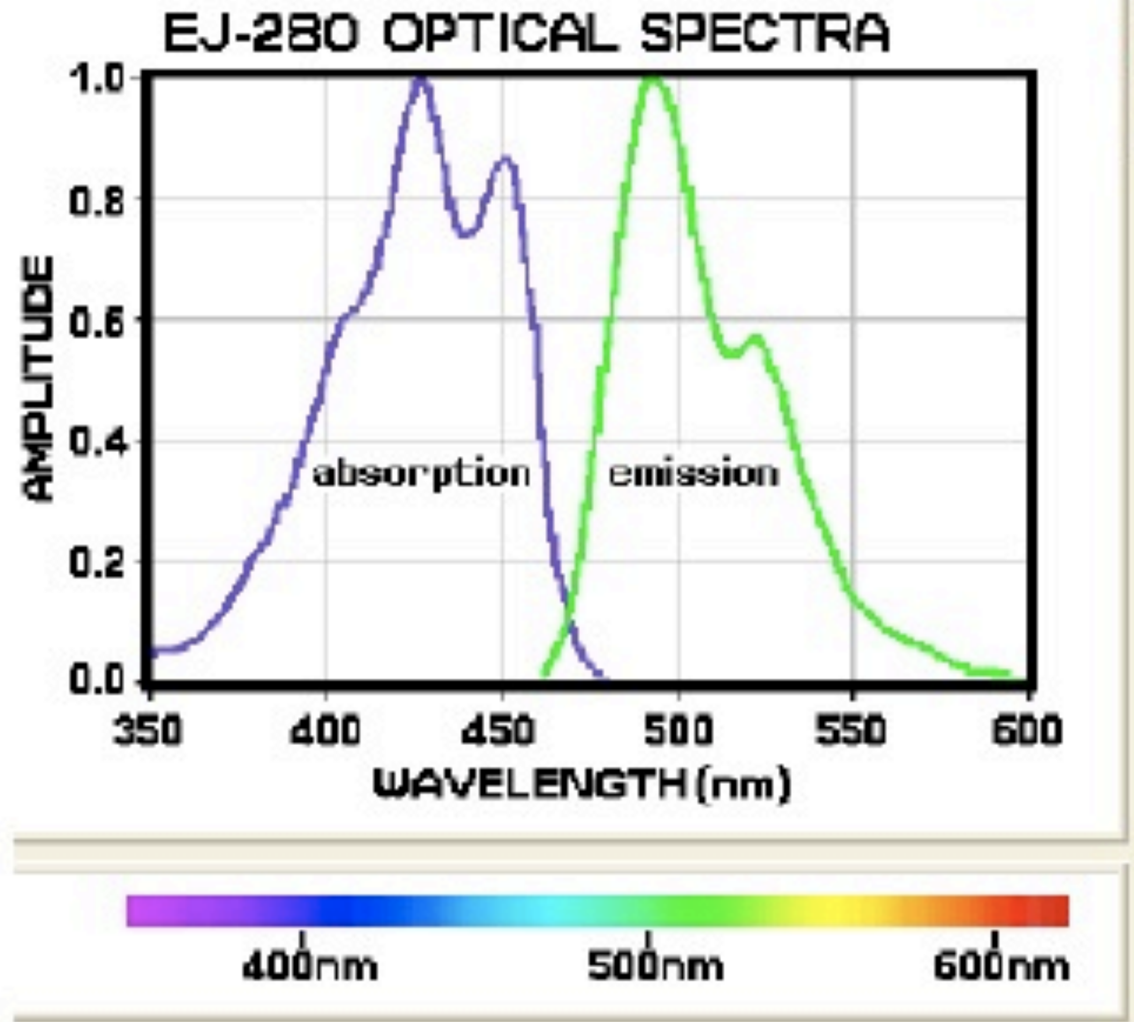
Dimensions: 3 x 3 x 100 mm³

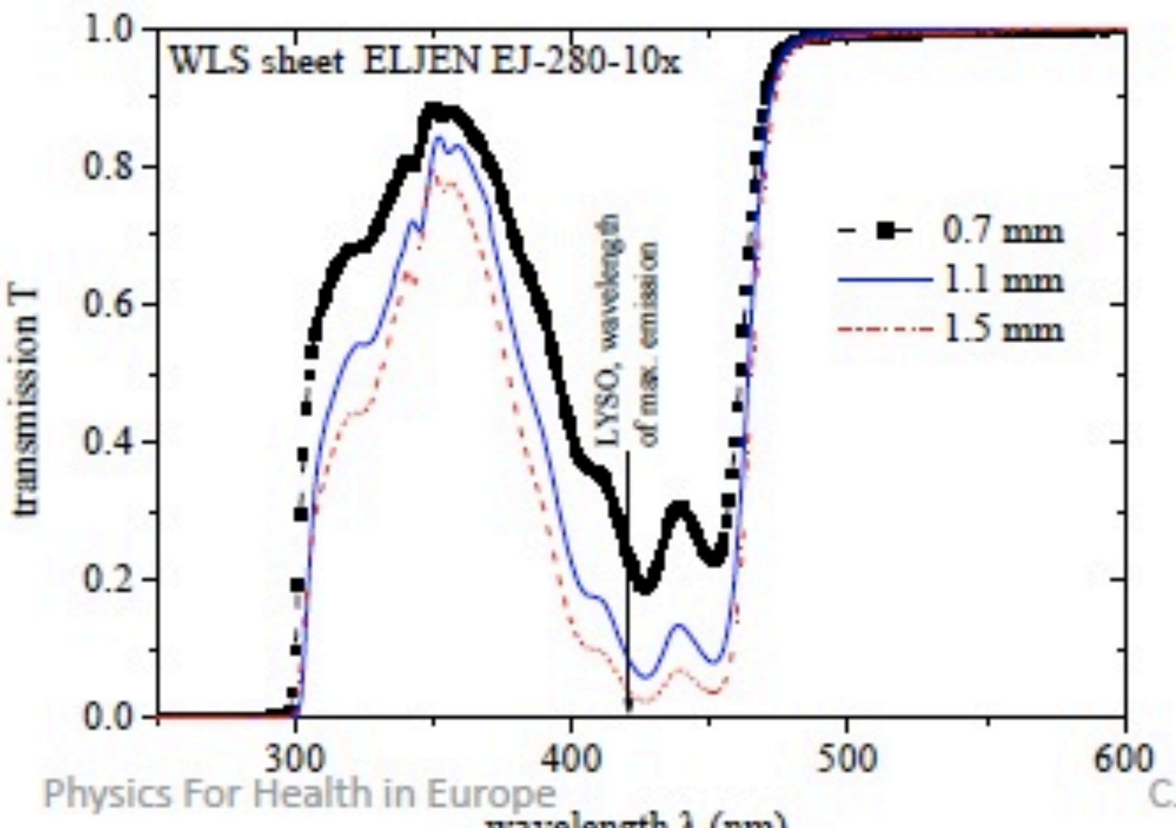
One end is read out, the other end is mirror-coated (evaporated Al-film).

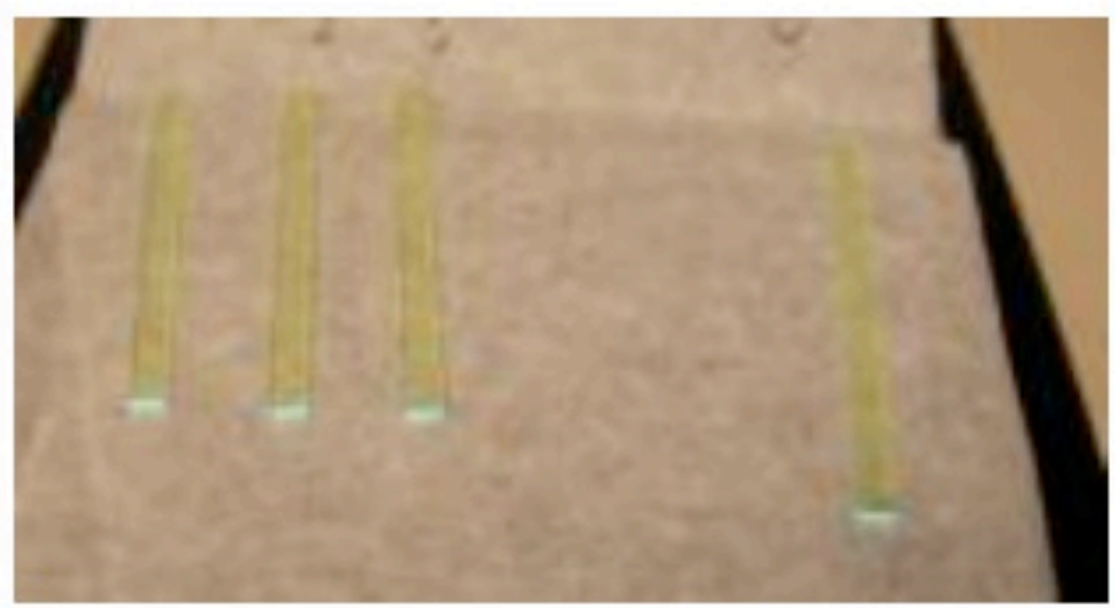
The **WLS strips** are of type EJ-280-10x from Eljen Technologies

- 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

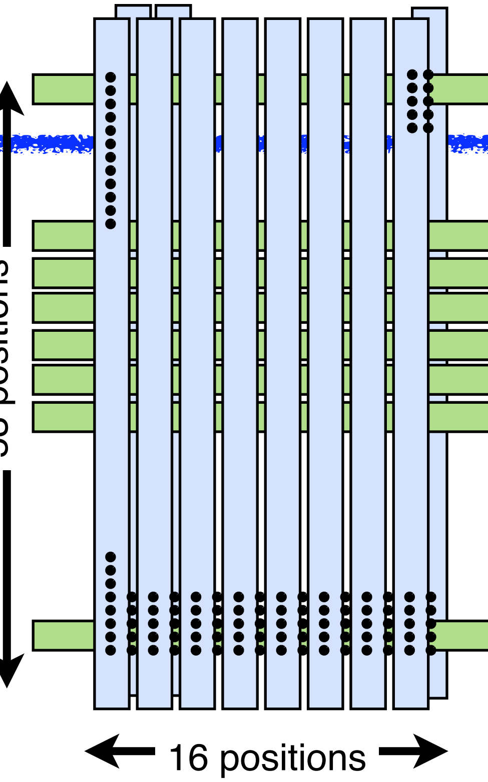
One end is read out, the other end is mirror-coated (evaporated Al-film).







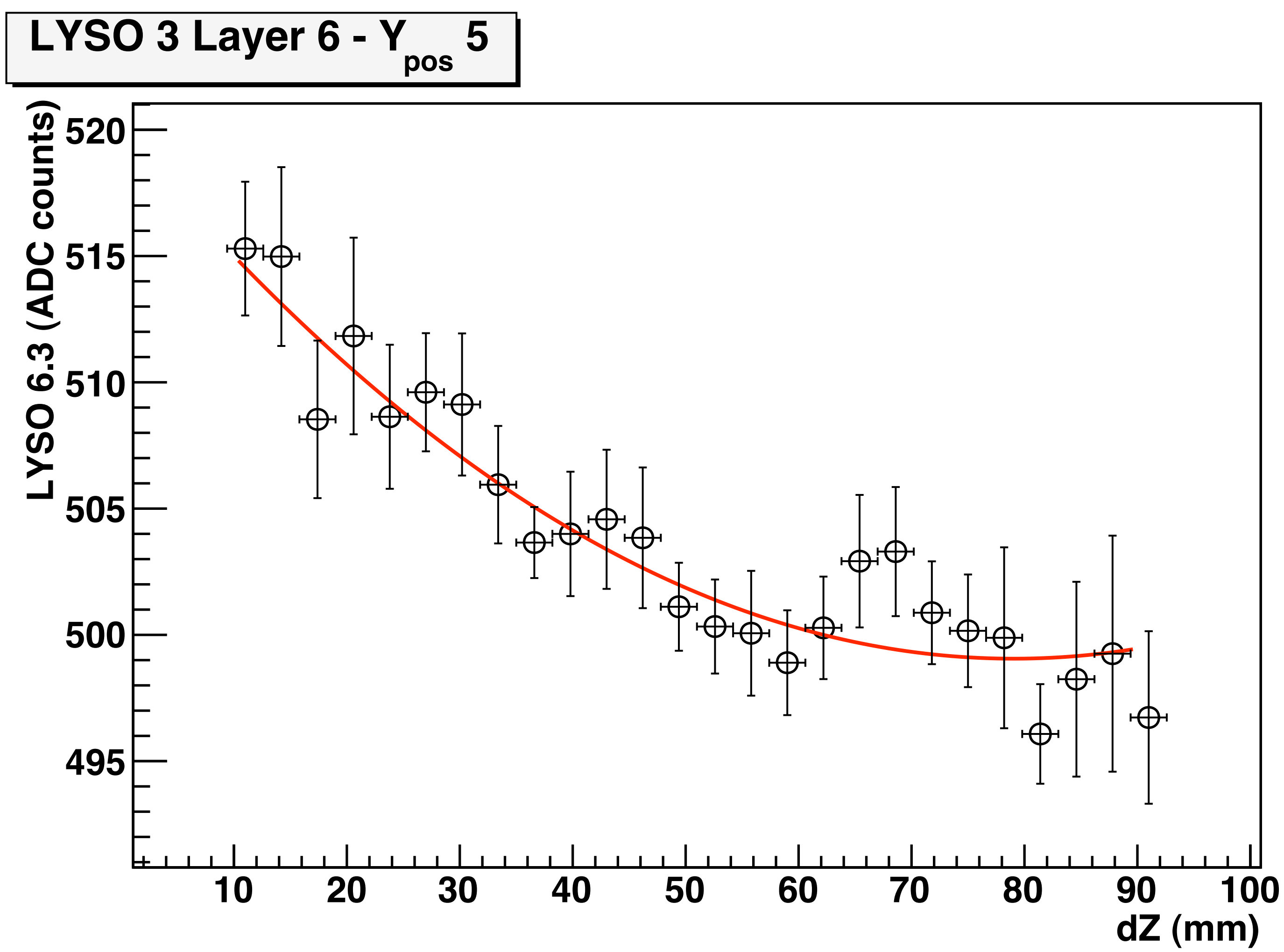
ATTENUATION LENGTH



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 ($\lambda_{attenuation}$)

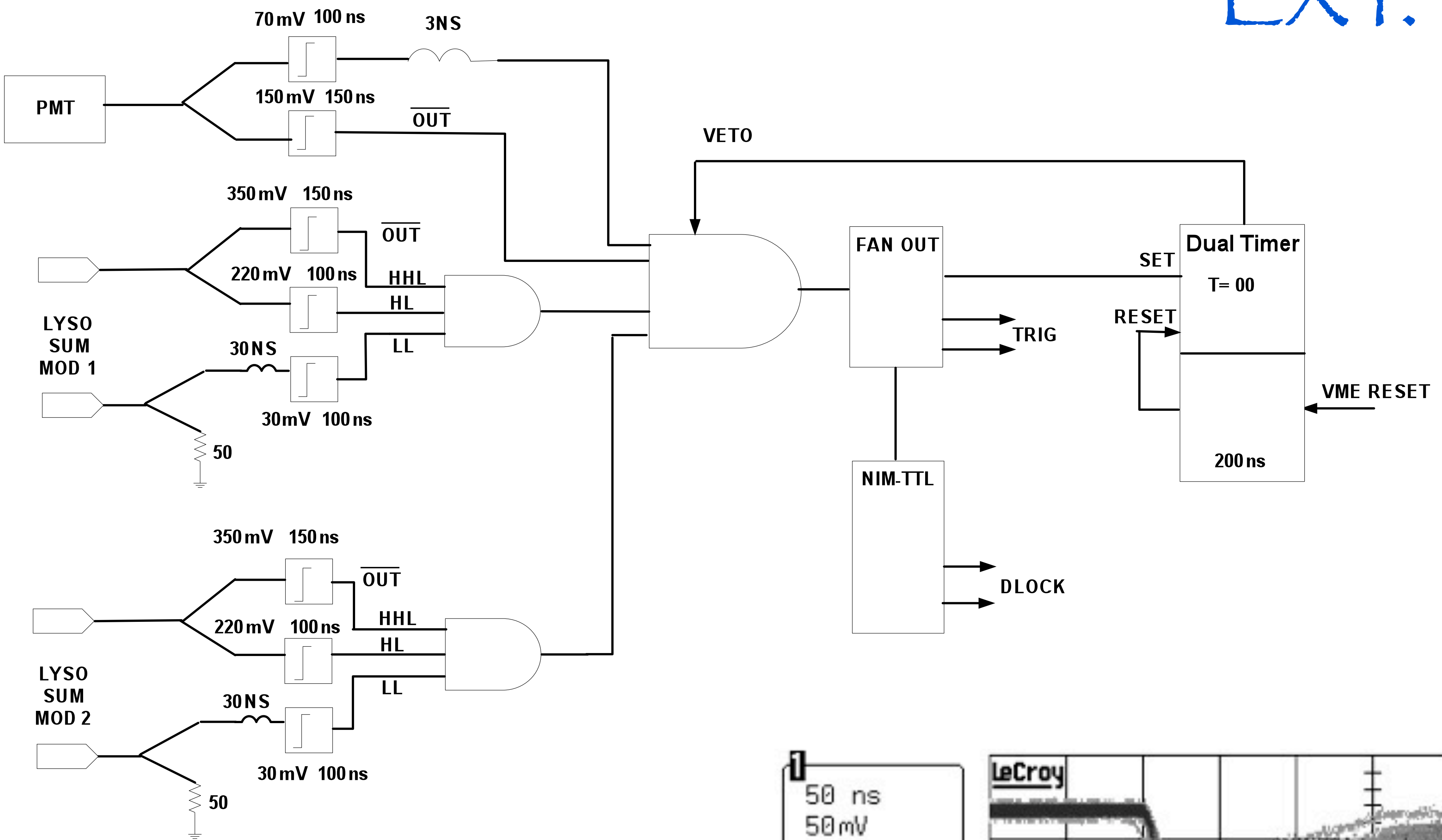
To achieve a good uniformity of the detector response :
- measure $\lambda_{attenuation}$ (**FULL SCAN** measurements)
- correct offline (on a channel by channel basis)

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

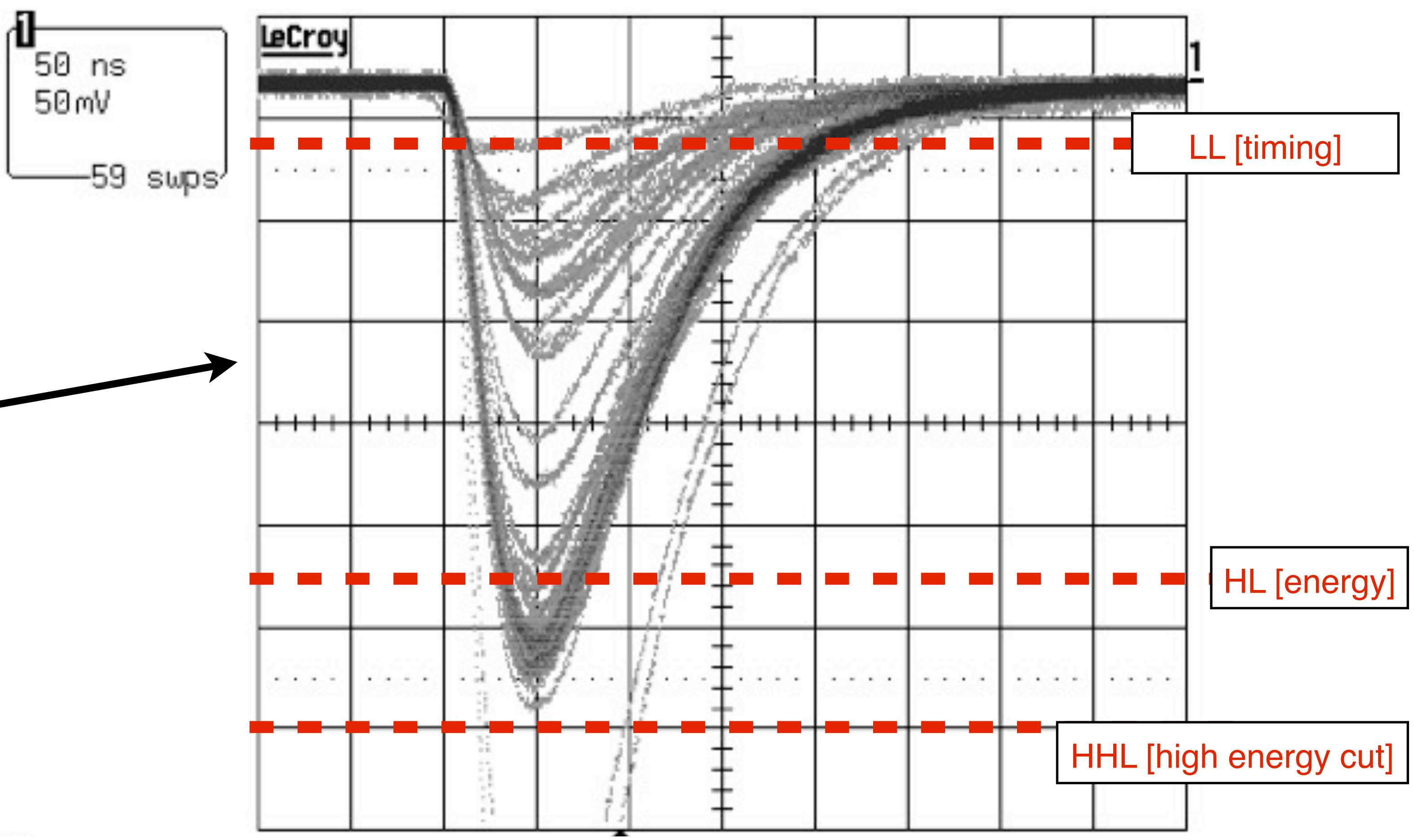


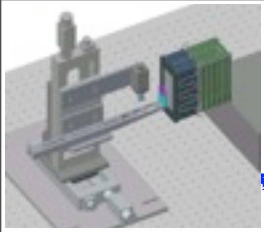
one LYSO example

EXT. TRIGGER



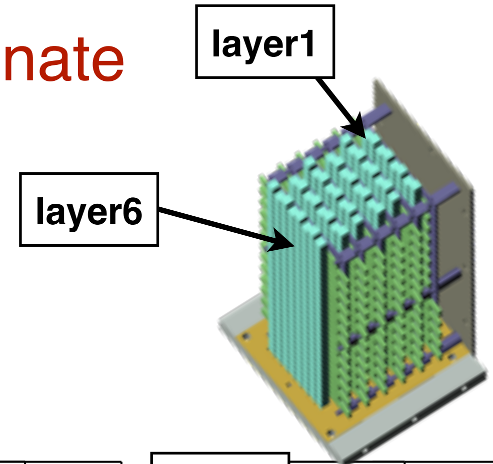
Summed LYSO signal, single module



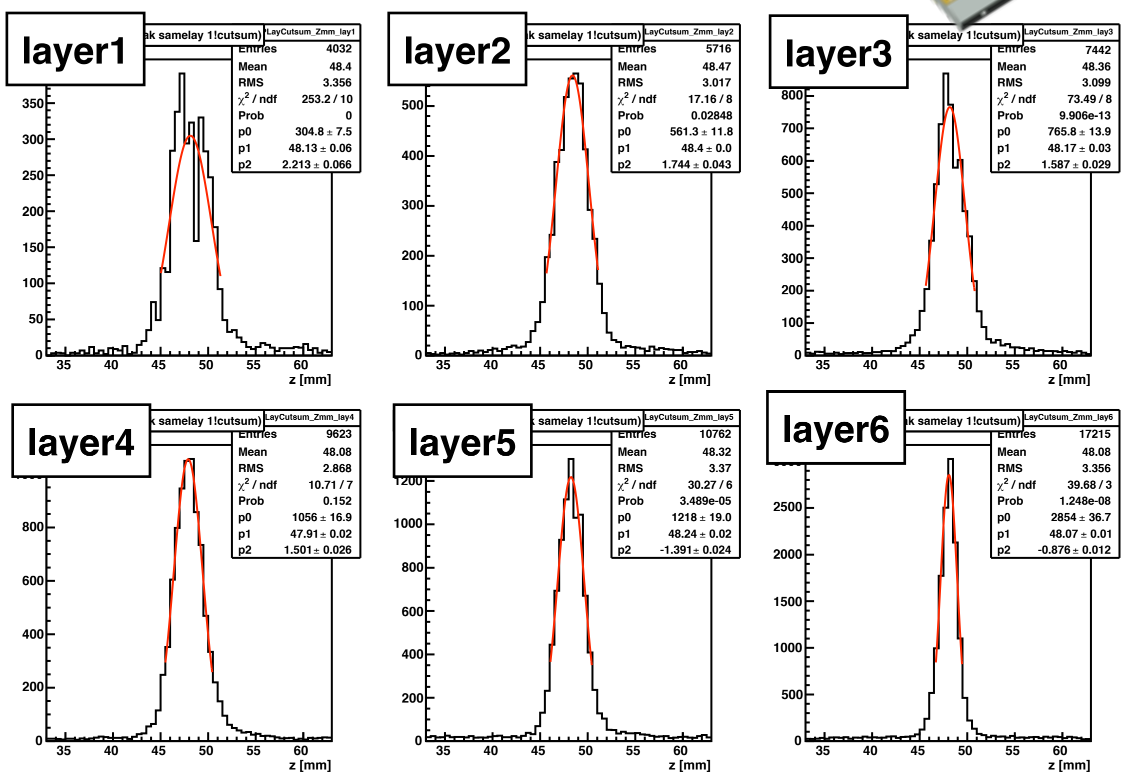


AXIAL RESOLUTION

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

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

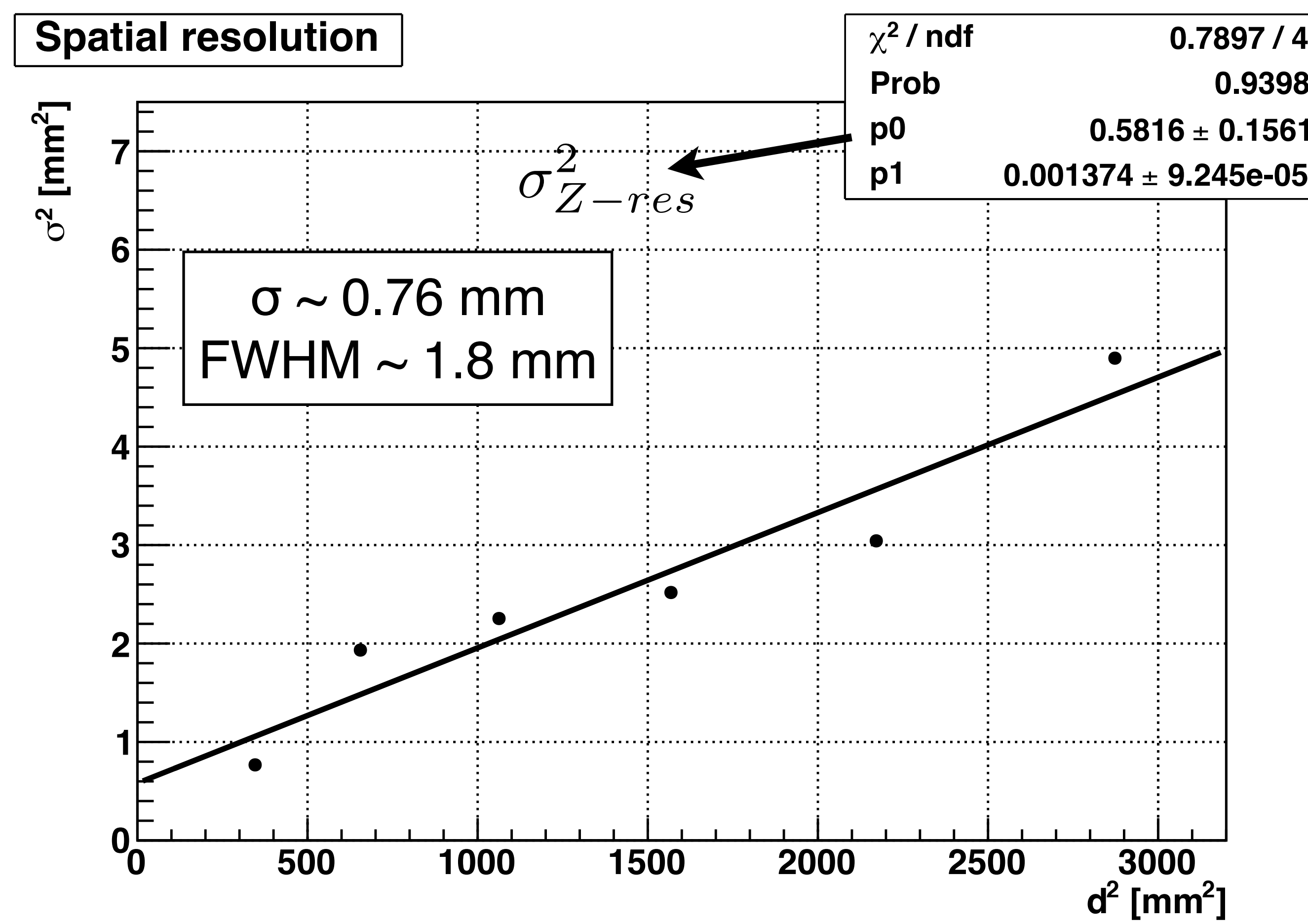
How to derive the intrinsic spatial resolution?

1. make hypothesis :

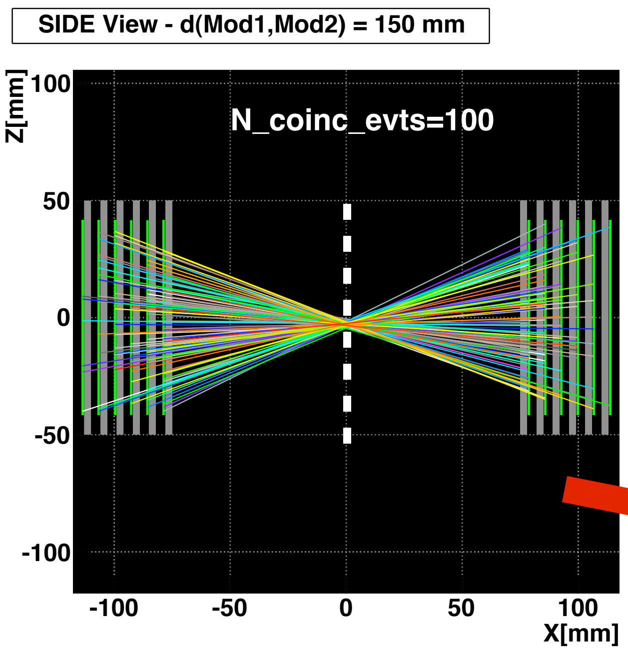
$$\sigma_{i\_beam} \propto d_i$$

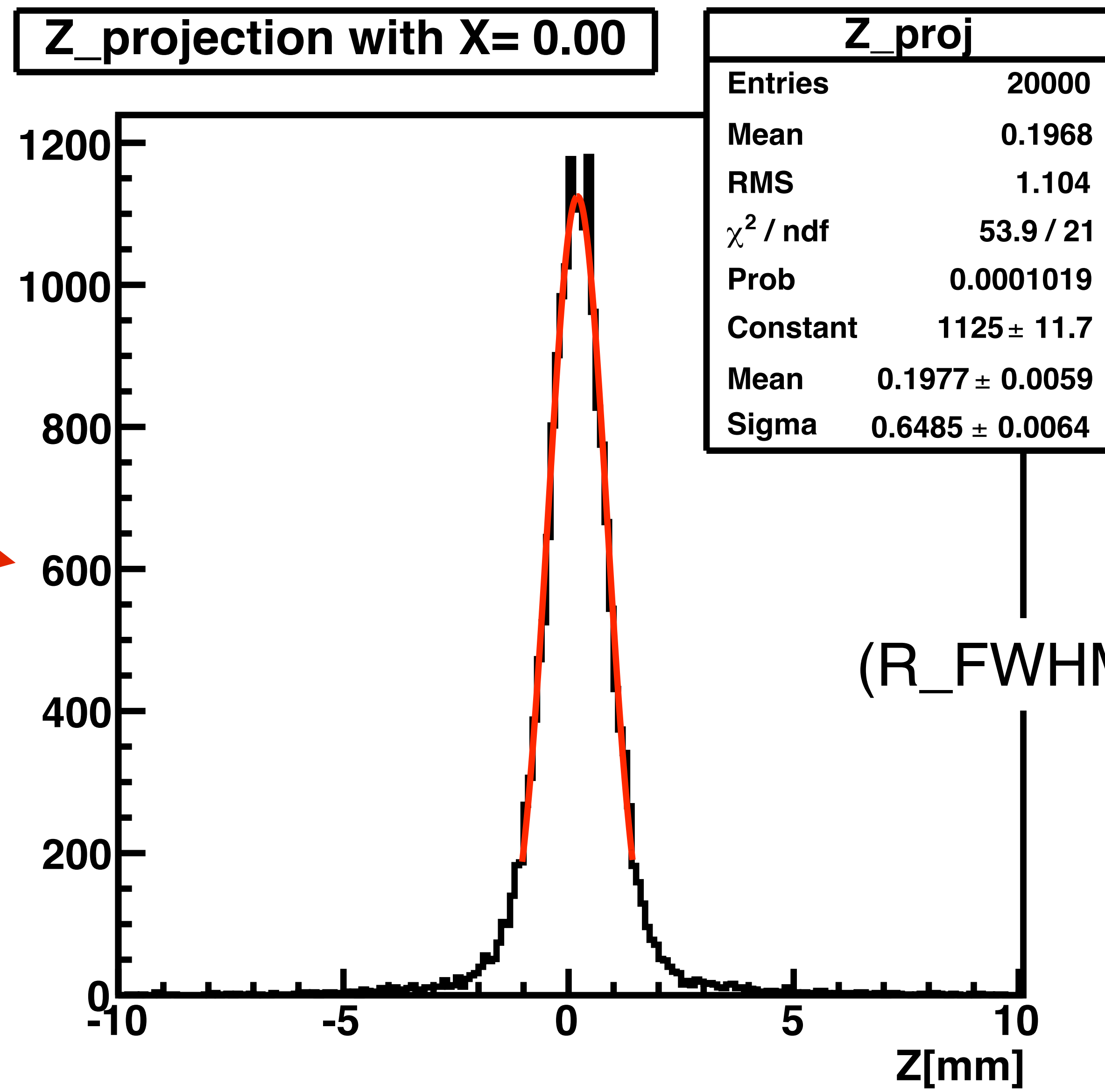
$$\sigma_i^2 = \sigma_{Z-res}^2 + \alpha d_i^2 \qquad \alpha = \frac{\sigma_{beam}^2}{d^2}$$

2. extrapolate at zero distance



AXIAL RESOLUTION





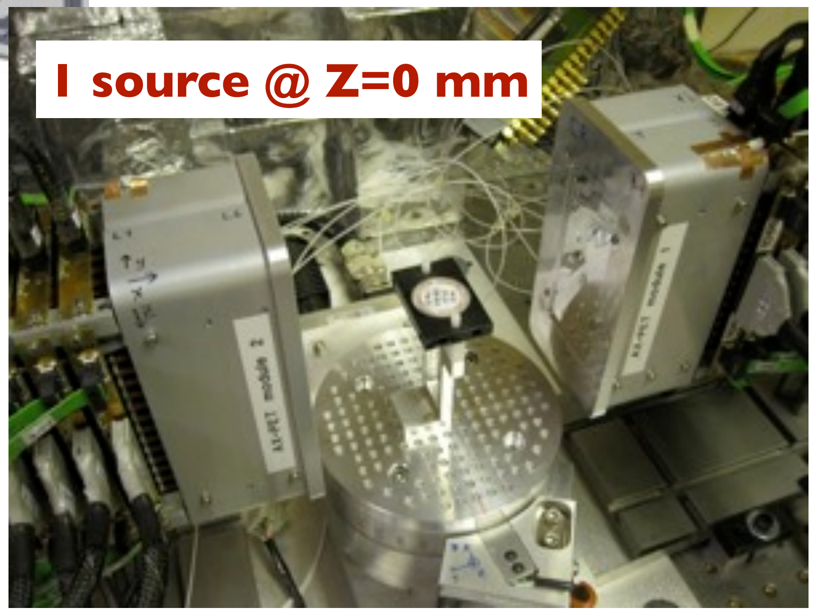
$(R\_FWHM)_Z \sim 1.5$ mm

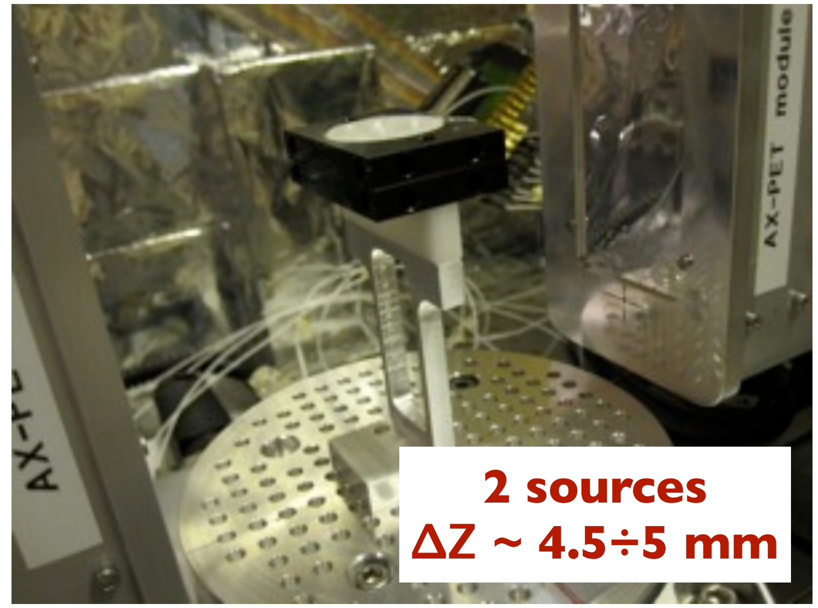
$$R_{intr} = \sqrt{R_{meas}^2 - R_\rho^2 - R_{180}^2} \approx \mathbf{1.35\ mm}$$

R_ρ^2: $(0.54\ \text{mm})^2$

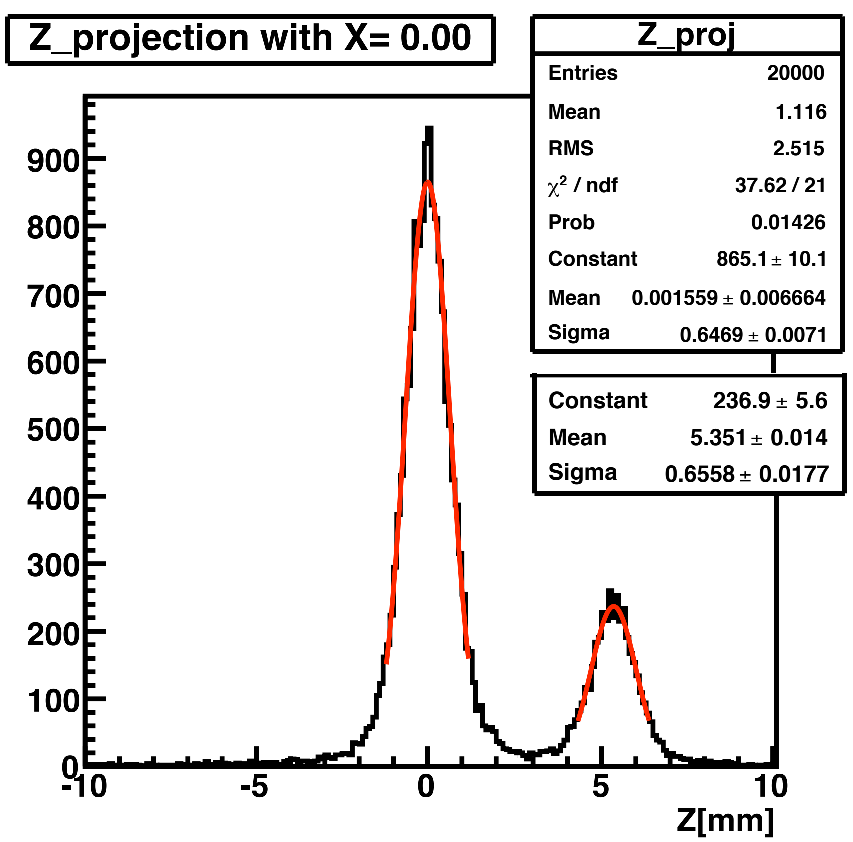
R_{180}^2: $[0.0022 \times \text{Diam} = 0.33\ \text{mm}]^2$

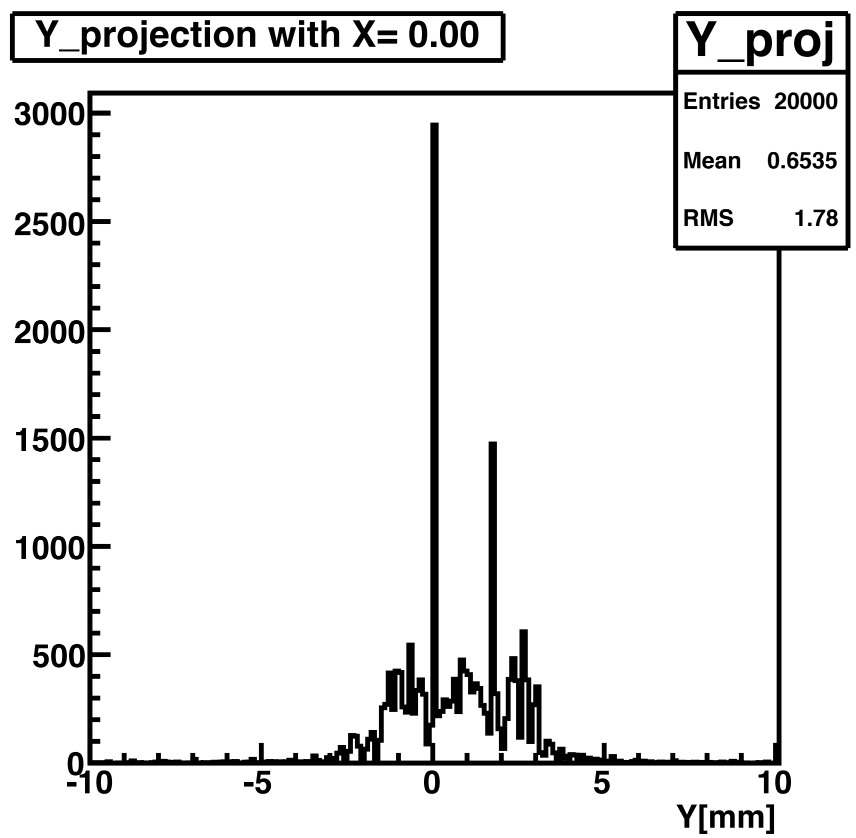
AXIAL RESOL. - two sources separation

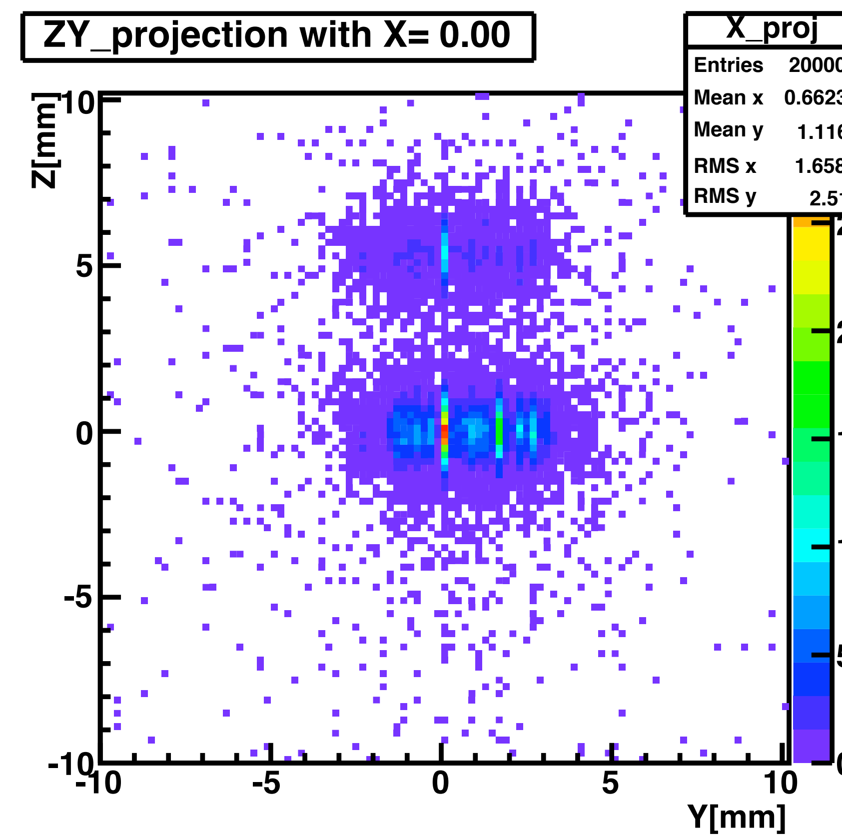




two sources :
1) A ~ 600 MBq ; in (0,0,0)
2) A ~ 100 kBq ; in (0,0,ΔZ)

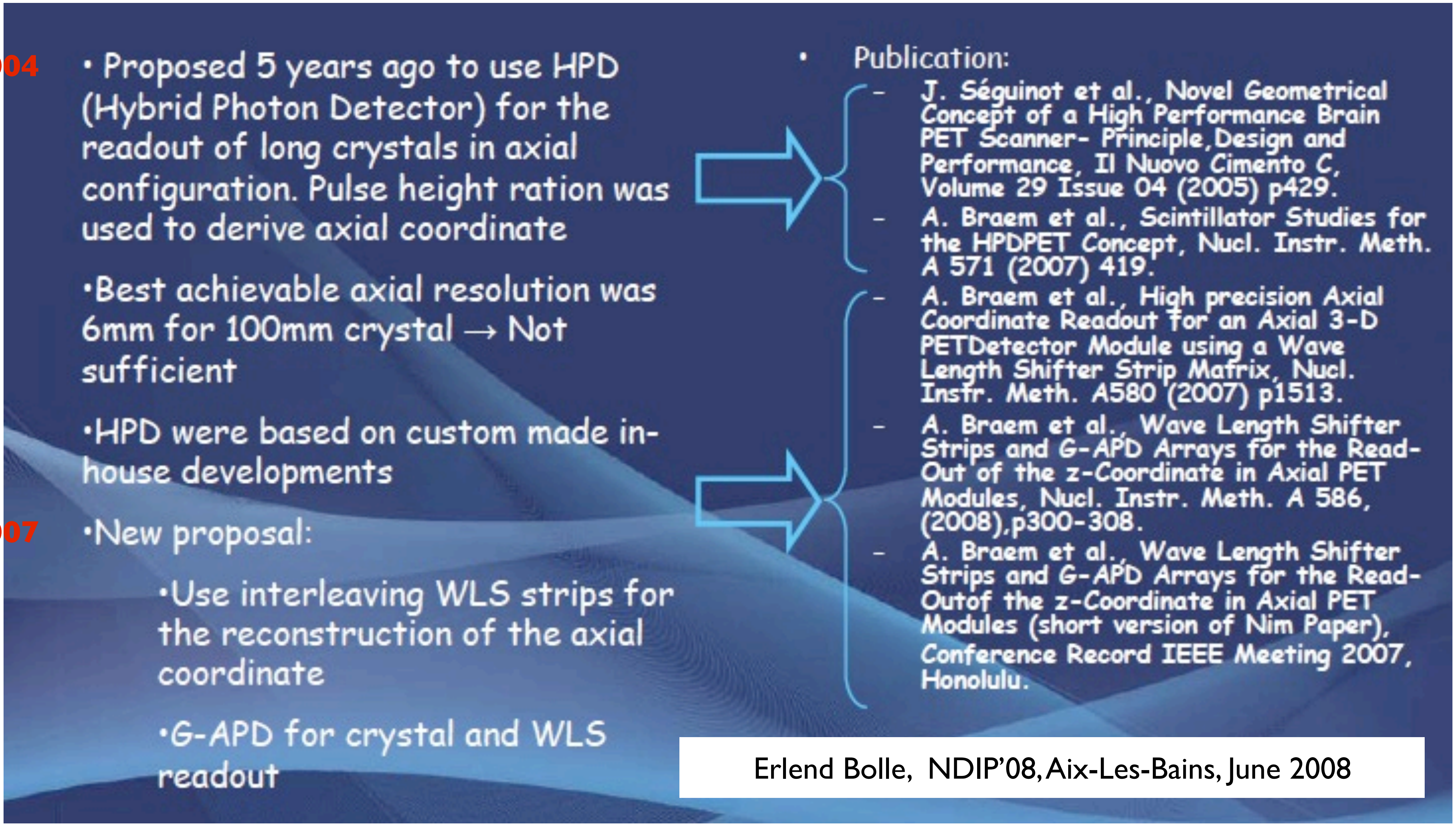






History and Publications

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

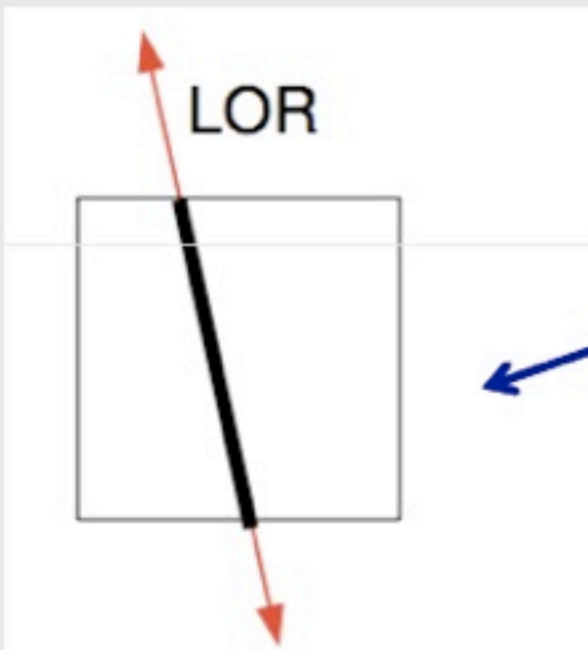


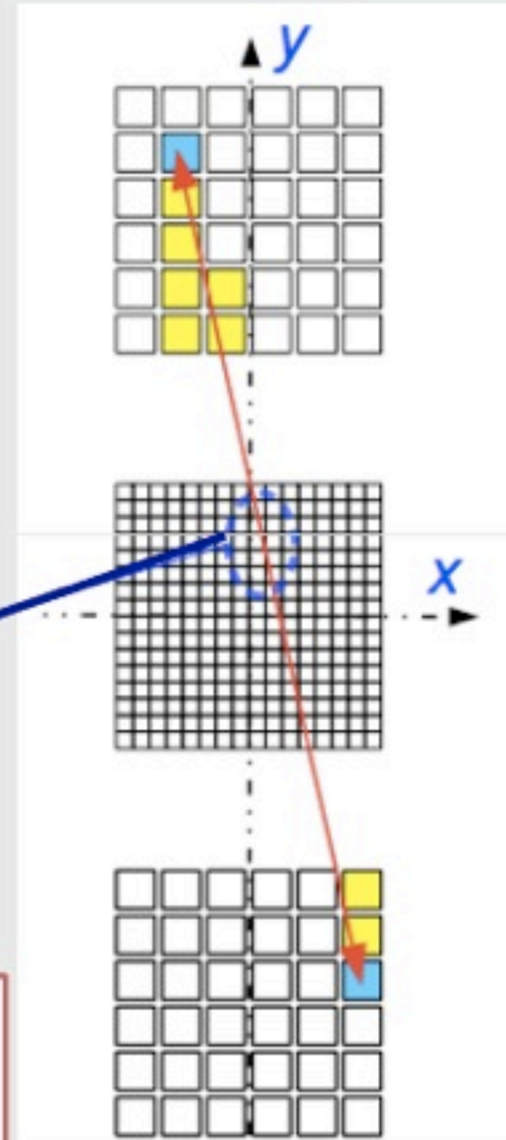
2009 :
- module constructions / performance assessment / single module characterization / 2 mods coincidence (with sources) **[PAPER IN PREPARATION]**
- software progress : simulations / reconstruction **[PAPER IN PREPARATION]**

2010 :
- measurements with phantoms

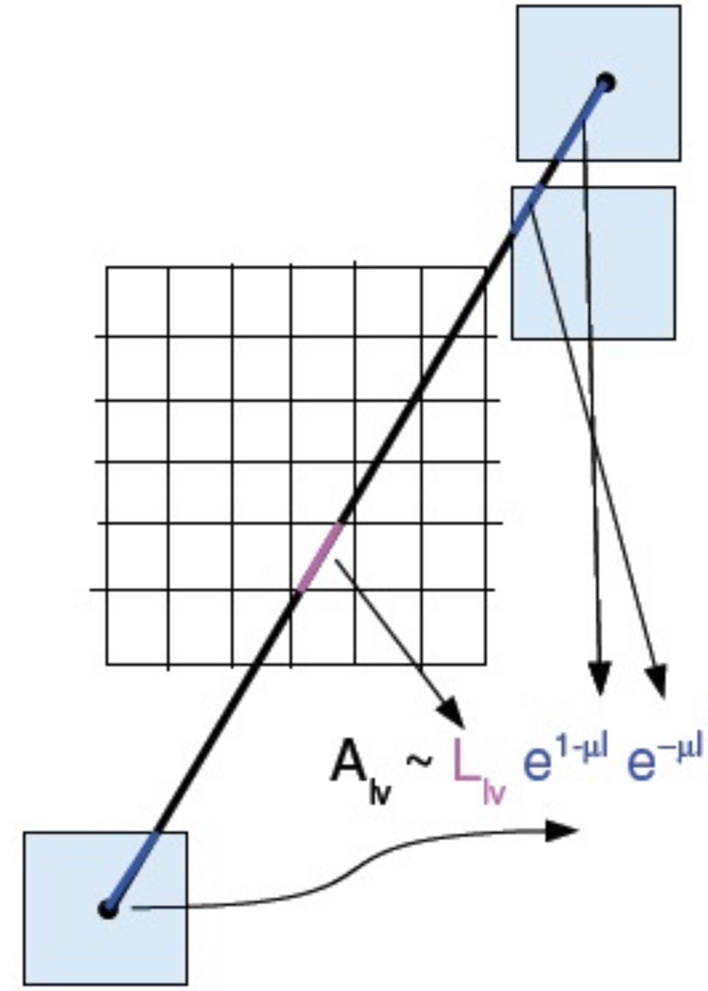
Modified Siddon's ray tracer approach

Simplistic approach: contribution to a voxel of the LOR is given by the intersection length.





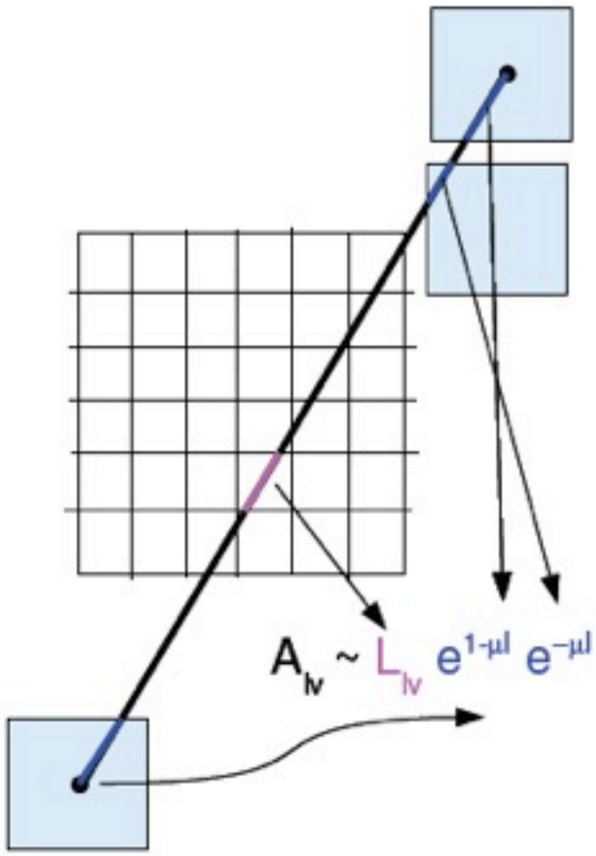
The screening effect due to neighboring crystals attenuating the gamma is also considered.

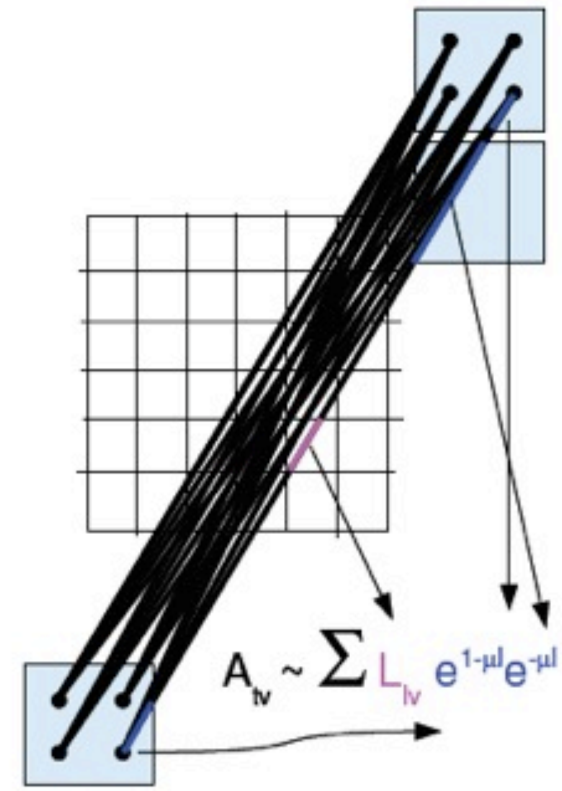


Outline of SM computation without subsampling

- 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.
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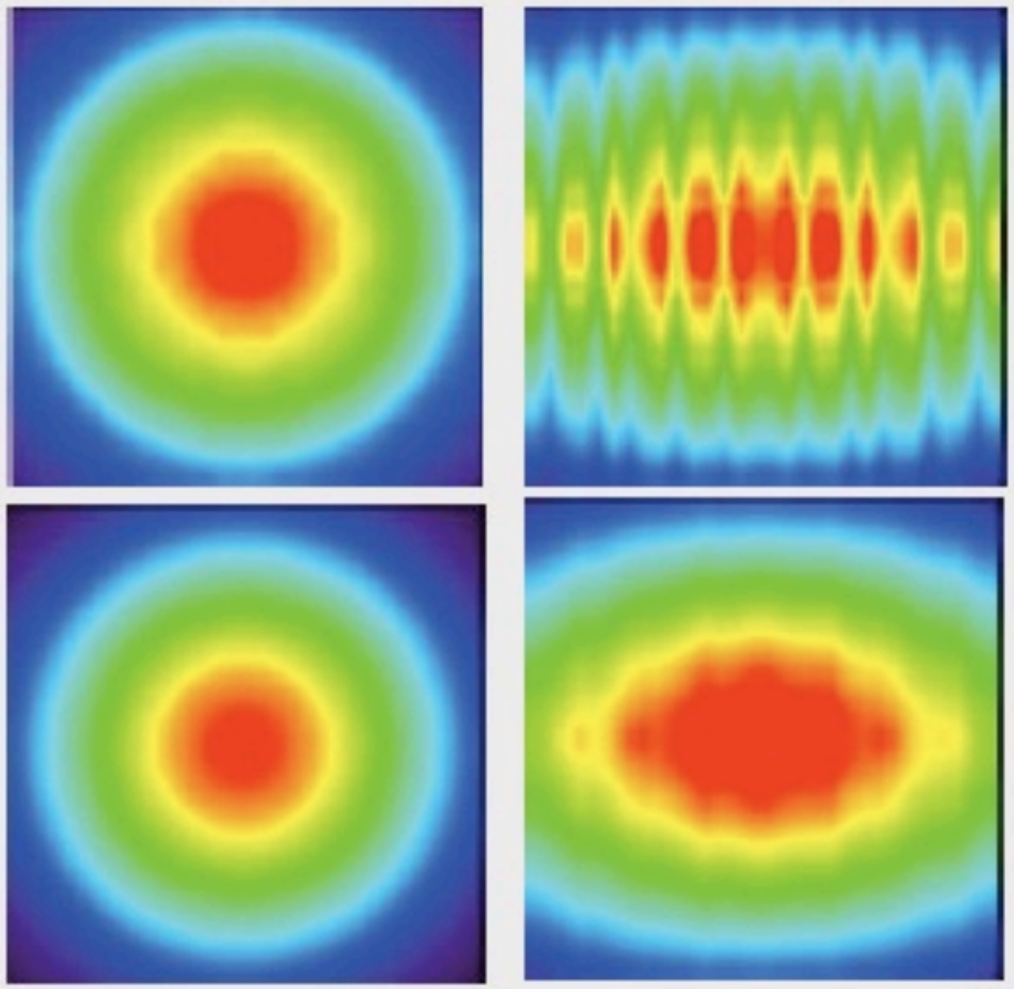
- Crystal penetration effects were considered.
- **Ignores effects due to the finite size of the crystals**

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

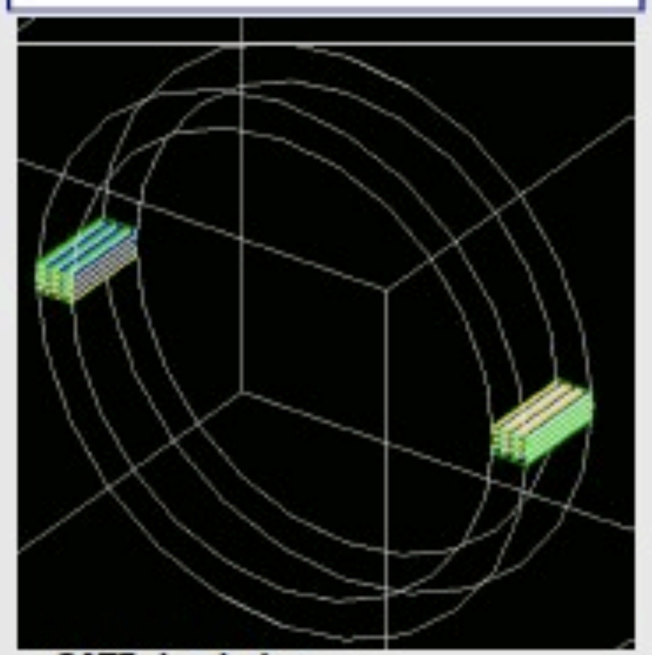
FOV

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

GATE simulation of the full module

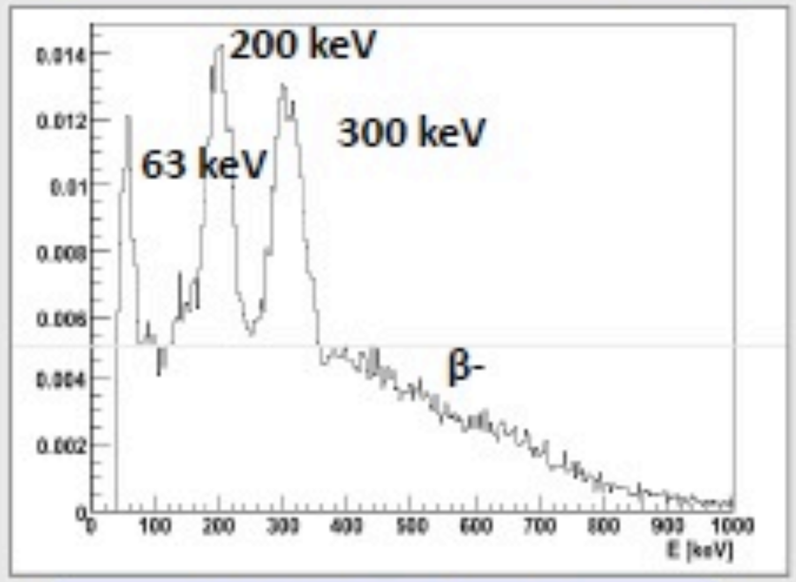
The AX-PET scanner is modeled by means of GATE. In order to correctly reproduce the achievable spatial resolution, the source code is modified to include the z coordinate parameterization according to WLS response.

Geometry modeled

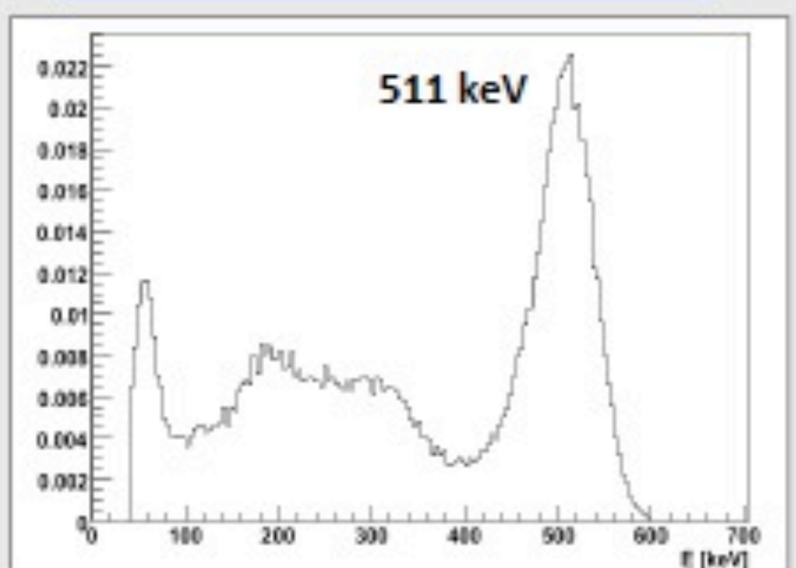


GATE simulation

Intrinsic radioactivity



Gamma source

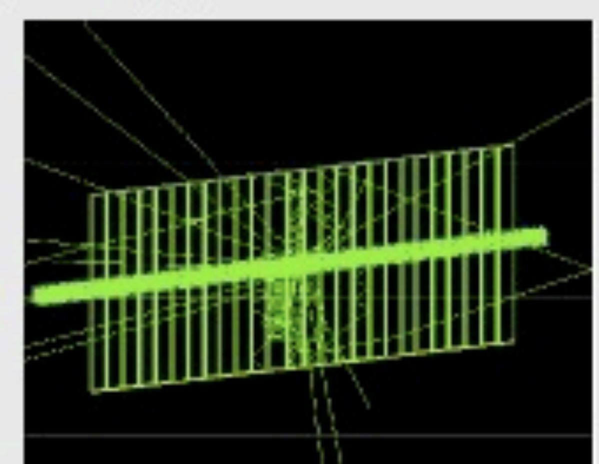


Digitizer

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

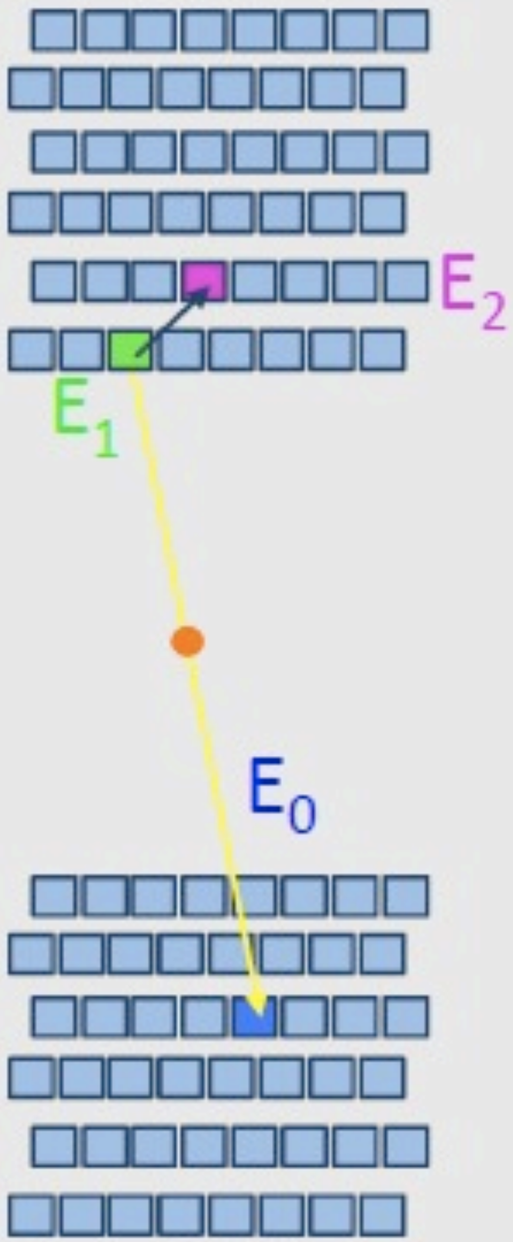
WLS parameterization

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



Geant4 simulation

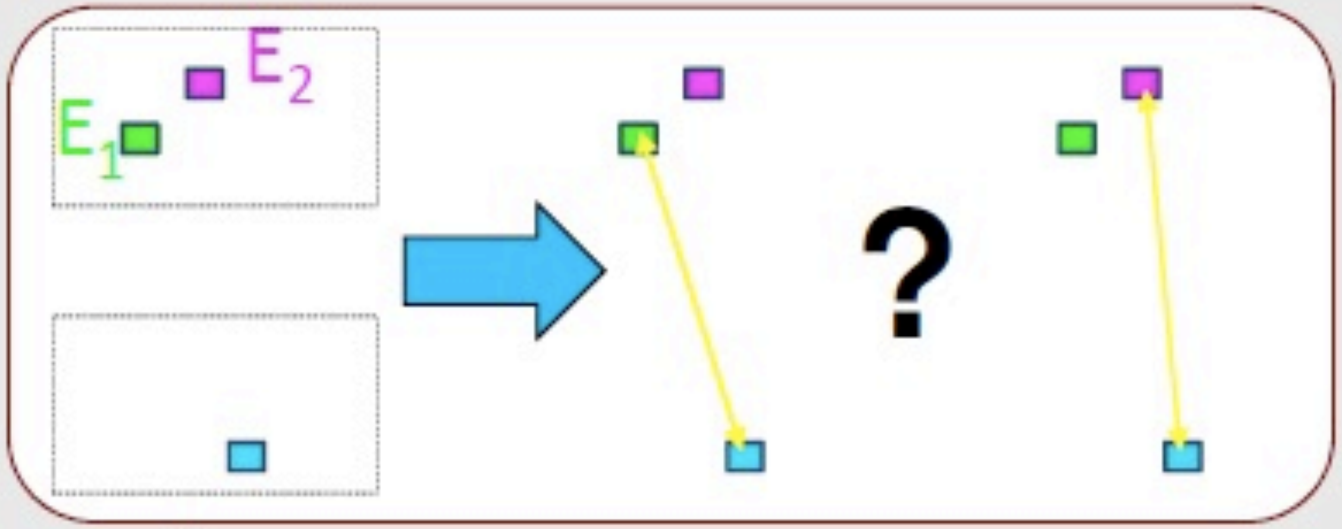
Investigate Inter-crystal scattering



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%