



# *Demonstration of an Axial PET concept for Brain and Small Animal Imaging*

Vienna Conference of Instrumentation 2010

Paolo Beltrame CERN - PH/DT



- The AX-PET concept
- The Demonstrator
- Characterization
- Simulation and Reconstruction
- Next steps and future plans

# The AX-PET Collaboration



Istituto Nazionale di Fisica Nucleare Bari (INFN)

Ohio State University (OSU)

European Organization for Nuclear Research (CERN)

University of Michigan

University of Rome La Sapienza (INFN)

Instituto de Fisica Corpuscular (IFIC)

Paul Scherrer Institute (PSI)

Eidgenössische Technische Hochschule (ETH)

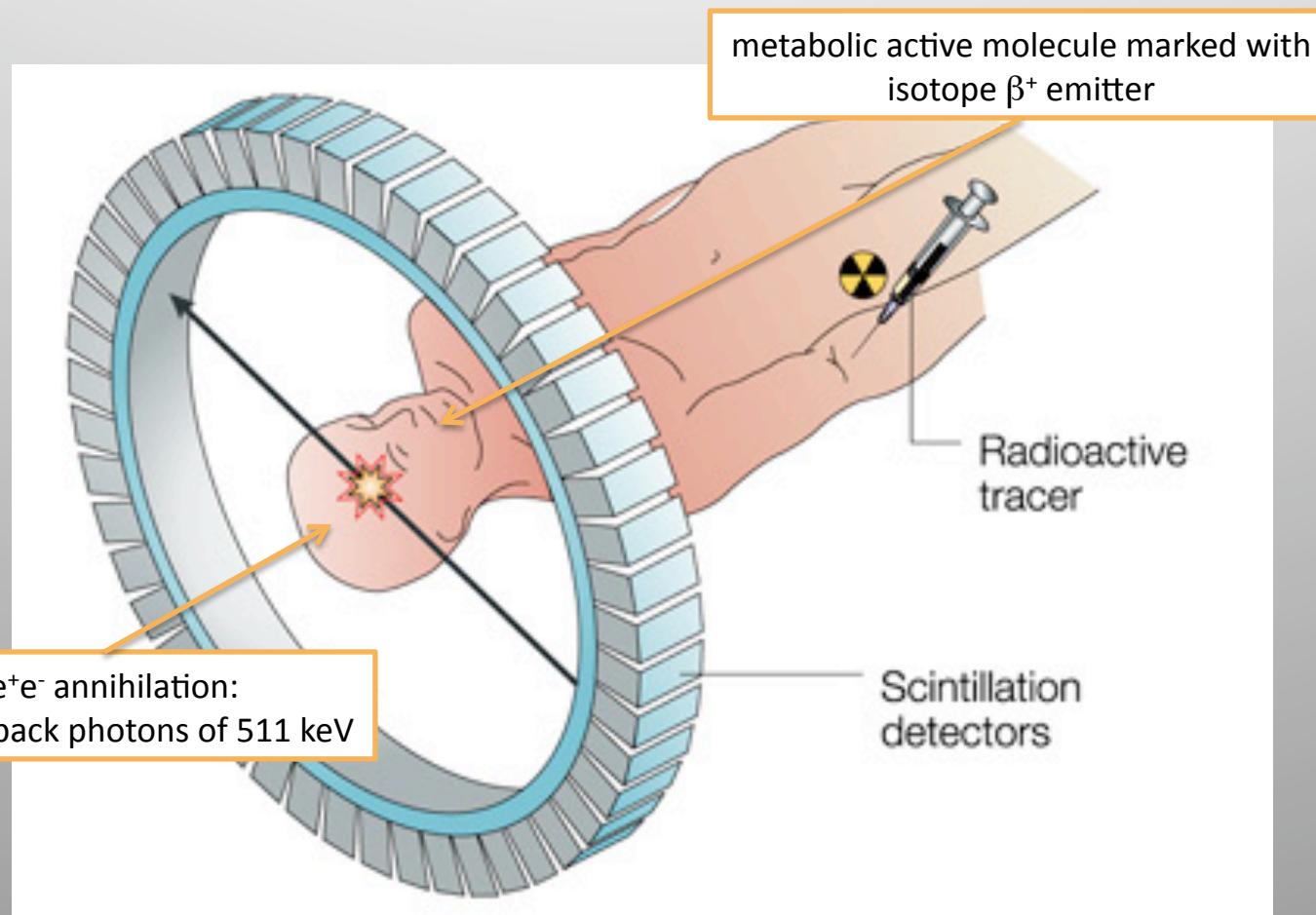


P. Beltrame, A. Braem, V. Fanti, C. Joram, T. Schneider,  
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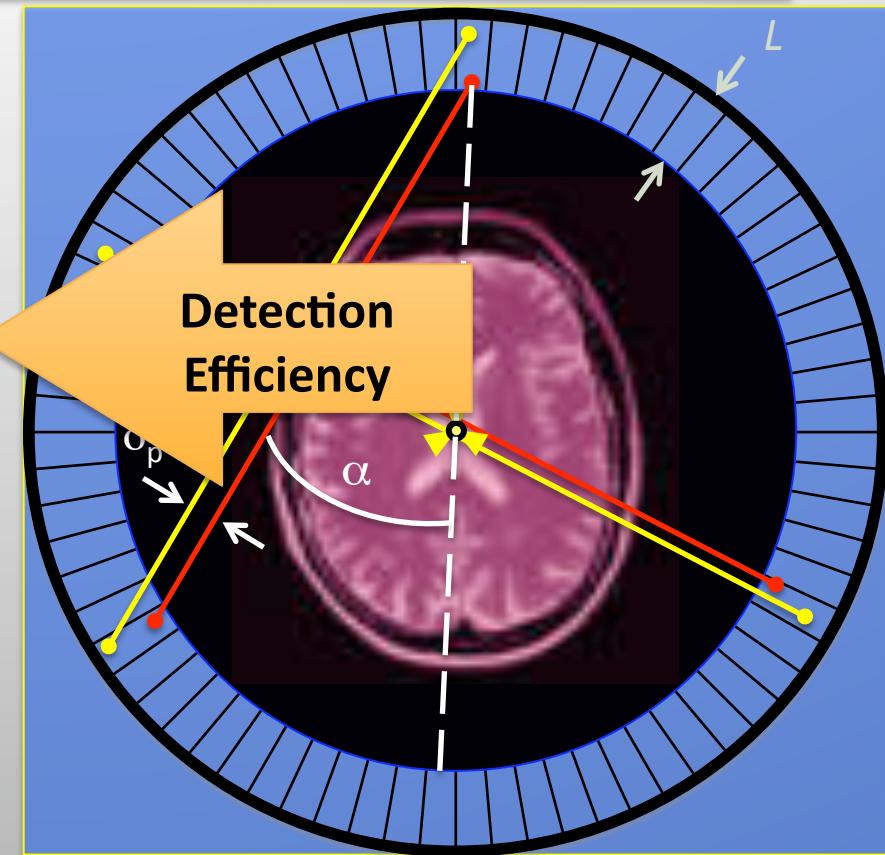
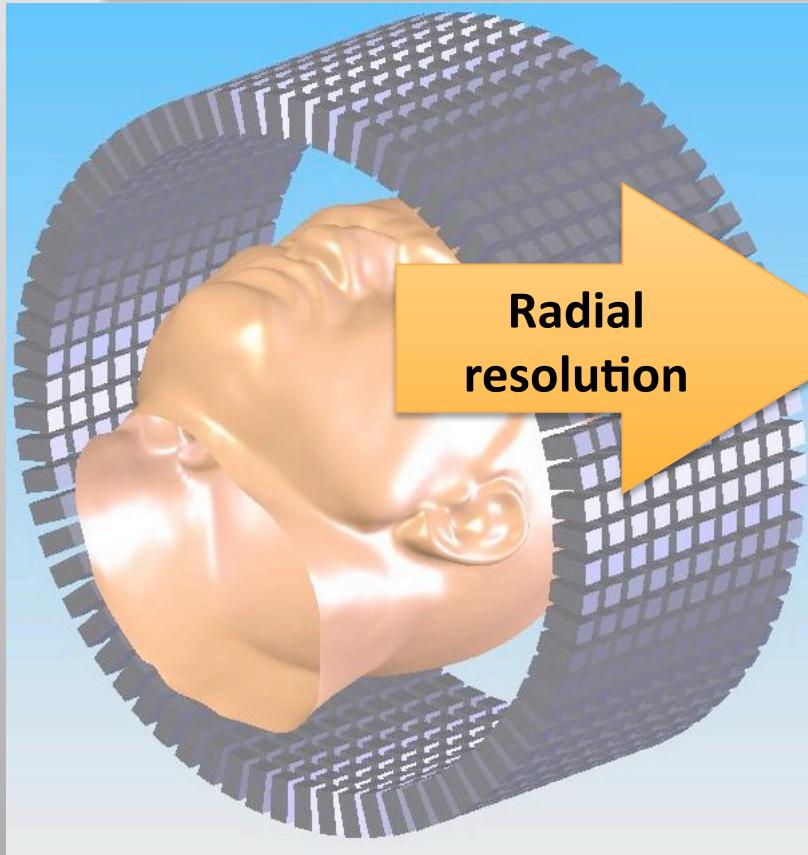
# General introduction



## PET: Positron Emission Tomography

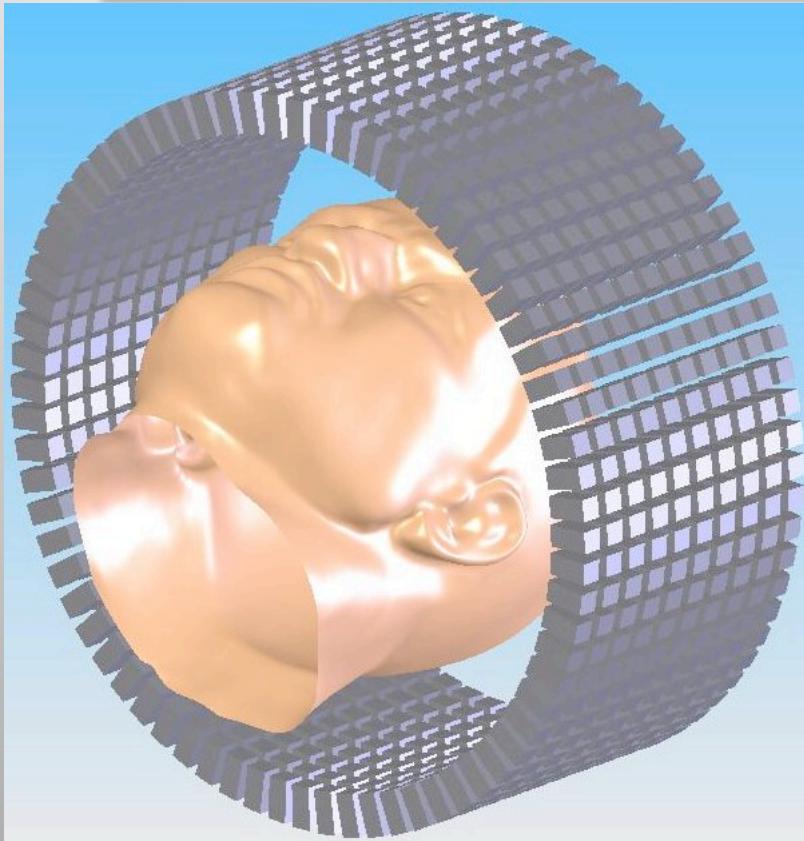


# The standard PET

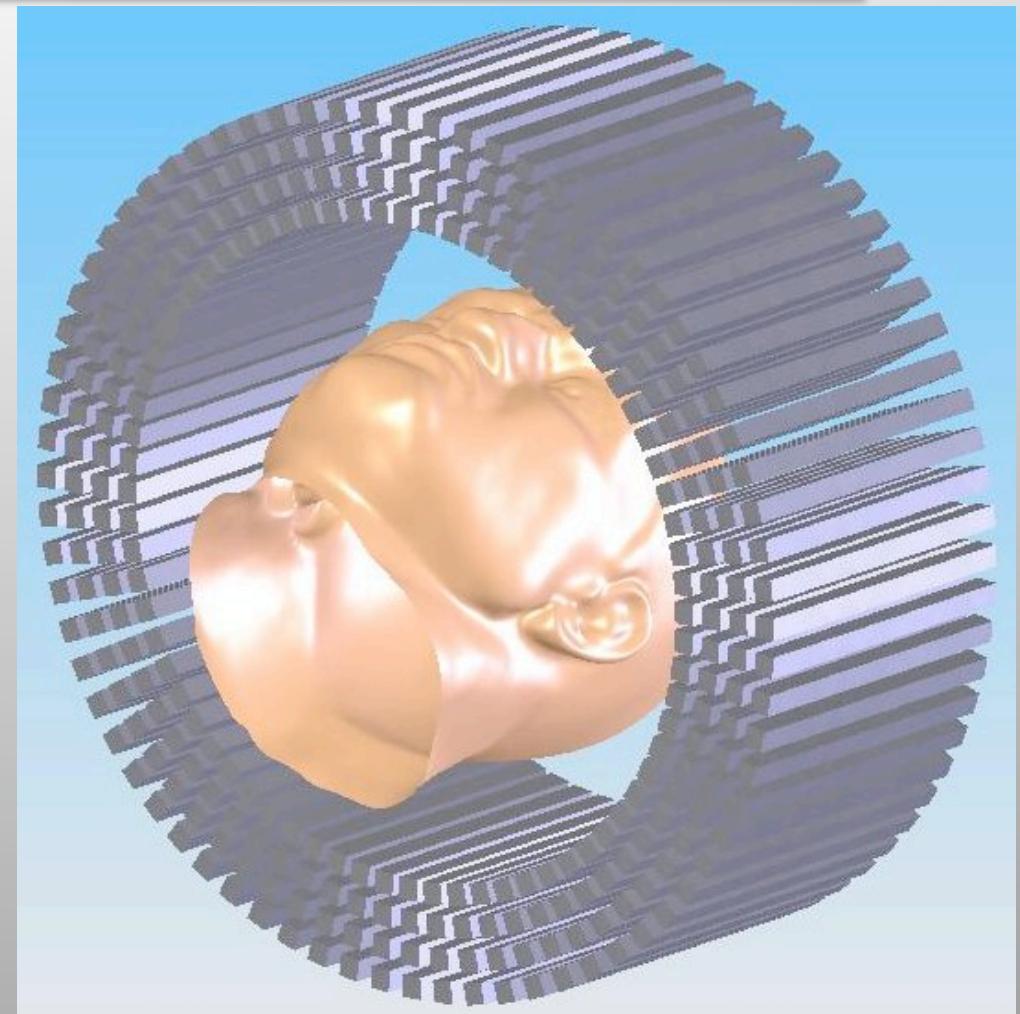


- Short, radially oriented crystals
- Readout in blocks by PMTs
- No Depth of Interaction  
(some exceptions)
- No Depth of Interaction knowledge  
→ Parallax error  $\delta_p = L \cdot \sin \alpha$
- Detection efficiency  $\varepsilon_2 = \left(1 - e^{-L/\lambda_a}\right)^2$

## *From PET to AX-PET*



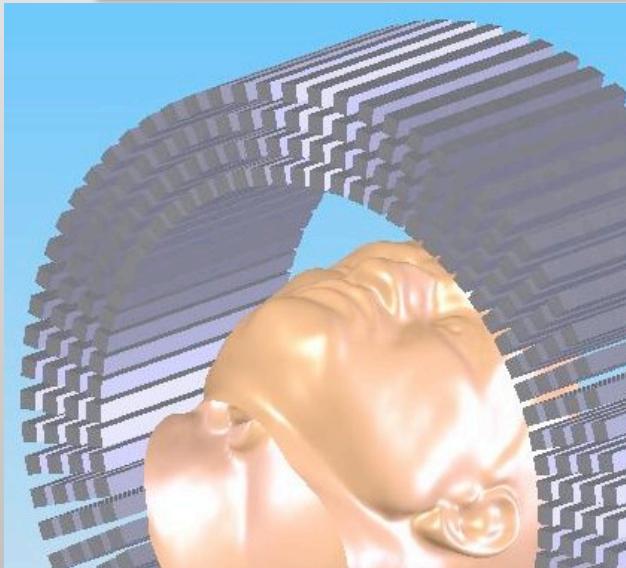
From short radial oriented,  
block readout  
crystals



... to long axially oriented,  
individually readout  
crystals

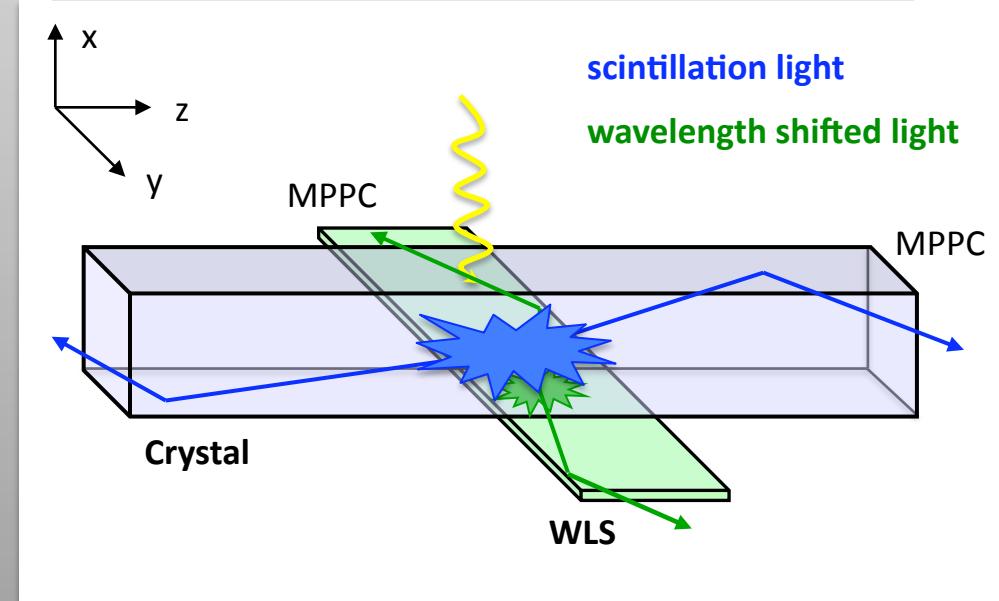
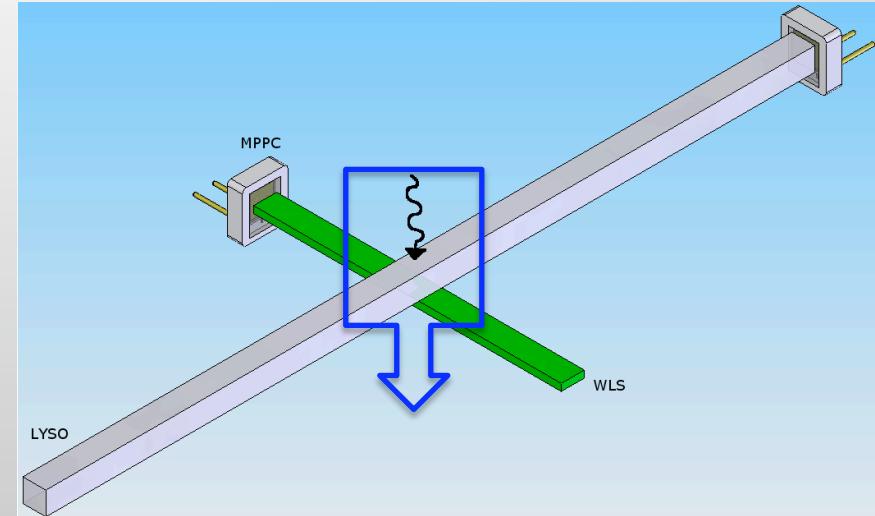
# *THE CONCEPT AND THE DEMONSTRATOR*

# The crystal+WLS “grid”

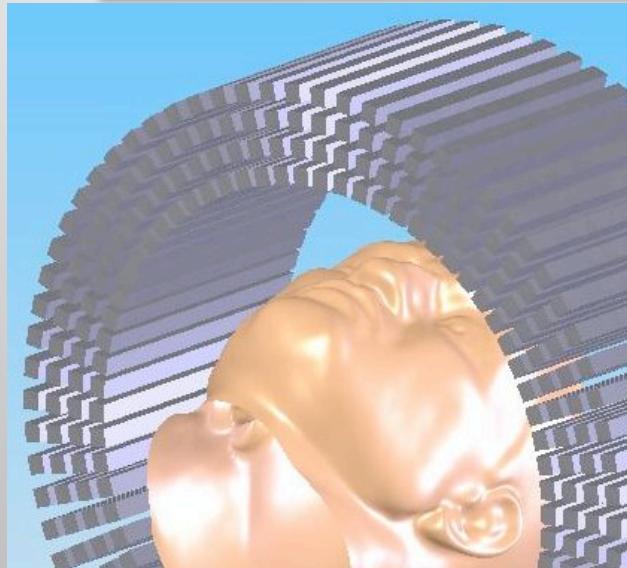


**How to measure  
the axial coordinate?**

- Light transport along the bars and the strips by means of **total internal reflection**
- Light detection
  - crystals: **energy** and **x,y-location**
  - WLS strips: **z-position** along the crystal

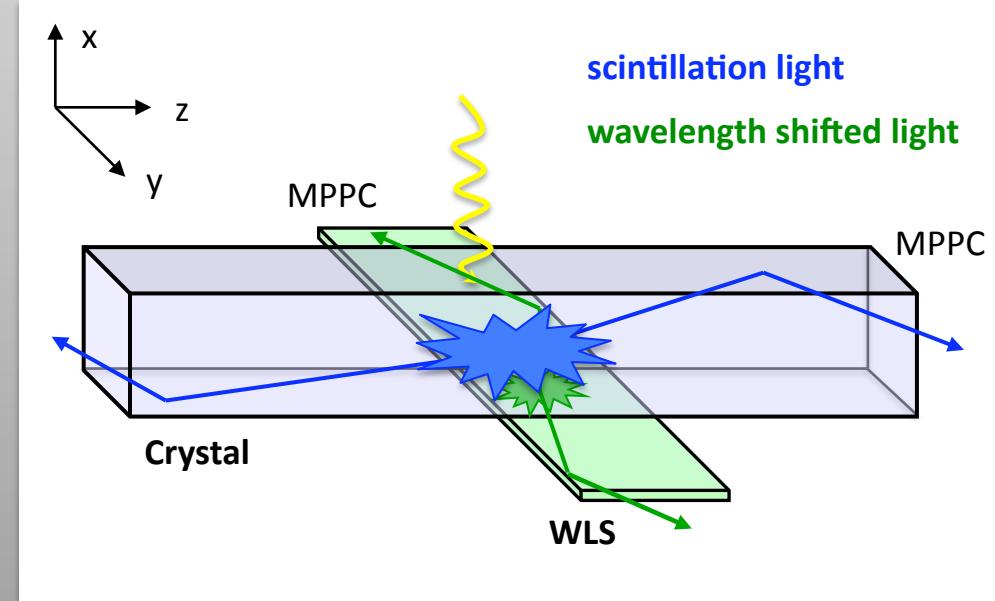
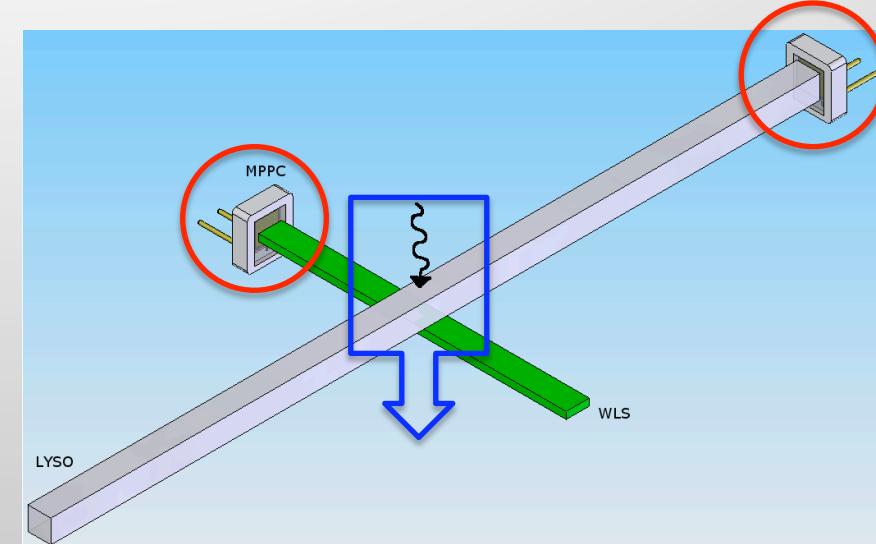


## The crystal+WLS “read out”



### How to read the crystals?

- Light detection by novel photo detectors **G-APD = MPPC = SiPM**
- High PDE: ~50%
- Very fast: <1 ns peaking time
- Immune to B-field (used in combination with MRI and CT)



# *The AX-PET components: LYSO*



**Crystal material:**

**LYSO**

**Manufacturer:**

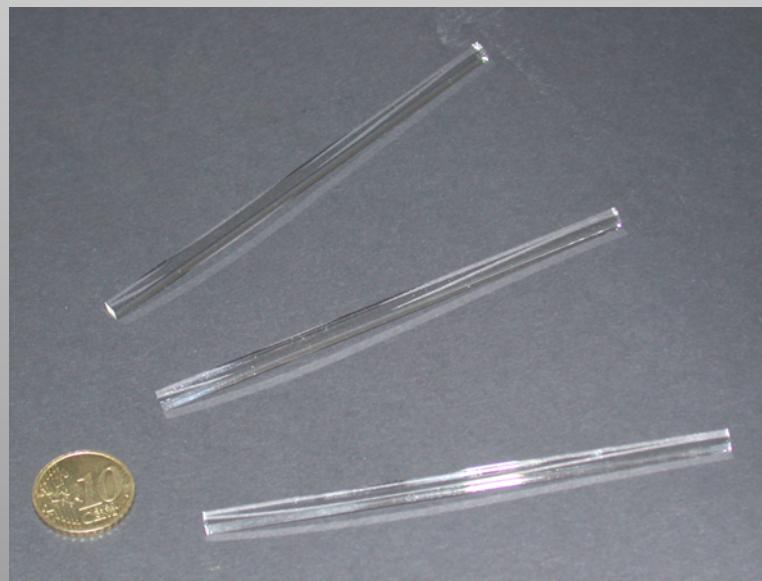
**Saint-Gobain**

**Dimensions:**

**3 × 3 × 100 mm<sup>3</sup>**

## **Prelude 420™**

- Chemical composition: Lu<sub>9</sub>YSiO<sub>25</sub>
- Non hygroscopic
- Density: 7.1 g/cm<sup>3</sup>
- Absorption length: 1.2 cm
- Peak emission spectrum: 420 nm
- Refraction index (420 nm): 1.81
- Light yield: 32 photons / keV
- Decay time: 41 ns, single exponential



# The AX-PET components: WLS



**WLS material:**

**Polyvinyltoluene + dopant**

**Manufacturer:**

**ELJEN Technology**

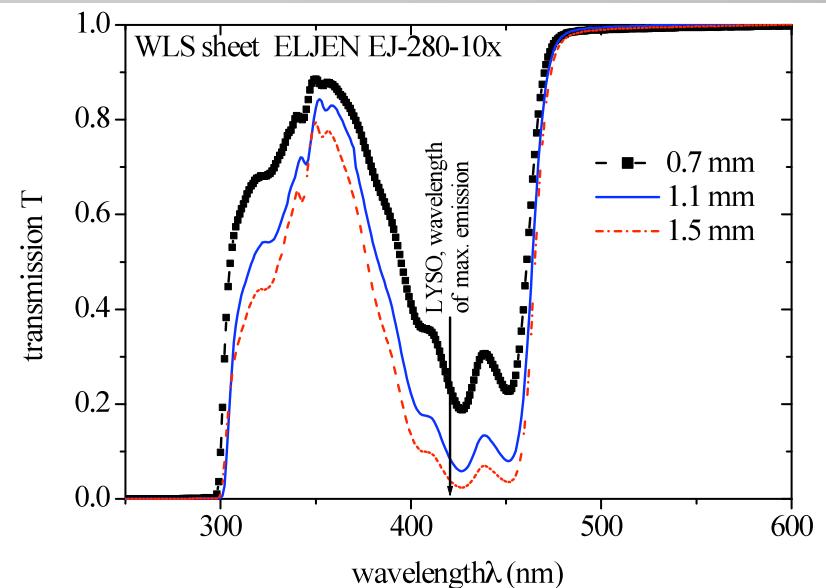
**Dimensions:**

**0.9 × 3 × 40 mm<sup>3</sup>**



## EJ 280

- Shifts blue light into green one
- Density: 1.023 g/cm<sup>3</sup>
- Maximum absorption: 425 nm
- Maximum emission: 490 nm
- Refraction index: 1.58
- Decay time: 8.5 ns
- QE (fluorescent material): 0.86%
- Doping: 10x with respect to standard



# *The AX-PET components: photo detectors*



MPPC

Manufacturer: Hamamatsu

Operational voltage: ~70 V

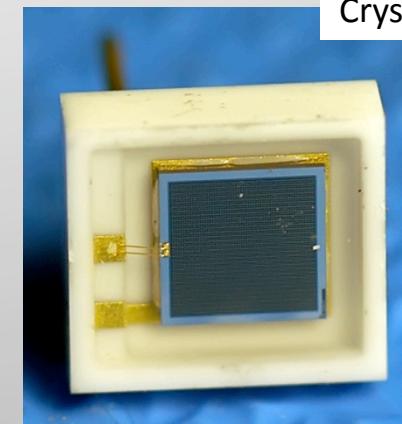
**MPPC LYSO: S10362-33-50-C**

active area:  $3 \times 3 \text{ mm}^2$

3600 pixels of  $50 \times 50 \mu\text{m}^2$

Gain:  $5.7 \times 10^5$

Ceramic package  $5.9 \times 6.6 \text{ mm}^2$



Crystal readout

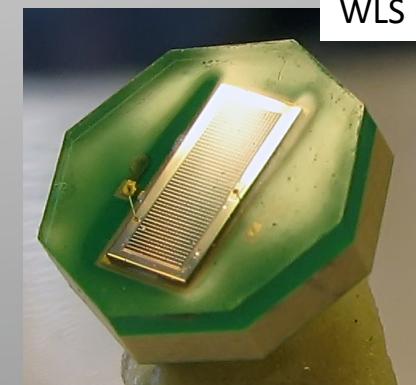
**MPPC WLS: MPPC-OCTAGON-SMD  
custom made**

active area:  $3.22 \times 1.19 \text{ mm}^2$

1200 pixels of  $70 \times 70 \mu\text{m}^2$

Gain:  $4 \times 10^5$

Octagonal plastic package



WLS readout

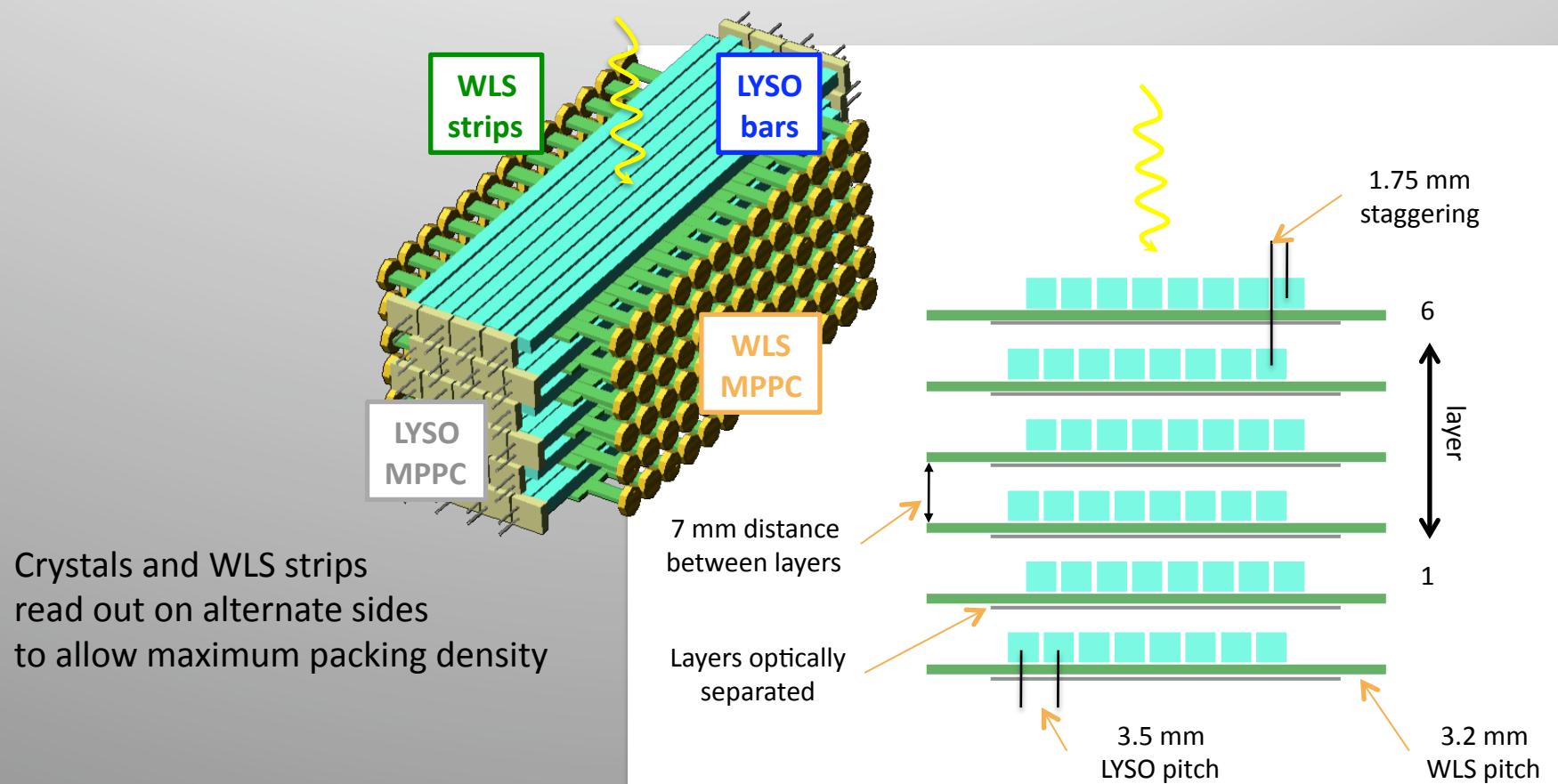
# The Demonstrator



- **Two identical modules.** Each module:

- 48 LYSO bars (6 layers x 8 crystals)
- 156 WLS strips (6 layers x 26 strips)

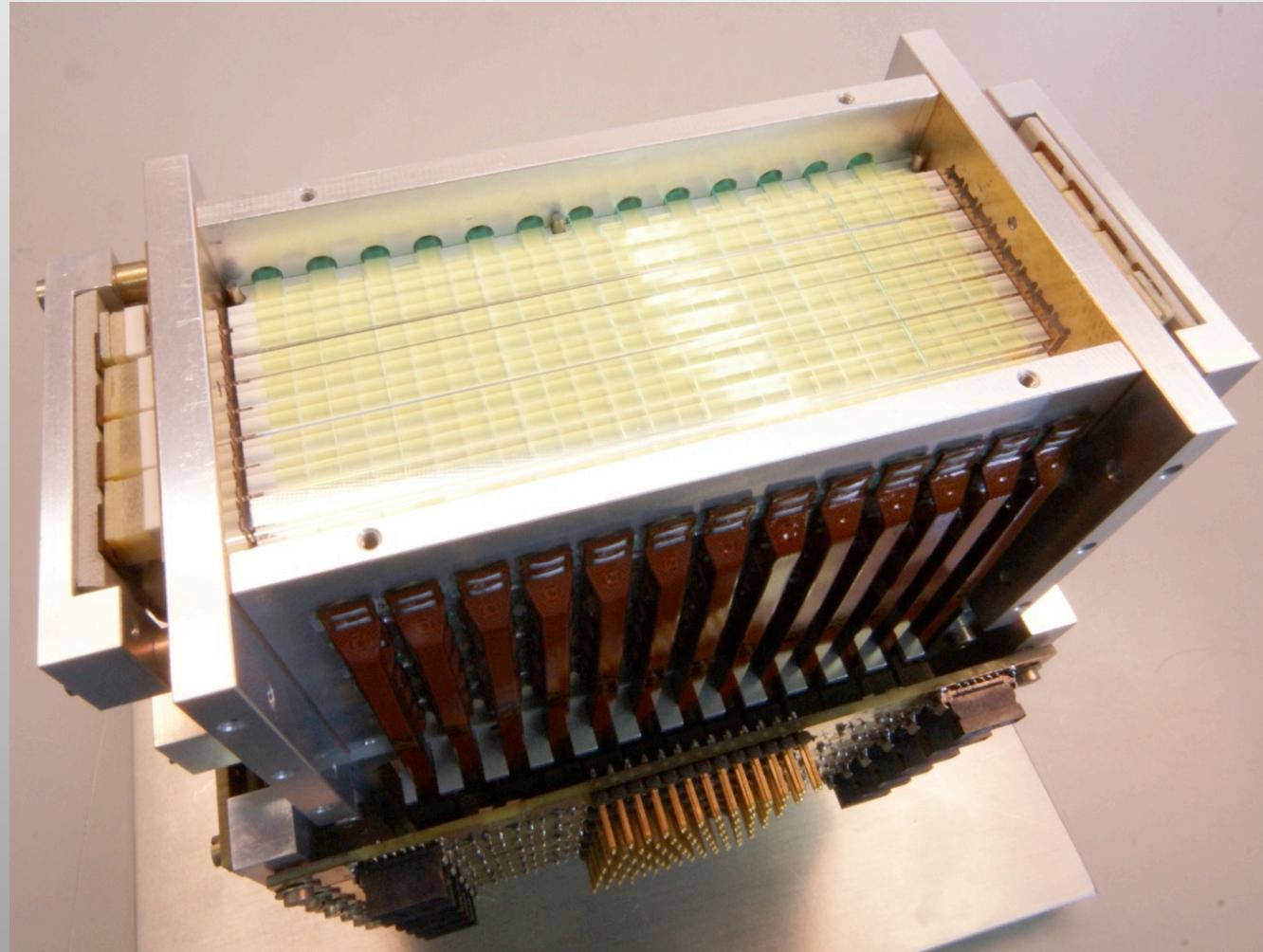
} 2 modules -> 408 channels



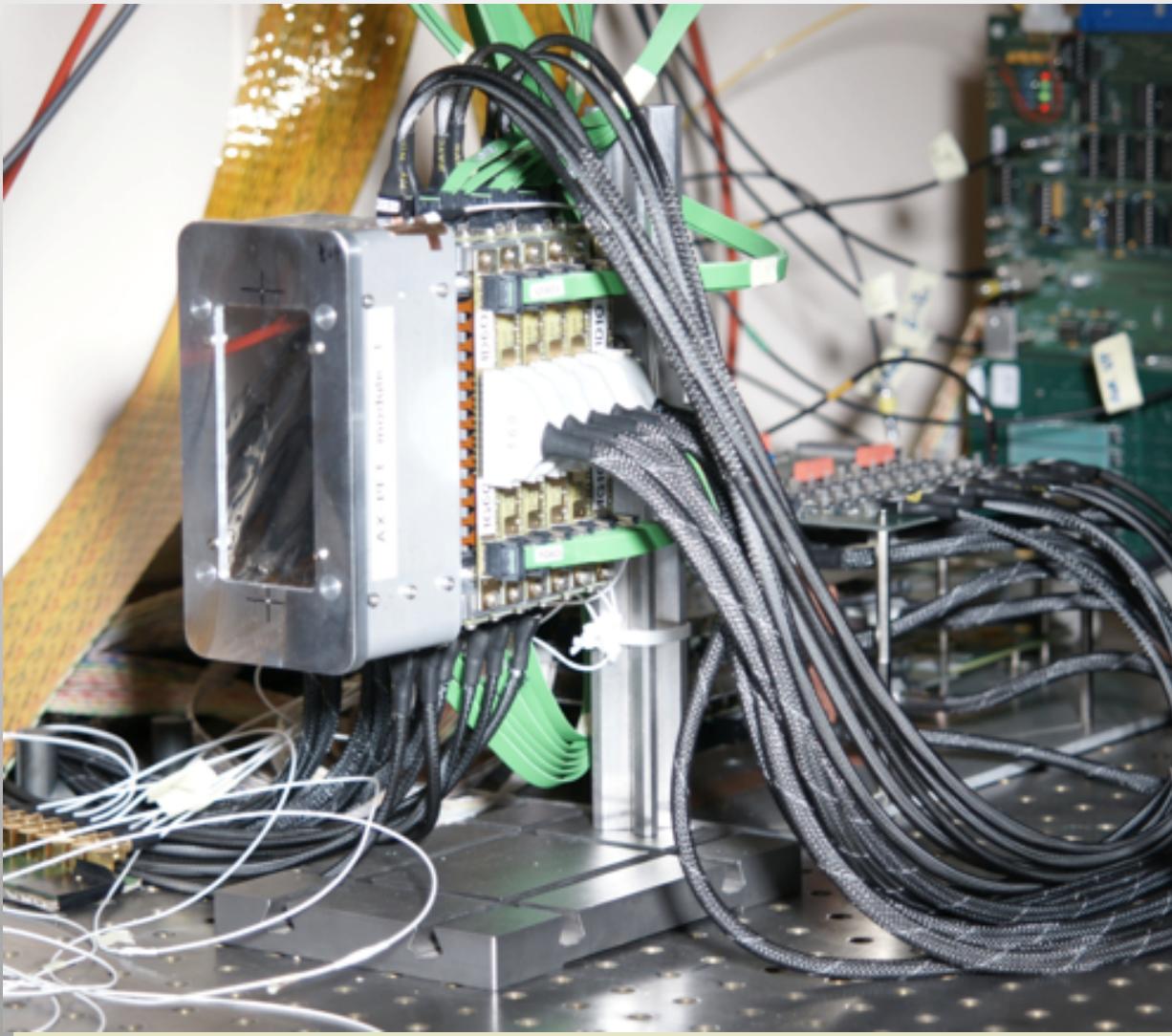
# *Putting everything together*



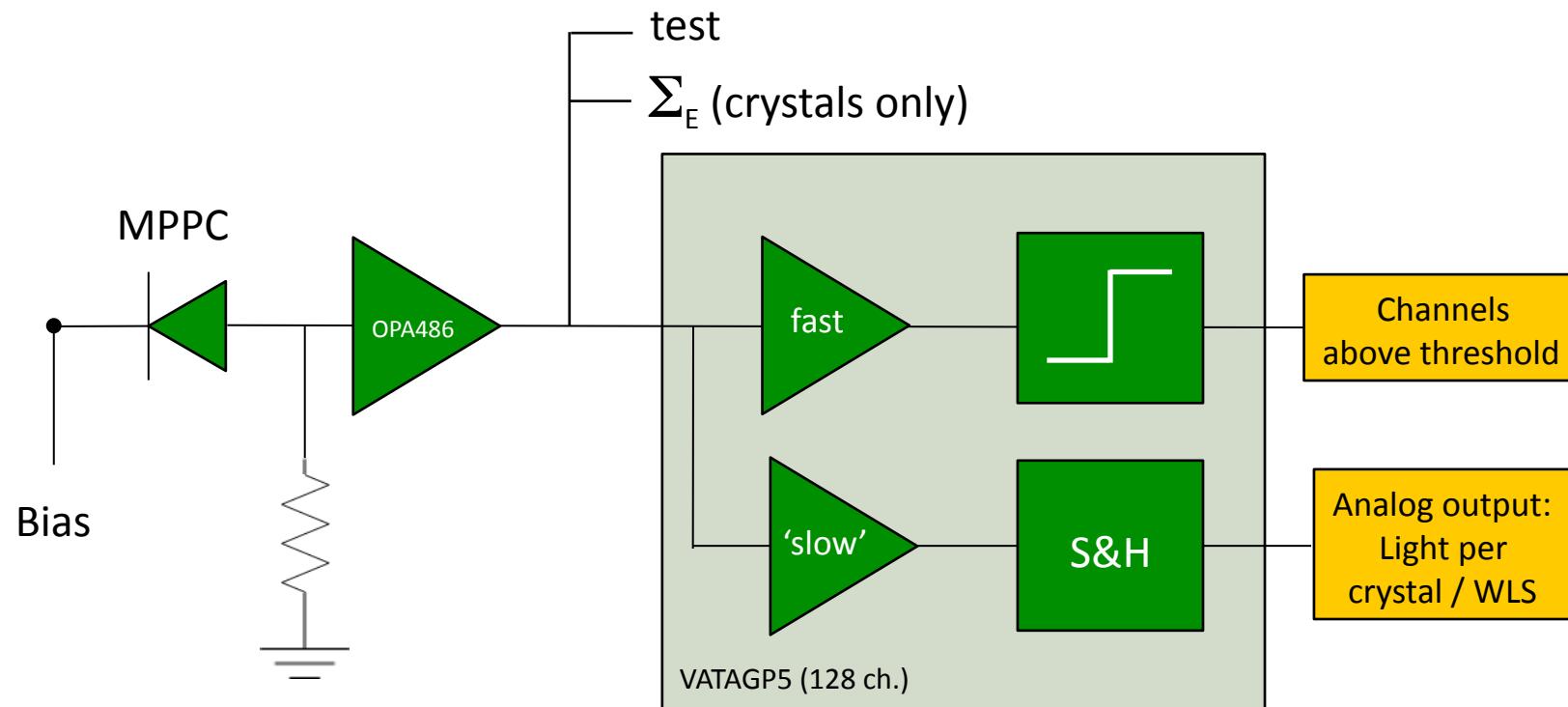
## *Fully assembled module*



*... with light protection cover and cables*



# Front-End electronics



- **Analog readout** of crystals and WLS strips
- Sequential or sparse (only channels above threshold)
- **Fast energy sum** of all crystals of 1 module
- Trigger on  $2 \times 511$  keV deposition in 2 modules



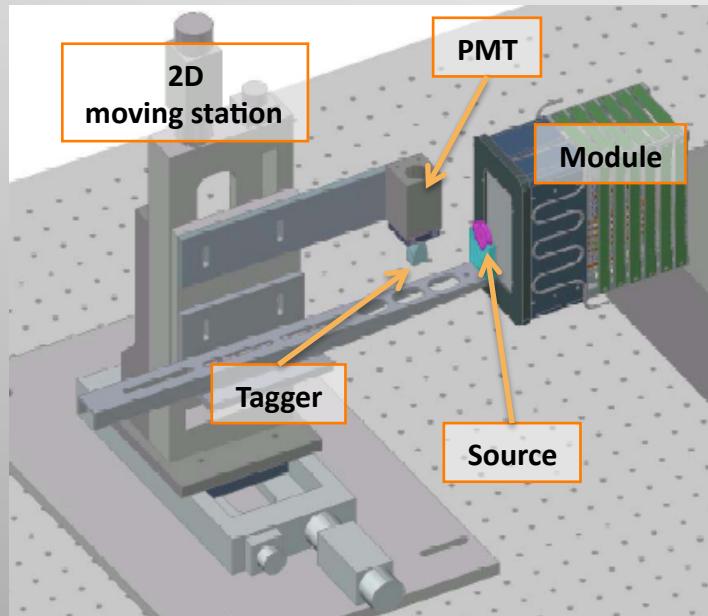
## *CHARACTERIZATION*

# Test set up

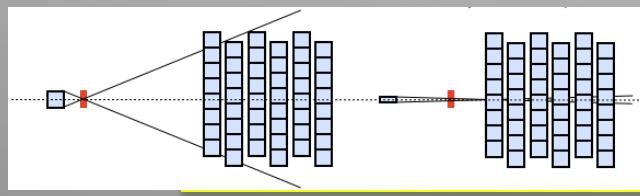


$^{22}\text{Na}$  source ( $\phi = 250\mu\text{m}$ ;  $A = \sim 900 \text{ kBq}$ )

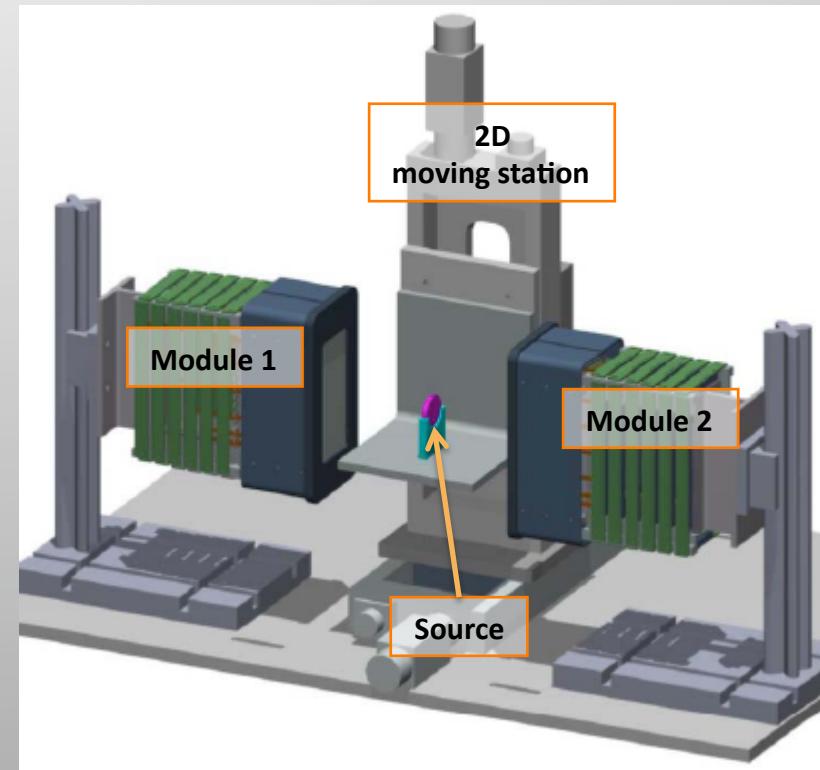
Single module characterization



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



Two module characterization



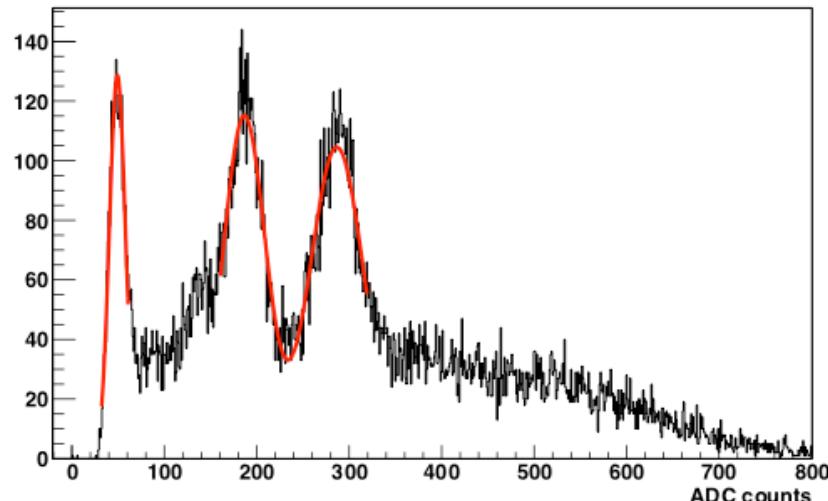
- Distance between modules = 15 cm

# Energy calibration

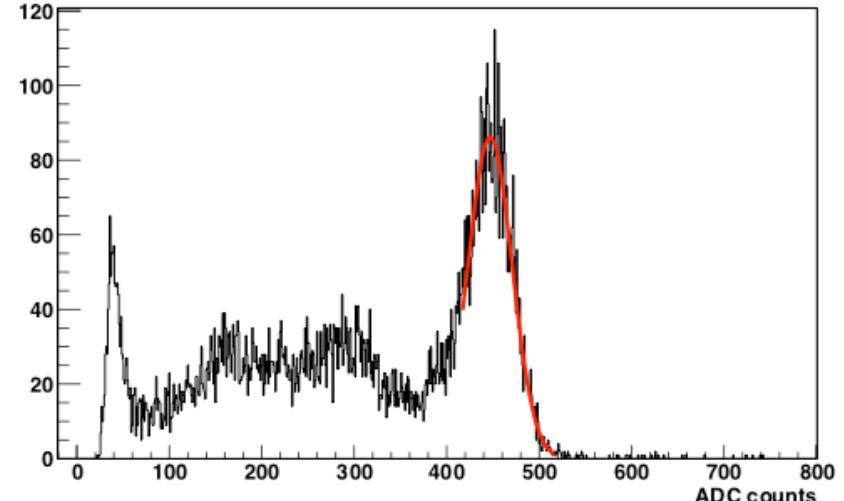


Intrinsic Lu radioactivity + Photopeak → “self-calibrating” device

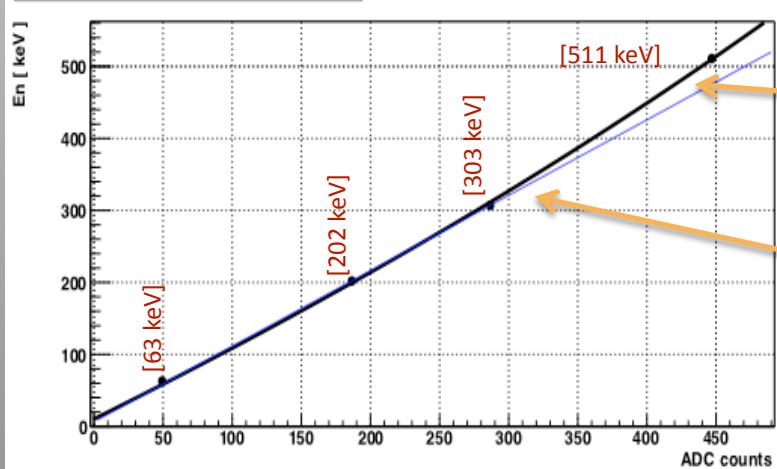
LYSO No. 21 - intrinsic radioactivity



LYSO No. 21 -  $^{22}\text{Na}$  coinc. trigger



Calibration:  $En$  vs  $ADC$  - LYSO21



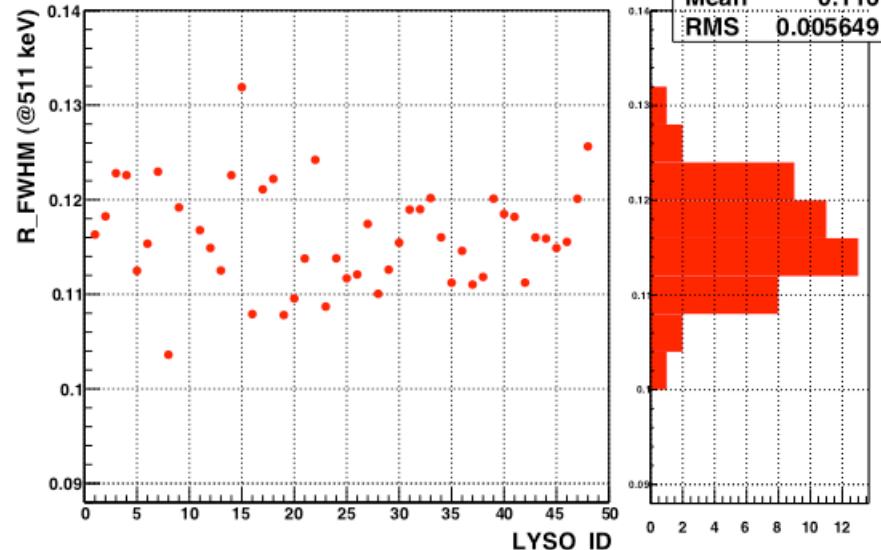
- Deviation from linearity due to MPPC saturation (3600 pixels), ~5% effect
- Parameterization: logarithmic function

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

# Energy resolution



LYSO Energy resolution

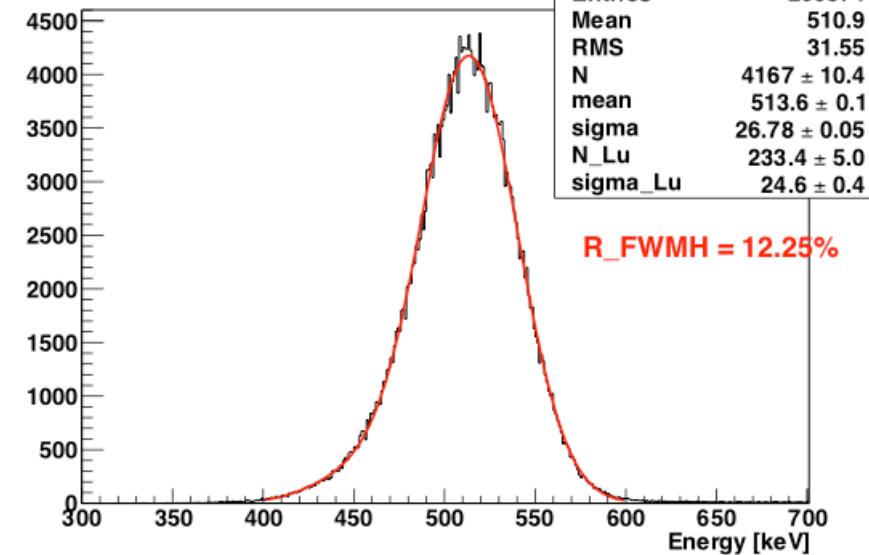


Sum signal (48 crystals)  
R\_FWHM\_Sum ~12.25% @511 keV  
(on the summed distribution)

## Individual crystals:

$\langle R_{FWHM} \rangle \sim 11.6\% @ 511 \text{ keV}$   
(averaged on all crystals)

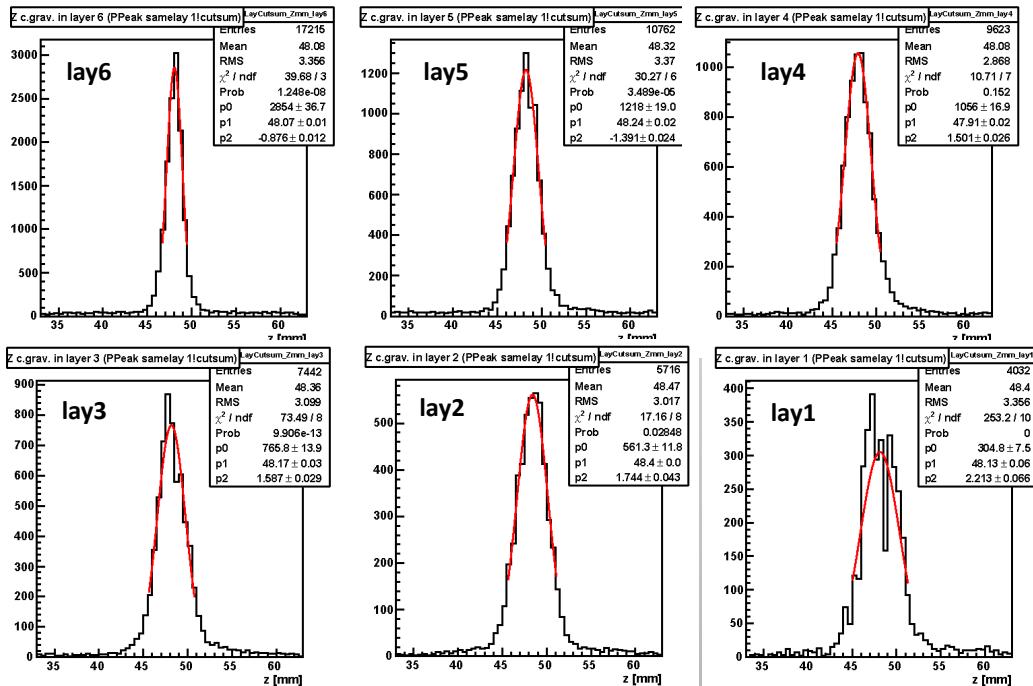
LYSO Sum



# Axial (z) resolution



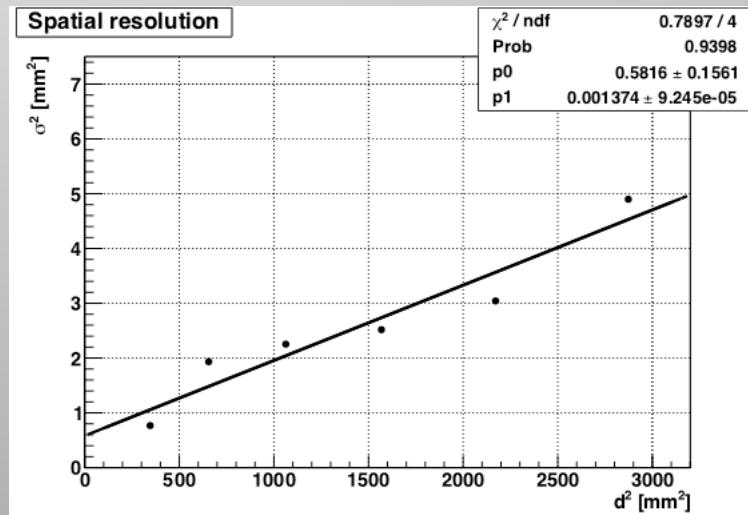
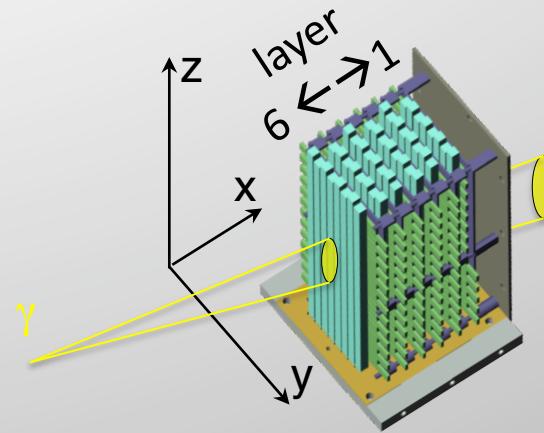
$z$  coordinate = CofG of hit WLS strips (typically 2-4)



$\sigma_i$  [ $i=1,6$ ] include:

- intrinsic spatial resolution
- beam spot size on each layer

$$\sigma_i^2 = \sigma_{i,\text{beam}}^2 + \sigma_{Z-\text{res}}^2$$

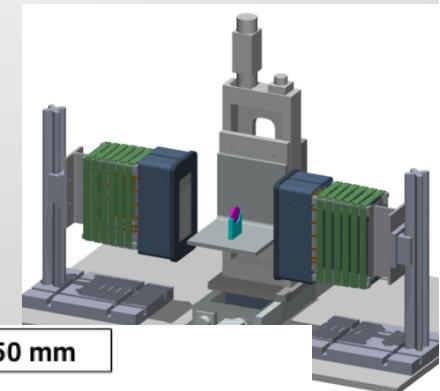


$\sigma(d=0) \sim 0.76 \text{ mm}$   
FWHM  $\sim 1.8 \text{ mm}$   
(still includes size of source)

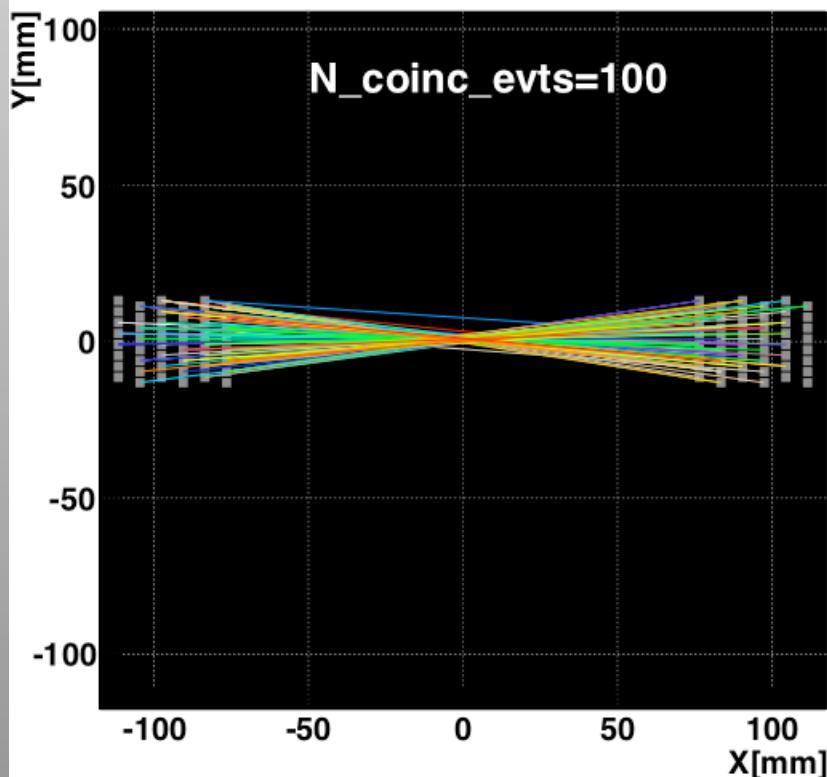
# *First coincidence measurements*



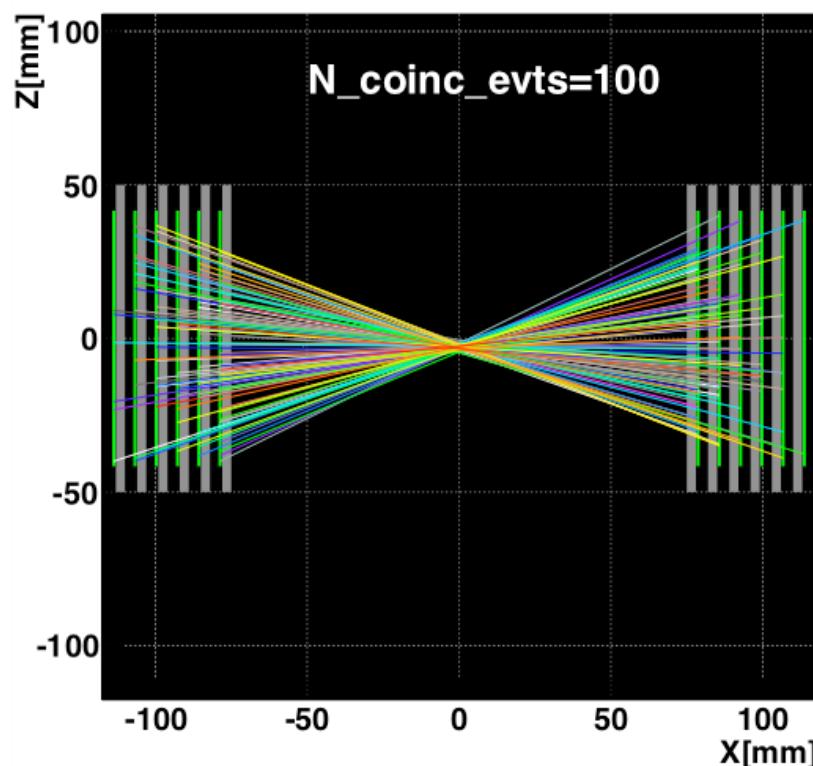
- Photoelectric events only (1 hit crystal per module)
- Draw “LOR” (pure geometrical)



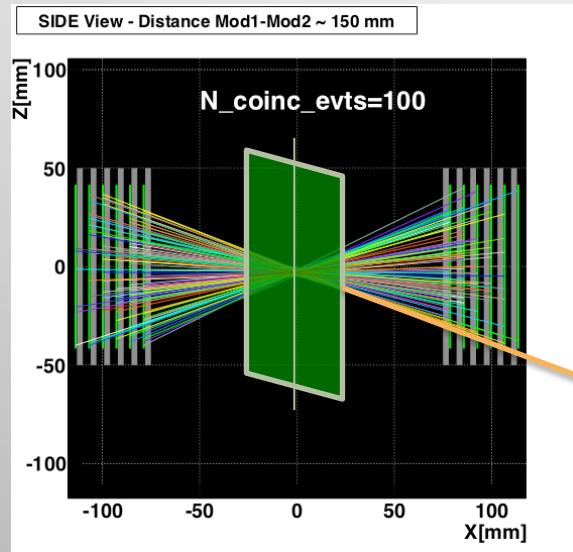
TOP View - Distance Mod1-Mod2 ~ 150 mm



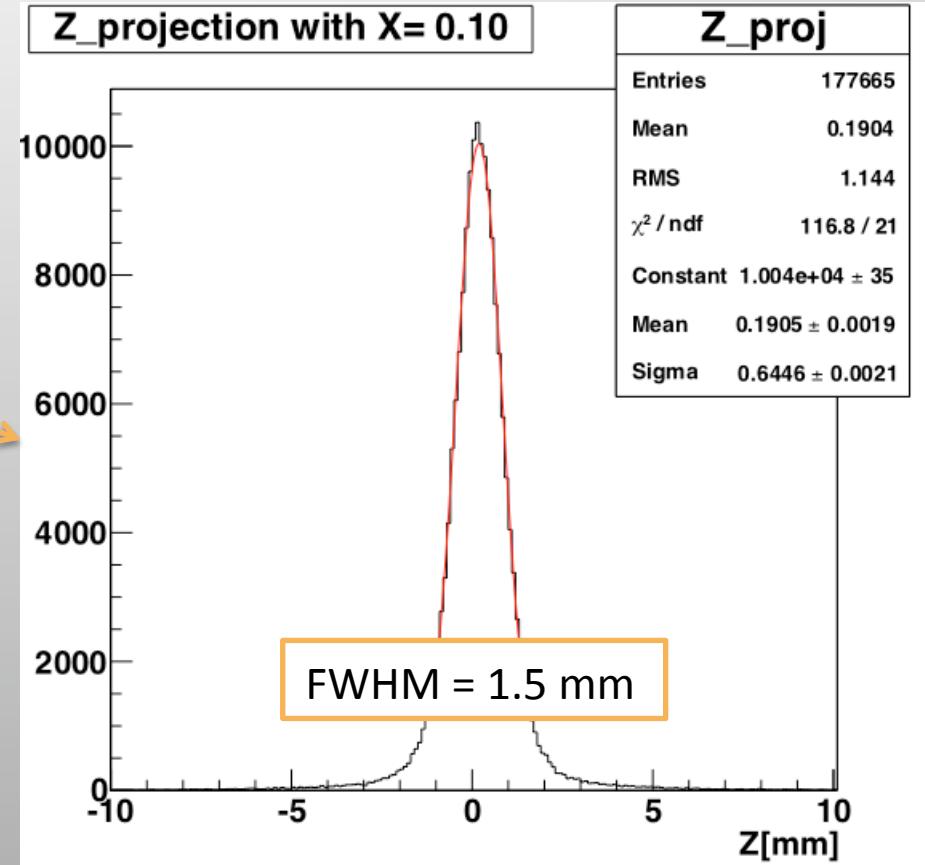
SIDE View - Distance Mod1-Mod2 ~ 150 mm



# *Estimate of axial resolution*



Intersection  
with central plane



Resolution still includes size of source.  
Finite positron range  
(in water:  $\langle \text{range} \rangle = 0.6 \text{ mm}$ )

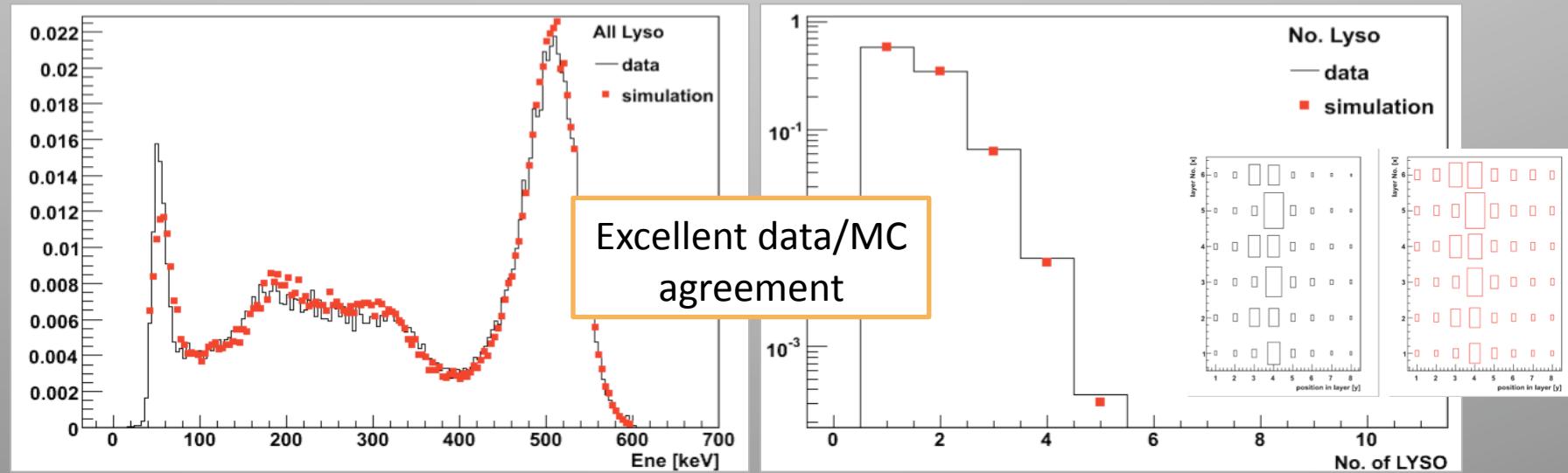
## ***SIMULATION AND RECONSTRUCTION***

# *Simulation*



- **Geant4**: multi-purpose Monte Carlo tool  
(optical transport, dedicated geometry)
  - **GATE**: PET dedicated MC  
(time dependent phenomena, scanner rotation,  
source/phantoms...)

Energy -  $E_{\text{LOW}}=40 \text{ keV}$ ,  $E_{\text{SUM}}=[400,600] \text{ keV}$

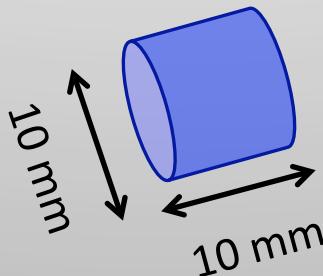


# Reconstruction



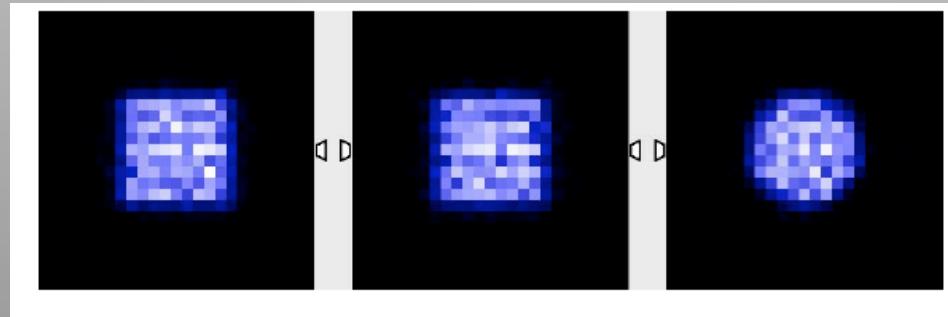
- Dedicated reconstruction code, based on MLEM (Maximum Likelihood Expectation Maximization)
- Geometrical component of the System Matrix computed using Siddon's ray-tracing technique. In addition, crystal attenuation and penetration effects also taken into account in the System Matrix
- Code tested with several Monte Carlo phantoms

**Monte Carlo data  
for a cylindrical source:**  
 $D = 10 \text{ mm}$ ,  $h = 10 \text{ mm}$



- FOV:  $25 \times 25 \times 25 \text{ mm}^3$
- Voxel:  $25 \times 25 \times 25 \text{ vox}^3$
- #steps = 6
- Distance = 10 cm

Projections (x, y, z)



3D image



# SUMMARY

+

# *NEXT STEPS AND FUTURE PLANS*

## *Summarizing the AX-PET main features*



- 3D localization of photons **parallax-free**
- Optimization of **spatial resolution** (reducing crystal and WLS strip dimensions) and **sensitivity** (adding layers) can be done independently.
- Possibility of identification a significant fraction of **Compton interactions** (**Inter Crystal Scatter**).  
ICS events can either be discarded (**resolution fully maintained**) or reconstructed (**increased sensitivity**).
- Scaling in **size** and **number of layers** to match specific needs: brain PET, small animal PET, PEM (mammography), full body PET.
- Concept and components are in principle MRI compatible and TOF extendable.

# *What's next*



## **At CERN**

- Mount set-up on a horizontal gantry (rotating source + 1 module rotation +/- 60°)

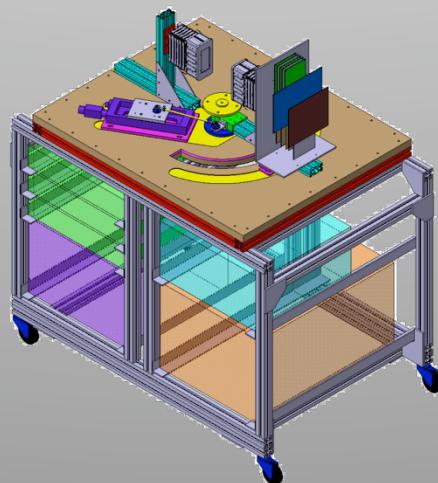
## **At ETH Zurich** in cooperation with Centre for radio-pharmaceutical Science

April 2010

- Tomographic reconstruction of small animal phantoms (FDG)
- Optimization of Monte Carlo and reconstruction code

## **Time scale 1 year**

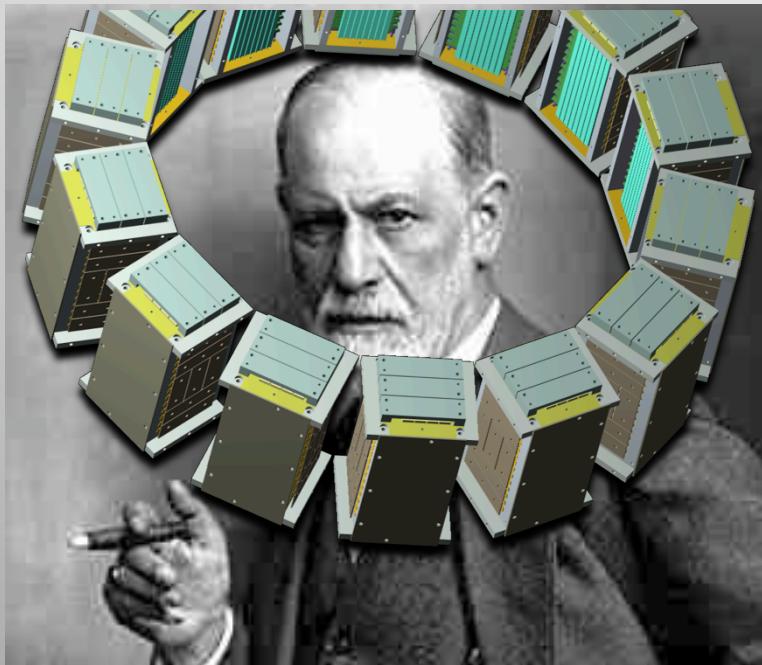
- Performance extrapolation (Monte Carlo) to full scanner and specific geometries



# *AX-PET a novel concept for ...*



brain



small animals



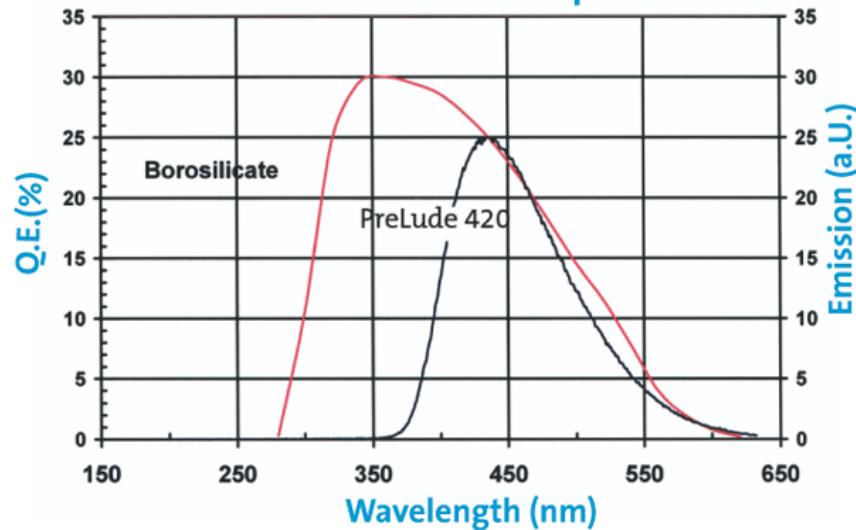
**THANKS FOR YOUR ATTENTION**



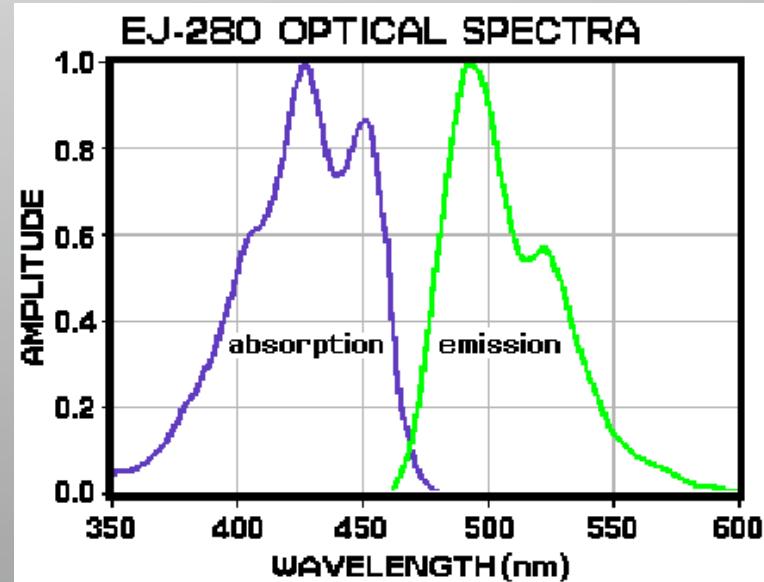
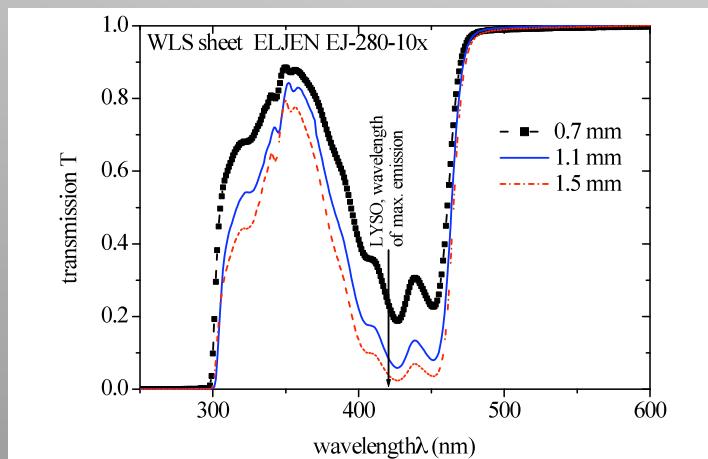
## ***BACK-UP SLIDES***

# LYSO and WLS

PreLude 420 Emission Spectrum



Density [g/cm <sup>3</sup> ]	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/cm <sup>3</sup> ]	~300
Effective optical absorption length [mm]	~420



## Preamplifiers

- Fast operational amplifiers (~1 GHZ gain x bandwidth)
- 50 ohm input impedance
- ~50 cm away from the modules, co-axial cables ( $50 \Omega$ )

## Sum signals of one module

- Coincidence Trigger

## DAQ... VATA GP5

- 128 channel charge integrating amplifier (64 channel used)
- Shaping time  $\sim 250$  ns
- Fast shaper  $\sim 40$  ns plus discriminators  
→ self triggering
- Hit register  
→ sparse mode readout

## Bias supply (custom designed)

- 256 channels (from 0 to 100 V)
  - AD5535; 32 channel HV DAC
  - Precision  $\sim 10$  mV
- after individual calibration of all channels
- USB interface

## Coincidence Trigger

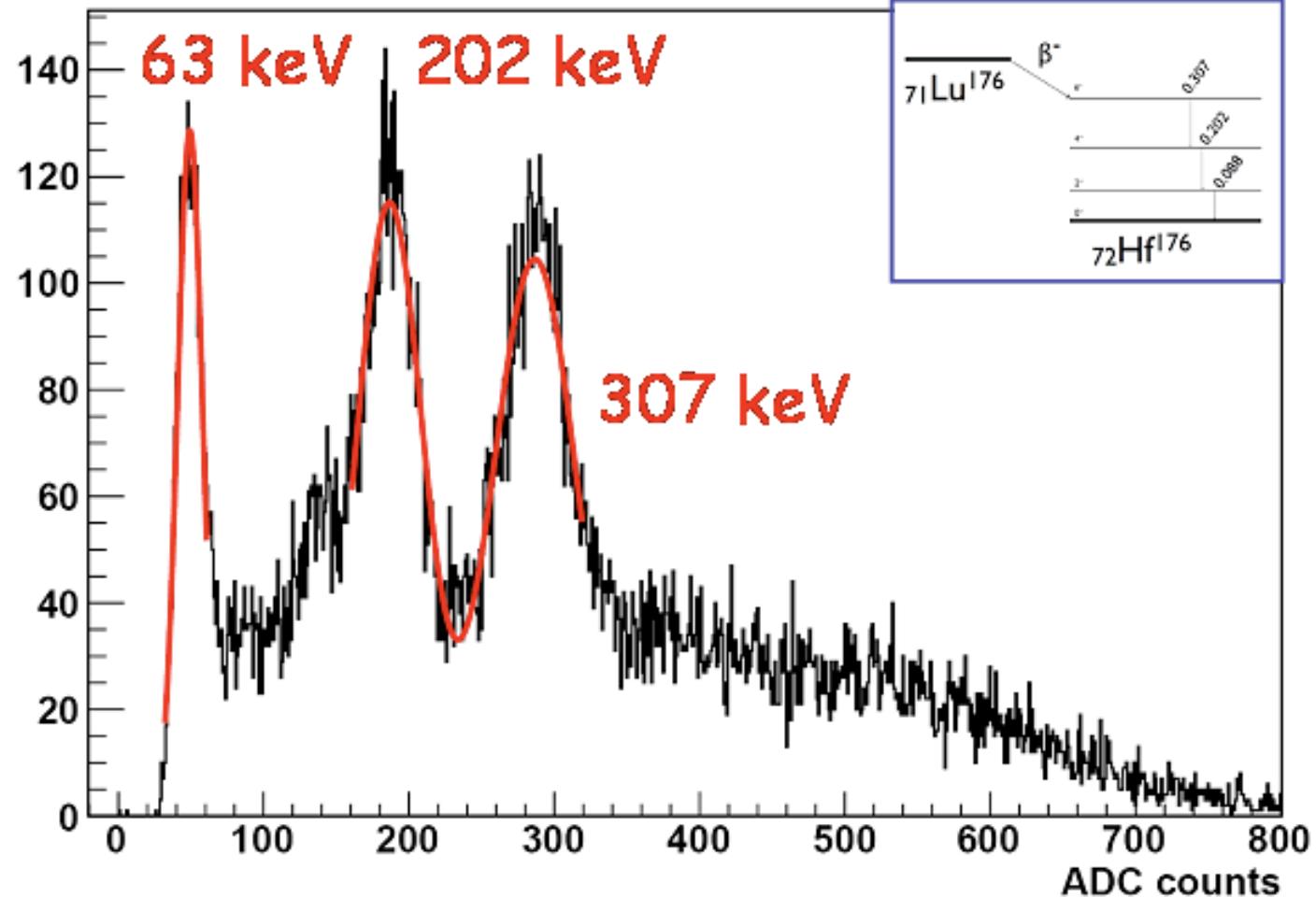
- Coincidence of sum of module signals with the other module
- Thresholds set using oscilloscope
- $e^+e^-$  annihilation events

## Self Triggering VATA GP5

- Moderate threshold  
→ LYSO intrinsic radioactivity
- Low threshold  
→ pedestal measurement

- **2 modules - dist = 15 cm : Multiplicities and Efficiencies**
  - Photopeak events (“1-1”) ~ 44 %
  - Events with 2 hits on 2 different layers in one of the 2 modules, 1 hit in the other (“1-2diff” or “2diff-1”) i.e. **candidate for ICS reconstruction** ~ 24%
  - **Efficiency of golden events** (photopeak, good cluster found) ~ 36%
    - cluster finding efficiency on single module (normalized on Evt with 1 LYSO) ~ 82 %
    - used to be ~ 97% on the single module setup

## LYSO No. 21 - intrinsic radioactivity



# Energy calibration



Fit a double Gaussian distribution to the sum of the energy depositions of all crystals of one module with mean values:

- $E_p$  = photo peak energy
- $E_p - 63$  keV  
to take into account the Lutheum  $K_{\alpha}$  escape line at 63 keV

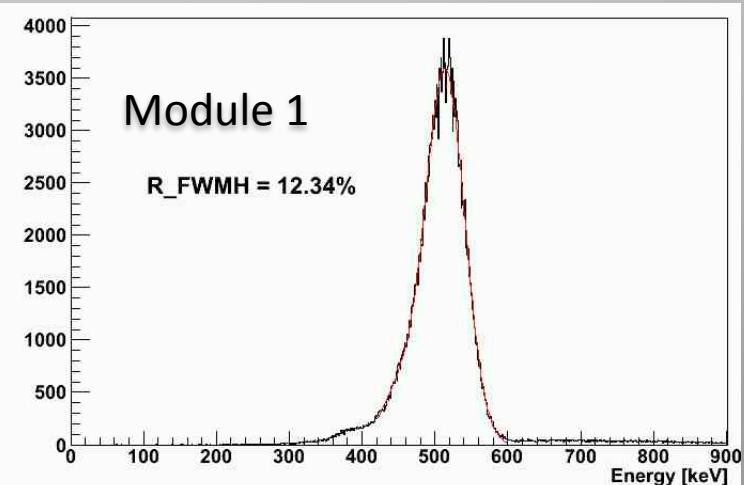
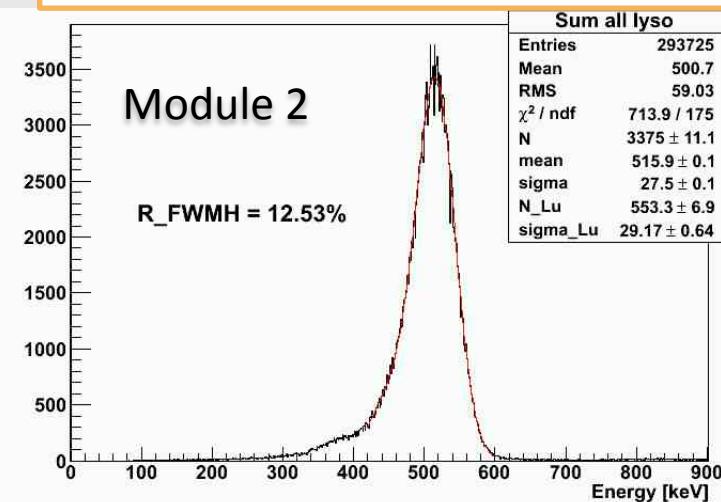
Energy resolution:

- 12.34% FWHM (Module 1)
- 12.53% FWHM (Module 2)

Peak Position:

- $(511.7 \pm 0.6)$  keV (Module 1)
- $(511.8 \pm 0.6)$  keV (Module 2)

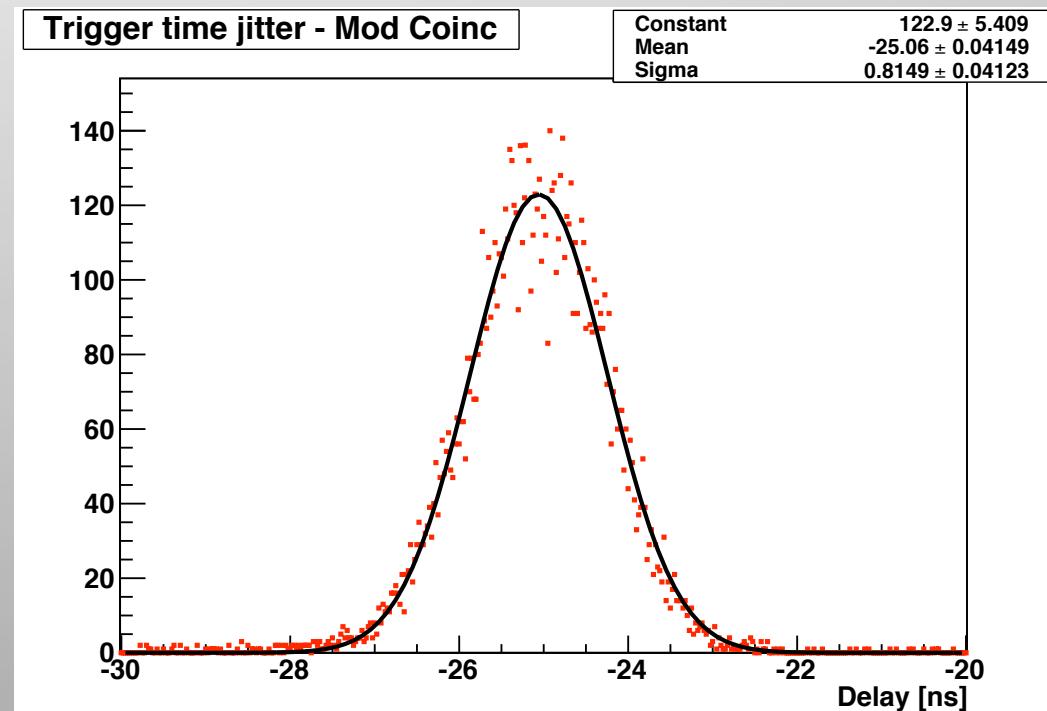
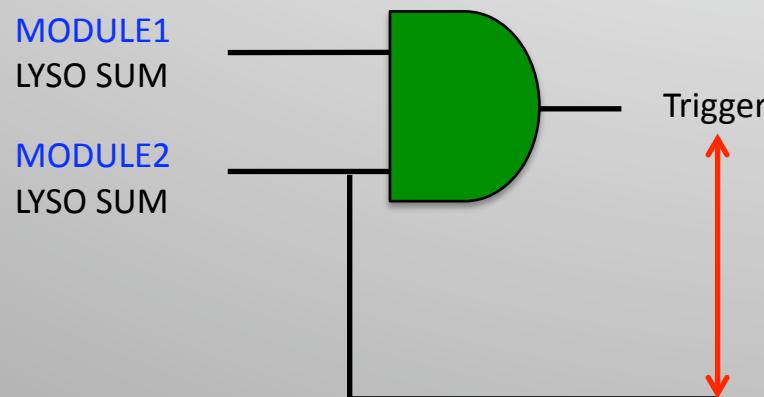
Sum of energy depositions  
in crystals of one module



# Time performances

**First estimate of the time resolution:**

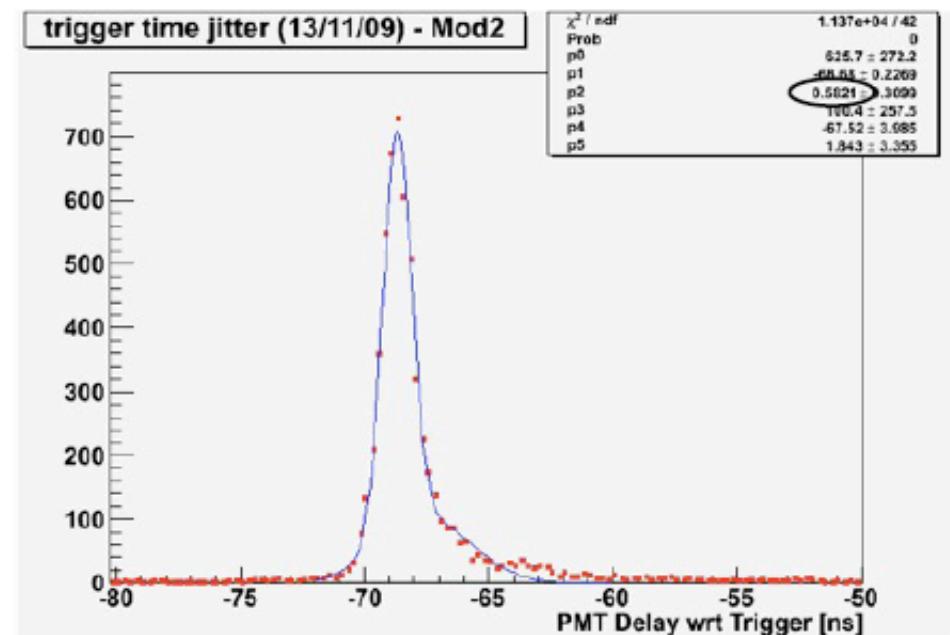
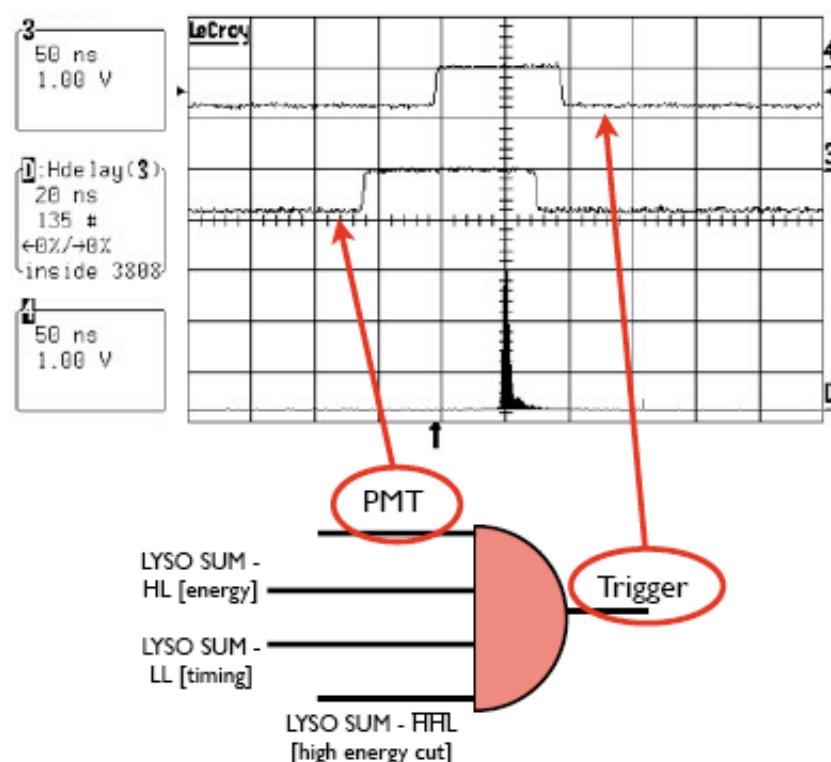
- measure delay of coincidence wrt Module2
- measurement from the scope [Lecroy Waverunner LT584 L 1GHz]



Time resolution :  $\sigma \sim 800$  ps

## First estimate of the time resolution :

- measure delay of coincidence (i.e. DAQ trigger) wrt PMT tagger
- measurement from the scope [Lecroy Waverunner LT584 L 1GHz]
- delay = “ time from the trigger (or t=0) to the first 50% transition”



time jitter :  $\sigma \sim 0.6$  ns