The AX-PET experiment:
A demonstrator for an axial Positron Emission Tomography

AX-PET

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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A demonstrator for an axial Positron Emission Tomography

Chiara Casella, ETH Zurich

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Outline

AX-PET : **AX**ial **P**ositron **E**mission **T**omography (PET)

- **PET** (Positron Emission Tomography)
- **Axial concept**
  high spatial resolution and high sensitivity solution
- **AX-PET detector**
- **AX-PET detector performance**
- **AX-PET simulations**
- **Image reconstructions** (few examples)

AX-PET : small size calorimeter, using scintillating crystals, WLS, photodetectors "borrowed" from HEP

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Positron Emission Tomography

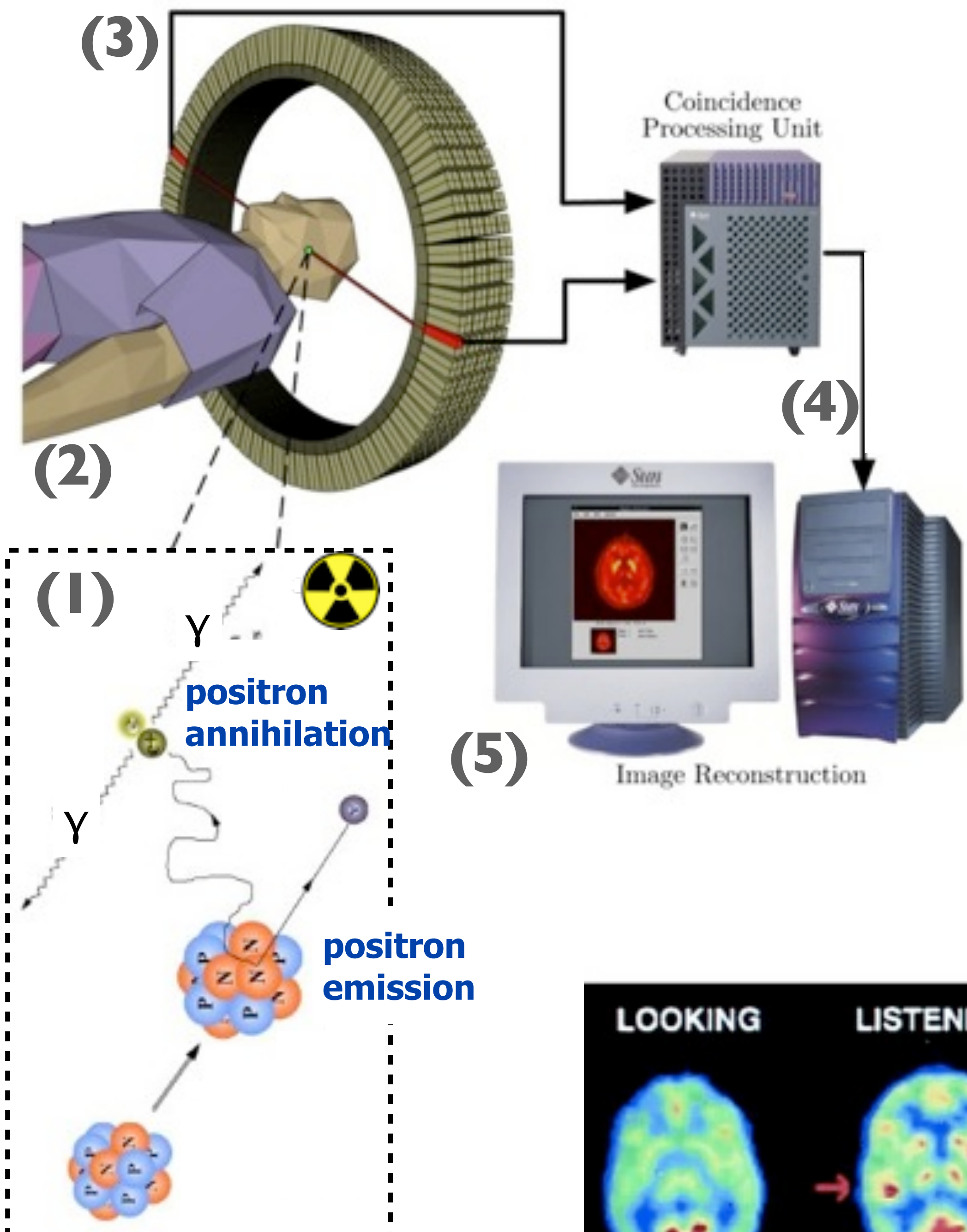
AX-PET

- PET : **"in-vivo" functional imaging** technique in nuclear medicine

Positron Emission : $p \rightarrow n + e^{+} + \nu_e$

Positron Annihilation : $e^{+}e^{-} \rightarrow \gamma\gamma$

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



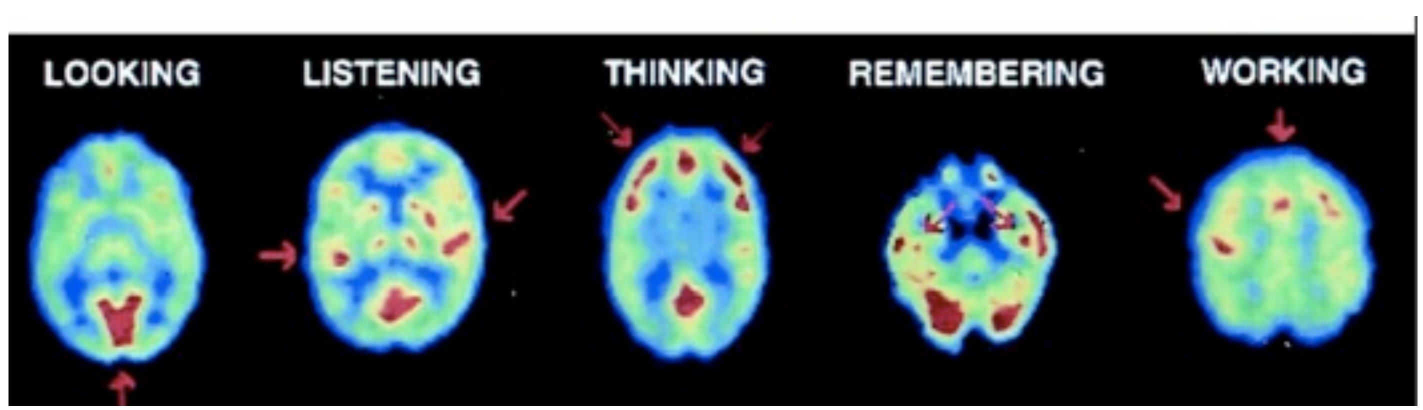
(1) Inject the **radiotracer into the body**
radiotracer : biologically active compound mixed to the positron emitter.

(2) Wait for uptaking period

(3) Start the acquisition (i.e. **detection of coinc. events**)
clear event signature : coincidence of 2 photons of known energy (511 keV) emitted co-linearly

(4) Feed the data into the reconstruction algorithms

(5) **image** of the **activity concentration**

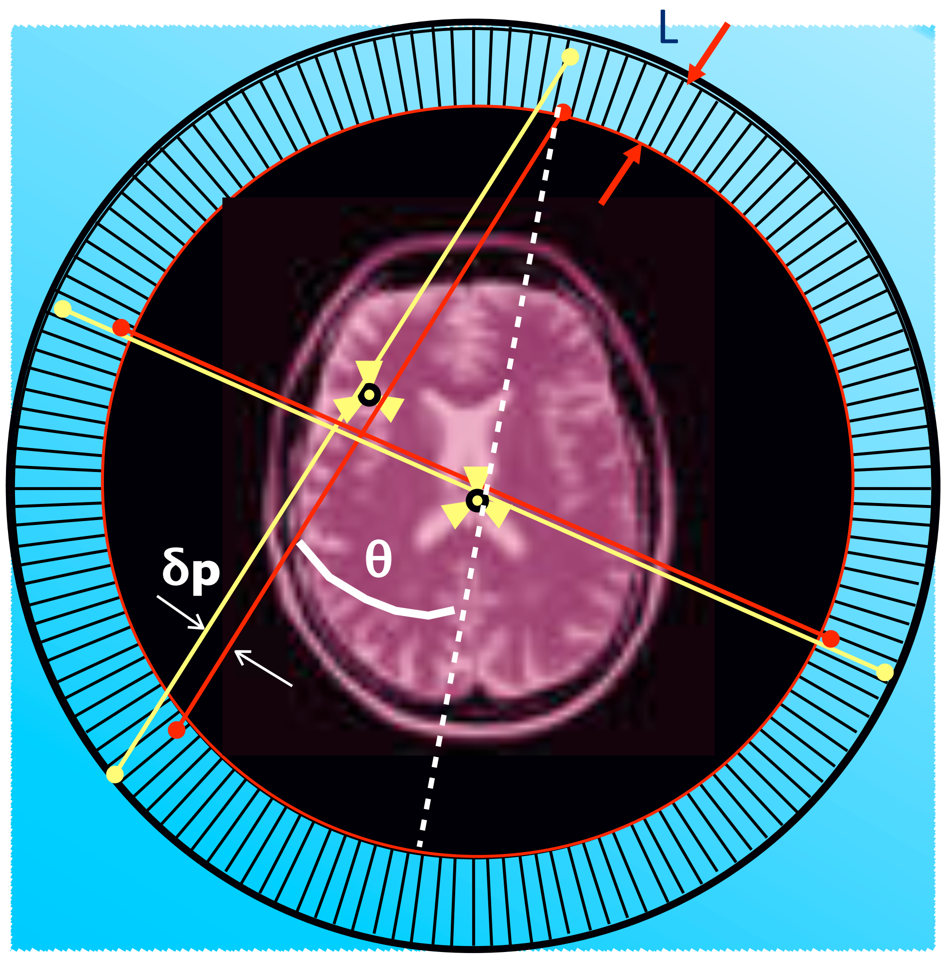


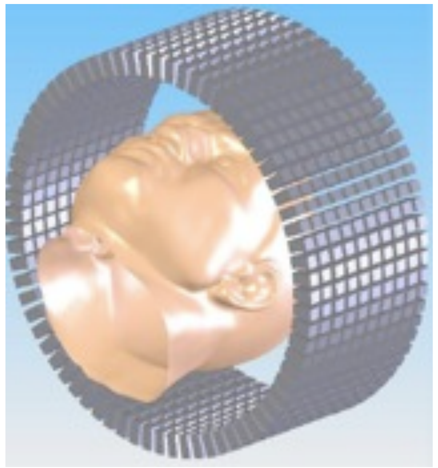
A.Del Guerra, CERN Academic Training 2009

- get a (quantitative) image of the radio-tracer concentration

Conventional PET approach

in "conventional" PET scanners :





scintillator based

radial arrangement

$$\epsilon = 1 - e^{-\mu \cdot L}$$

max **interaction efficiency, long L**

$$\delta p = L \cdot sin\theta$$

min **parallax error**
- deterioration of the spat. resol.
- non uniformity in the field of view

short L

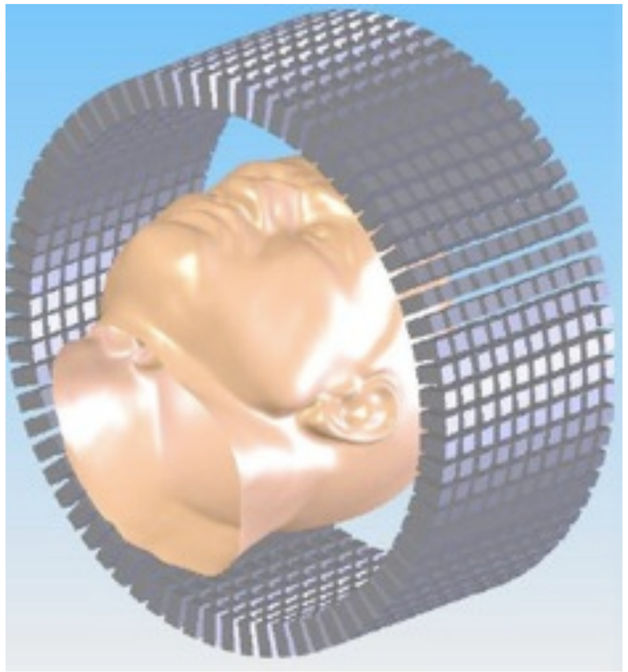
- **always a compromise between**
  - **good spatial resolution (small L, small δp)**
  - **good detection efficiency (long L, high ε)**

- **solution** : add **DOI** (Depth Of Interaction) **information**
  - several attempts / different strategies - but only a partial DOI info can be achieved

The axial concept

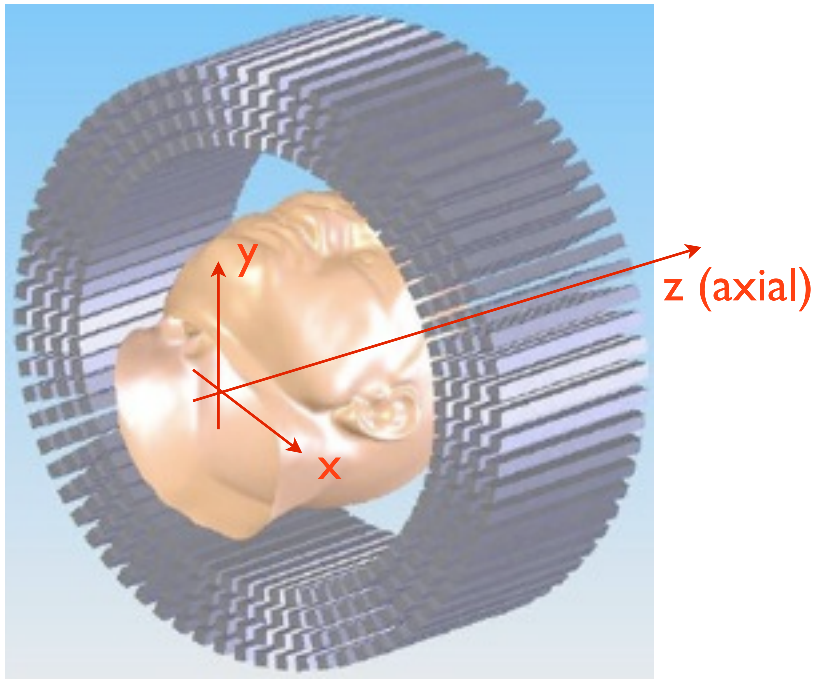
AX-PET approach to the DOI problem : **change the geometry !**

from radial ...



- short and radially oriented crystals

... to axial !



- long and axially oriented crystals
- several layers one on top of the other

Advantages of the axial approach :

- DOI information (x,y) = position of the hit crystal
- resolution in the (x,y) plane : given by the size of the crystals (d)

- improve resolution => reduce crystal size
- improve sensitivity => increase number of layers
- **parallax free system**, with **resolution and sensitivity decoupled !**

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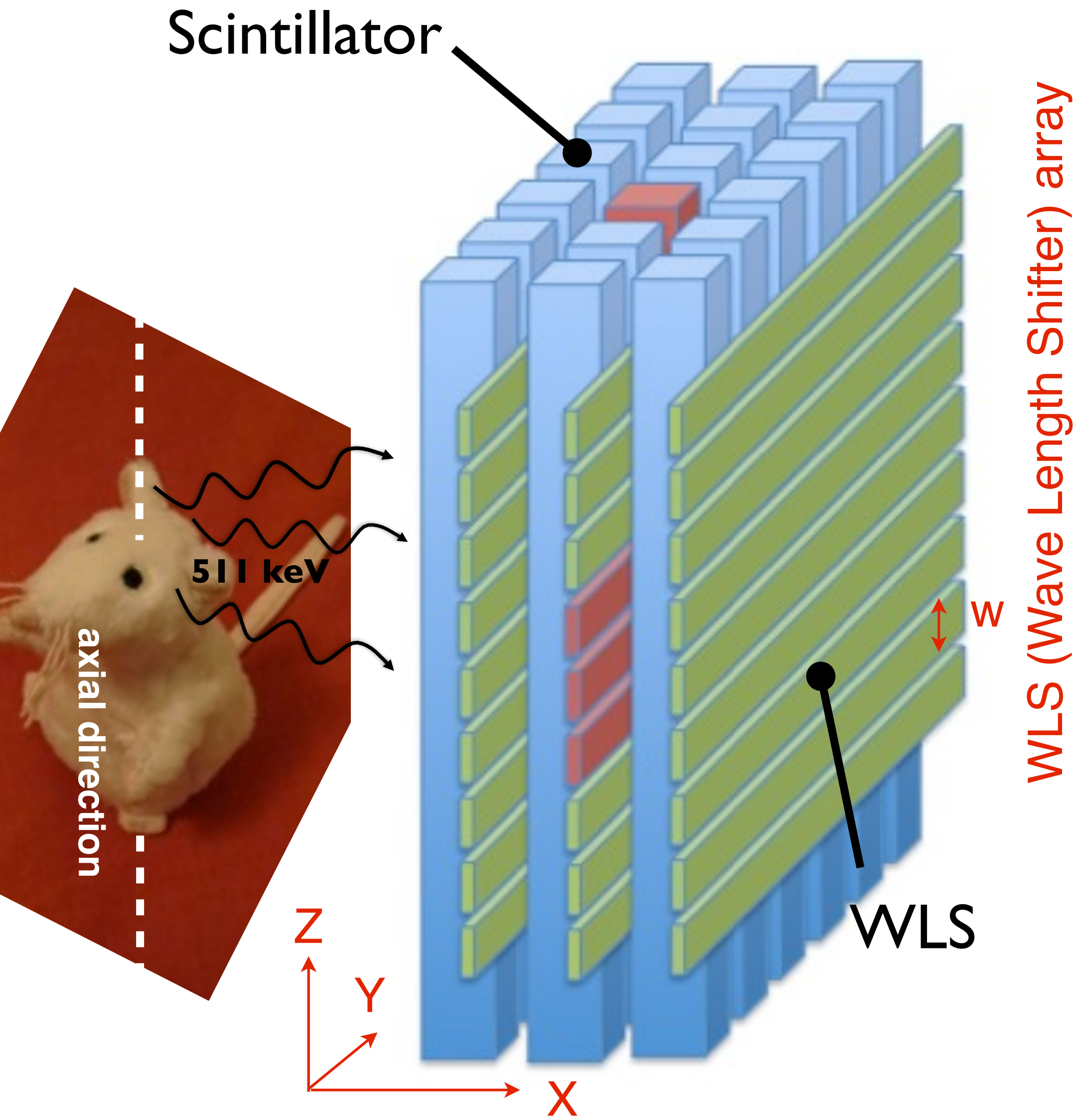
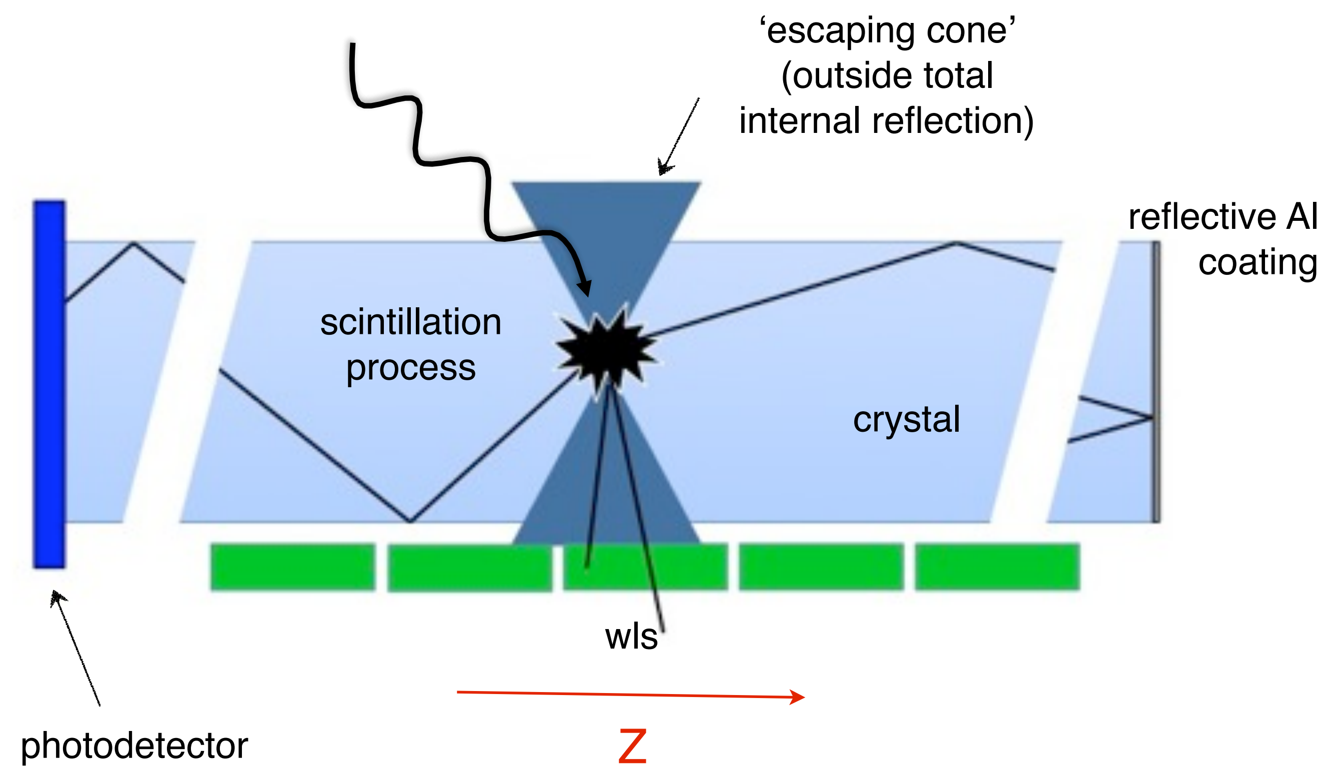
Detector solution

AX-PET





- Axial coordinate : center of gravity method
- Axial resolution **< w**

(1) crystals =>
TRANS-AXIAL COORDINATE (x,y)
ENERGY INFORMATION

(2) wave lenght shifters =>
AXIAL COORDINATE (z)

- 3D localization of the photon interaction point
- no compromise between spatial resolution and sensitivity
- high granularity => possibility to identify Compton scattering events in the detector

AX-PET collaboration

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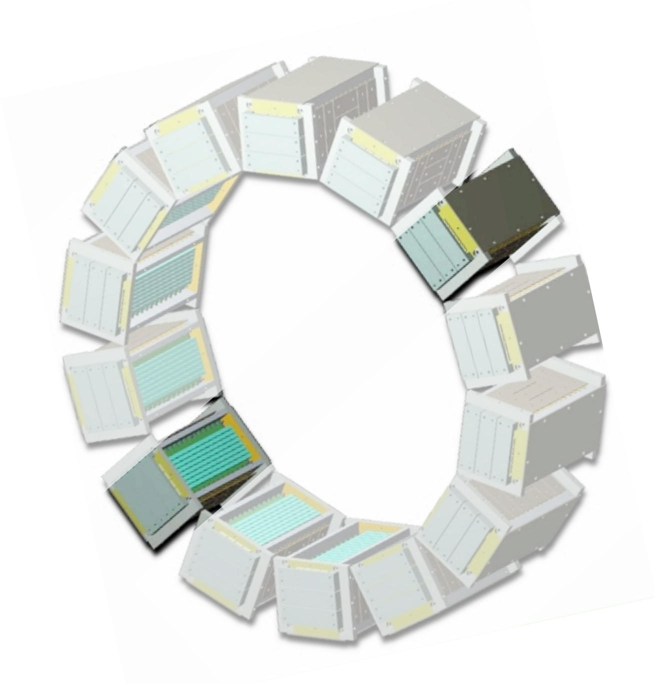
Goal of the AX-PET collaboration:

Build and fully characterize a **"demonstrator"** for a PET scanner based on the axial concept. Assess its performances.

demonstrator <=> Two identical AX-PET modules, used in coincidence

Characterization / Performance =>
- test each individual module in a dedicated setup
- characterization in the coincidence setup
- reconstruction of the images of extended objects
- simulations



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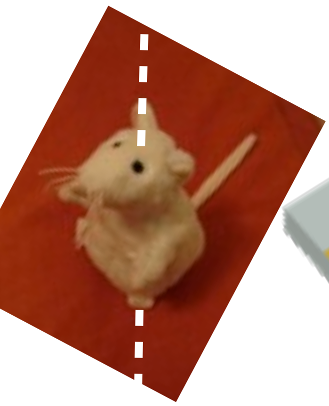
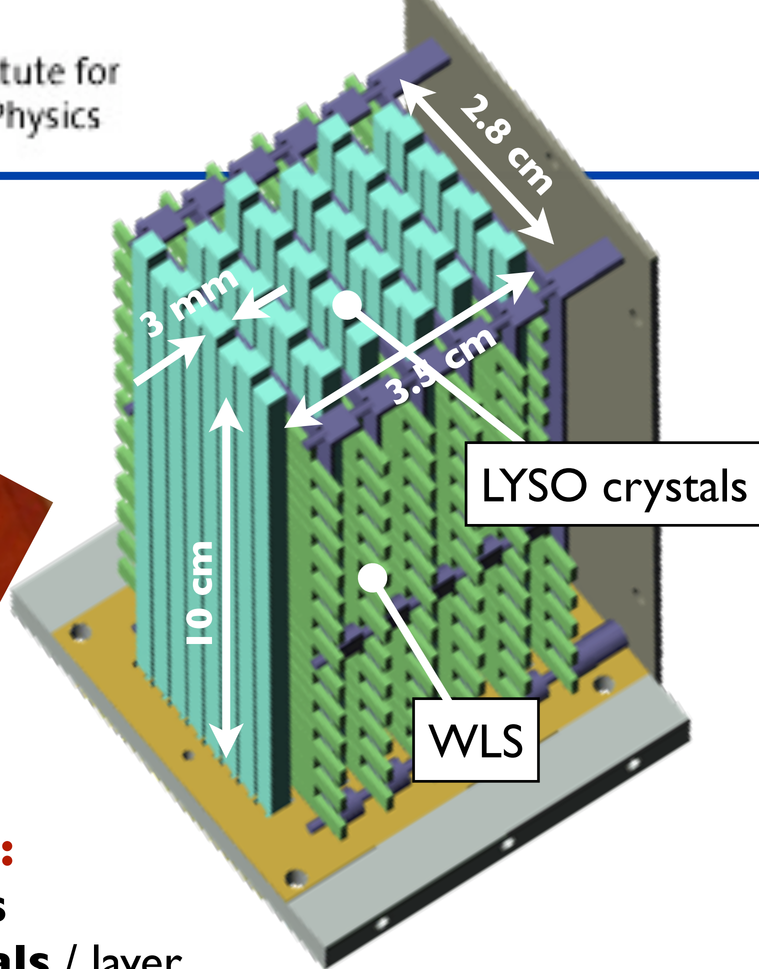
AX-PET Module





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/cm^3)
  - λ @511 keV ~ 1.2 cm
  - quick decay time (τ = 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 absorption
- **0.9 x 3 x 40 mm^3**

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

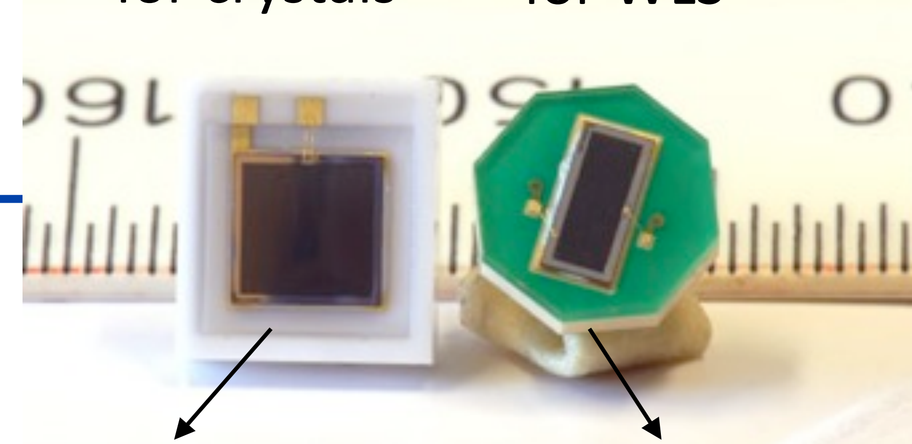
Photodetectors

- MPPC (Multi Pixel Photon Counter) from Hamamatsu

- also known as **SiPM / G-APD**
  - high PDE (~ 50%) √
  - high gain (10^5 to 10^6) at low bias voltage √
  - **insensitive to magnetic field** √
  - **compact size** √

  - temperature dependent √
  - dark rate √

for crystals for WLS



MPPC S10362-33-050C :

- 3x3 mm^2 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 mm^2 active area
- 70 µm x 70 µm pixel
- 1200 pixels
- Gain ~ 4 x 10^5
- custom made units

LYSO energy response

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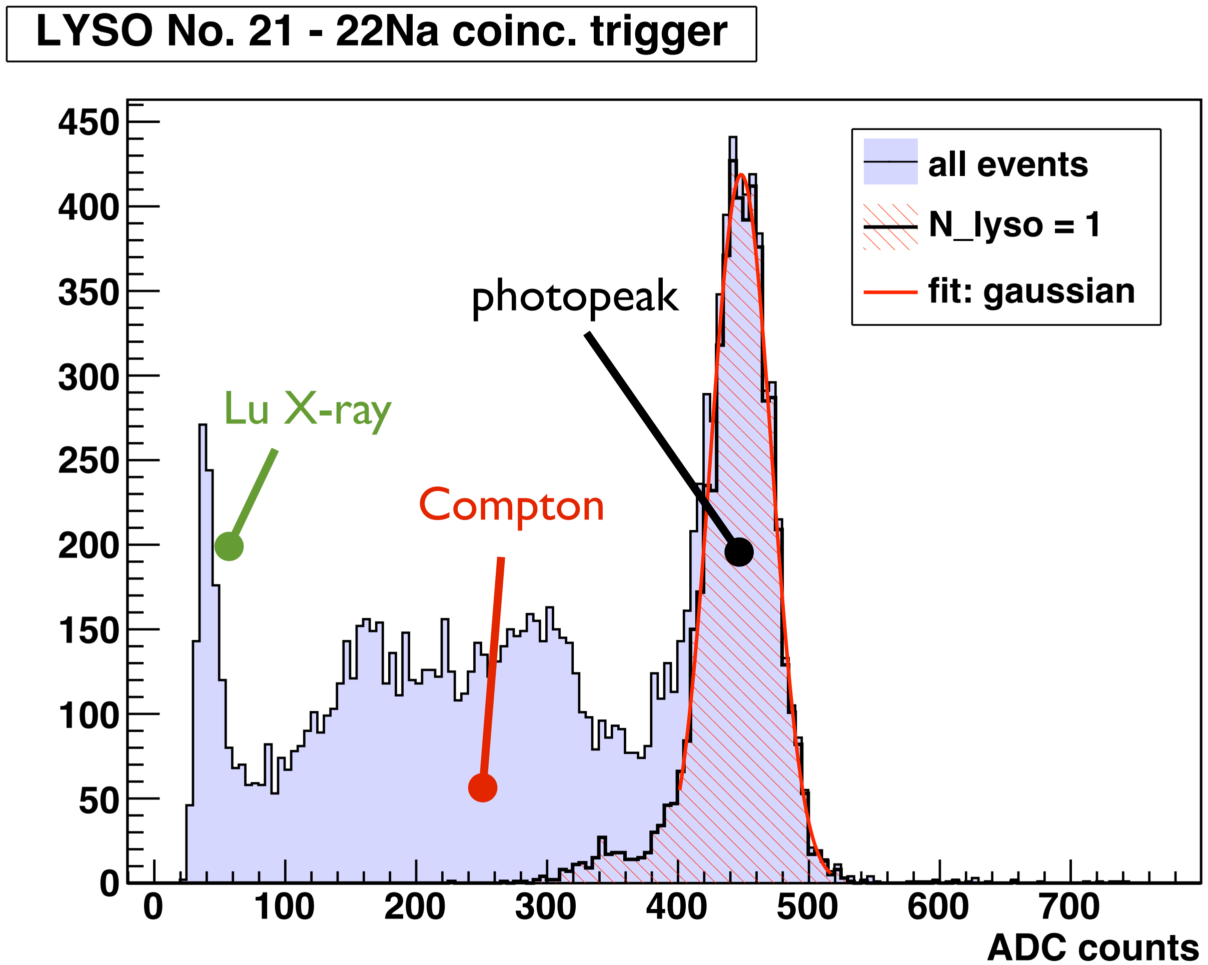
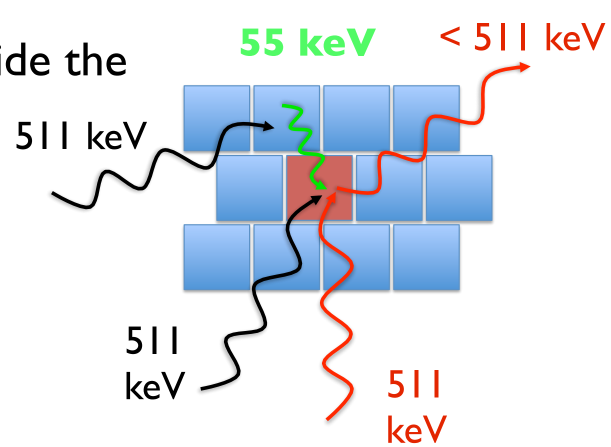
AX-PET

Characterization measurements with point-like ^{22}**Na source** (diam = 0.25 mm, A~900 kBq) , @ CERN



typical energy spectrum of one LYSO inside the module :

- photopeak (511 keV)
- Compton continuum (0 - 340 keV)
- Lu X-ray peak (~ 55 keV)

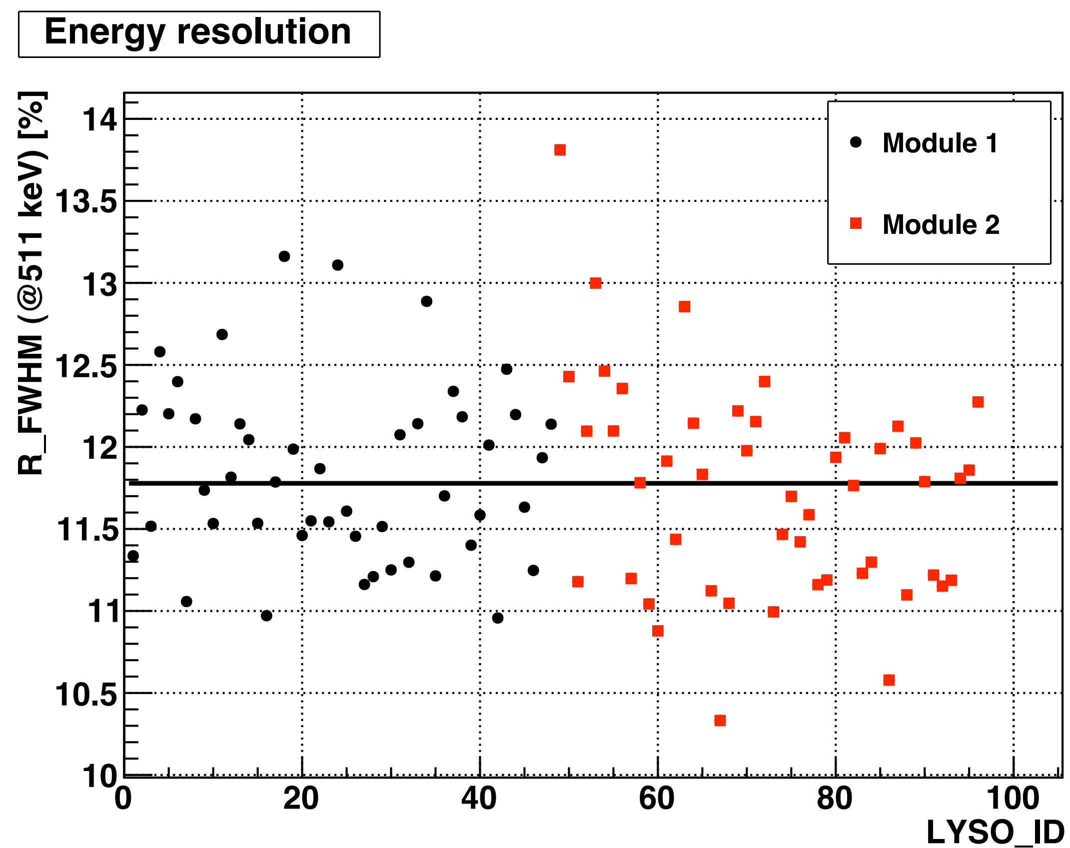


Light yield at 511 keV ~ 1000 pe

(from independent calibration measurements)

Energy resolution

- from gaussian fit of the photopeak
- AFTER ENERGY CALIBRATION



< R_FWHM > ~ 11.8% @511 keV

(averaged on 96 LYSO crystals)

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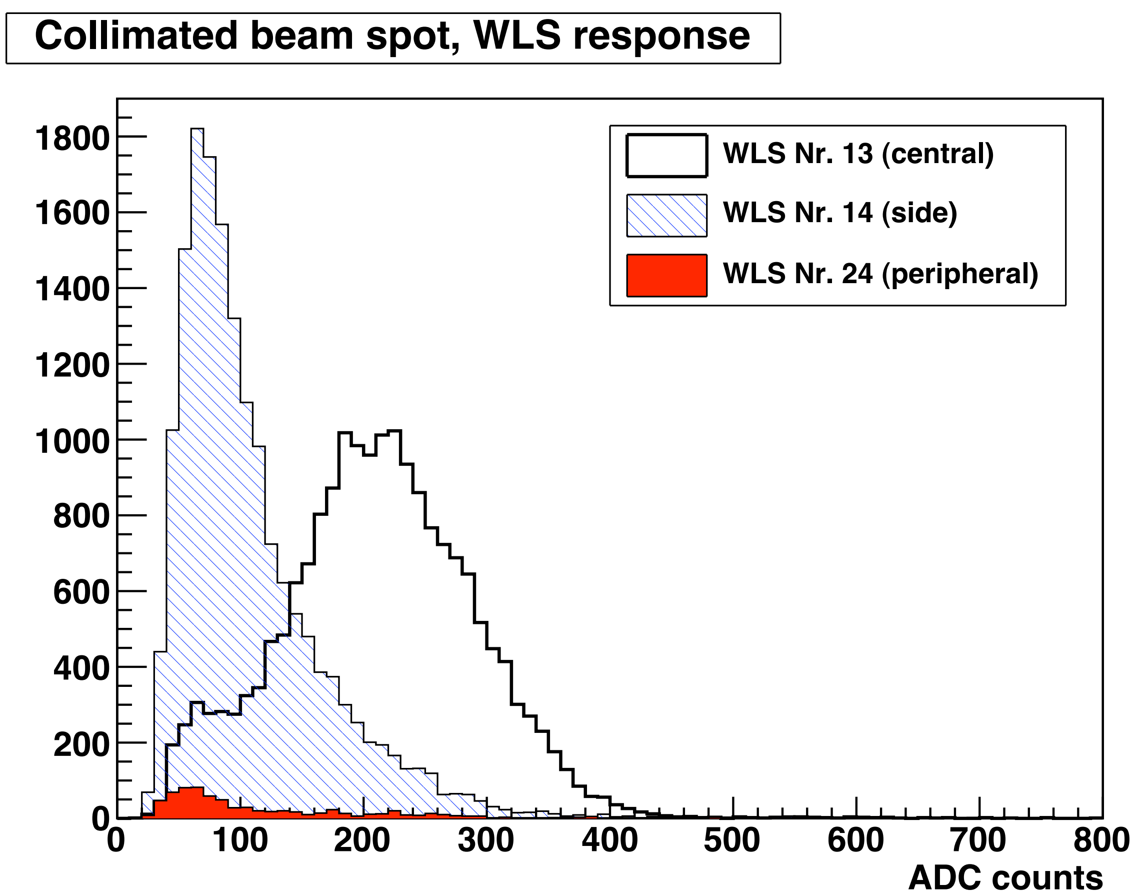
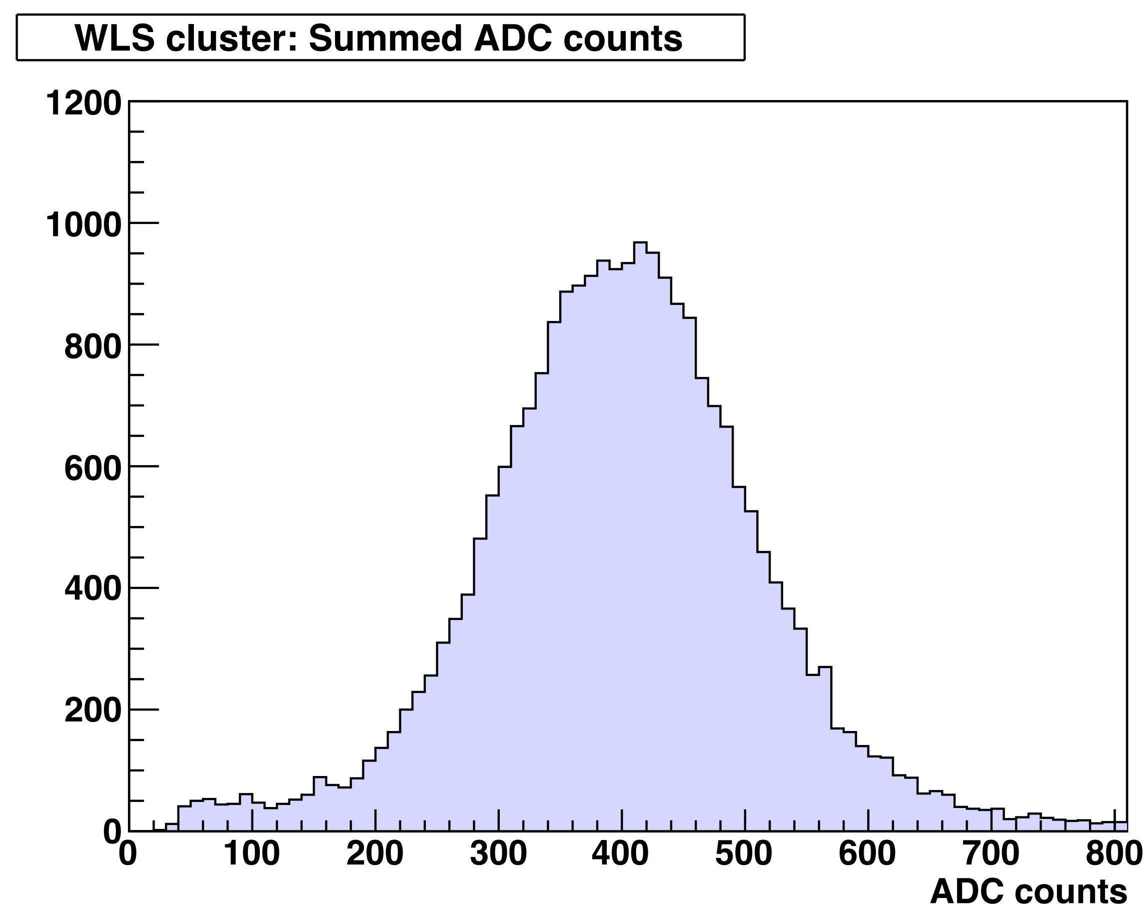
WLS response

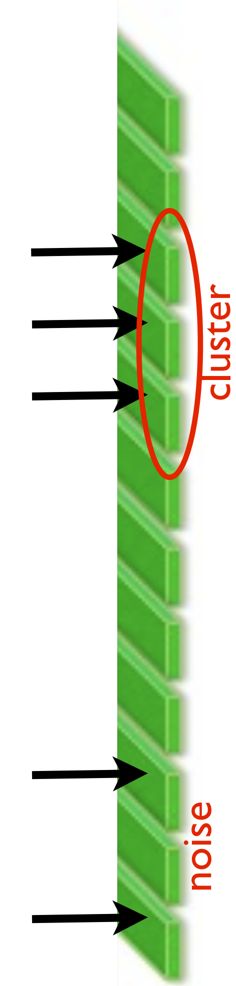
Characterization measurements with point-like ^{22}**Na source** (diam = 0.25 mm, A~900 kBq) , @ CERN

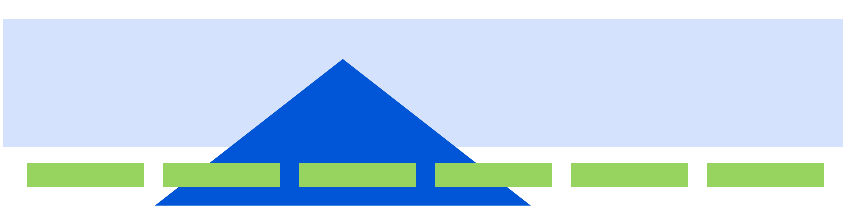
typical integrated raw spectra of few WLS strips

- beam spot collimated at the center of the module (WLS 13)
- 511 keV energy deposition in the LYSO









- more than1 WLS participates to the event (typically 2-4)
- noise should not be included

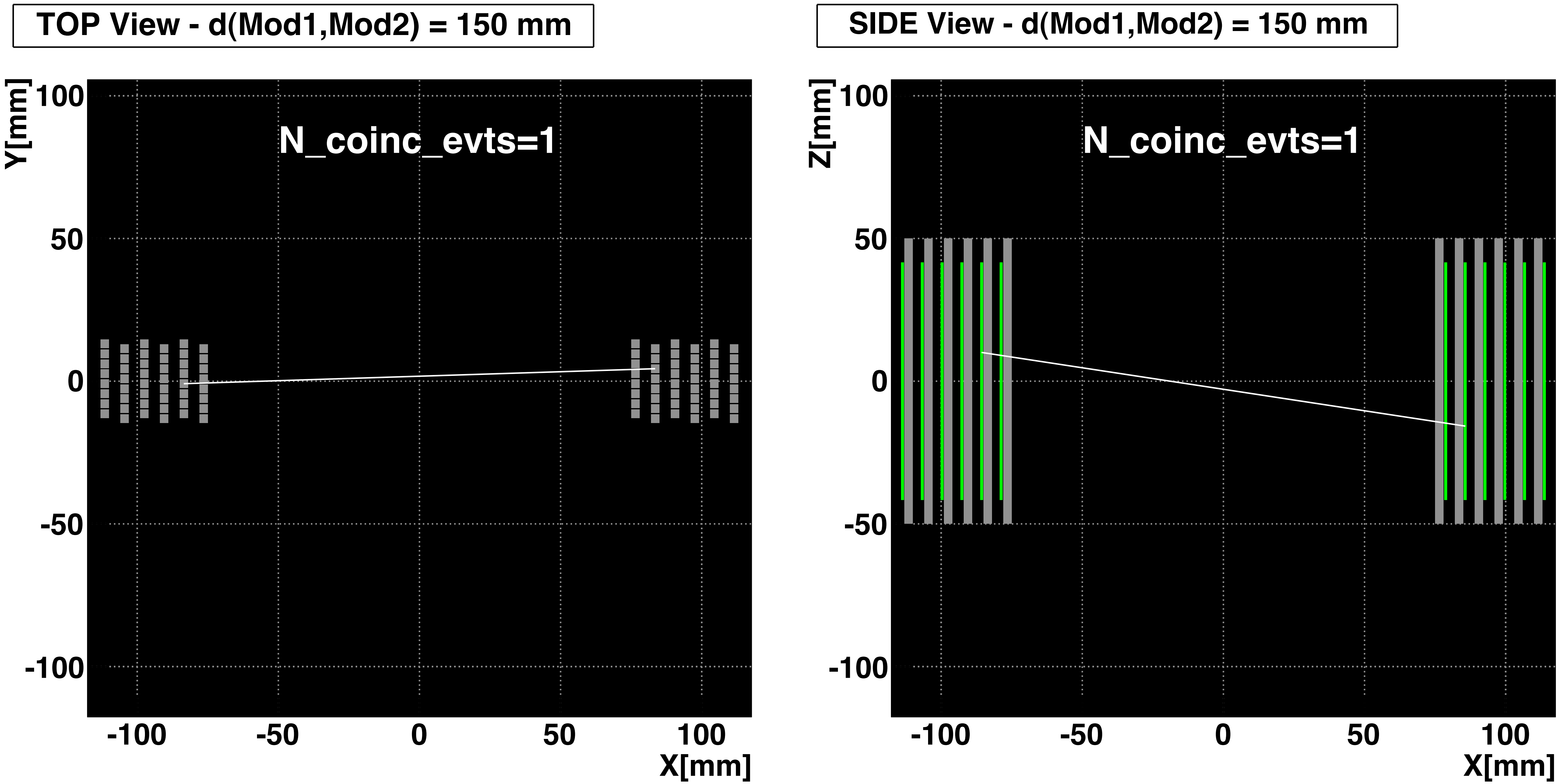
Light yield in WLS cluster ~ 100 pe
@511 keV LYSO energy deposition

(from independent calibration measurements: 1pe ~ 4 ADC)

axial coordinate :
derived from center of gravity method
from all the WLS participating to the cluster

Two modules coincidence

Characterization measurements with point-like ^{22}**Na source** (diam = 0.25 mm, A~900 kBq) , @ CERN



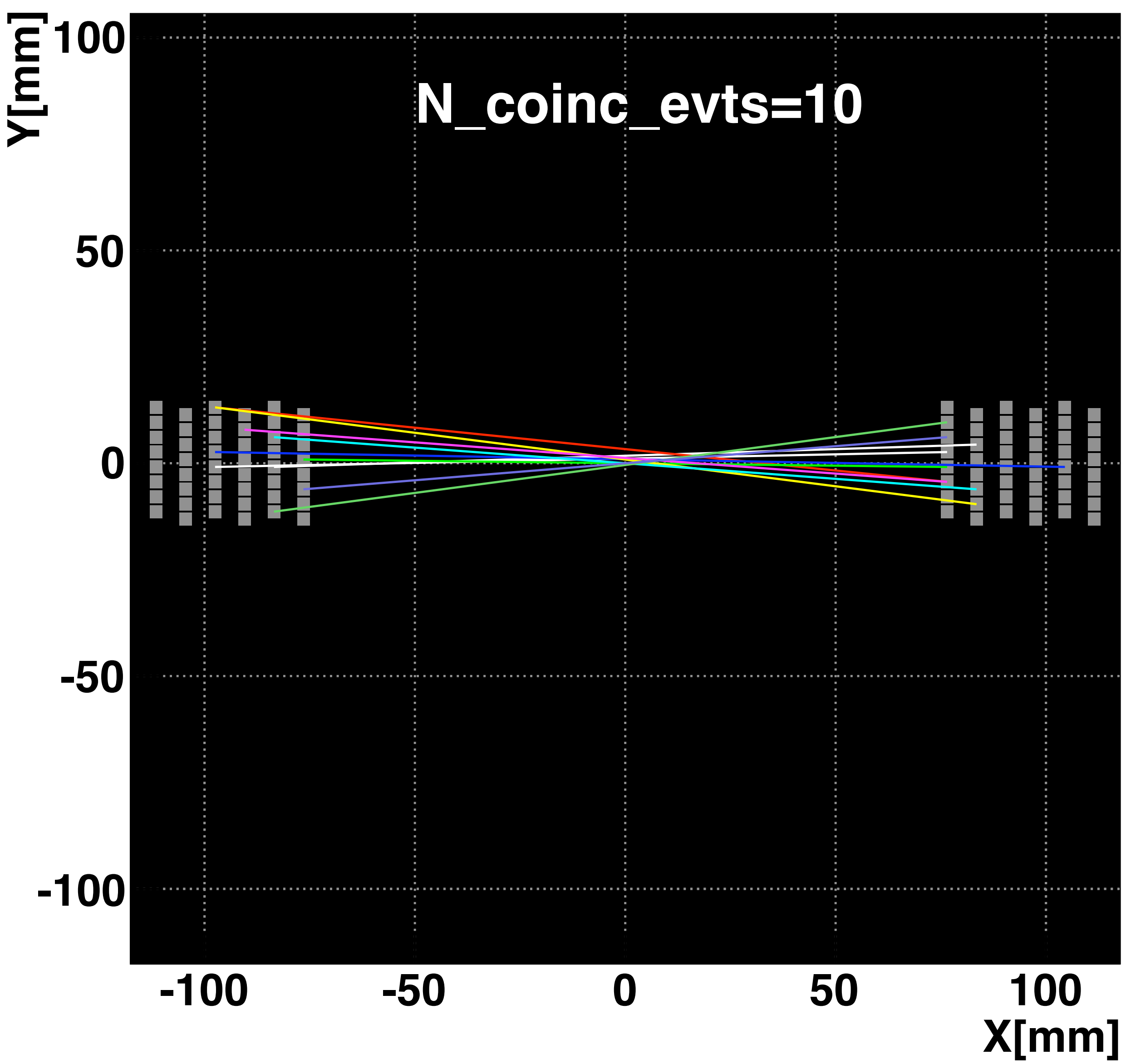
AX-PET very first coincidence event !

/home/daq/axpet/log/run02730.log INFO: Run Start Time: Mon Nov 23 12:01:20 2009

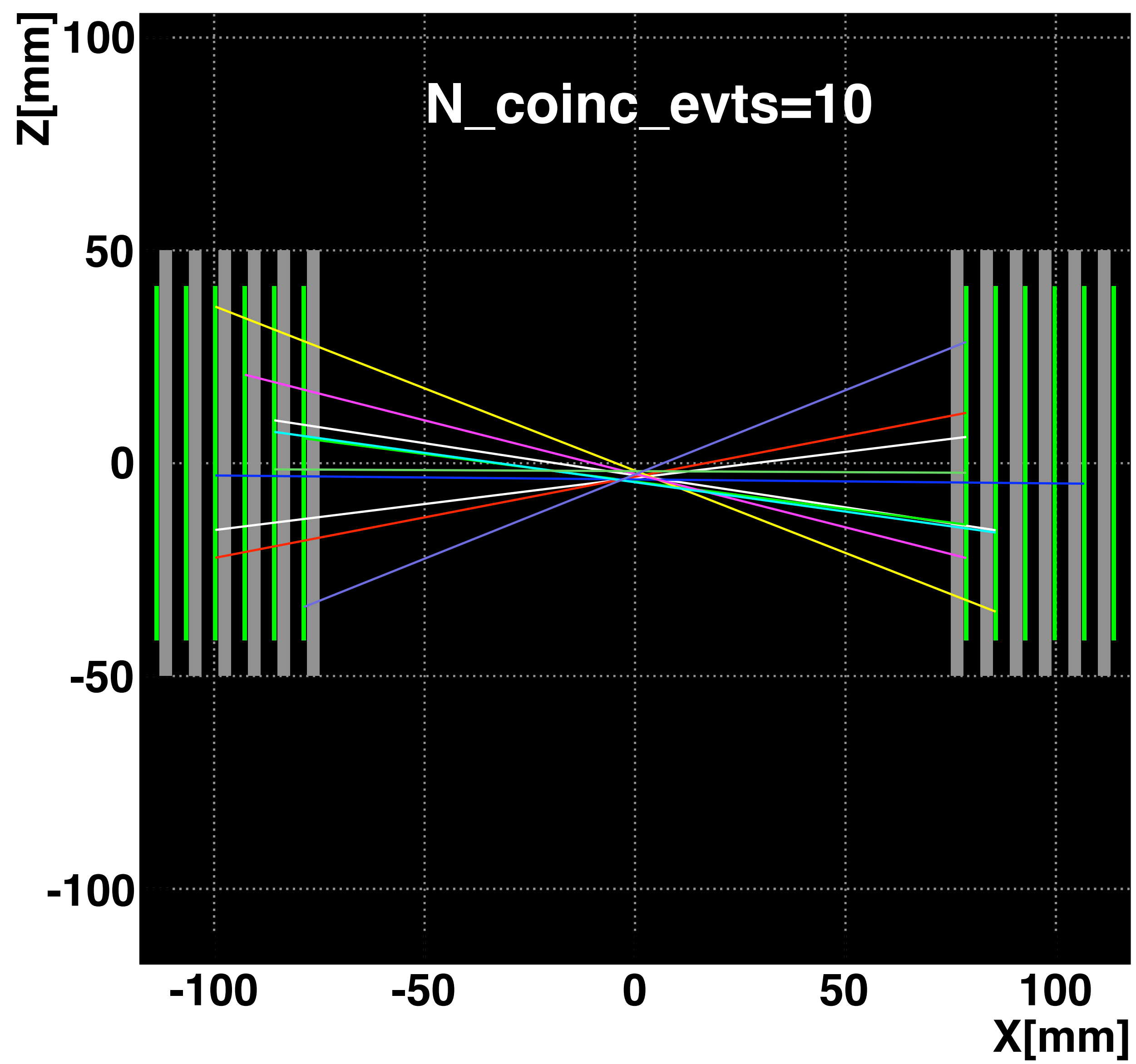
Two modules coincidence

Characterization measurements with point-like ^{22}**Na source** (diam = 0.25 mm, A~900 kBq) , @ CERN

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



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



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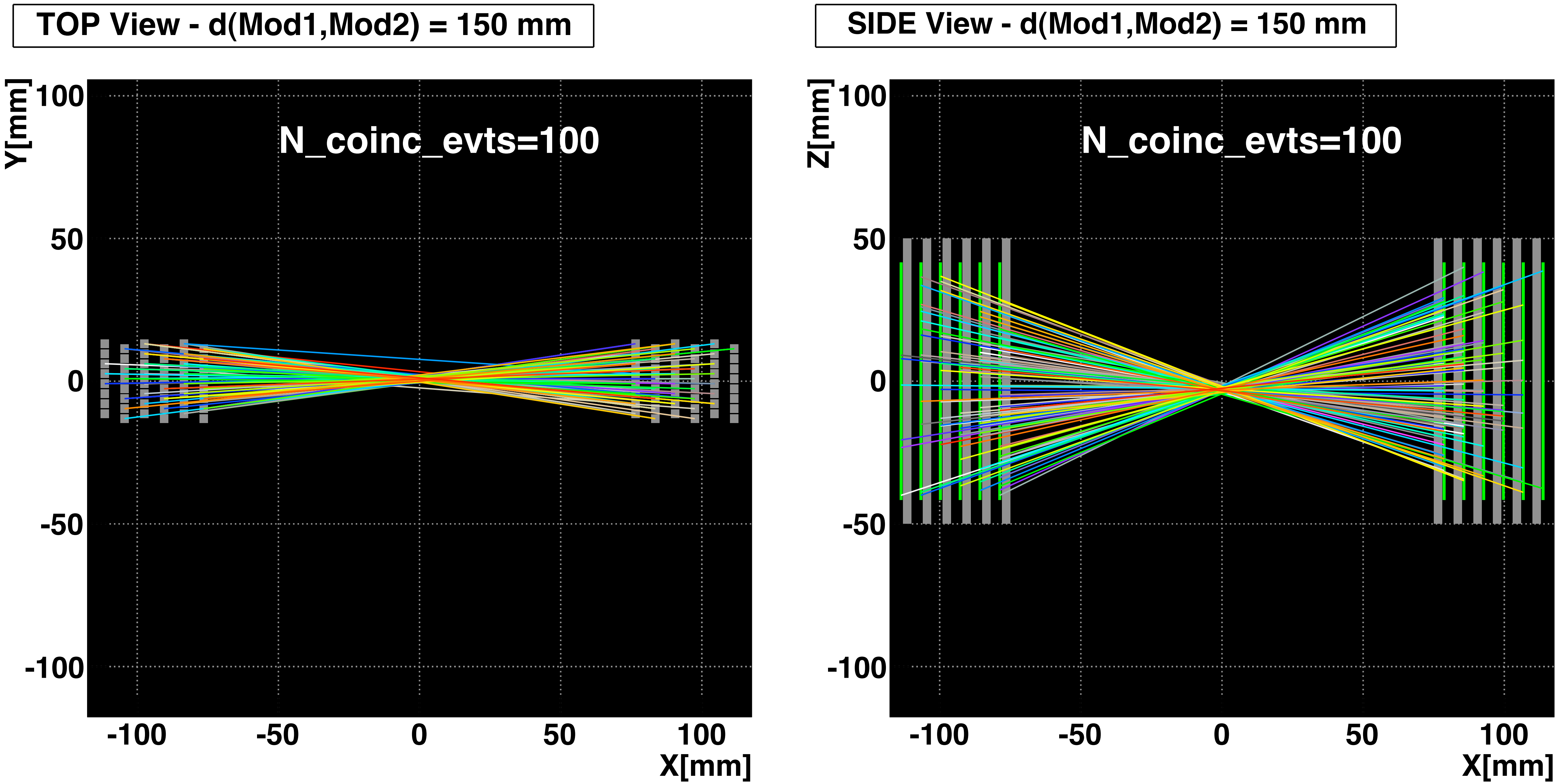
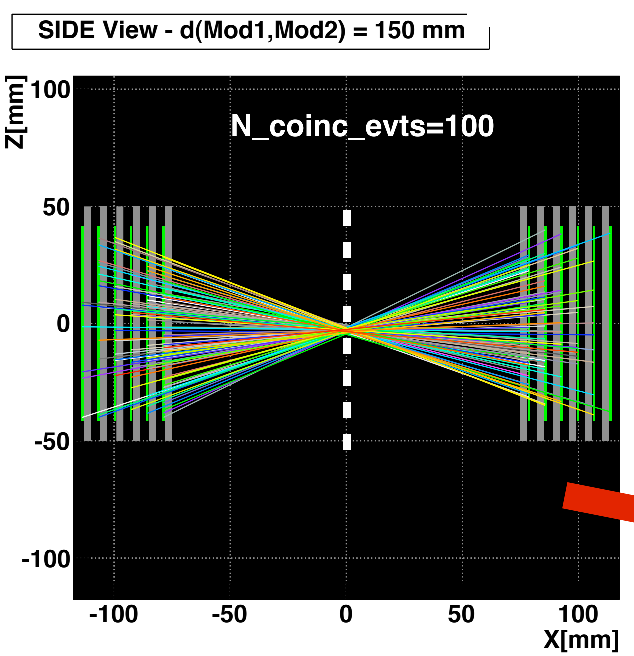
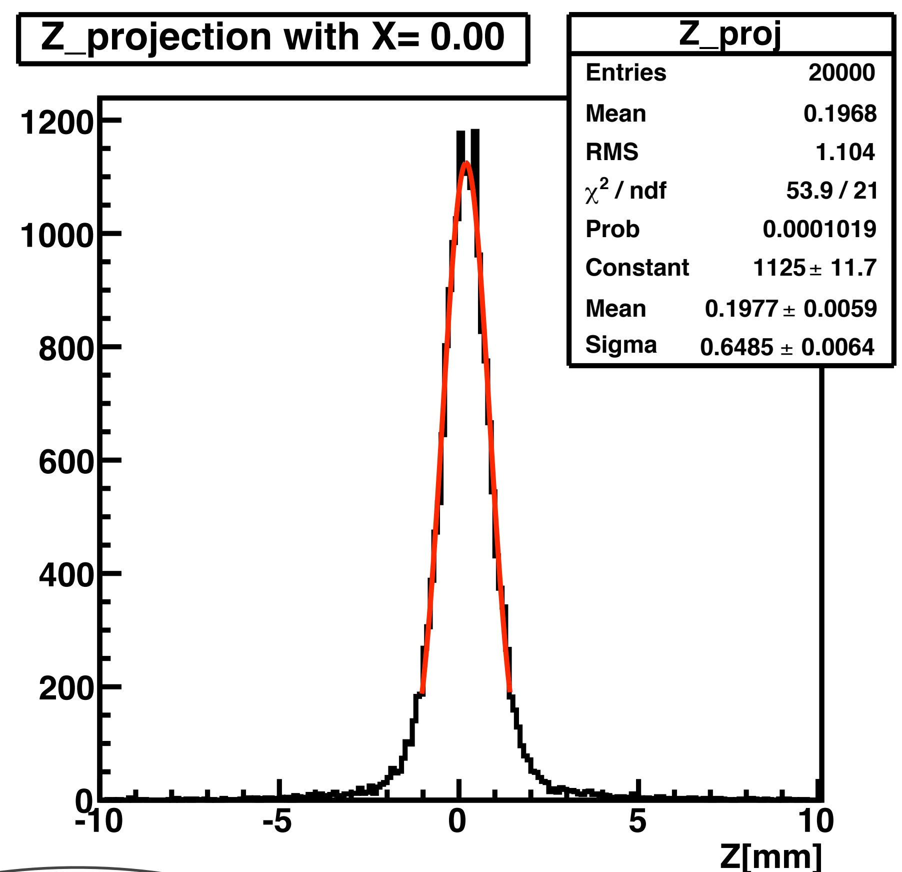


Axial resolution

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





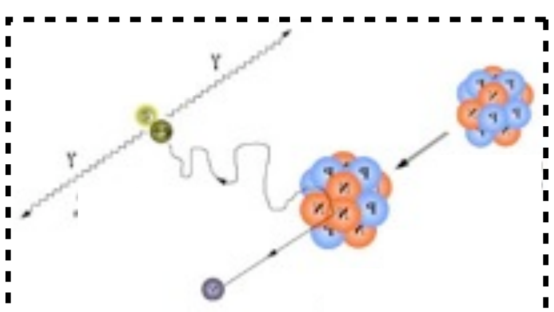
$(R\_FWHM)_Z \sim 1.5$ mm

including :

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

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

≈ 1.35 mm, FWHM



fundamental limits to the achievable spatial resolution in a PET system, due to the **physics of positron emission** :

•**positron range** : $R_\rho{}^2 = [\ 0.54 \text{ mm }]^2$

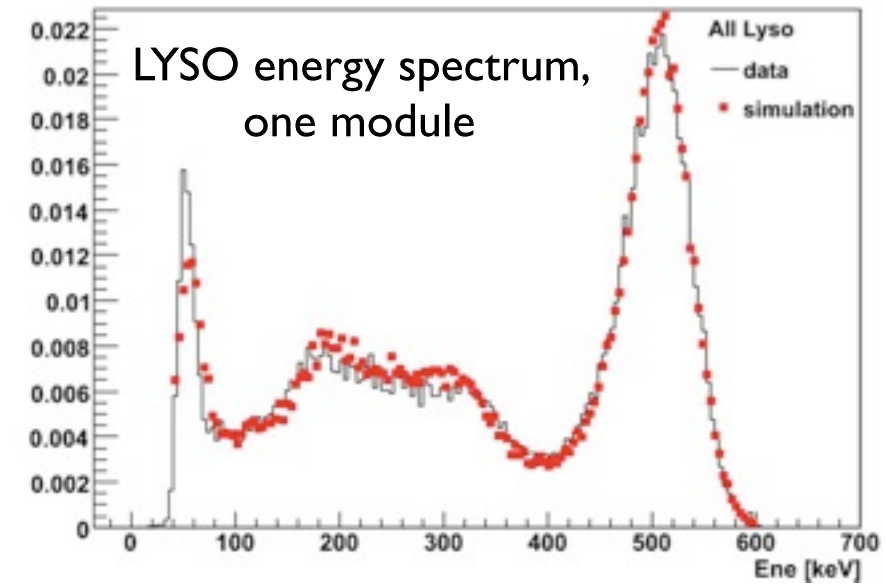
•**non collinearity** : $R_{180}{}^2 = [\ 0.0022 \times \text{Diameter }]^2 = [\ 0.33 \text{ mm }]^2$

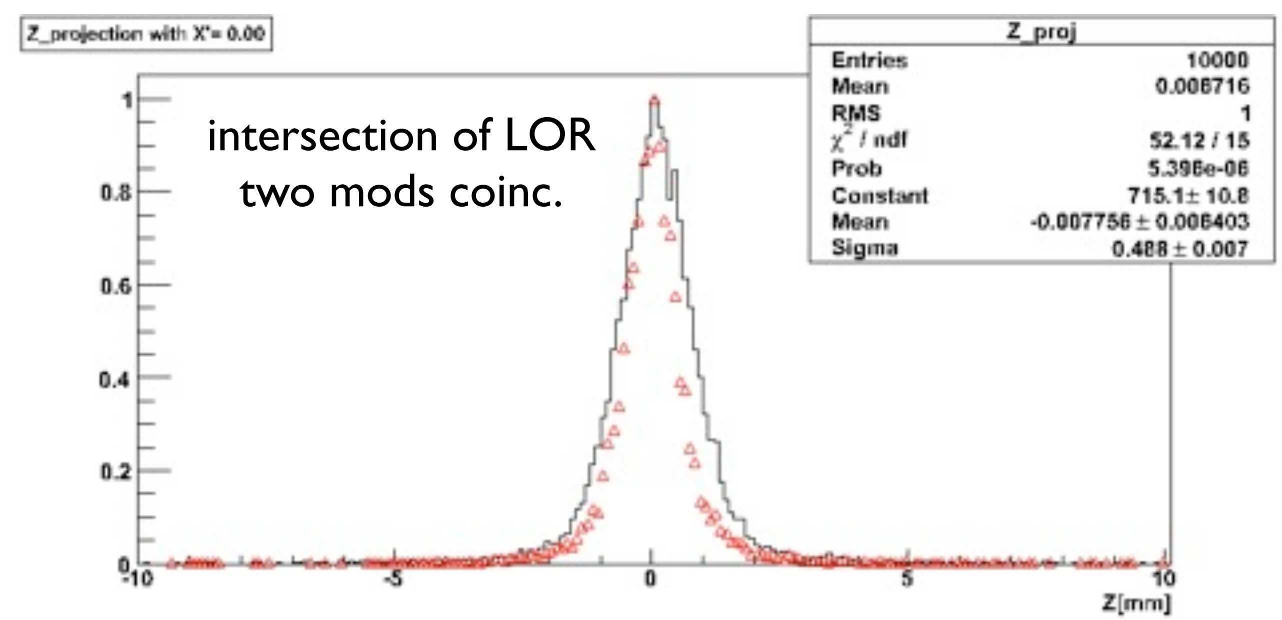
resolution in the trans-axial direction (digital - from crystal size):

R_x,y= (3mm/√12)x2.35 ~ 2 mm FWHM

Simulations

- **AX-PET : fully simulated device !**
- Excellent agreement between data and simulations
- GATE (G4 toolkit for PET) - with modified standard templates to cope with the non conventional nature of AX-PET (geometry, WLS, sorter for the coincidences...)





- identify Compton scattering events
- several identification algorithms tested

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

- identification rate ~ 60%

Simulations

ETH Institute for Particle Physics

AX-PET

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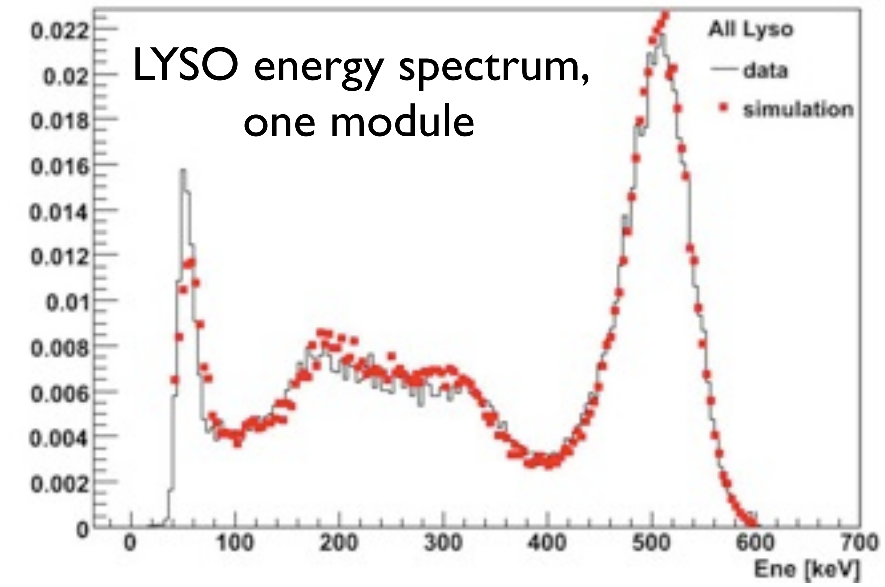
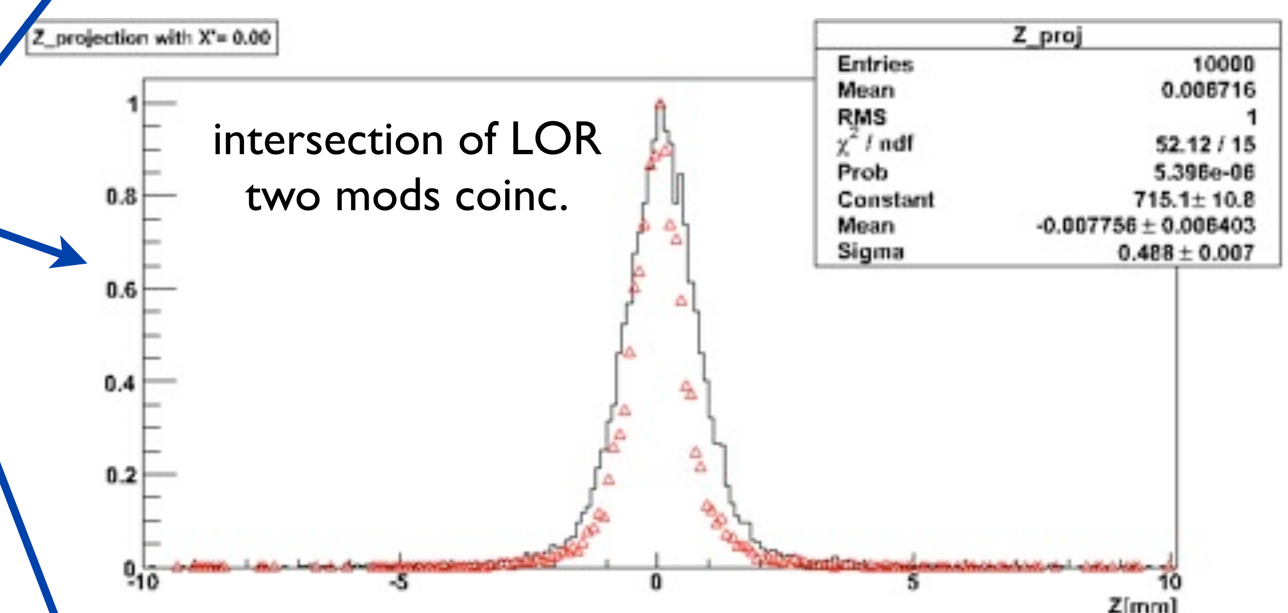
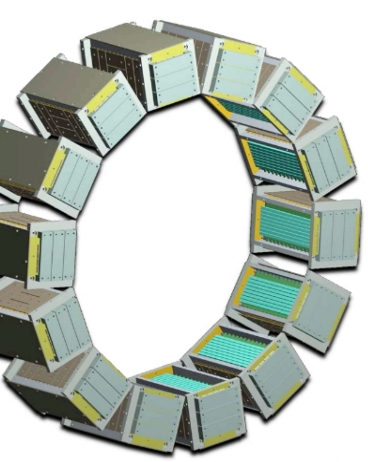
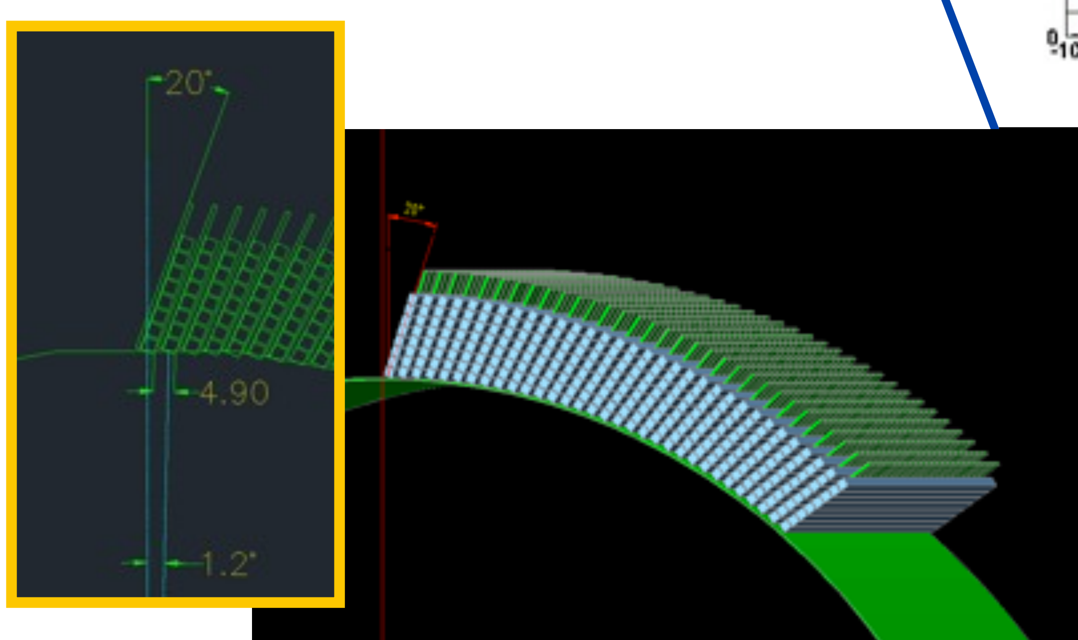
Simulation approach :
1. Use demonstrator data to fully validate the simulations
2. Simulate an hypothetical full ring scanner. Derive its performance









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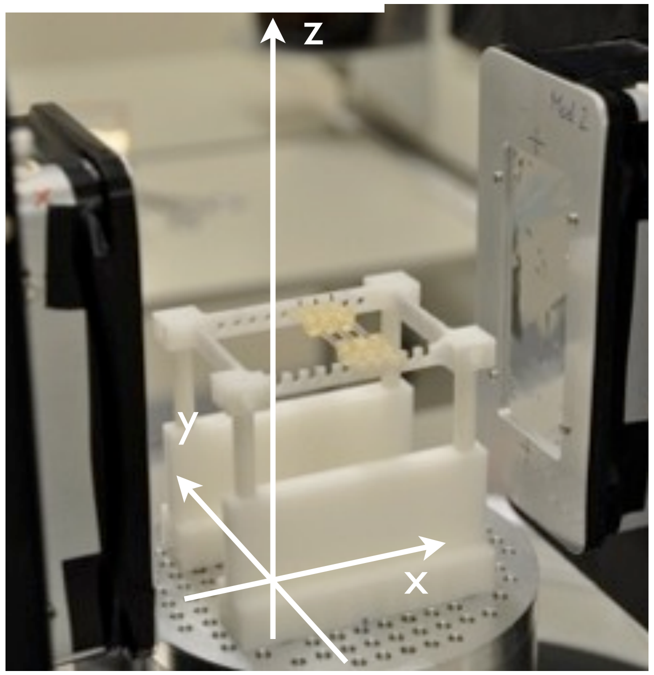
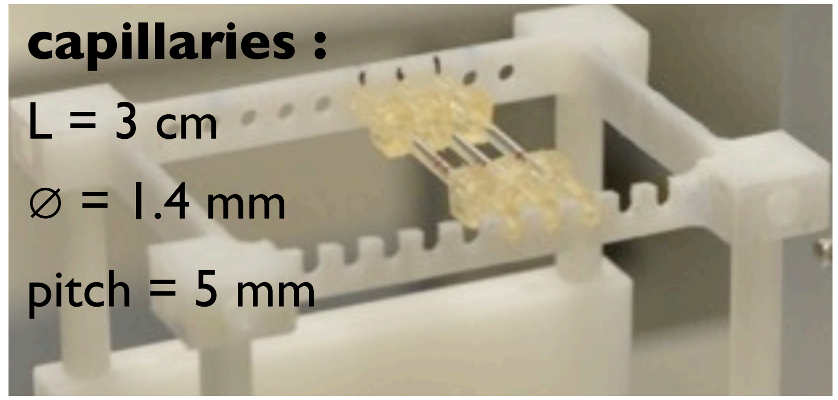
Simple image reconstruction

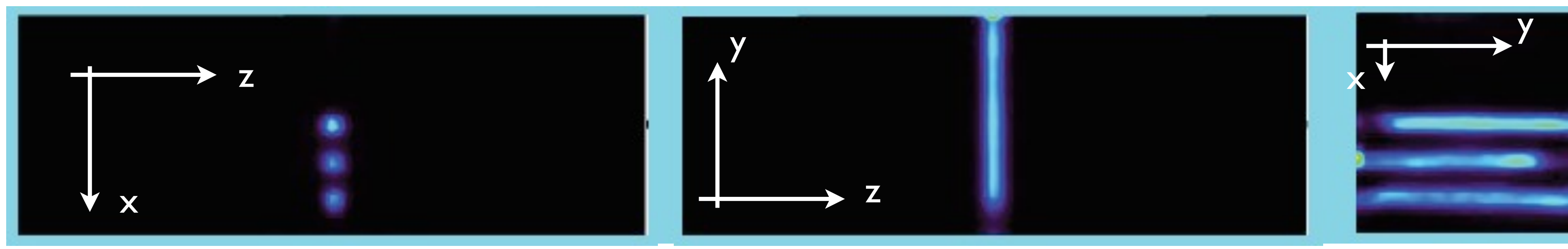
AX-PET

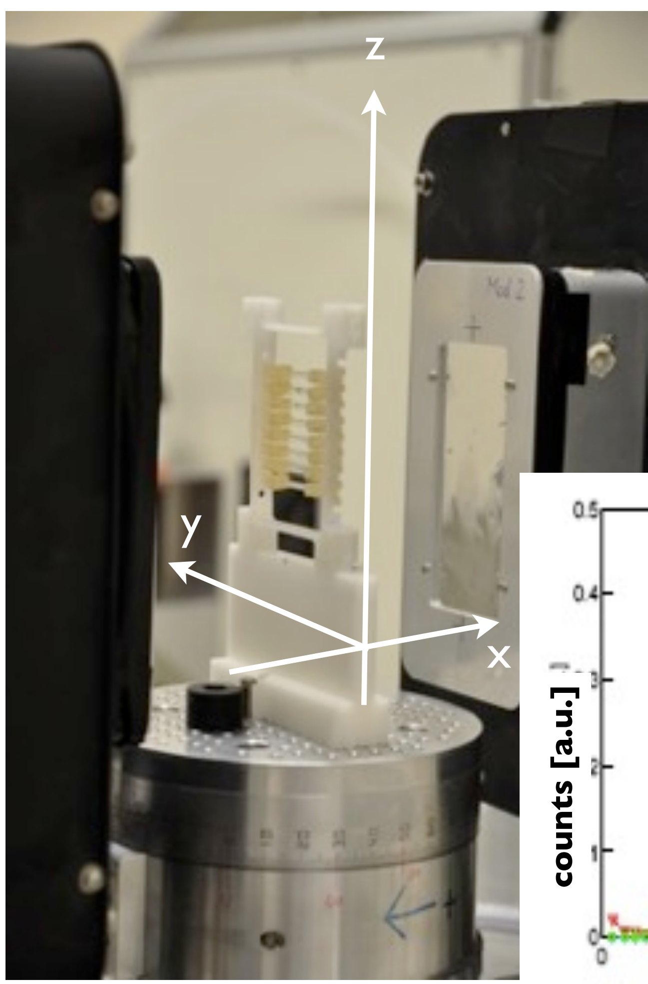


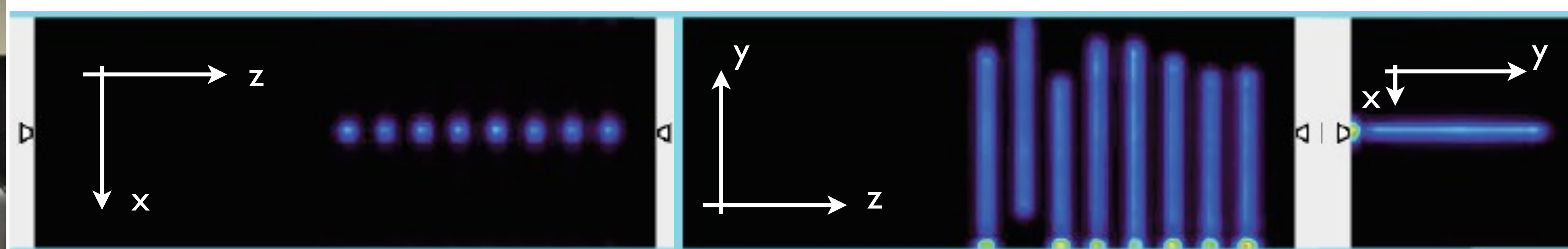


central FOV
no modules rotation

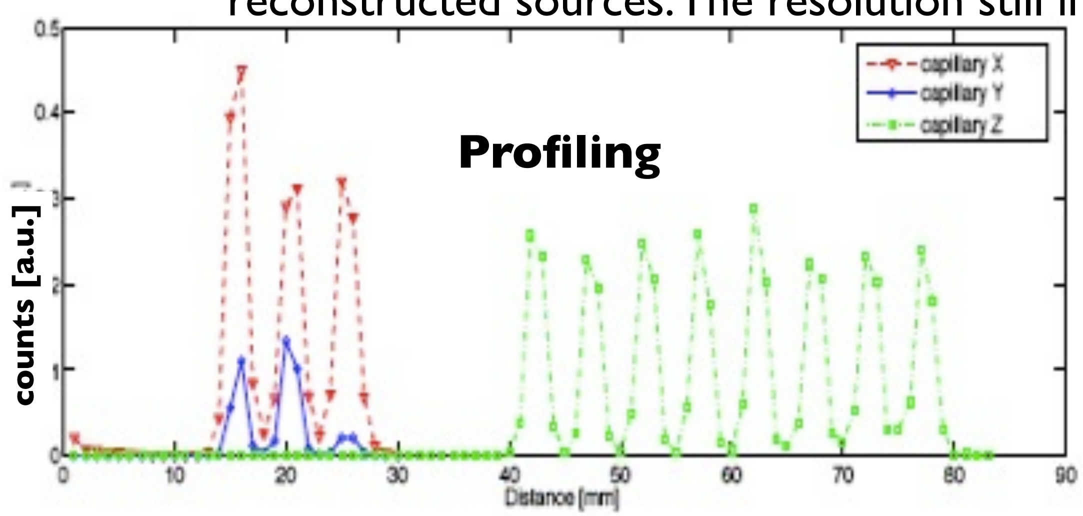
ETH, Radiopharmaceutical Institute
Apr 2010

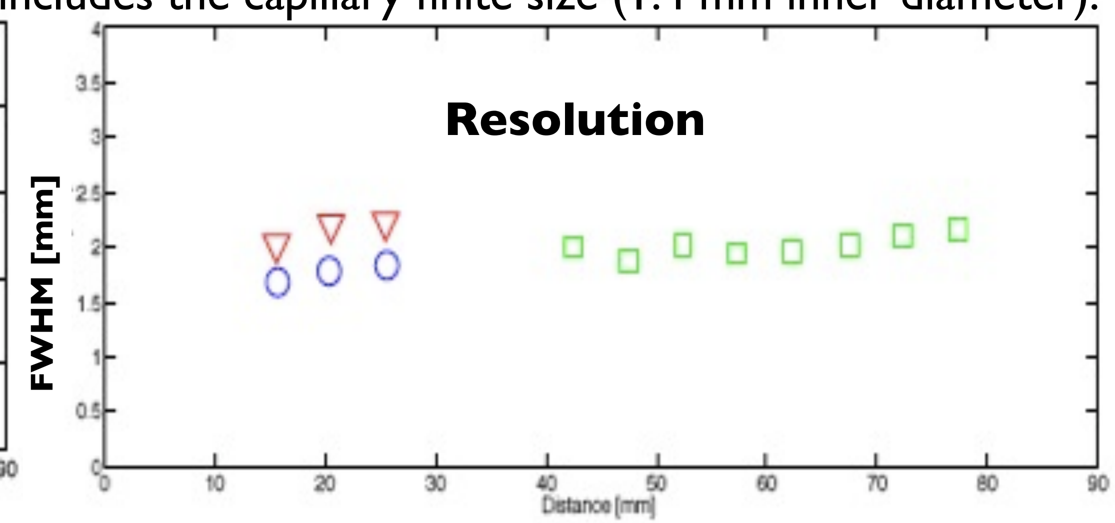






Profiling of the reconstructed capillaries (3 different measurements) and resolutions (FWHM) of reconstructed sources. The resolution still includes the capillary finite size (1.4 mm inner diameter).





NEMA Phantom

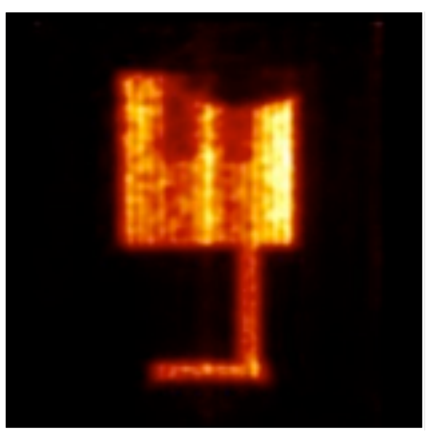
extended FOV
2nd module rotation
AAA (Advanced Acceleration Applications)

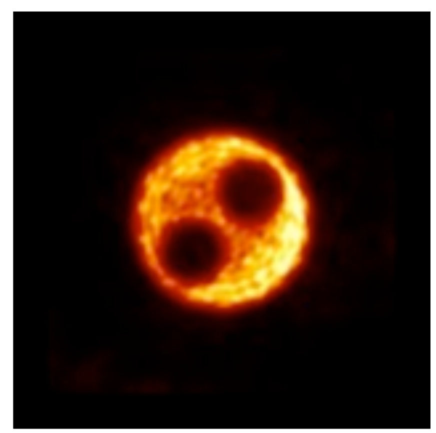
Three regions in the same phantom to address three different aspects

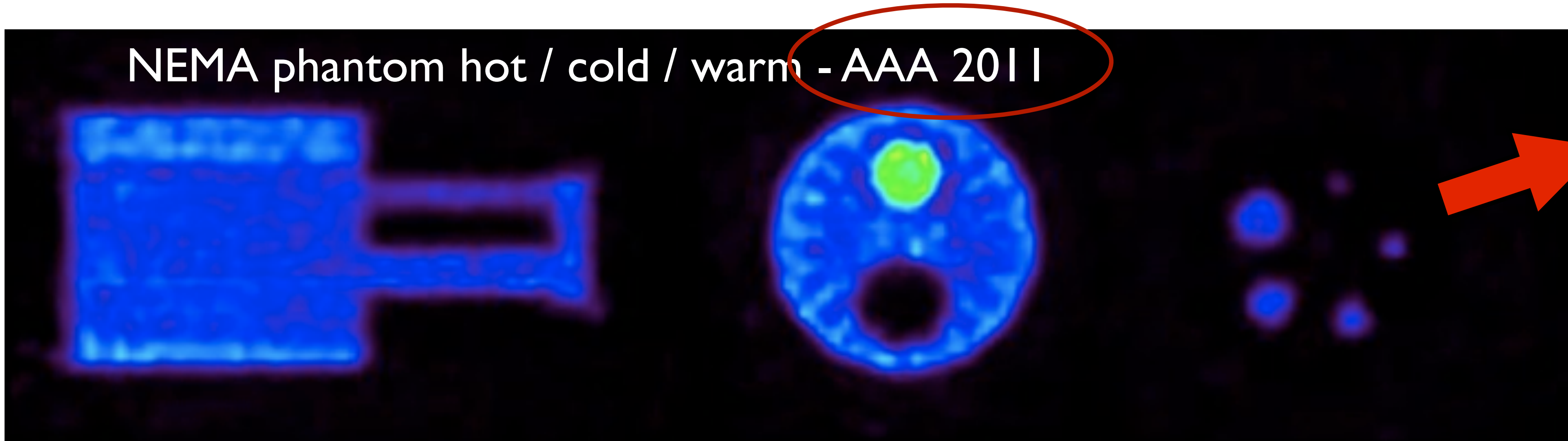
Hot & Cold rods for **contrast**

Homogeneous cylinder for assessing the **ability to reconstruct homogeneous distributions**

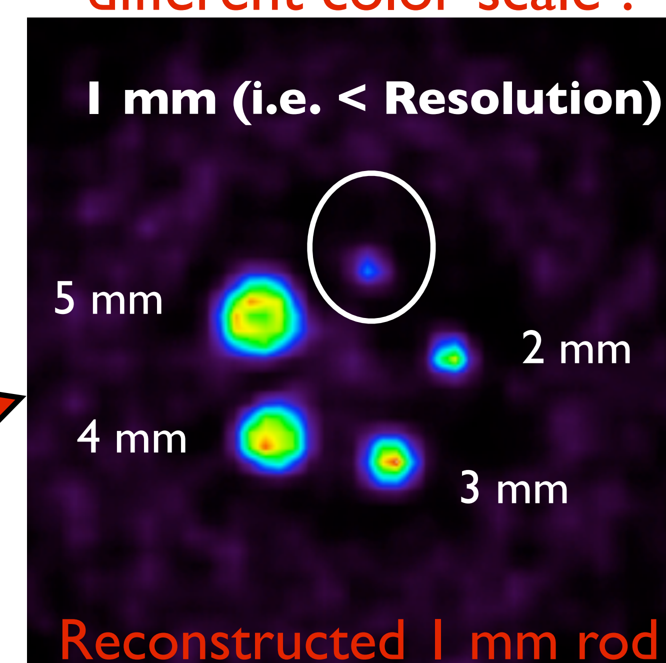
Series of small rods for **resolution**







different color scale !



=> FWHM ~ 1.6 mm

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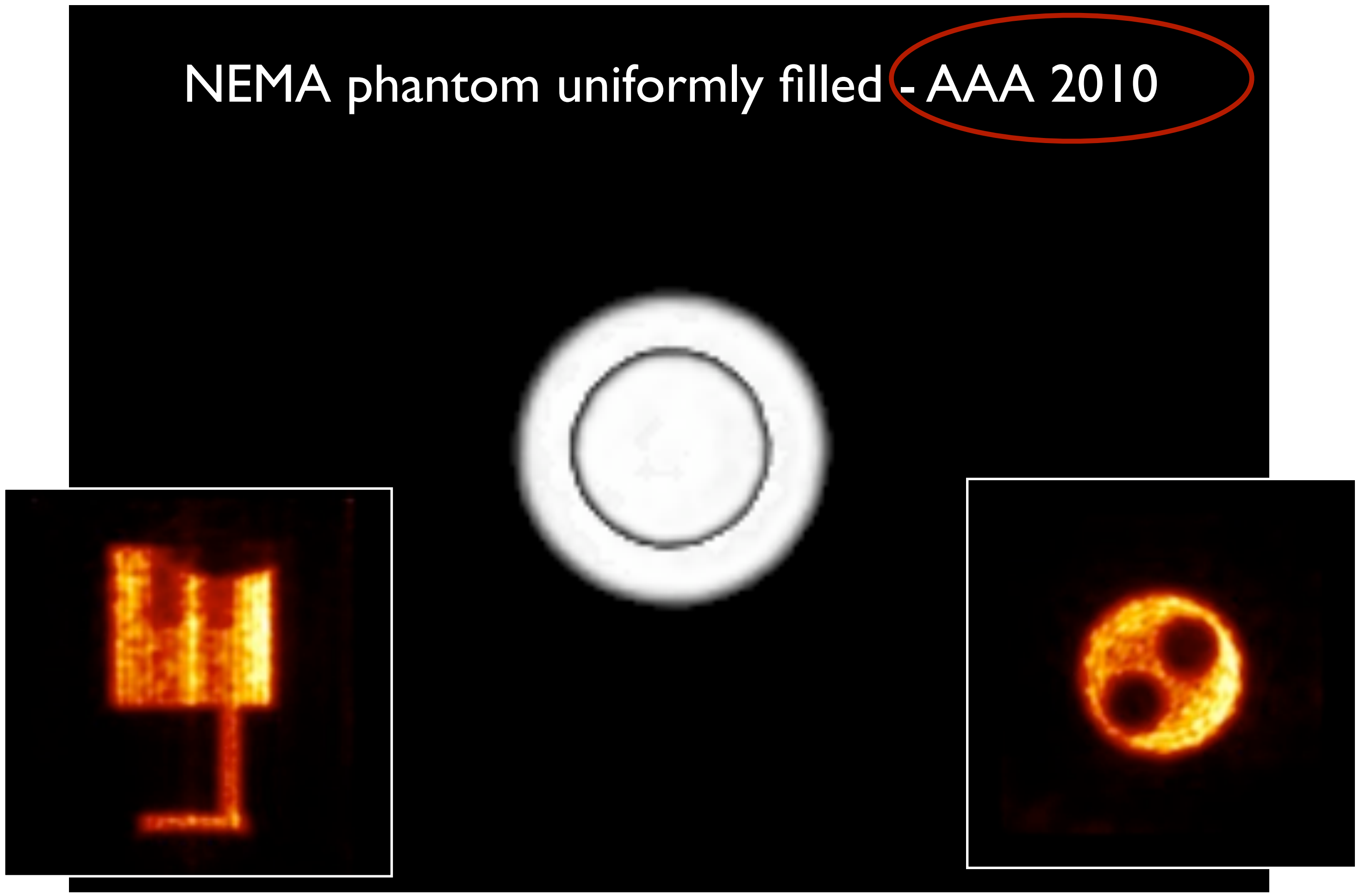

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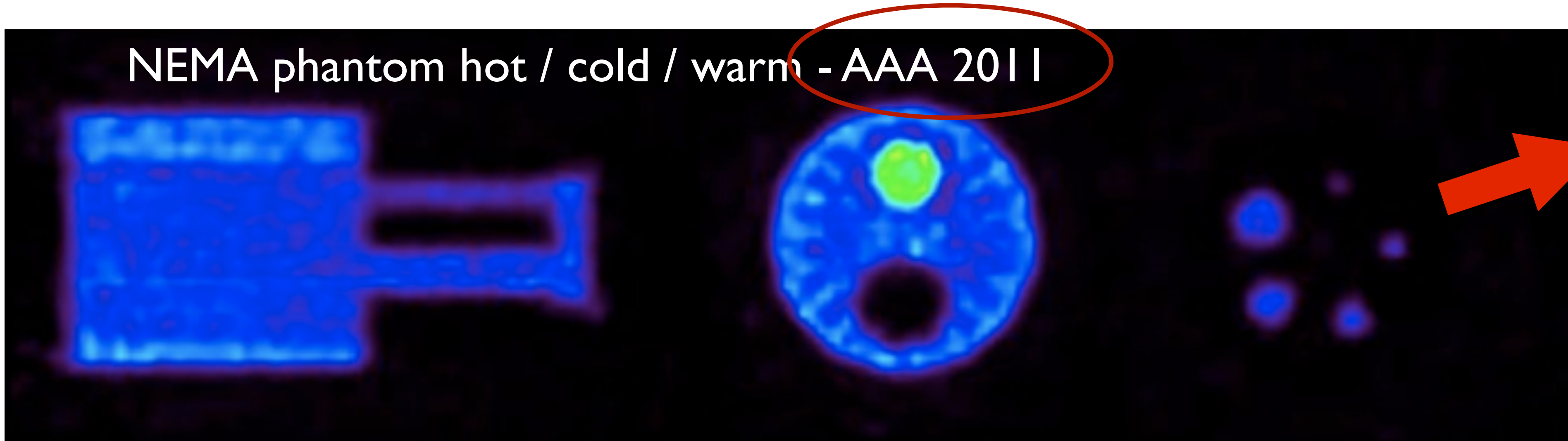

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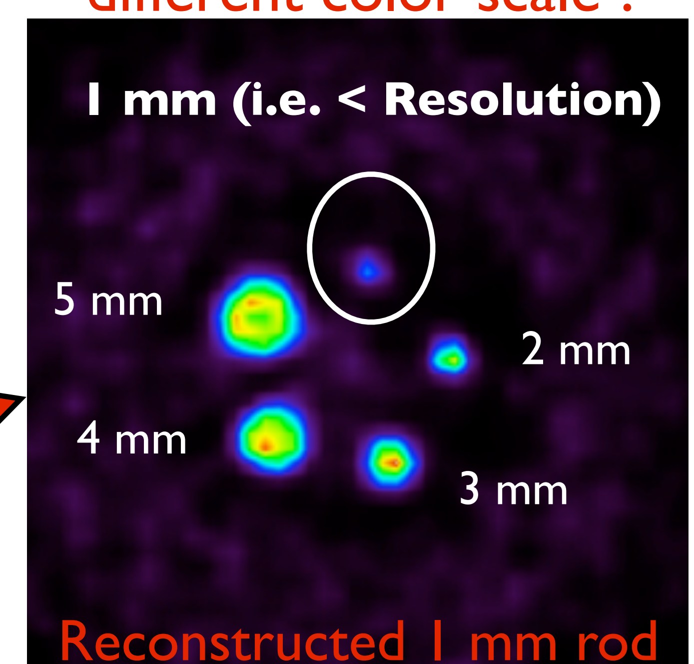
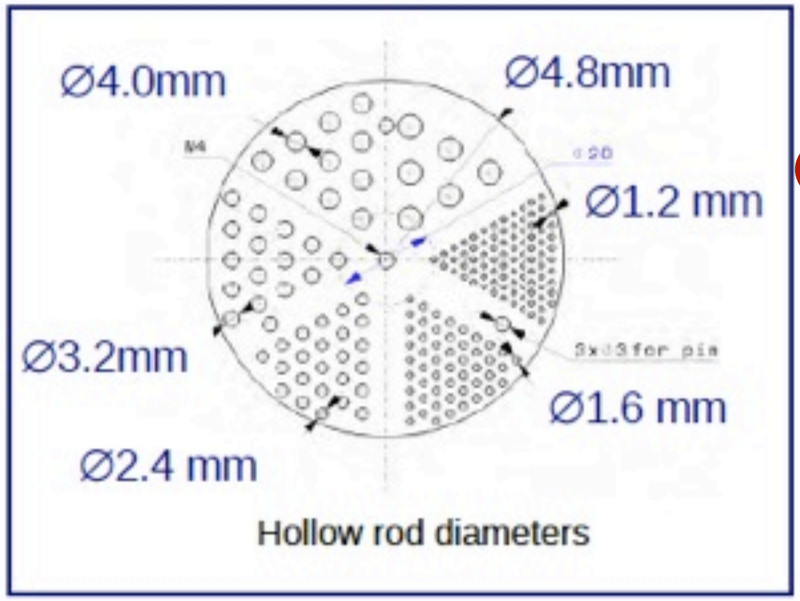


=> FWHM ~ 1.6 mm

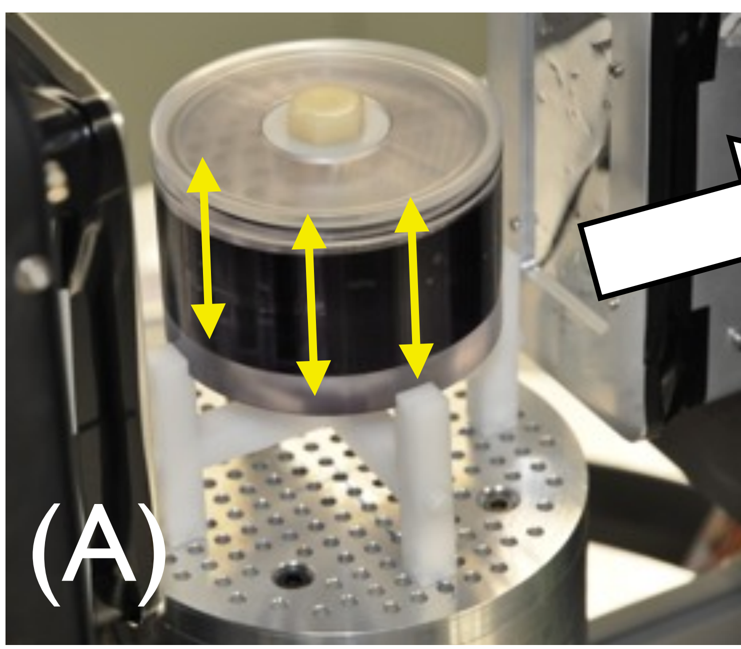
Resolution Phantom

Mini Deluxe phantom

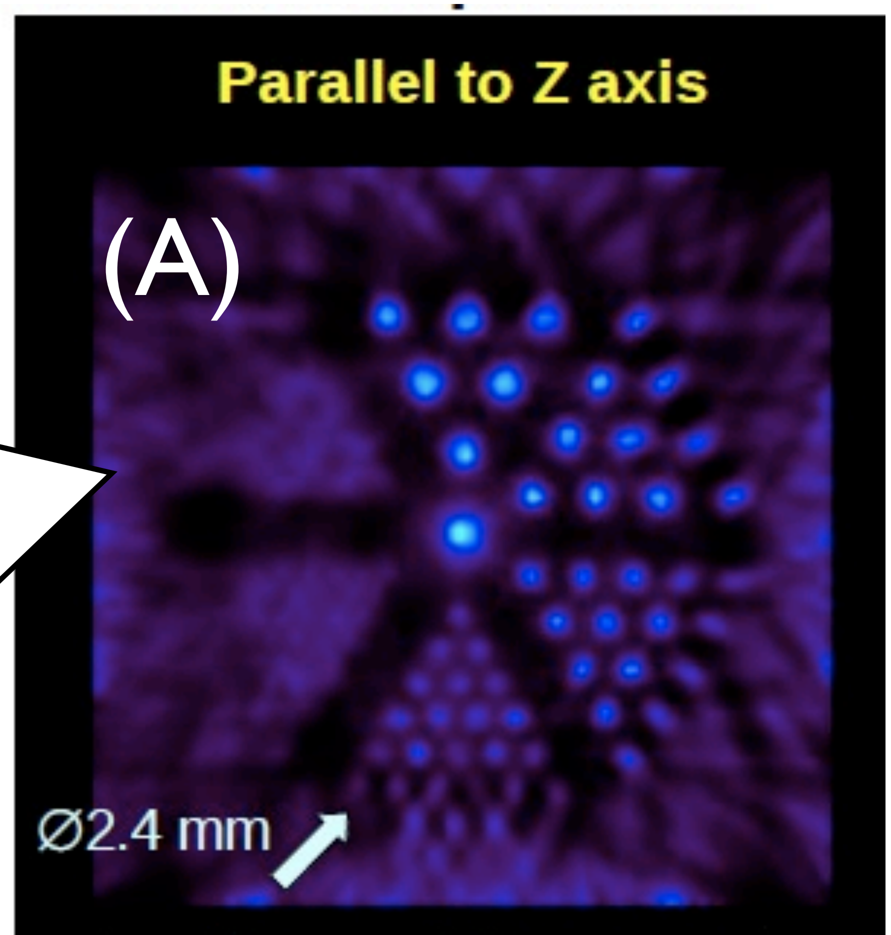


extended FOV
2nd module rotation

AAA 2011



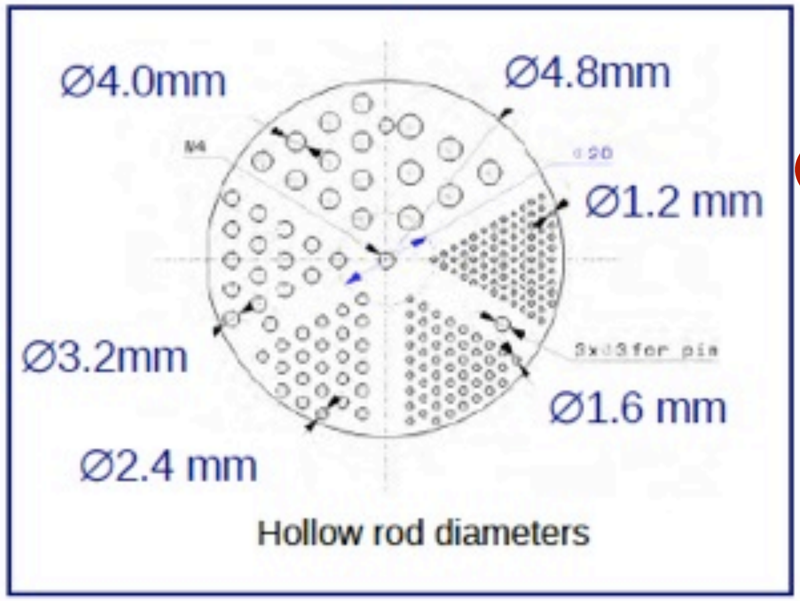
Rods oriented parallel to Z axis



- Fixed time acquisition: 120 s /step
- 60 iterations + post-reconstruction smoothing
- No corrections
- Artefacts due to data truncation (FOV too small...)

Resolution Ph

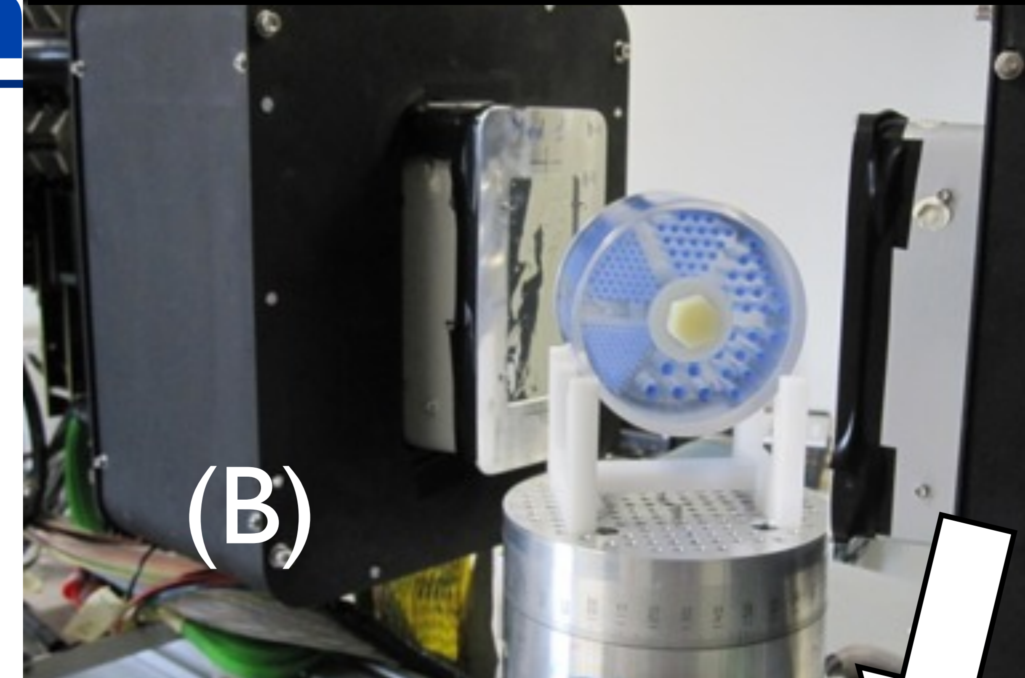
Mini Deluxe phantom

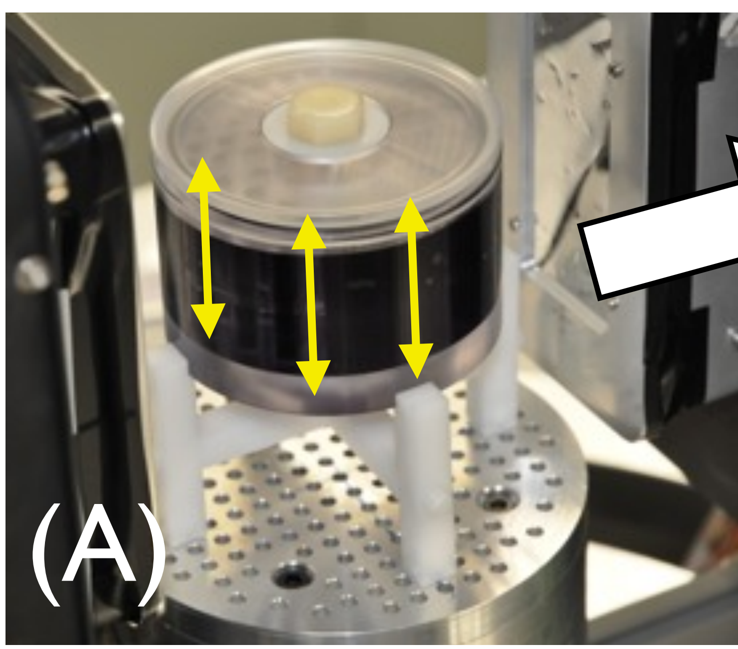


extended FOV
2nd module rotation

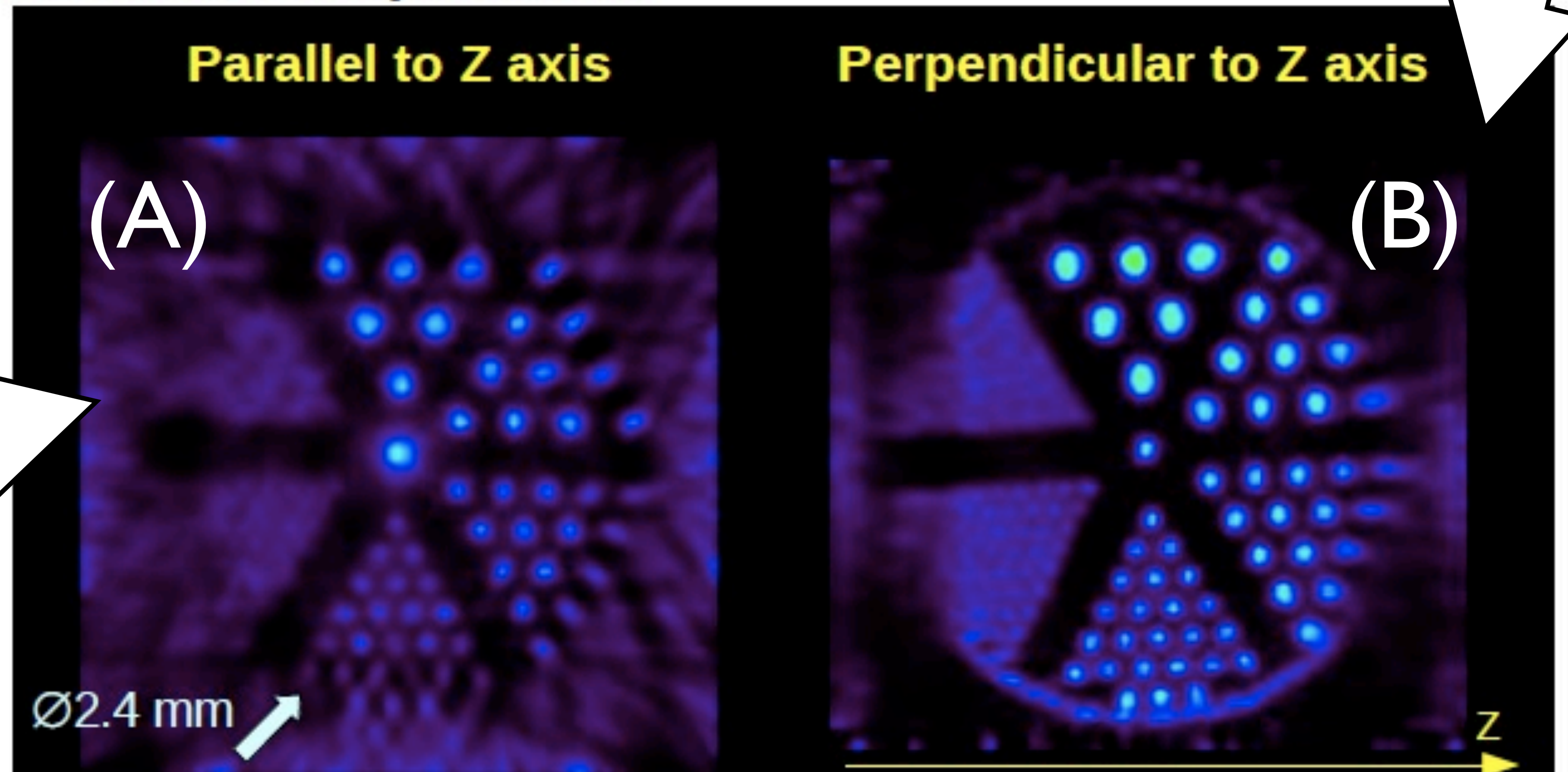
AAA 2011

Rods oriented perpendicular to Z axis





Rods oriented parallel to Z axis



- Fixed time acquisition: 120 s /step
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- No corrections
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Results presented in Valencia, IEEE 2011

Conclusions

Axial concept for a PET scanner :

i.e. long and axially oriented scintillation crystals

Intrinsically parallax free system (DOI information directly from the axial geometry)

Spatial resolution and sensitivity could both be optimized

AX-PET implementation :

3D spatial information of the photon interaction point with :

matrix of LYSO crystals and WLS strips

individual readout of each channel (Si-PM)

Two modules built (i.e. **AX-PET demonstrator**)

Energy resolution ~ 12% FWHM,@ 511 keV

Spatial resolution ~ 1.35 mm FWHM

(competitive with state of the art PET)

- in HEP approach : **calorimeter with tracking capabilities** (granularity)
- in PET detectors domain : **novelty as a PET detector :**
  - geometry
  - WLS implementation
  - Compton scattering reconstruction

Fully simulated device

Simulations - fully validated on the demonstrator - will assess the final performance of an hypothetical full ring scanner. **Flexible design**: scalable in size / dimensions / nr. layers....

=> flexibility in the final target of AX-PET (small animal PET / brain PET)

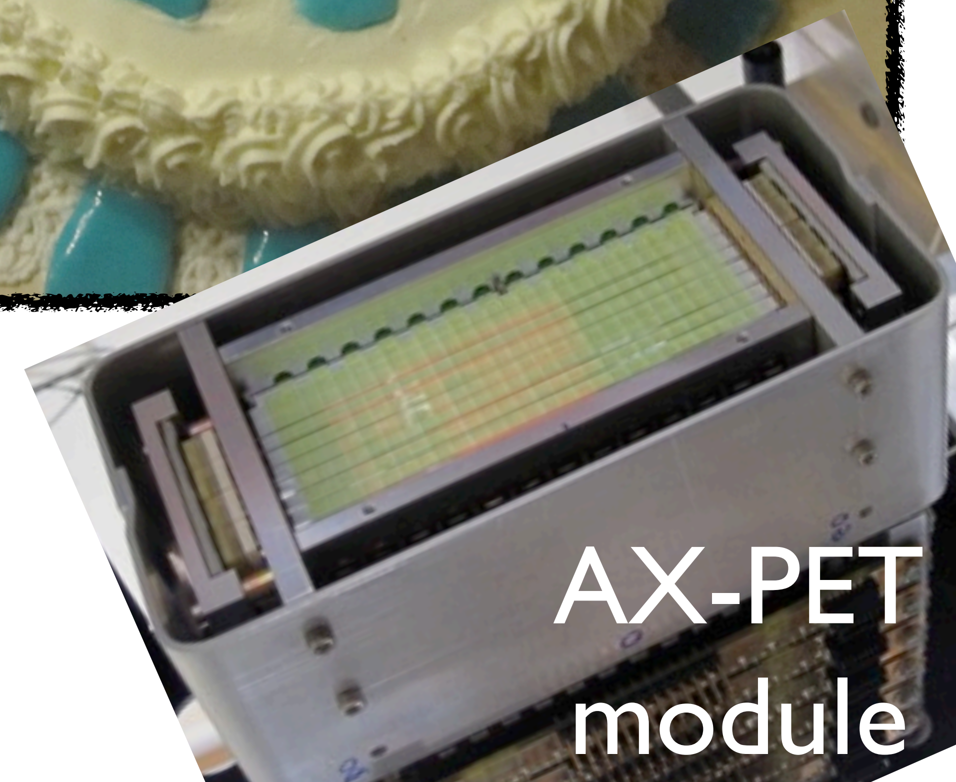
AX-PET demonstrator :
Extensively tested with sources and successfully used with phantoms !

NIM A 654 (2011) 546-559

more details : **https://twiki.cern.ch/twiki/bin/view/AXIALPET/WebHome**

Can this be useful in positronium physics ?

ETH Institute for Particle Physics



AX-PET