Imaging results and TOF studies with an axial PET detector

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for the AX-PET collaboration

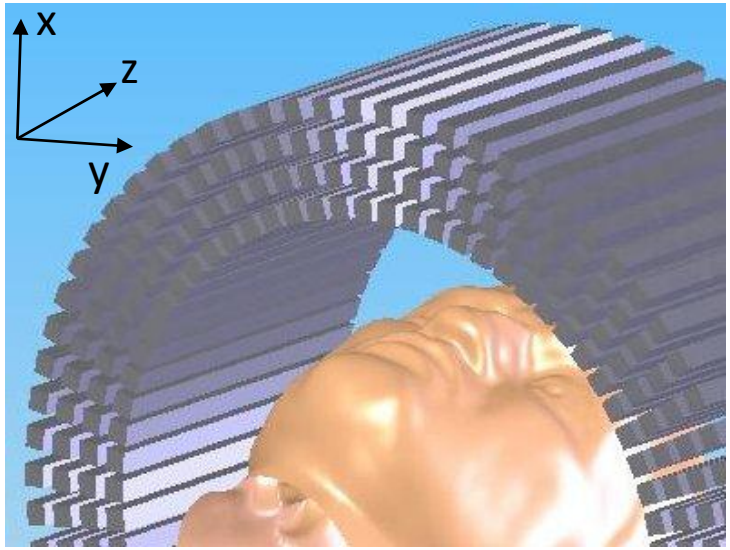
Outline

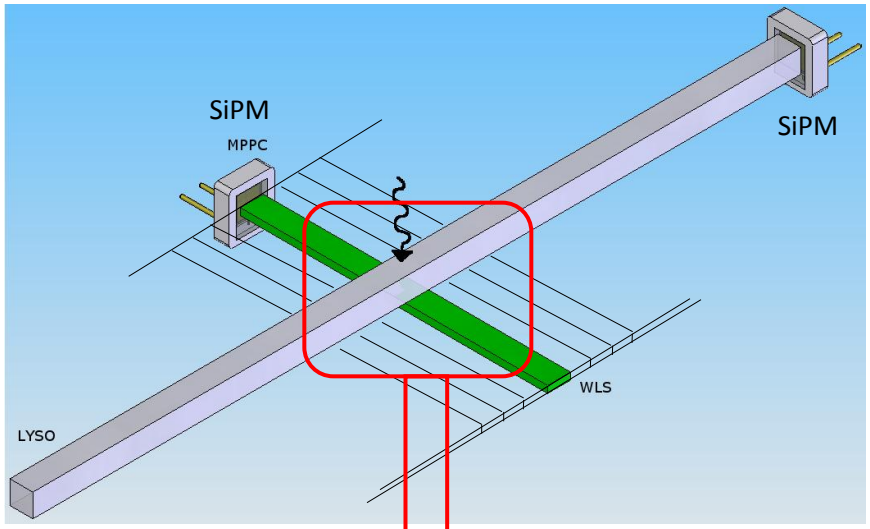
- Axial PET – the basic idea
- The AX-PET demonstrator set-up
- Tomographic imaging of phantoms and small animals
- The Digital SiPM by Philips
- TOF-PET studies with digital axial modules

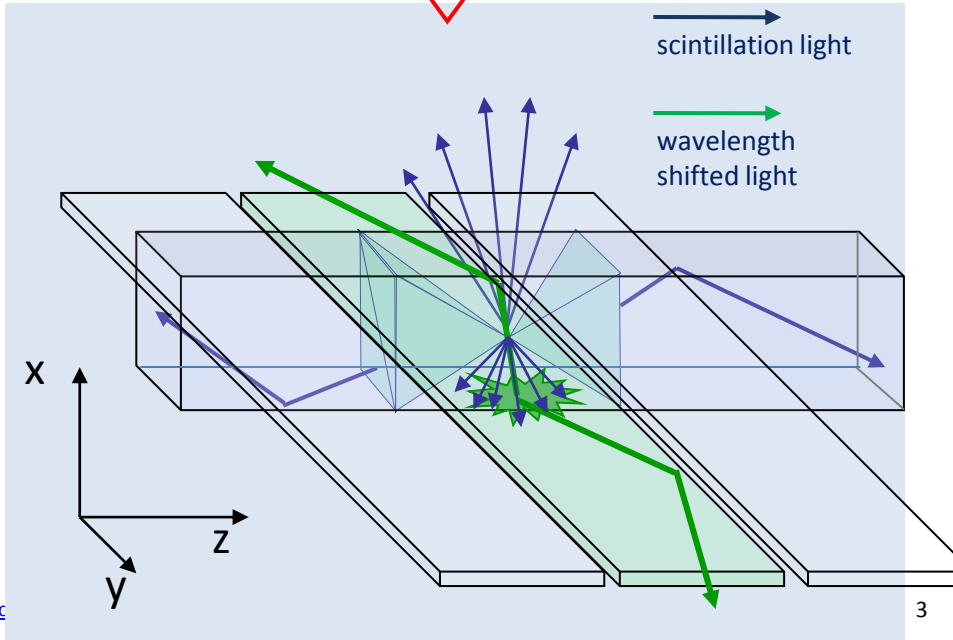
www.cern.ch/ax-pet

P. Beltrame et al., **The AX-PET demonstrator—Design, construction and characterization**, NIM A 654 (2011) 546-559
P. Beltrame et al., **The AX-PET Concept: New Developments And Tomographic Imaging**, 2011 IEEE NSS Conf. Rec. MIC22-5
P. Solevi et al., **A Monte–Carlo based model of the AX-PET Demonstrator and its experimental validation**, subm. to Phys. Med. Biol.
M. Rafecas et al., **Rodent imaging using AX-PET, a novel PET concept with axially-oriented crystals and wave-length shifting strips**, subm. to Phys. Med. Biol.
C. Casella et al., **A High Resolution TOF-PET Concept with Axial Geometry and Digital SiPM Readout**, to be submitted to NIM A.

The AX-PET concept







- Long axially oriented crystals, individual read out by SiPMs. → **x-y coordinate**. Precision given by crystal cross-section.
- Orthogonal arrays of WLS strips (with SiPM readout) → **z-coordinate**. Precision given by strip width + centre-of-gravity algorithm.
- Additional layers allow to increase sensitivity, without compromising resolution.

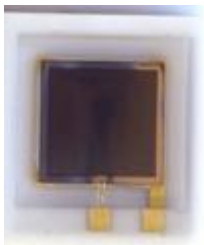
→ **Spatial resolution and sensitivity are decoupled and can be optimized independently. Practically parallax error-free!**

The AX-PET Demonstrator

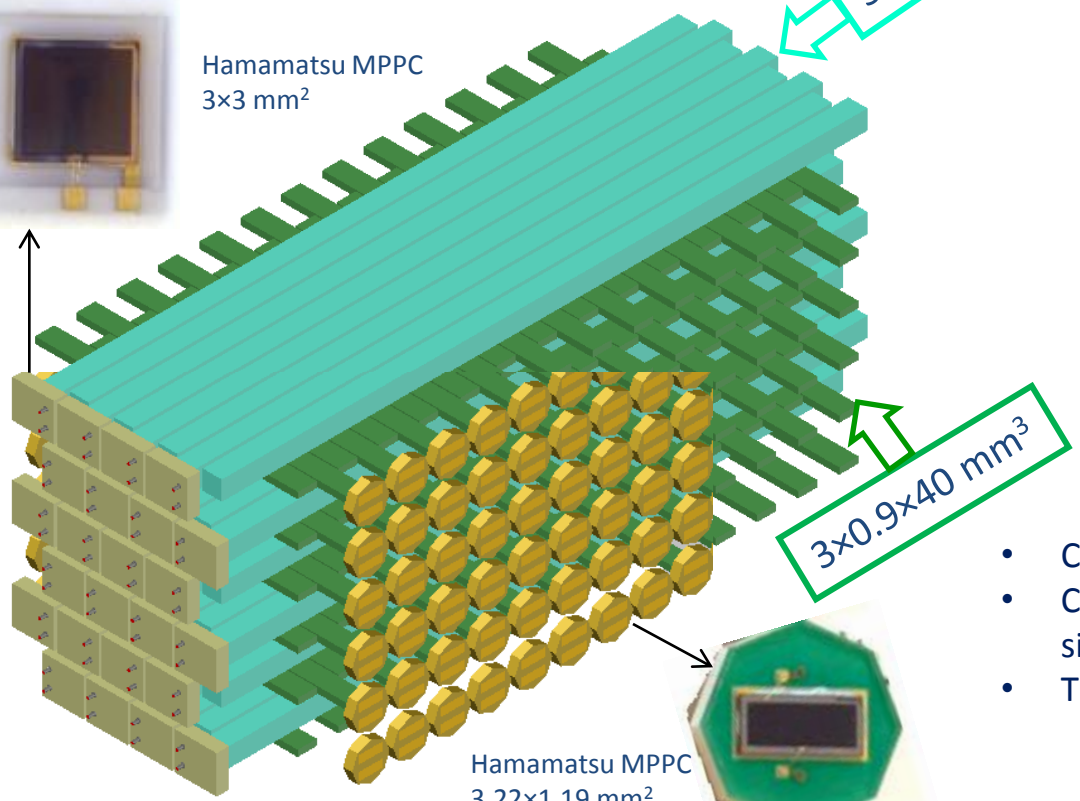
Since 2008, the AX-PET collaboration (Bari, Cagliari, CERN, Michigan, Ohio, Oslo, Tampere, Valencia, Zurich, < 10 FTE) has built and tested a fully operational PET demonstrator scanner.

It consists only of **two camera modules** à

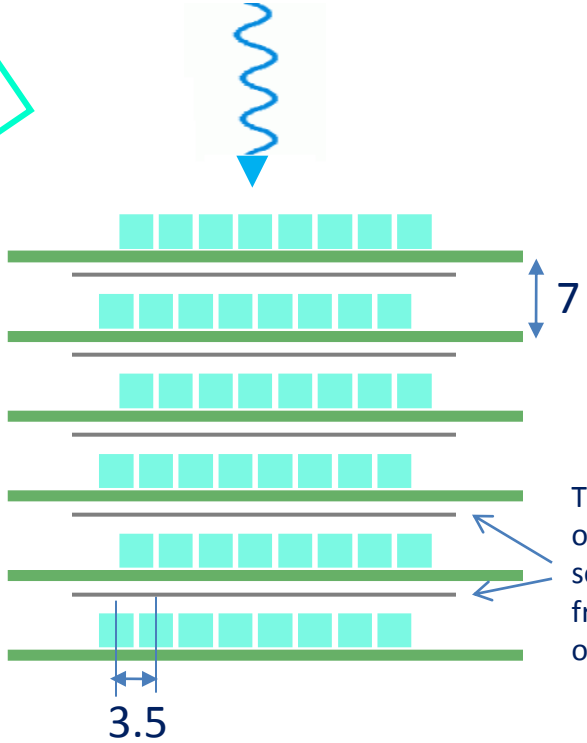
- 48 LYSO crystals (6 layers x 8 crystals)
- 156 plastic WLS strips (6 layers x 26 strips)



Hamamatsu MPPC
3×3 mm^2



Hamamatsu MPPC
3.22×1.19 mm^2

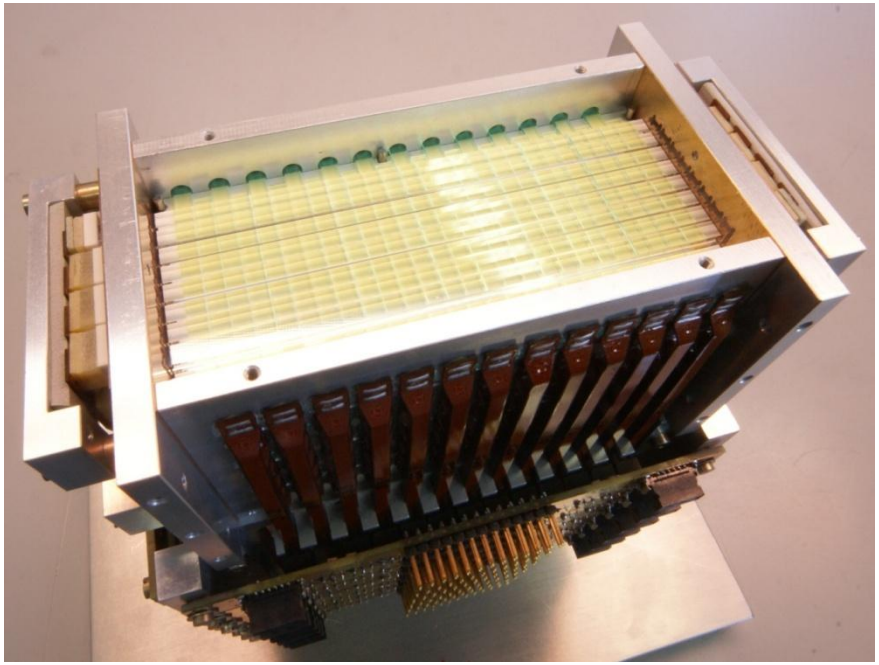


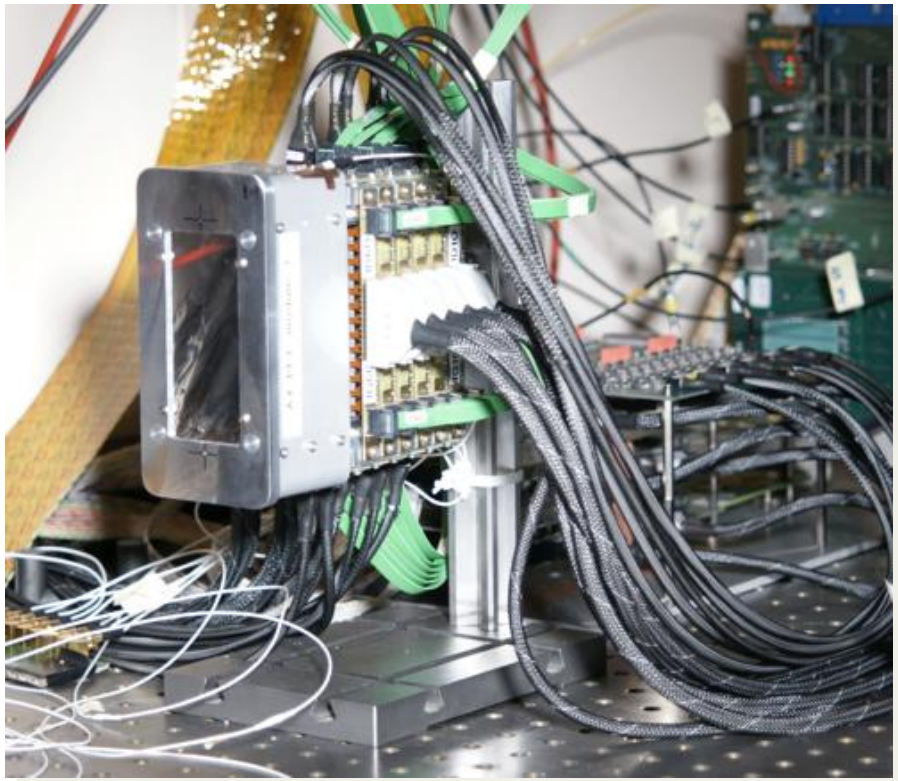
The layers are optically separated from each other.

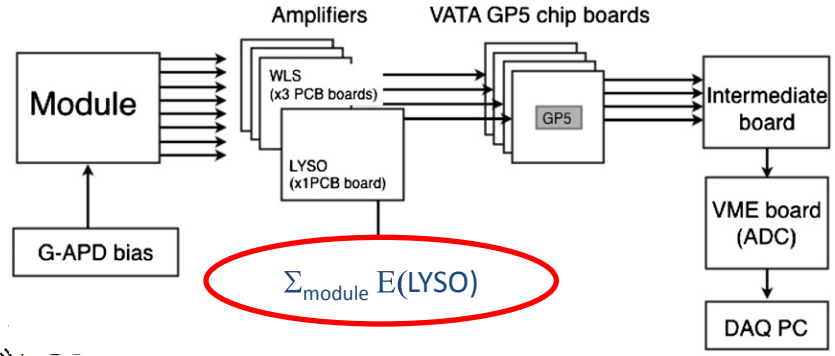
- Crystals are staggered by 2 mm.
- Crystals and WLS strips are read out on alternate sides to allow maximum packing density.
- The other side is Al-coated, i.e. mirrored.

The AX-PET Demonstrator

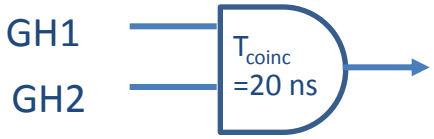
Fully assembled module. 204 RO channels
→ lots of cables: 204 x (bias + signal out)







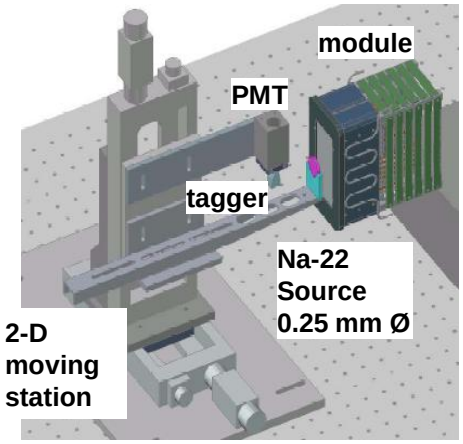
Σ_{module} E(LYSO) = 511 keV ➔ GoodHit



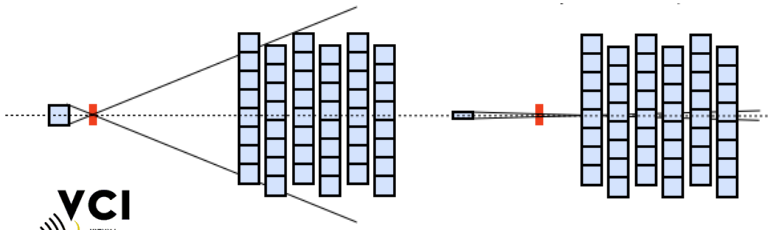
Max Readout rate ~ 20 kHz

Test set-ups

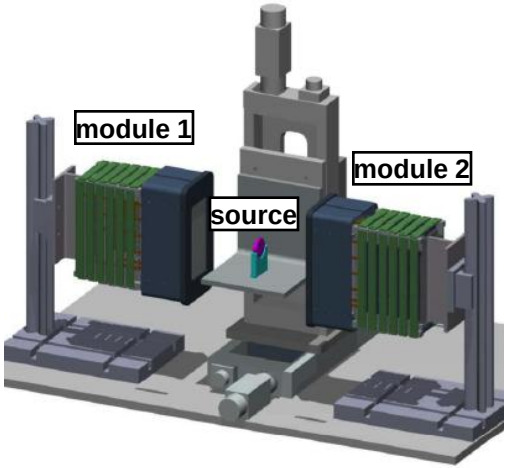
A) Single module characterization



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

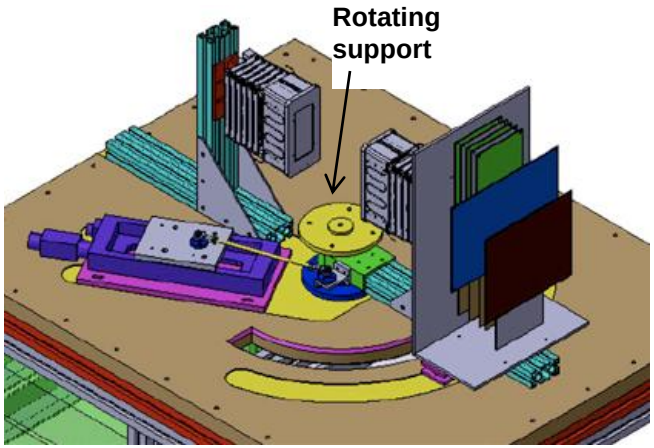


B) Coincidence of 2 modules

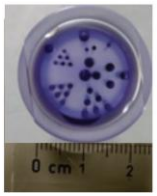


- Distance between modules = 15 cm

C) Gantry for tomographic measurements

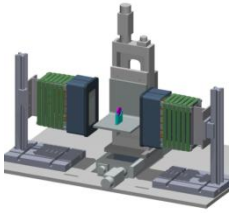


- Allows imaging of phantoms and small animals.

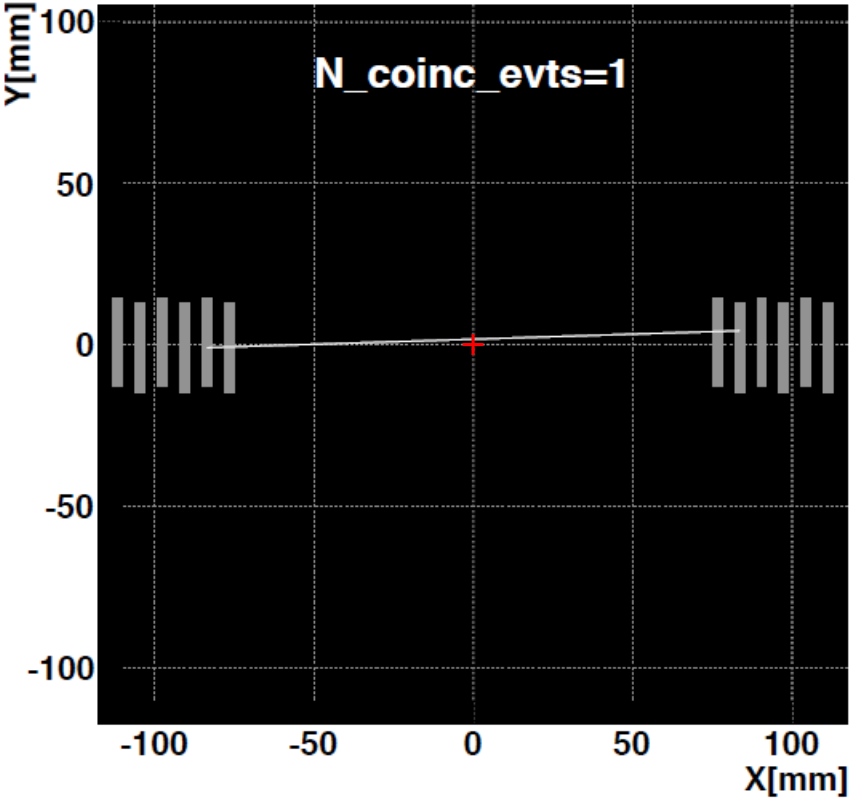


Coincidence measurements

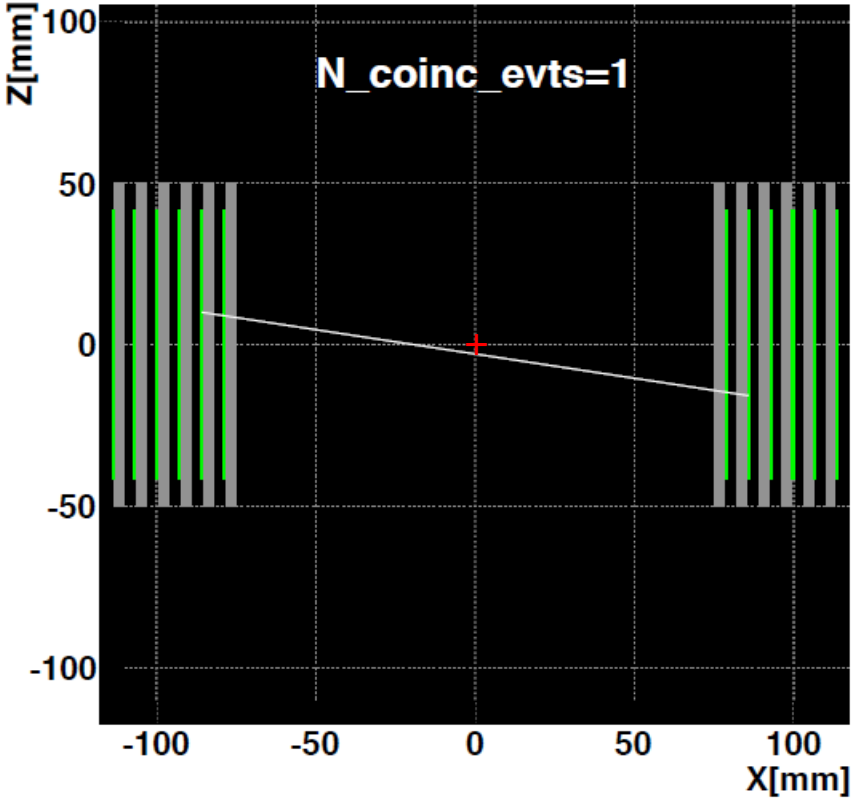
- Point-like ^{22}Na source (0.25 mm Ø)
- Photoelectric events only (1 hit crystal per module)
- Draw "LOR" (pure geometrical, no tomographic reconstruction)



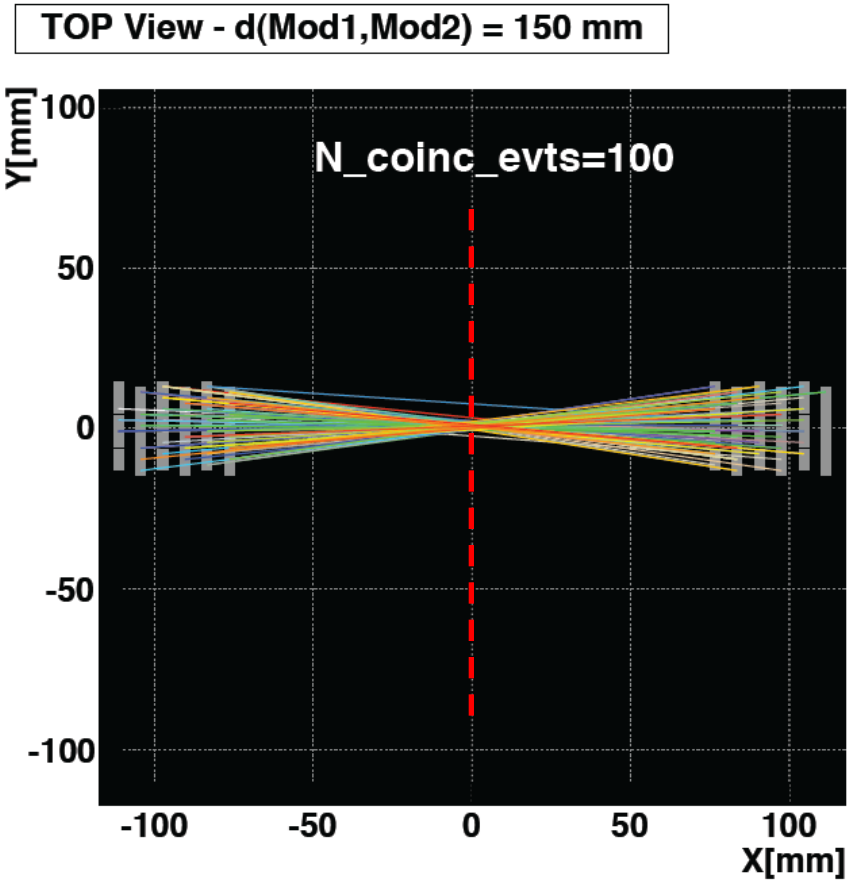
TOP View - d(Mod1,Mod2) = 150 mm

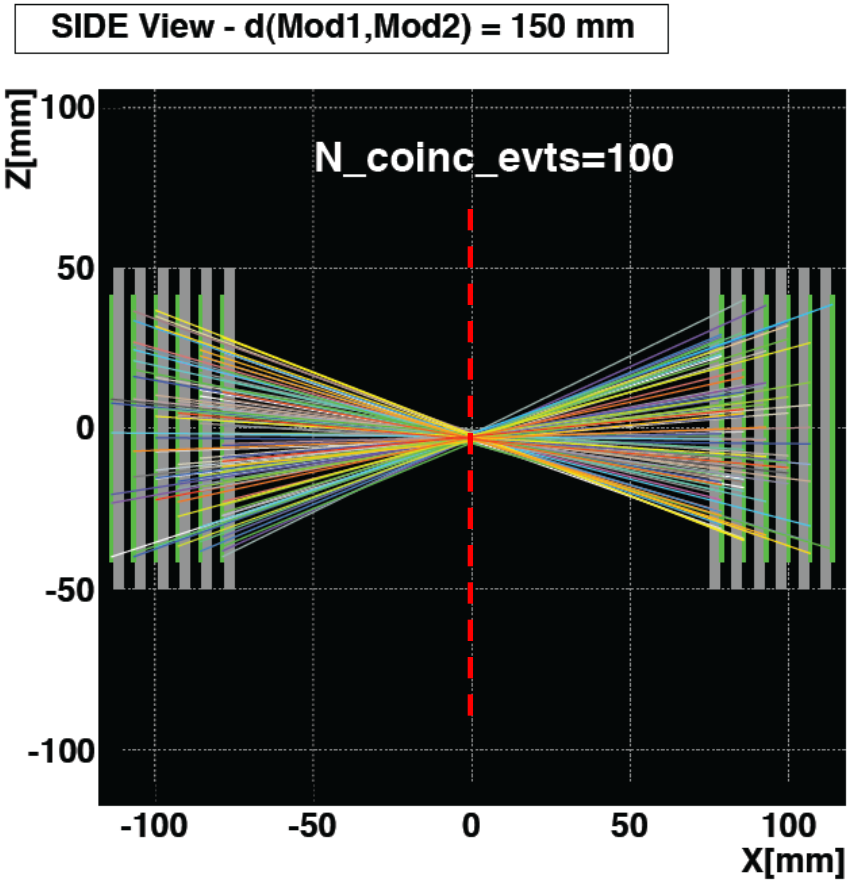


SIDE View - d(Mod1,Mod2) = 150 mm



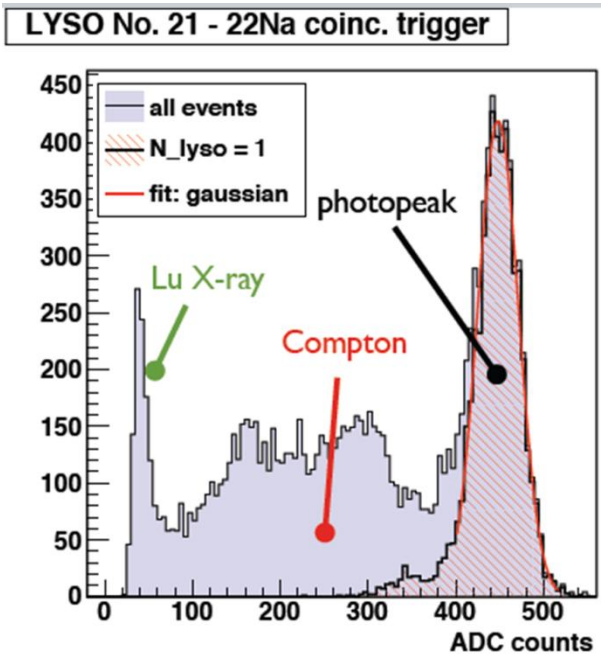
First coincidence measurements





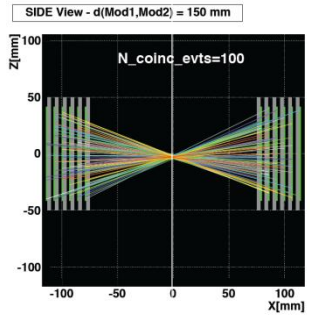
Basic performance figures

Yield LYSO: ~1100 pe / 511 keV
Yield (2-3) WLS: ~100 pe / 511 keV

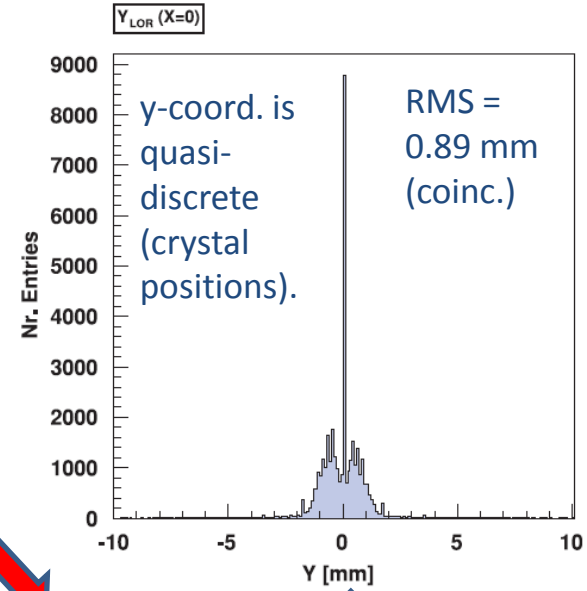


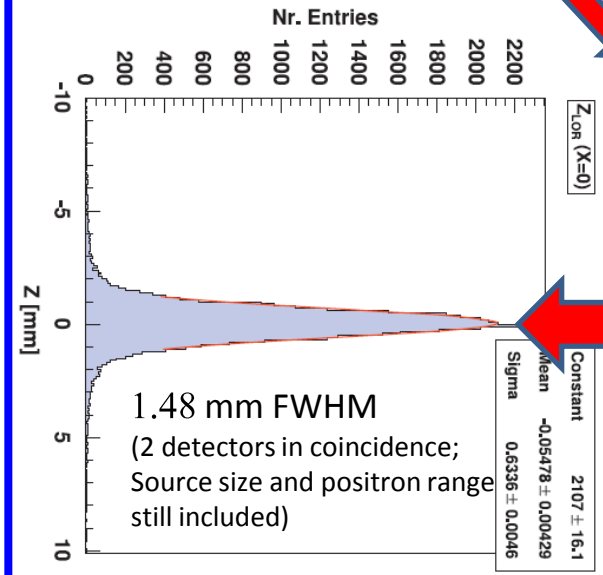
$<R_E>_{511}$ = 11.7 % (FWHM)

Calibrated and averaged over all crystals.

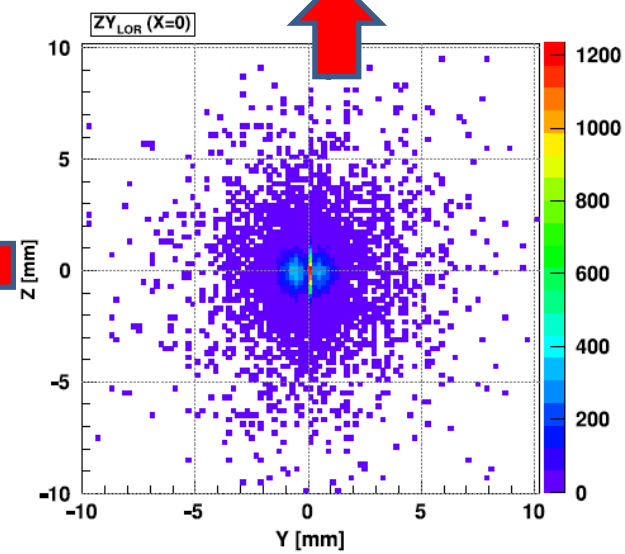


Look at the YZ distribution at x=0 ("confocal reconstruction")



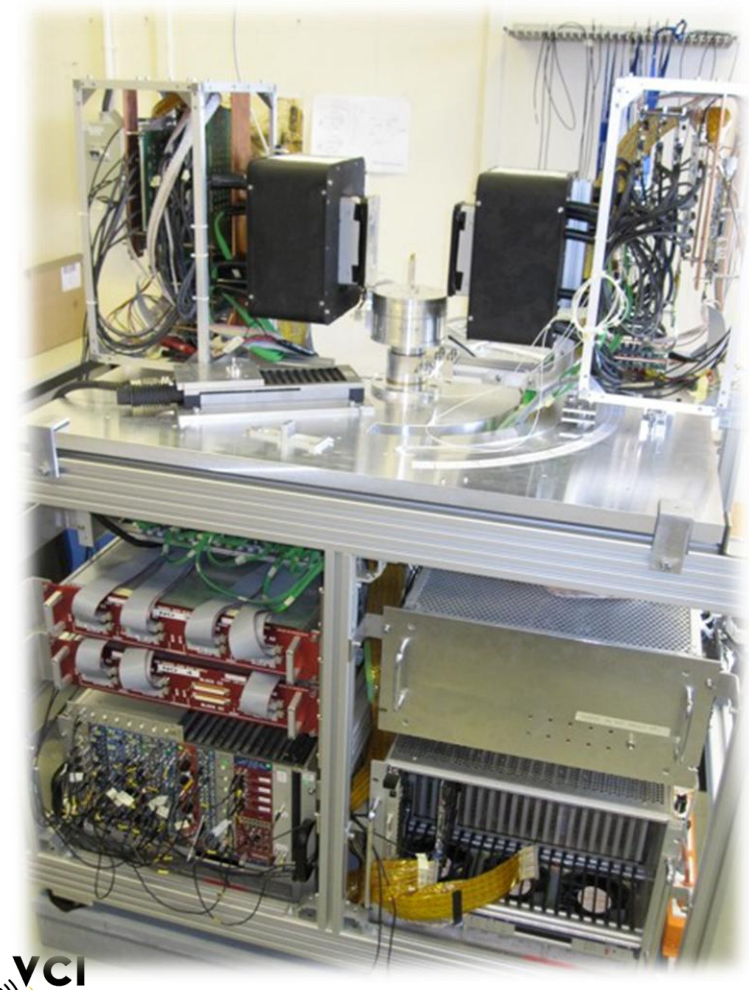


1.48 mm FWHM
(2 detectors in coincidence; Source size and positron range still included)



AX-PET in motion

The AX-PET Demonstrator set-up has exactly the size of a EURO palette. Very useful for measurement campaigns at other places



Measurements with phantoms or animals can't be made at CERN!

ETH Zurich, PET lab, 2010
AAA* (Saint Genis, F) 2010
AAA (Saint Genis, F) 2011
} phantoms

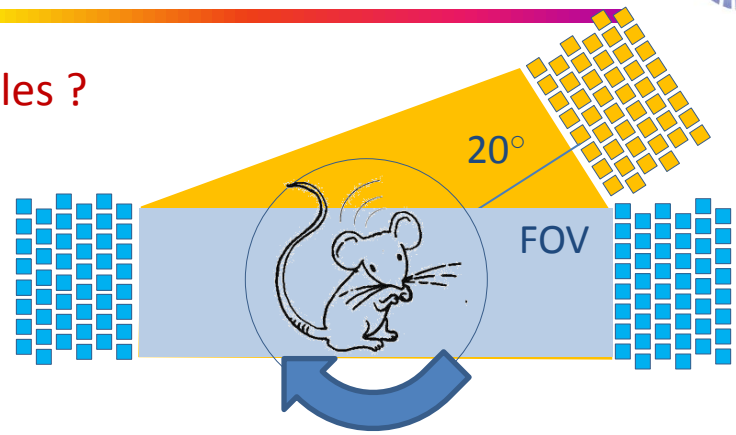
ETH Zurich, PET lab 2012 — animals

*Advanced Accelerator Applications www.adacap.com

Unloading at ETH-Zurich

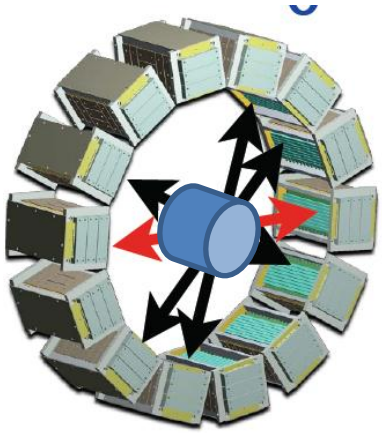
Tomographic measurements with just 2 modules ?

How do we get all these angles with just 2 modules ?

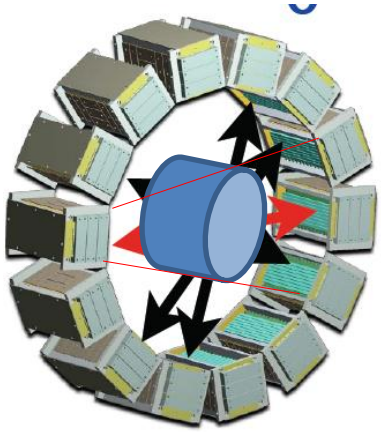


"Step and shoot"
Rotate object in 9 steps of 20 deg.

"Step and shoot"
1.) Rotate object in 9 steps of 20 deg.
2.) Rotate 1 module by 20 deg.
3.) Rotate object in 18 steps of 20 deg.



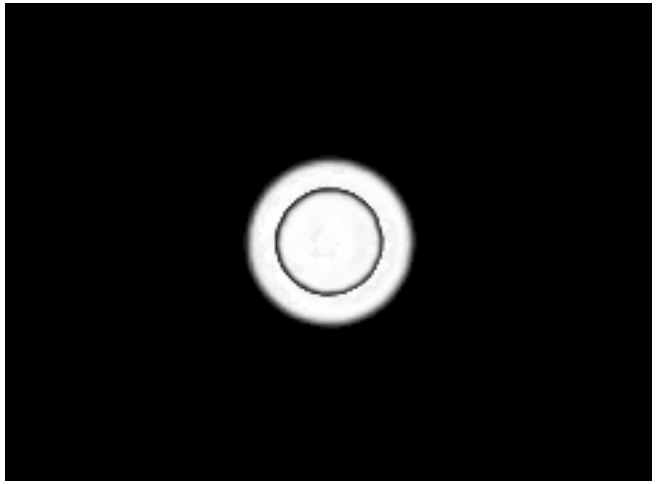
Price to pay:
- Longer acquisition times (several h).
- Decaying activity
- Changing conditions (pile-up, dead time)

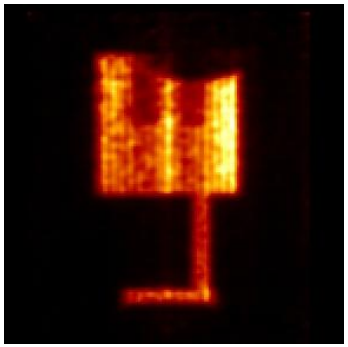


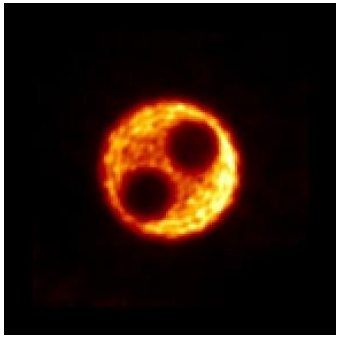
We mimic a 18-module scanner, however with a very limited FOV (width and length of 1 module). We allow only coincidences between opposite modules.

Now we allow coincidences between opposite ±1 modules. → Larger FOV.

Examples of reconstructed phantoms







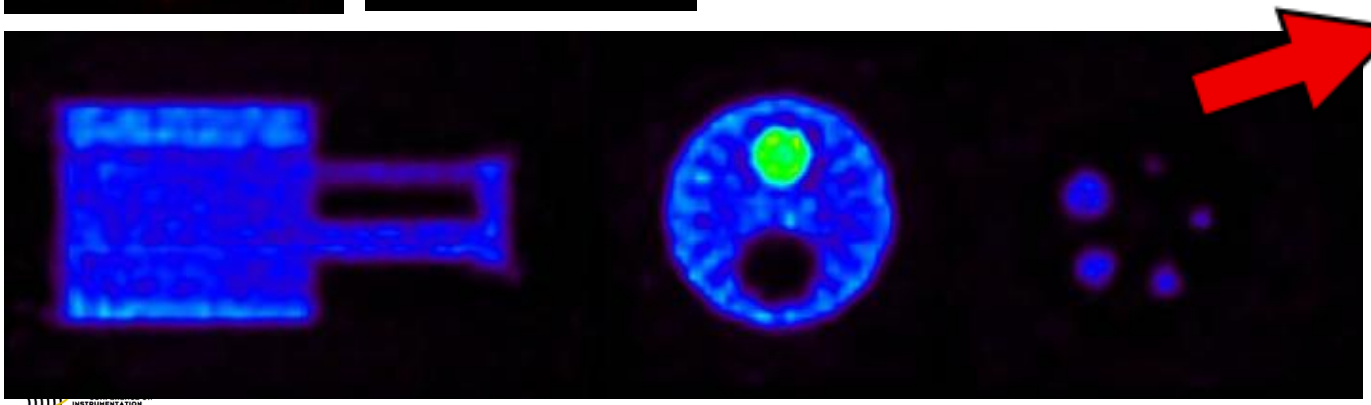
Three regions in the same phantom to address three different aspects

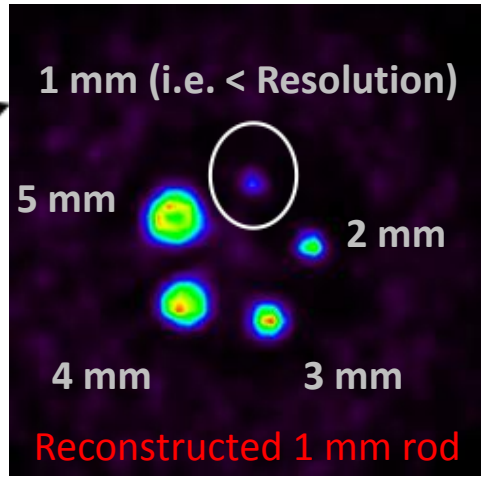
Hot & Cold rods for contrast

Homogeneous cylinder for assessing the ability to reconstruct homogeneous distributions

Series of small rods for resolution

NEMA mouse phantom



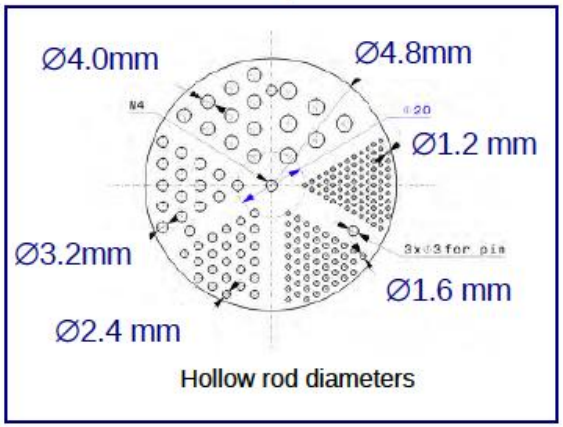


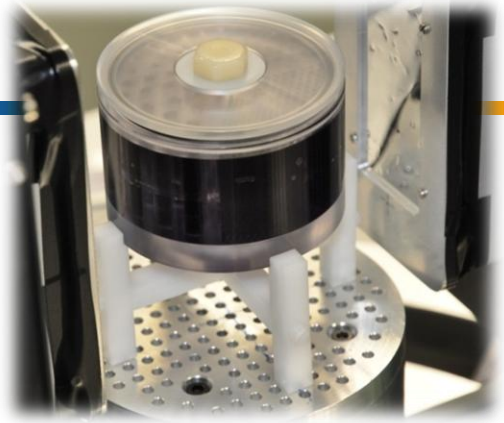
Reconstructed 1 mm rod

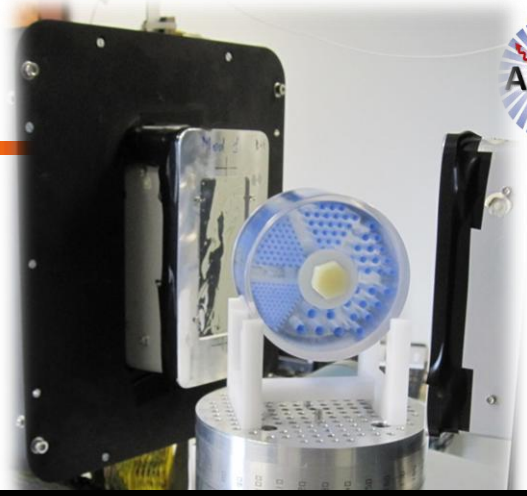
=> **FWHM ~ 1.6 mm**

Phantoms …

Mini Deluxe phantom

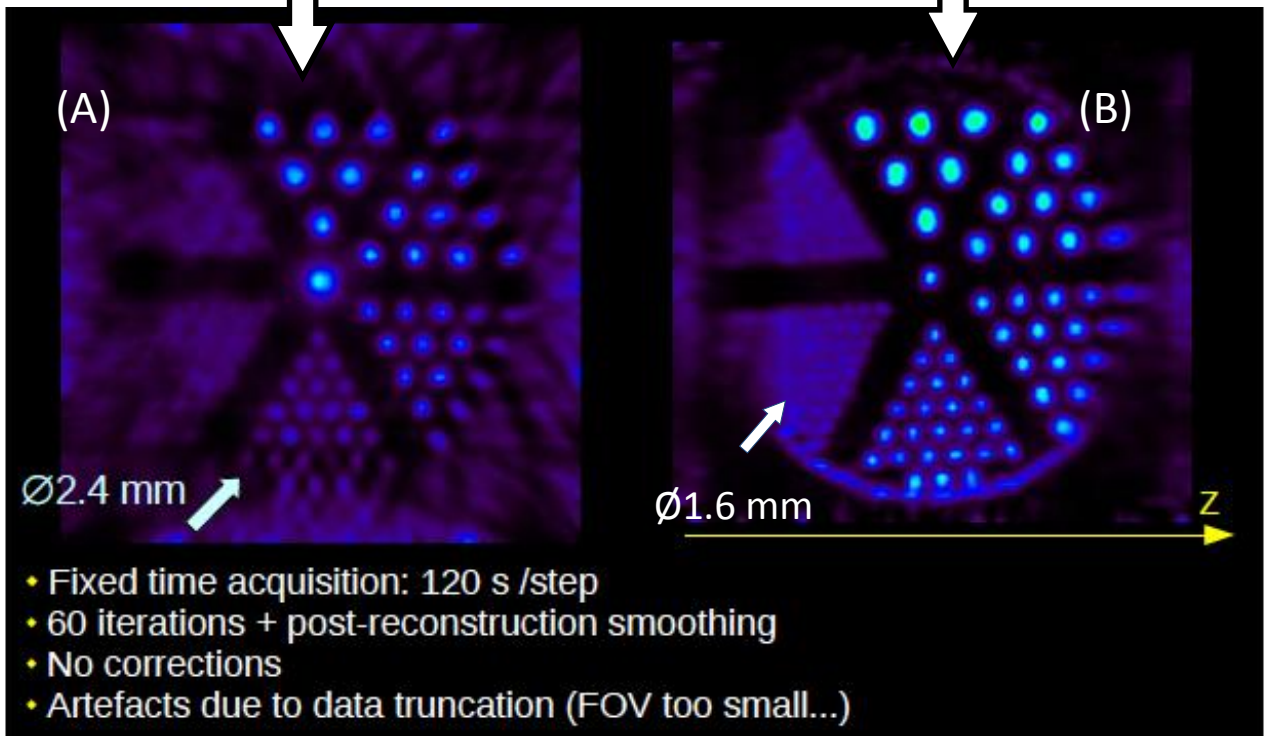






Rods oriented parallel to Z axis

Rods oriented perpendicular to Z axis



- High density resolution phantom
- Diameter (75 mm) is larger than the extended FOV

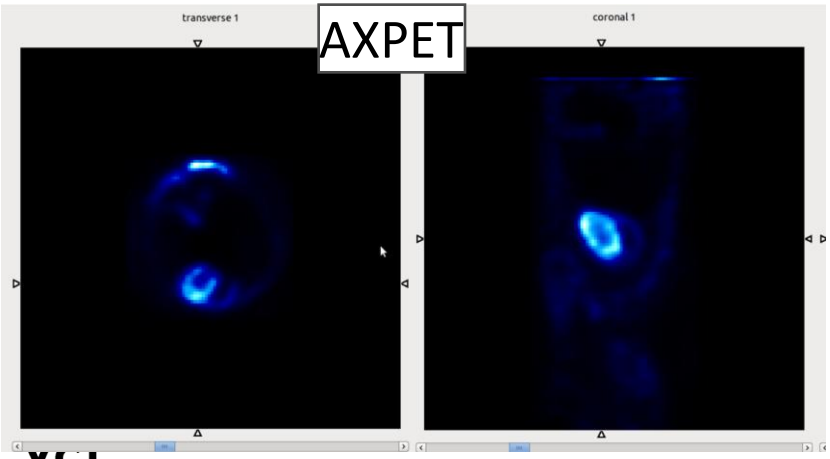
Small Animal Tests

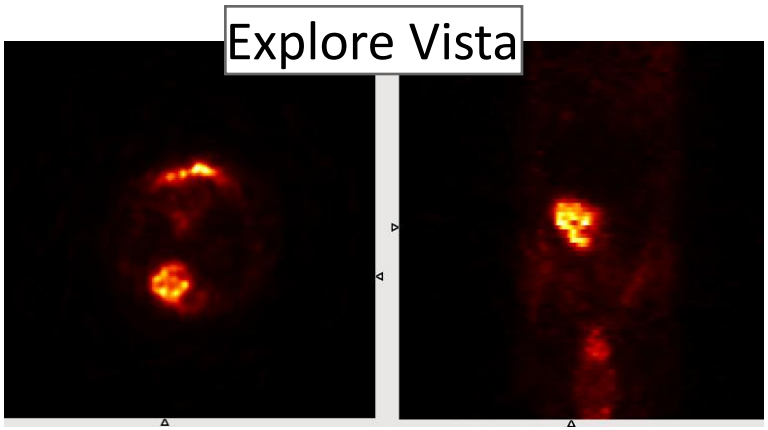
- June 2012, small animals tests campaign at ETH Zurich, Radiopharmaceutical Inst. (S. Kramer et al.)
- Possibility to use their GE Explore Vista PET/CT scanner as reference. This is a dedicated small animal scanner with 1.45 x 1.45 mm crystals. Block readout. DOI via Phoswich approach.
- one mouse, FDG
- one (young) rat, FDG

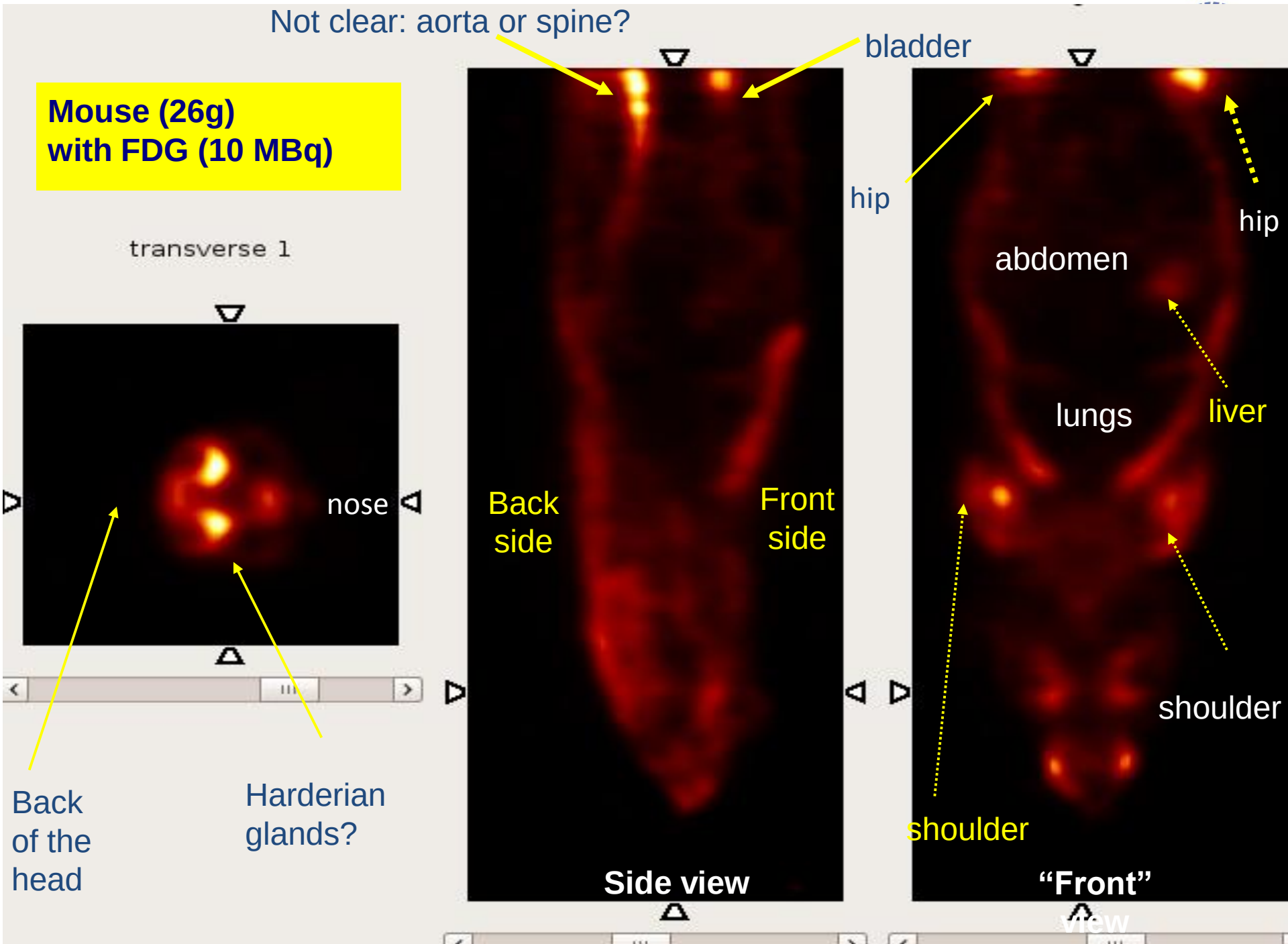
=> organs structure

- one (young) rat, 18-F => bones, skeleton structure

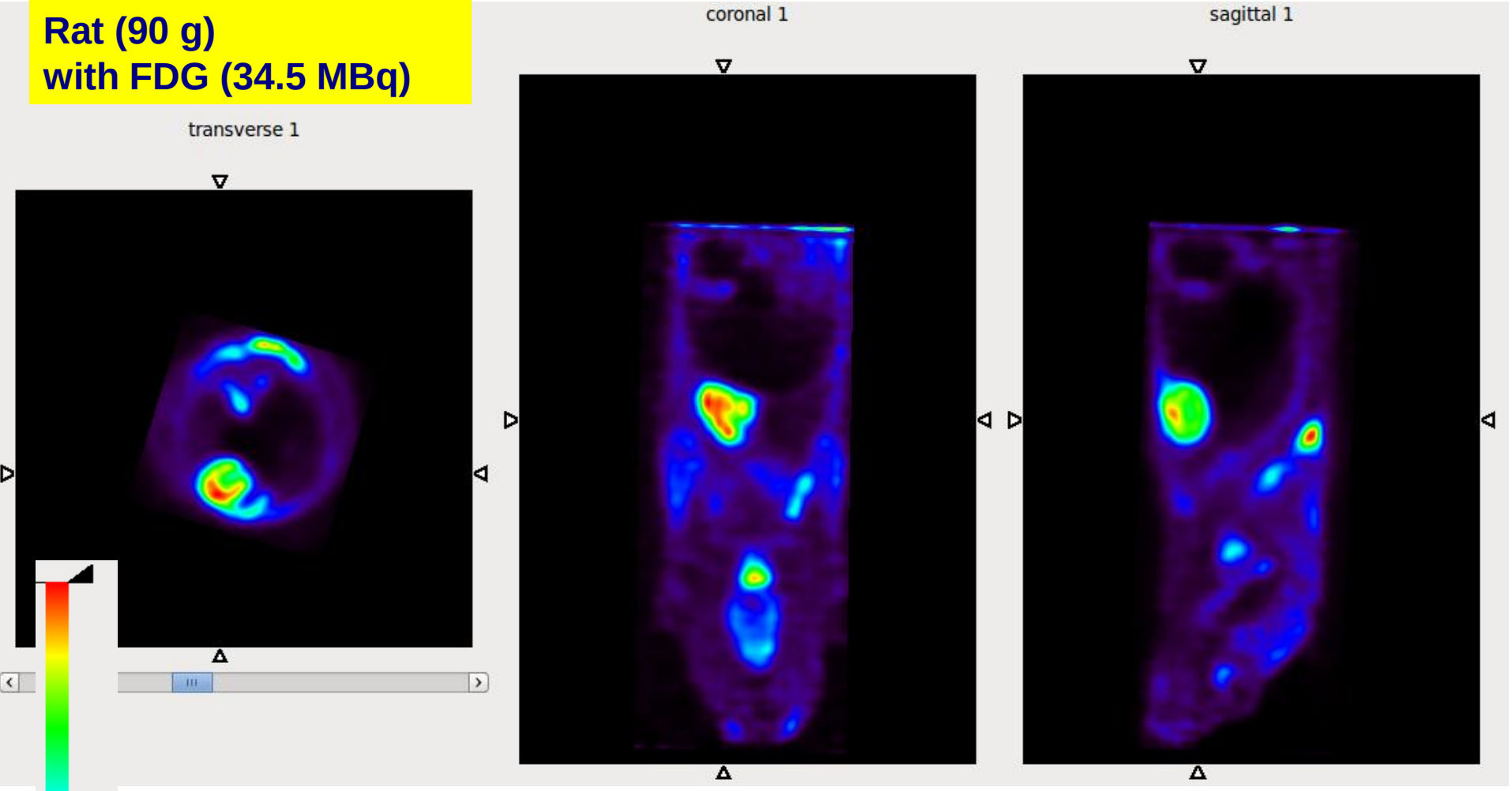
Rat, FDG - Details of the heart





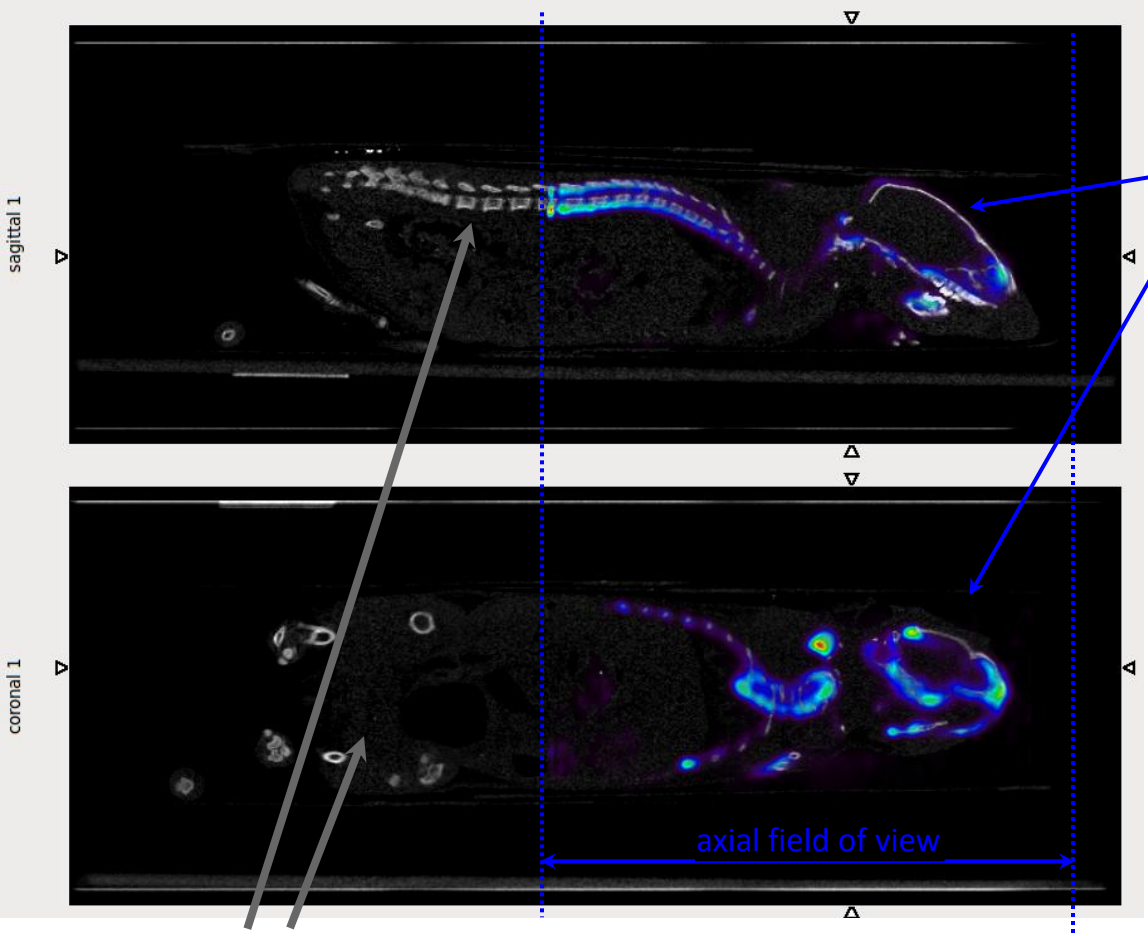

Not clear: aorta or spine?
bladder
Mouse (26g)
with FDG (10 MBq)
transverse 1
nose
Back
of the
head
Harderian
glands?
Back
side
Front
side
Side view
hip
hip
abdomen
lungs
liver
shoulder
shoulder
"Front"
view

Rat (90 g)
with FDG (34.5 MBq)

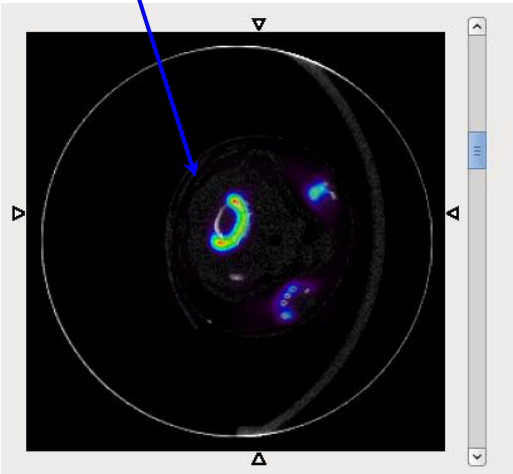


Two heart ventricles can be seen!

Rat 76g , F-18 (65 MBq) Details of the skeleton + CT image overlaid

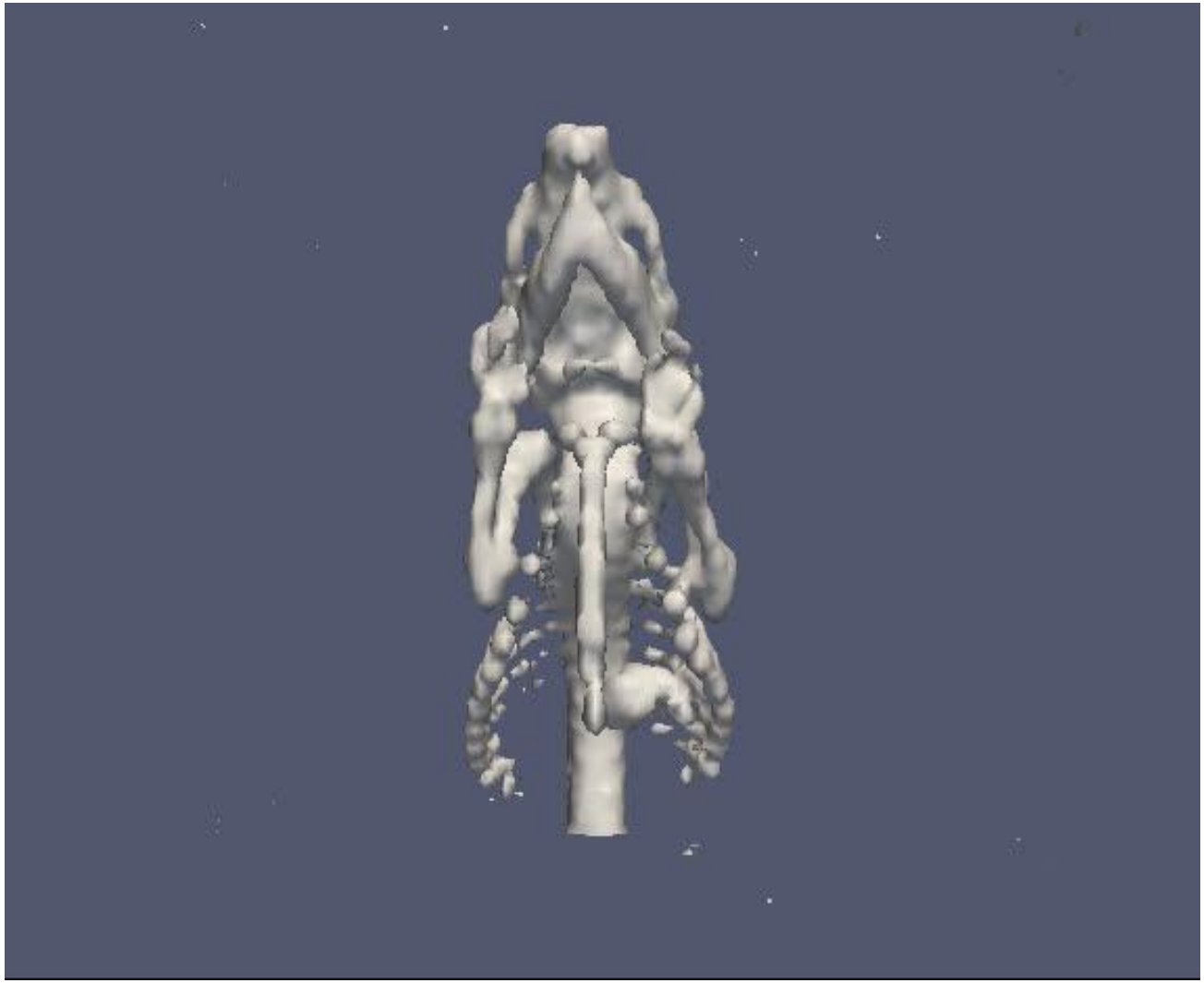


AXPET reconstructed image



CT image from GE Explore Vista
(not enough activity left for the PET acquisition with Explore Vista)

Rendered F-18 image of rat



Lab tests and imaging results of phantoms and small animals **demonstrated the feasibility and large potential** of an axial PET geometry with individual crystal readout.

Other groups picked up some of the ideas and develop dedicated applications: COMPET, a small animal PET (U. Oslo), a dedicated PET probe at Tampere UoT, a further (still confidential) project is in preparation. But so far, there is unfortunately no clear interest from industry.

In the mean time …

We have learned about the **digital SiPM technology** which offers a number of very attractive features like high level of integration, compactness, excellent timing resolution, no afterpulses, reduced temperature sensitivity…

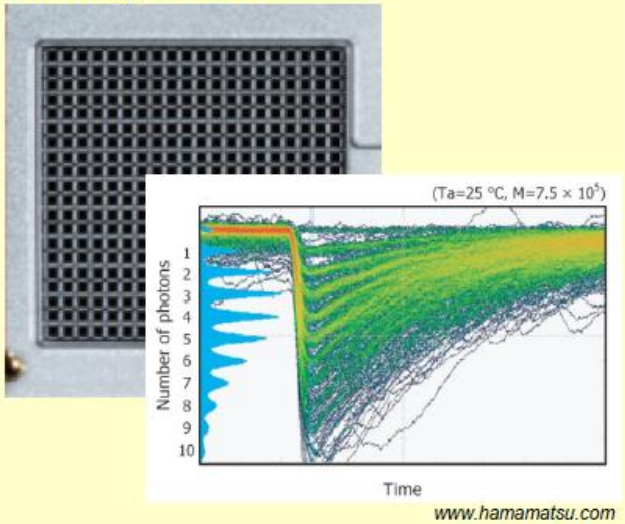
(1) Can an axial PET be built based on the digital SiPM technology ?

(2) Can one extend an axial PET by a 4th dimension → TOF-PET ?

Digital SiPM (by Philips)

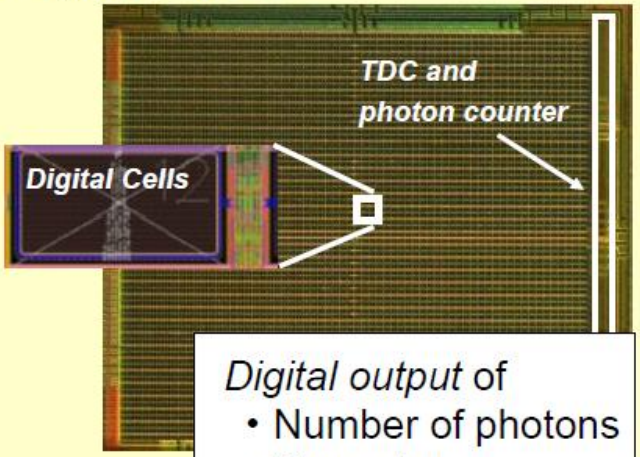
The cells/pixels of a SiPM are essentially binary devices. Instead of adding their signals in analog form, followed by electronic amplification, shaping, conversion, a digital SiPM just counts the number of fired cells.

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

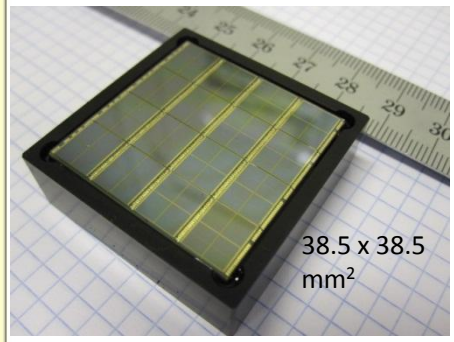
Digital SiPM (by Philips)



Digital output of
- Number of photons
- Time-stamp

- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

A tile with 64 dSiPMs

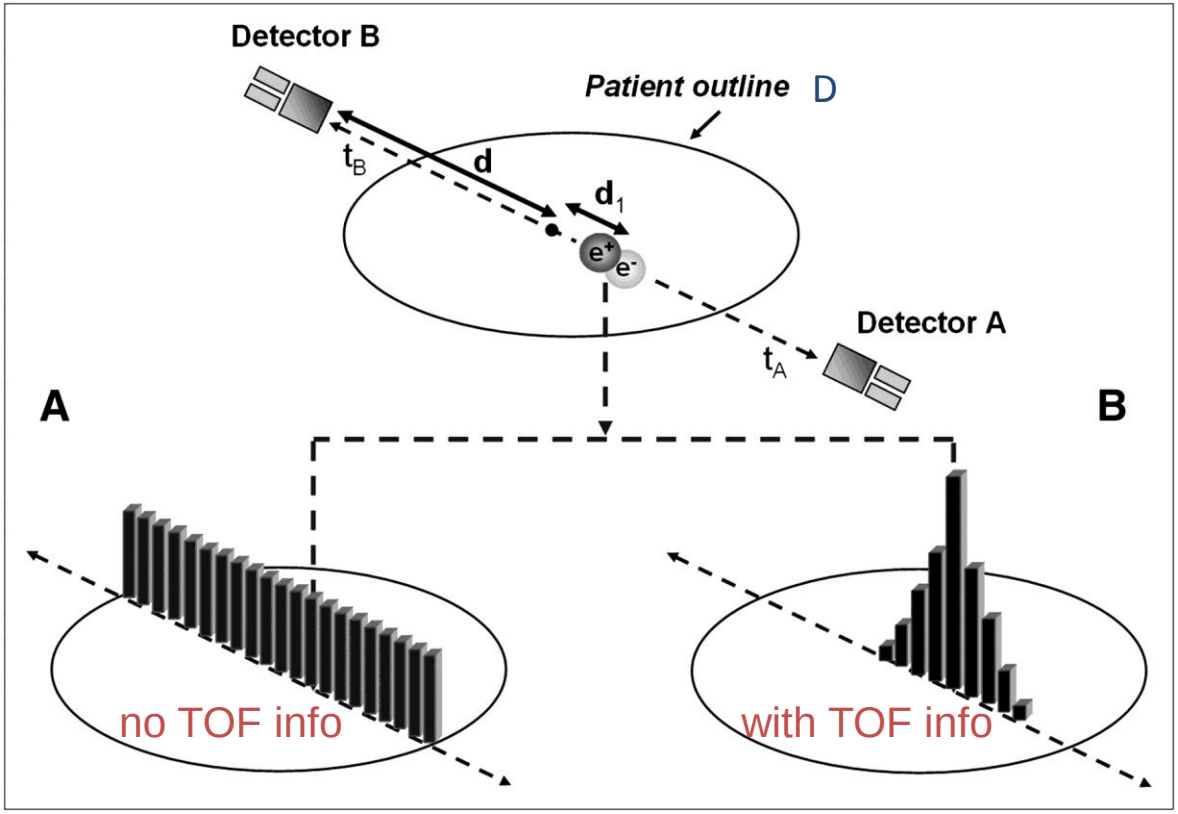


Packaged module, as delivered to clients (DPC3200-22-44). Includes a 100 μm thick protective glass layer.

http://www.philips.com/digitalphotoncounting

Principle of TOF-PET

Idea: use time information to localize annihilation along the line of response. LOR does no longer contribute uniformly to all pixels but according to the measured time and its resolution.
Images contain less noise and show better contrast (particularly noticeable for large scanners and big patients)



$\Delta t = 2 \cdot \Delta x / c$

→ Need δt = 66 ps
for δx = 1 cm

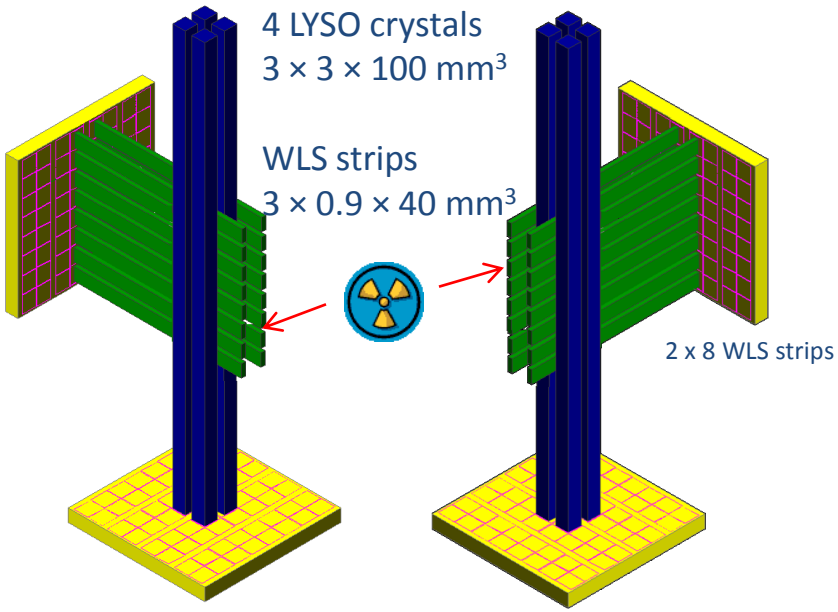
Gain of a TOF system over a non-TOF system is

$G = 2D / c \cdot \delta t$

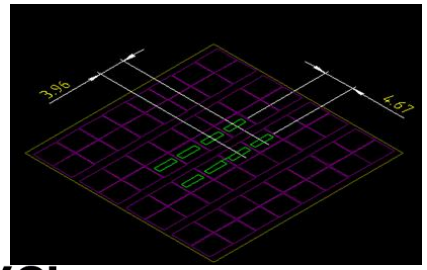
= dimension of object being imaged.

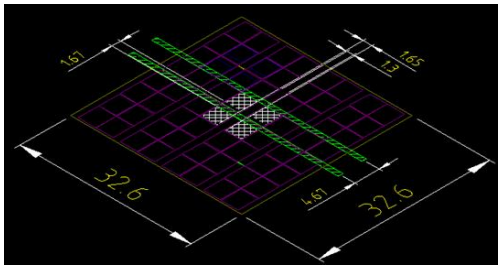
Test set-ups

AX-PET like geometry

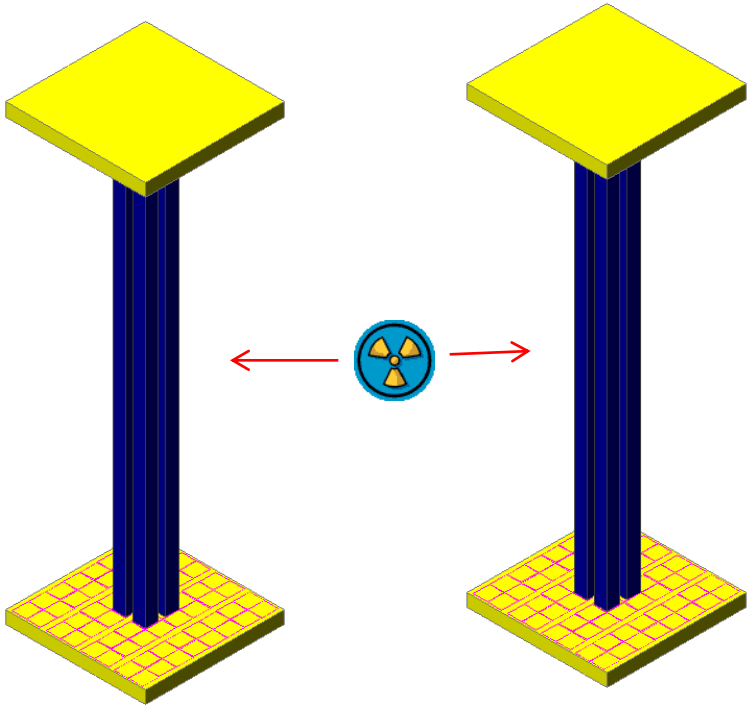


Luckily, crystals and WLS would just fit (without big compromises) on the existing Philips 64 channel DSiPM modules DLS-3200



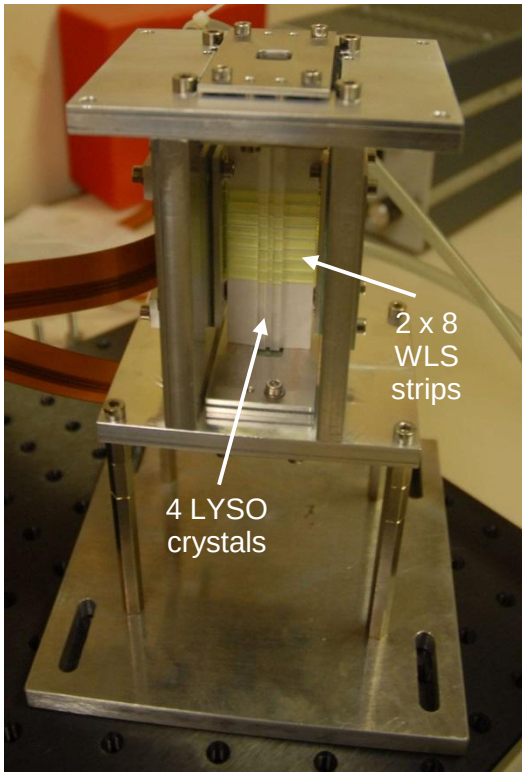


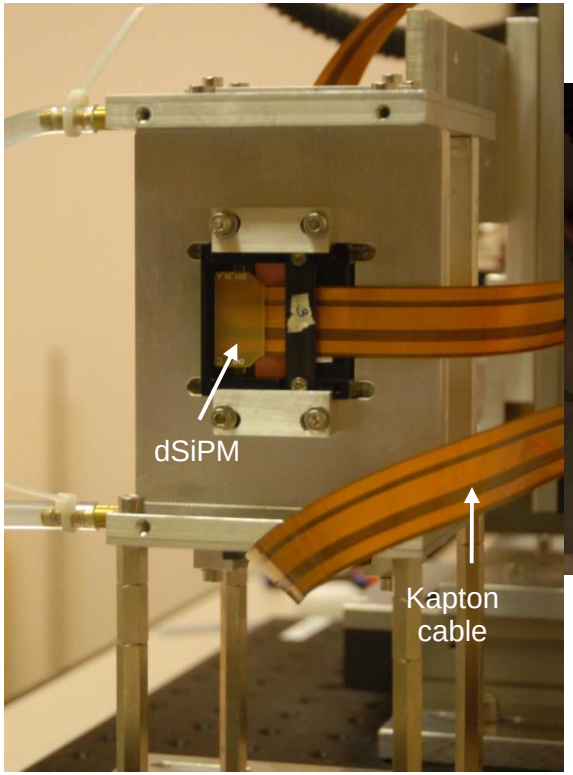
Dual-sided readout



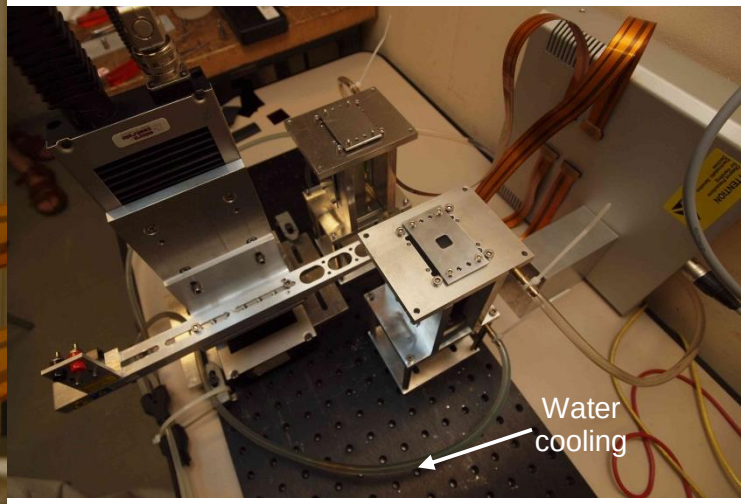
Consider dual-sided readout of long crystals to get rid of propagation delays

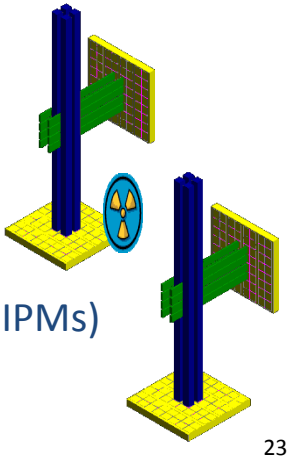
Verification of general AX-PET characteristics





Two modules setup. Single sided readout plus WLS strips.





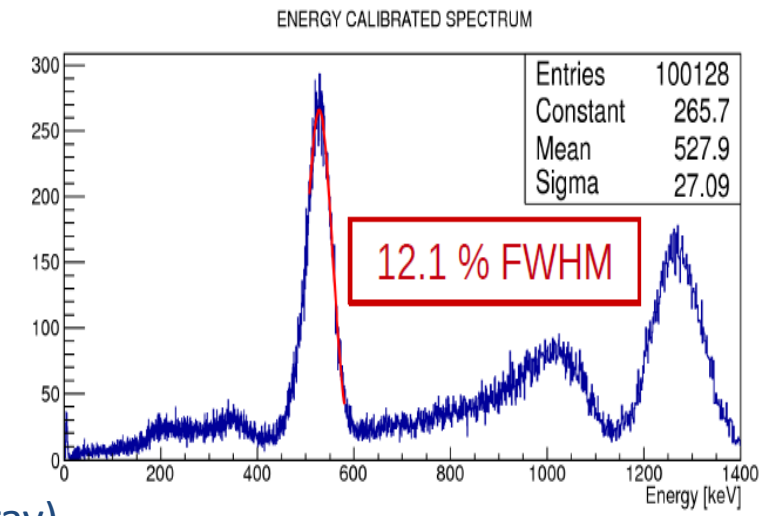
Flow of chilled water through the set-up ensures constant temperature of 15°C (at the dSIPMs)

General performance of a digital AX-PET like set-up

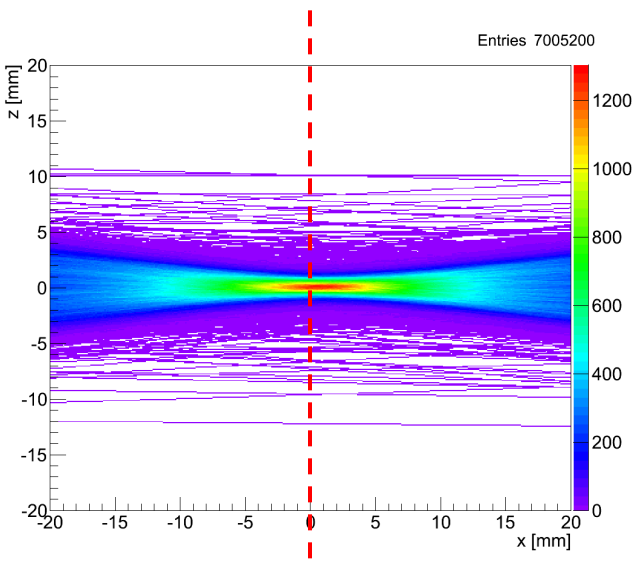
Single sided readout + WLS strips

Energy resolution
(single sided readout)

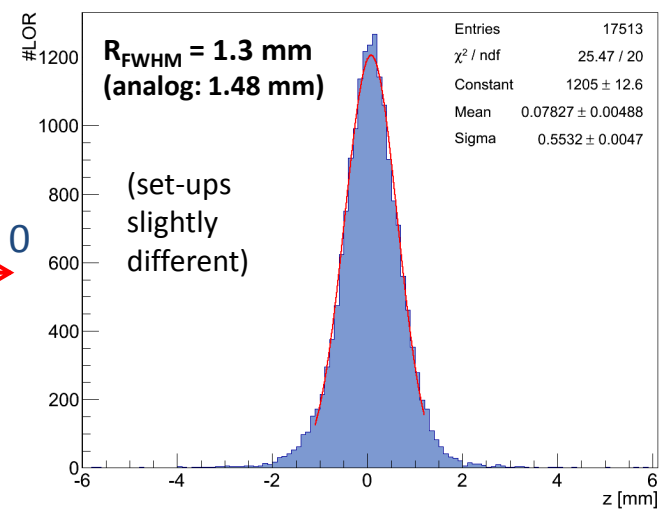
- N_{pe} = ~1300 at 511 keV (analog 1100)
- $\Delta E/E$ = 12.1 % FWHM (analog: 11.7%)



Confocal reconstruction in axial direction (WLS array)



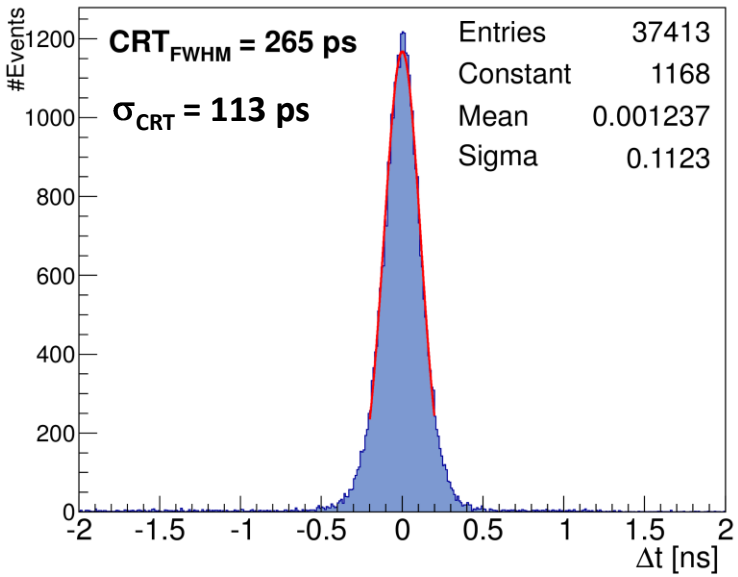
intercept at x = 0

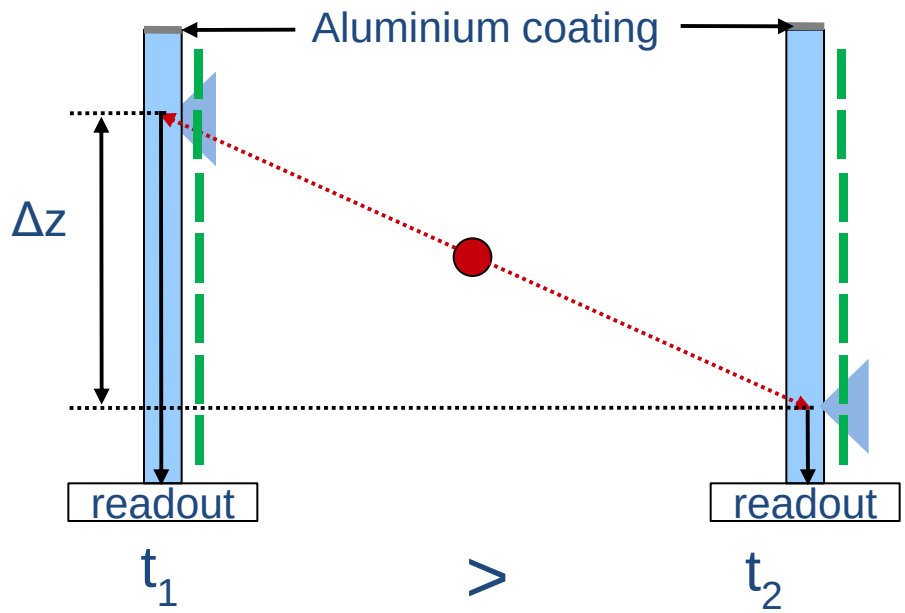


Coincidence time resolution

Single sided readout + WLS strips

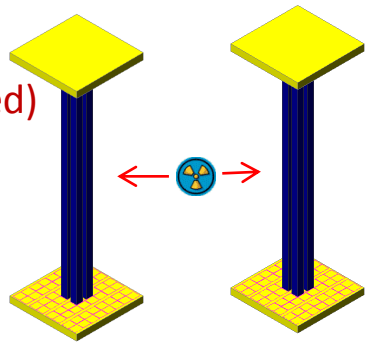
Such a good result is of course only possible after correcting for light paths using WLS information





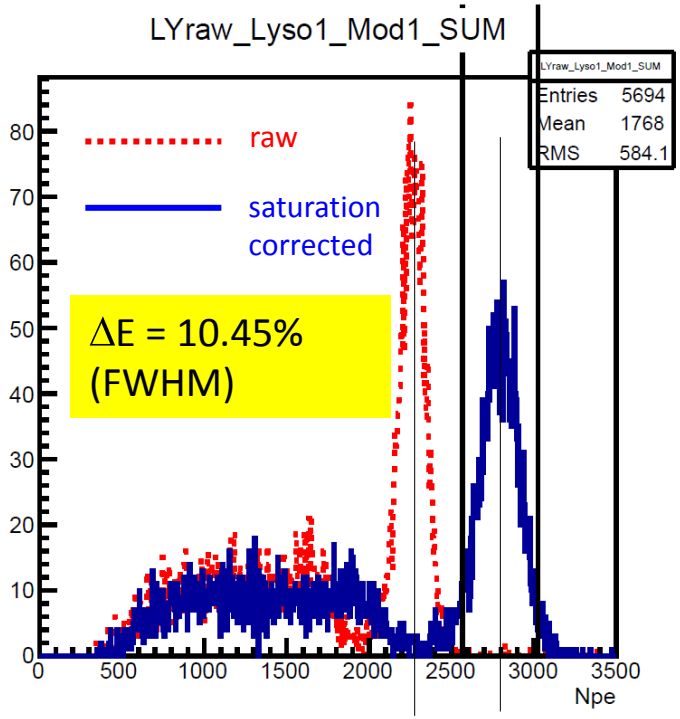
Energy and coincidence time resolution

Double sided readout
(WLS information not used)

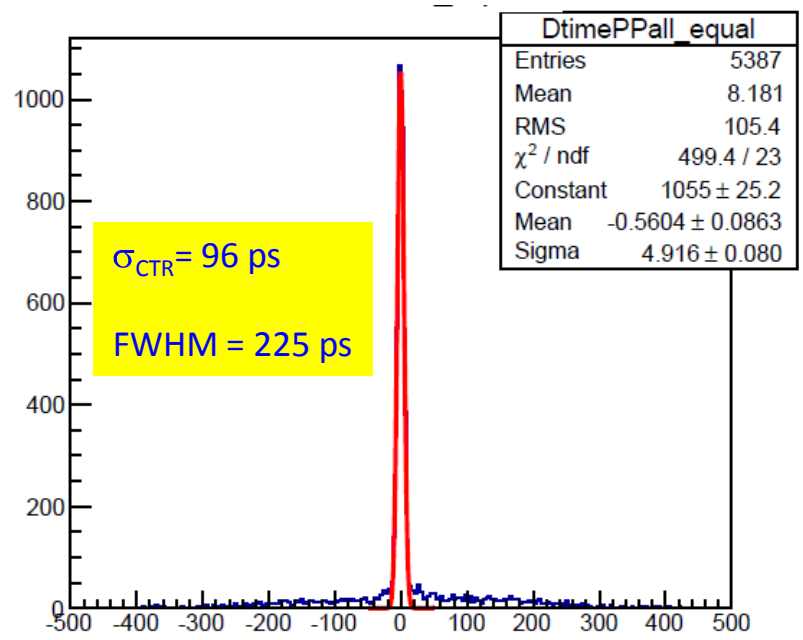


$\Delta t_{mean} = \langle t_1 \rangle - \langle t_2 \rangle$
$= \frac{1}{2} \cdot (t_{1,up} + t_{1,down}) - \frac{1}{2} \cdot (t_{2,up} + t_{2,down})$

Mean Timing corrects automatically for light propagation times in the crystals. The resolution becomes fully independent of the source position in the FOV.



2250 → 2800
(25%)



Δt_{mean} [TDC ticks (19.5 ps)]

Summary and Conclusions

An AX-PET like detector (100 mm long LYSO crystals) with digital SiPM readout achieves the same performance as the analog brother/sister.

In addition to high level of integration, compactness, ease of use, …

… it achieves really excellent time resolution. The dual sided readout pushes the Coincidence Time Resolution to impressive σ_{CTR} <100 ps.

With small (3 x 3 x 3 mm^3) crystals, σ_{CTR} = 60 ps was observed.

The obvious question: Can one suppress the WLS strips and reconstruct the axial coordinate from Δt or/and light yield ratio ?

↓ would need σ_t ~10 ps ! Not in reach (yet)

↓ worth (re-)considering it, but σ_z = 1-2 mm is hard to reach!

F. ur-Rehman et al., Improvement in Spatial Resolution of Dual-Ended Readout of 100 mm Long LYSO Crystals through Use of Systematic Crystal Surface Roughing", IEEE NSS MIC Conf Rec MIC18-M12