Imaging results and TOF studies with an axial PET detector

Christian Joram
CERN / PH Department

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
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. \( \rightarrow \) **x-y coordinate**. Precision given by crystal cross-section.

- Orthogonal arrays of WLS strips (with SiPM readout) \( \rightarrow \) **z-coordinate**. Precision given by strip width + centre-of-gravity algorithm.

- Additional layers allow to increase sensitivity, without compromising resolution.

\( \rightarrow \) **Spatial resolution and sensitivity are decoupled and can be optimized independently. Practically parallax error-free!**
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)

- 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)

\[ \sum_{\text{module}} E(\text{LYSO}) = 511 \text{ keV} \Rightarrow \text{GoodHit} \]

GH1
GH2
\[ T_{\text{coinc}} = 20 \text{ ns} \]
Coinc. Trigger
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 $\varnothing$)
- Photoelectric events only (1 hit crystal per module)
- Draw “LOR” (pure geometrical, no tomographic reconstruction)

**TOP View - $d(\text{Mod1, Mod2}) = 150$ mm**

**SIDE View - $d(\text{Mod1, Mod2}) = 150$ mm**
First coincidence measurements

TOP View - $d(\text{Mod1, Mod2}) = 150 \text{ mm}$

SIDE View - $d(\text{Mod1, Mod2}) = 150 \text{ mm}$

$N_{\text{coinc evts}}=100$

Christian.Joram@cern.ch

11-15 February 2013
Basic performance figures

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

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

- RMS = 0.89 mm (coinc.)
- y-coord. is quasi-discrete (crystal positions).

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

Calibrated and averaged over all crystals.

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
ETH Zurich, PET lab 2012

phantoms
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.

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.

Now we allow coincidences between opposite ±1 modules. \( \Rightarrow \) Larger FOV.

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.
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

Reconstructed 1 mm rod => FWHM ~ 1.6 mm

NEMA mouse phantom

Series of small rods for resolution

1 mm (i.e. < Resolution)

34 mm Ø

5 mm 2 mm

4 mm 3 mm

63 mm

1 mm (i.e. < Resolution)
Phantoms ...

Mini Deluxe phantom

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

Rods oriented parallel to Z axis

Rods oriented perpendicular to Z axis

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

Ø1.6 mm

Ø2.4 mm
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
- one (young) rat, 18-F

\[\text{=> organs structure}\]

\[\text{=> bones, skeleton structure}\]

Rat, FDG - Details of the heart
Mouse (26g) with FDG (10 MBq)

Not clear: aorta or spine?

nose

Back of the head

Harderian glands?

Transverse view

Back side

Front side

Side view

“Front” view

bladder

hip

abdomen

lungs

liver

shoulder

shoulder

not clear: aorta or spine?
Two heart ventricles can be seen!
Rat 76g, F-18 (65 MBq) Details of the skeleton + CT image overlaid

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.

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

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

http://www.philips.com/digitalphotoncounting

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

\[ \Delta t = \frac{2 \cdot \Delta x}{c} \]

\[ \Rightarrow \text{Need } \delta t = 66 \text{ ps for } \delta x = 1 \text{ cm} \]

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

\[ G = \frac{2D}{c \cdot \delta t} \]

= dimension of object being imaged.
Test set-ups

**AX-PET like geometry**

4 LYSO crystals
3 x 3 x 100 mm$^3$

WLS strips
3 x 0.9 x 40 mm$^3$

2 x 8 WLS strips

**Dual-sided readout**

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

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

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)

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

Confocal reconstruction in axial direction (WLS array)

Energy resolution
(single sided readout)

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

Confocal reconstruction in axial direction (WLS array)

Energy resolution
(single sided readout)

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

Confocal reconstruction in axial direction (WLS array)

Energy resolution
(single sided readout)

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

Confocal reconstruction in axial direction (WLS array)
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

\[ \Delta z \]

\[ \text{CRT}_{\text{FWHM}} = 265 \text{ ps} \]
\[ \sigma_{\text{CRT}} = 113 \text{ ps} \]

Entries 37413
Constant 1168
Mean 0.001237
Sigma 0.1123

\( t_1 \) > \( t_2 \)
Energy and coincidence time resolution

Double sided readout
(WLS information not used)

\[ \Delta t_{\text{mean}} = <t_1> - <t_2> = \frac{1}{2} \cdot (t_{1,\text{up}} + t_{1,\text{down}}) - \frac{1}{2} \cdot (t_{2,\text{up}} + t_{2,\text{down}}) \]

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

\( \sigma_{\text{CTR}} = 96 \text{ ps} \)

FWHM = 225 ps

\( \Delta t_{\text{mean}} \) [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 $\sigma_{\text{CTR}} < 100$ ps.

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

Would need $\sigma_t \sim 10$ ps ! Not in reach (yet)

Worth (re-)considering it, but $\sigma_z = 1$-$2$ mm is hard to reach!

With small (3 x 3 x 3 mm$^3$) crystals, $\sigma_{\text{CTR}} = 60$ ps was observed.

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