Demonstration of a novel PET concept

Chiara Casella, ETH Zurich
DPNC - Université de Genève, March 14th 2012
**Outline**

**AX-PET:** AXial Positron Emission Tomography (PET)

- **Brief introduction about PET** (Positron Emission Tomography)
- **Axial concept**
  - What is it? Why?
- **AX-PET detector**
  - choice of the detector elements
  - AX-PET modules
  - “demonstrator” for a PET scanner
- **AX-PET detector performance**
  - from characterization measurements with 22-Na sources
- **Simulations**
- **Tomographic image reconstruction**
  - description of the reconstruction methods
  - measurements campaigns with phantoms and radiotracers
  - reconstructed images
- **Perspectives**
  - preliminary results with Digital Si-PM as alternative photodetectors
- **Conclusions**
AX-PET in the context of HEP

- Long tradition of using technologies from High Energy Physics into other fields, and particularly medical applications.
- AX-PET: small size calorimeter, using scintillating crystals, WLS, photodetectors “borrowed” from HEP

Selection of most relevant AX-PET papers:

**Novel Geometrical Concept of a High Performance Brain PET Scanner Principle, Design and Performance Estimates**

**High precision axial coordinate readout for an axial 3-D PET detector module using a wave length shifter strip matrix**
A. Braem et al, NIM A 580 (2007), 1513-1521

**Wavelength shifter strips and G-APD arrays for the read-out of the z-coordinate in axial PET modules**
A. Braem et al, NIM A 586 (2008), 300-308

**The AX-PET demonstrator—Design, construction and characterization**
P. Beltrame et al, NIM A 654 (2011) 546-559

**The AX–PET Concept: New Developments And Tomographic Imaging**
P. Beltrame et al, 2011 IEEE NSS Conference Record MIC 22-5

for more details: [https://twiki.cern.ch/twiki/bin/view/AXIALPET/WebHome](https://twiki.cern.ch/twiki/bin/view/AXIALPET/WebHome)
Positron emission / annihilation

- Basis of the PET system: **Positron Emission**: \( p \rightarrow n + e^+ + \nu_e \)
- \( \beta^+ \) decay of different radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half life</th>
<th>E_{max e^+}(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{11}\text{C})</td>
<td>20.4 min</td>
<td>0.96</td>
</tr>
<tr>
<td>(^{15}\text{O})</td>
<td>122 sec</td>
<td>1.73</td>
</tr>
<tr>
<td>(^{18}\text{F})</td>
<td>109.8 min</td>
<td>0.63</td>
</tr>
<tr>
<td>(^{22}\text{Na})</td>
<td>2.6 years</td>
<td>0.55</td>
</tr>
</tbody>
</table>

- **Positron Annihilation**: \( e^+ e^- \rightarrow \gamma \gamma \)

**Physics of the positron annihilation** => fundamental limits to the spatial resolution of PET

- **Finite positron range** \((\rho)\)
  - Annihilation position ≠ emission point
  - \( \rho \) depends on the energy of the positron (i.e. on the radioisotope)

- **Non-collinearity of the 2 photons**
  - Residual momentum of the e+e- at the annihilation
  - The 2 photons are emitted with a small deviation from 180° \((\Delta \theta \sim 0.5^\circ)\)
  - Blurring of the spatial resolution \( R_{\text{FWHM}} \sim 0.0022 \times D \) [mm]
PET detector principle:
Coincidence of 2 photons of defined energy (511 keV) and emitted on the same line ("back to back")

1. Inject the radiotracer into the body
2. Wait for uptaking period
3. Start the acquisition (i.e. detection of coinc. events)
4. Feed the data into the reconstruction algorithms
5. Image of the activity concentration

PET: "in-vivo" functional imaging technique
- Get a (quantitative) image of the radio-tracer concentration

Clinical applications
- Oncology (tumor diagnosis)
- Neurology (e.g. brain disease diagnosis)
- Map normal human brain / heart functions

Small animal scanners
- Pre-clinical studies
  - Cancer research
  - New tracers development
  - Pharmacokinetics

Full body / brain scanners
- Clinical applications

Requirements for an ideal PET

number of counts does matter !!!

- how to improve counting statistics ?
  - increase radio-tracer concentration
  - extend the scan duration time

- OPTIMIZED DETECTOR SENSITIVITY
  ( geometry / materials )

- HIGH SPATIAL RESOLUTION (=> be able to resolve small structures)

- GOOD TIMING RESOLUTION (small coincidence window => reduce random coincidences)

- GOOD ENERGY RESOLUTION (=> reject scattering events in the body)
Requirements for an ideal PET

Number of counts does matter!!!

- How to improve counting statistics?
  - Increase radio-tracer concentration
  - Extend the scan duration time

- Optimized detector sensitivity
  (geometry / materials)

- High spatial resolution
  (=> be able to resolve small structures)

- Good timing resolution
  (small coincidence window => reduce random coincidences)

- Good energy resolution
  (=> reject scattering events in the body)
High resolution vs high sensitivity

in “conventional” PET scanners:

- scintillator based radial arrangement

always a compromise between

- good spatial resolution (small L, small $\delta p$)
- good detection efficiency (long L)

solution: add DOI (Depth Of Interaction) information

- several attempts / different strategies

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

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

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Conventional PET schemes

DOI attempts:

(a) **multiple crystals/photodetector layers**

(b) **dual-ended photodetectors**
DOI from the ratio of the 2 PD responses

(c) **Phoswich design**
different types of crystals with diff decay times
=> DOI from pulse shape discrimination

(d) **monolithic**. Iterative stat. models with DOI from light output intensity and/or light spread profiles

(e) **dual layer offset position**.
DOI from different light output profiles

only partial DOI information!

need a precise 3D identification of the photon interaction point
The AXIAL concept

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

from radial ... ... to axial!

- long and axially oriented crystals
- DOI information = position of the hit crystal
### The detector concept

(1) **TRANSAXIAL COORDINATE (x,y)**

- Transaxial coordinate: from position of the hit crystal
- Transaxial resolution = \( d/\sqrt{12} \) FWHM

- **To increase spatial resolution** => Reduce crystals size (d)
- **To increase sensitivity** => Add additional layers
The detector concept

(1) TRANSAXIAL COORDINATE (x,y)
- Transaxial coordinate: from position of the hit crystal
- Transaxial resolution = \( \frac{d}{\sqrt{12}} \) FWHM

(2) AXIAL COORDINATE (z)
- Axial coordinate: center of gravity method
- Axial resolution < w

- To increase spatial resolution => Reduce crystals size (d)
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The detector concept

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(2) AXIAL COORDINATE (z)
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- Axial resolution < \( w \)

- To increase spatial resolution => Reduce crystals size (d)
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3D localization of the photon interaction point without compromising between spatial resolution and sensitivity

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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
Detector choice: Scintillator

detect photons, $E_\gamma = 511$ keV  
=>  
  • inorganic scintillator  
  • high Z, high $\rho$

bare scintillating crystals with escaping light  
=>  
  • non hygroscopic  
  • nude crystals (i.e. unwrapped, uncoated)  
  • perfectly polished surfaces ; sharp edges

**LYSO crystals (Lu$_{1.8}$Y$_{0.2}$SiO$_5$: Ce)**  
Prelude 420 from Saint Gobain:

- lyso bars : $3 \times 3 \times 100$ mm$^3$ each
- Al coated on the non-readout face ($R \sim 80$-$85\%$)
- measured : $\lambda_{\text{opt}} = (412 \pm 31)$ mm ; $(\Delta E/E)_{\text{intr}} = (8.3 \pm 0.5)\%$ FWHM , @511 keV

176-Lu is a naturally radioactive $\beta$ emitter  
(A $\sim 39$ Bq/g; $\beta$-decay followed by a $\gamma$-cascade)  
useful for the calibration
Detector choice: WLS strips

- **requirement**: high absorption of the crystal scintillation photons (blue)

- **EJ-280-10x from Eljen Technology**
  - blue to green WLS
  - highly doped (x10 higher dye concentration than standard) to maximize the absorption (absorption length _ blue light ~ 0.4 mm)

- each WLS strip: **3 x 0.9 x 40 mm³**

- decay time = 8.5 ns

- measurements: \( \lambda_{opt} = (188 \pm 36) \) mm
Detector choice: Photodetectors

- newest frontier in photo-detection: **SiPM** (Si photomultipliers)
  - also called **G-APD** (Geiger-mode APD)
  - also called **MPPC** (Multi Pixel Photon Counter) - from Hamamatsu

- array of commonly biased APD used in Geiger mode
- output: analogue sum of all the firing APD cells

- excellent photon counting capabilities ✓
- high gain ($10^5$ to $10^6$) at low bias V (~ 70 V) ✓
- advantages of a Si sensor:
  - high QE ✓
  - compactness ✓
  - insensitive to magnetic field (MRI comp.) ✓

- temperature dependent ✓
- dark rate (~ 1 MHz @ thr = 0.5 pe) ✓

**MPPC S10362-33-050C:**
- 3x3 mm$^2$ active area
- 50 μm x 50 μm pixel
- 3600 pixels

**MPPC 3.22×1.19 Octagon-SMD:**
- 1.2 x 3.2 mm$^2$ active area
- 70 μm x 70 μm pixel
- 782 pixels
- custom made units

<table>
<thead>
<tr>
<th></th>
<th>crystal MPPC</th>
<th>WLS MPPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>S10362-33-050c</td>
<td>custom tailored</td>
</tr>
<tr>
<td>charge gain $G$</td>
<td>$6 \cdot 10^5$</td>
<td>$1 \cdot 10^6$</td>
</tr>
<tr>
<td>$dG/dV$</td>
<td>$55 \cdot 10^4 \text{ V}^{-1}$</td>
<td>$110 \cdot 10^4 \text{ V}^{-1}$</td>
</tr>
<tr>
<td>noise rate at 0.5 pe</td>
<td>4.7 MHz</td>
<td>3.2 MHz</td>
</tr>
<tr>
<td>noise rate at 1.5 pe</td>
<td>0.9 MHz</td>
<td>0.5 MHz</td>
</tr>
</tbody>
</table>

Table 1: Main characteristics of the MPPCs. Gain and noise rates refer to temperature of 25°C.
The AX-PET module

MODULE
- 6 layers
- 8 crystals / layer
- 26 WLS / layer
- 48 crystals + 156 WLS = 204 channels
- staggering in the crystals layout to optimize photon interaction probability
- optical separation between layers
- each crystal and WLS strip individually coupled to its photodetector
- crystals / WLS strips readout on alternate sides (to optimize packing density)
The AXPET module

Chiara Casella,
Individual analogue readout of MPPC output
Custom designed DAQ system

- **fully analogue** readout chain
- **not optimized** at all for this specific application

- **Amplifiers:** OPA486 (Lyso) / OPA487 (WLS)
- Fast **energy sum** for all the crystals in the module
- **VATA GP5 chip**
  - 128 ch charge sensitive integrating
  - fast (~ 50ns shaper + discriminator) / slow (~ 250ns shaper) branches
  - **sparse readout** mode: only the channels above thr are multiplexed into the output
- analogue info processed by custom made VME ADC

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Fast energy sum & Trigger

- analogue sum of the whole module (i.e. total energy over 48 crystals)
- with a proper threshold choice (LL x HL x notHHL)
  => select only events with 511 keV total energy deposition

TRIGGER

\[ \sum_{E_{\text{Mod1}}} \sum_{E_{\text{Mod2}}} \]

TRIGGER = 2 modules
- each one discriminated @ 511 keV energy sum
- used in coincidence

=> Selection of the good events
Compton scattering

Compton scattering in the detector

- fast energy sum & trigger
- high granularity in the module
- good energy resolution

Possibility to tag Compton scattered events in the detector

“Inter-Crystal Scattering” events (ICS)

if the event is:
- correctly identifiable (e.g. Compt. kinematics)
  => the event can be included in the reconstruction
- ambiguous (1-2 OR 2-1 ?)
  => the event is rejected

=> improved sensitivity

=> improved resolution

win - win situation!

Compton scattering in the body

Events killed by the trigger!

E_{\text{sum}} = 511 \text{ keV}

E_{\text{sum}} < 511 \text{ keV}
AX-PET inspired other developments

**COMPET**:
University of Oslo, Norway - E. Bolle et al.

Research project for a pre-clinical PET scanner with high sensitivity, high resolution. MRI compatible

- no axial geometry
- 3D reco of photon interaction point with LYSO + WLS + G-APD

E. Bolle et al, NIM A 648(2011) S93-S95

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**Tampere University** (Finland):
build a small specific scanner based on AX-PET (toward possible commercialization...)

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**Low cost planar detector for PET**
Triumph, Canada - F. Retiere et al.

Characterization measurements

with point-like $^{22}\text{Na source}$ (diam = 0.25 mm, $A\sim$900 kBq), @ CERN

- two different taggers
- different distances tagger / source / module

=> both uniform illumination of the module and precisely collimated beam spot

**AX-PET performance:**

1. Energy measurement / energy calibration => LYSO response
2. Position measurement / spatial resolution => WLS response
LYSO energy response

**LYSO No. 21 - 22Na coinc. trigger**

![Energy Spectrum Diagram](image)

**Energy resolution**

- From gaussian fit of the photopeak
- AFTER ENERGY CALIBRATION

**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**

\[ <R_{FWHM}> \approx 11.8\% @511\text{ keV} \]

(averaged on 96 LYSO crystals)

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**LYSO energy calibration**

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

- LYSO No. 21 - 22Na coinc. trigger

  - with source, coincidence
  - no source, internal trg.

  ![ADC counts vs Energy](image1.png)

- LYSO contains Lu-176
- A ~ 39 cps/g
  - => ~ 250 Bq / bar
  - => ~ 12 kHz / module

- MPPC saturation. Due to:
  - limited nr of cells in the MPPC (3600)
  - important light yield in the scintillator (~1000).

\[
E_{n}(ADC) = E_0 - a \times \ln \left(1 - \frac{ADC}{b}\right)
\]

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

same procedure applied identically for every channel
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

**Collimated beam spot, WLS response**

- more than 1 WLS participate 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: 1 pe ~ 4 ADC)

**axial coordinate**: derived from center of gravity method from all the WLS participating to the cluster
Axial spatial resolution

z coordinate (COG):

each measured $\sigma_z$ includes:
- intrinsic spatial resolution
- positron range ($\rho \sim 0.54$ mm)
- non collinearity ($\div d$)
- beam divergency ($\div d$)
- (source dimensions; $\varnothing = 250\mu$m)

Intrinsic axial spatial resolution

Mod 1: $1.75$ mm FWHM
Mod 2: $1.83$ mm FWHM

Trans-axial spatial resolution

- $\langle \sigma_x \rangle = d/\sqrt{12} = 0.87$ mm (digital); FWHM $\sim 2$ mm
- $\langle \sigma_y \rangle = d/\sqrt{12} = 0.87$ mm (digital); FWHM $\sim 2$ mm
Two modules coincidences

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

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

\[N_{\text{coinc\_evts}} = 1\]

AX-PET very first coincidence event!
Two modules coincidences

TOP View - $d(\text{Mod}1,\text{Mod}2) = 150$ mm

SIDE View - $d(\text{Mod}1,\text{Mod}2) = 150$ mm

N_coinc_evts=10
Two modules coincidences

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

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

\(N_{\text{coinc\_evts}} = 100\)
Axial resolution

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

\[ R_{intr} = \sqrt{R_{meas}^2 - R_\rho^2 - R_{180}^2} \approx 1.35 \text{ mm} \]

\[ (0.54 \text{ mm})^2 \]

\[ [0.0022 \times \text{Diam} = 0.33 \text{ mm}]^2 \]

\[ (R_{FWHM})_z \sim 1.5 \text{ mm} \]

including:
- intrinsic resolution
- positron range
- non collinearity
- (source dimensions ; \( \varnothing = 250 \mu m \))
Parallax free demonstration

Parallax error is more and more important outside the center of the FOV.

Intersection of LORs with the plane containing the source.

F2F

OBL

Intrinsic resolution is **not degraded by parallax effects**, even in very oblique configuration!
Simulations

**AX-PET is a fully simulated system**

**Dedicated Monte Carlo simulations** for AX-PET.

Why?  
(1) get a better understanding of the detector  
(2) train Compton reconstruction algorithms  
(3) support image reconstruction  
(4) simulate an hypothetical full ring scanner and estimate its potential performance

**GATE simulation package** (Geant4 application for tomographic emission)

**Non conventional nature of AX-PET**

=> several challenges for simulations (standard templates could not be applied)  
- geometry (axial; staggering; layered structure)  
- WLS modeling  
- dedicated sorter for the coincidences (module sum; trigger logic... up to DAQ rate modeling)
Simulations: some results

Excellent agreement data / simulations:

One AXPET Module illuminated by a collimated 511 keV gamma beam:
Data and Simulations

Two AXPET Modules in coincidences

Inter-Crystal Scattering (ICS)

- identify ICS events before image reconstruction.
- several identification algorithms tested

<table>
<thead>
<tr>
<th>Max. E</th>
<th>Compton K.</th>
<th>Klein-Nishina</th>
<th>Neural Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>61%</td>
<td>65%-66%</td>
<td>61%-63%</td>
<td>75%</td>
</tr>
</tbody>
</table>

• identification rate for ICS ~ 60%

very incomplete collection of results here!
simulations paper is in preparation!
Towards a tomographic reconstruction...

How to mimic a full scanner with 2 modules only available?

Central FOV:
- rotating the phantom...

θ = 0°, 20°, 40°... 180° *(9 steps)*

Extended FOV:
- ...and rotating also the module

θ = 0°, 20°, 40°... 360° *(18 steps)*

1 tomographic acquisition = 27 steps acquisition

mimics a 18-modules ring, with coincidences between face-to-face ± one adjacent modules

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Setup for tomographic reconstruction

The two modules are mounted on top of a portable platform, which houses also the electronics, power supply, etc...

- One rotating motor for the source / phantom
- One module fixed (Mod1); the other rotating (Mod2)

setup @ CERN, Big 304
Measurements with phantoms

Three different measurement campaigns:

@ ETH Zurich (CH), Radio-Pharmaceutical Institute - **Apr 2010**

@ AAA (Advanced Acceleration Applications) St. Genis-Pouilly (FR) - **July 2010**

@ AAA (Advanced Acceleration Applications) St. Genis-Pouilly (FR) - **July 2011**

in-situ cyclotron production of the radiotracer.

- Phantoms filled with **F-18** based tracers (F-18 in water solution)
- $t_{1/2} \sim 110$ mins
- Concentration diluted in water; $A_0$: few MBq up to $\sim 100$ MBq
Measurements with phantoms

Three different measurement campaigns:

@ ETH Zurich (CH), Radio-Pharmaceutical Institute - Apr 2010
- very first measurements with high activity and extended objects
- limited to the central FOV (i.e. fixed modules, rotating source)

@ AAA (Advanced Acceleration Applications) St. Genis-Pouilly (FR) - July 2010
- extended FOV coverage (one module rotating, rotating source)
- larger phantoms / placed off-centered phantoms

@ AAA (Advanced Acceleration Applications) St. Genis-Pouilly (FR) - July 2011
- extended FOV as before
- improved DAQ performance
- improved acquisition methods

in-situ cyclotron production of the radiotracer.

- Phantoms filled with F-18 based tracers (F-18 in water solution)
- $t_{1/2} \sim 110$ mins
- Concentration diluted in water; $A_0$: few MBq up to ~ 100 MBq
Phantoms for reconstruction

(1) capillaries
- L = 3 cm
- Diam = 1.4 mm
- Pitch = 5 mm

(2) micro Derenzo
- H = 1.5 cm
- Diam = 2 cm
- Rods_Diam = 0.8±2 mm

(3) mini DeLuxe
- H = 5 cm
- Diam = 7.5 cm
- Rods_Diam = 1.2±4 mm

(4) homogeneous cylinder
- H = 9 cm
- Diam = 6 cm

(5) NEMA phantom
- H = 6.3 cm
- Diam = 3.3 cm

pictures not on scale!
**Goal**: recover the activity distribution, starting from the acquired data

**Data**: LOR of the various coincidence events i.e. **projections** (typically organized in “sinograms”)

Two different approaches:

**ANALYTICAL METHOD**
- Filtered Back Projection (FBP):
  1) Fourier analysis of the projection data
  2) Different weight to different frequencies (“filtering”)
  3) “Back-Project”
- **simple and fast** 😊
- **not extremely accurate** 😞
- assumption : measured data are perfectly consistent with the source object (never true: e.g. noise, gaps between detector...)

**ITERATIVE METHOD**
- **slow and CPU consuming** 😞
- accurate model of the emission and detection processes
- **accurate reconstruction** 😊
- optimization procedure until the best estimate is found
- several optimization strategies exist
Iterative reconstruction method
Iterative reconstruction method

1. Initial estimate of the object count distribution (typically: uniform)

2. Obtain the projection that would derive from such an object
Iterative reconstruction method

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Iterative reconstruction method

1. Initial estimate of the object count distribution (typically: uniform)
2. Obtain the projection that would derive from such an object
3. Build up correction coefficients

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Iterative reconstruction method

- Activity distribution $f_j$
- Measured projections $p_i$
- Back projection
- Correction matrix
- Estimated projections $\sum_k a_{ik} \hat{f}_k$
- Forward projection
- Current estimate $\hat{f}_j$

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Iterative reconstruction method

Requires a description of the physical model of emission and detection processes:

**SYSTEM MATRIX** $M_{ij}$

Probability of the activity in the $j$-voxel to be detected by the $i$-LOR includes:

- **geometry** description
- **physics** (e.g.: attenuation)
- **variable fraction of the voxel** contributes to the counts
- ...
Iterative reconstruction method

AX-PET uses ML-EM

two steps per iteration:
1. Expectation step: form the likelihood of any reconstructed image given the measured data
2. Maximization step: find the image with the greatest likelihood

includes:
- geometry description
- physics (e.g.: attenuation)
- variable fraction of the voxel contributes to the counts
- ...

SYSTEM MATRIX

Mij

probability of the activity in the j-voxel to be detected by the i-LOR
Simple reconstructed images: capillaries

**Capillaries:**
- L = 3 cm
- Ø = 1.4 mm
- Pitch = 5 mm

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

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

extended FOV
2nd module rotation
NEMA phantom

extended FOV
2nd module rotation

Three regions in the same phantom to address three different aspects

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NEMA phantom

Extended FOV
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NEMA phantom uniformly filled - AAA 2010
NEMA phantom

Extended FOV
2nd module rotation

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- Hot & Cold rods for **contrast**
- Homogeneous cylinder for assessing the **ability to reconstruct homogeneous distributions**
- Series of small rods for **resolution**

NEMA phantom uniformly filled - AAA 2010
NEMA phantom hot / cold / warm - AAA 2011

Reconstructed 1 mm rod => FWHM ~ 1.6 mm

different color scale!
NEMA phantom

extended FOV
2nd module rotation

Three regions in the same phantom to address three different aspects

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Reconstructed 1 mm rod => FWHM ~ 1.6 mm
Resolution phantom: Mini Deluxe

Mini Deluxe phantom

- Extended FOV
- 2nd module rotation

Parallel to Z axis

(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...)

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Resolution phantom: Mini Deluxe

Mini Deluxe phantom

Results presented in Valencia, IEEE 2011
What’s next (1/3)?
What’s next (1/3) ?

- **improve the reconstruction algorithms**
- **include ICS (Inter Crystal Scattering) events in the reconstruction**

**preliminar!**

- ICS included:
  - only “triple” coinc. (1+2)
  - simplest weighting (50% ; 50%)
- Simulated One-Pass List-mode reconstruction (SOPL)
- No image deterioration when ICS events are included!
What’s next (2/3)?

- **full ring simulations:**
  - performance of (hypothetical) full ring (e.g. resolution, sensitivity, NEC...)
  - two different approaches
What’s next (3/3) ?

• **images of** (probably dead) **small animal**
  • new measurement campaign
  • @ETH Zurich, Radiopharmaceutical Institute
  • Spring 2012 ?
  • F-18 (bone scan) or FDG ?

Mouse bone scan, NanoSPECT (Bioscan)
What’s next (3/3) ?

• **images of** (probably dead) **small animal**
  • new measurement campaign
  • @ETH Zurich, Radiopharmaceutical Institute
  • Spring 2012 ?
  • F-18 (bone scan) or FDG ?

• **test digital Silicon Photomultipliers** (from Philips) **as alternative photodetectors**
  • extremely good timing performance
  • GOAL : demonstrate the possibility a TOF-PET with the axial concept
**Digital Silicon Photomultiplier (D-SiPM)**

**D-SiPM:**
Single Photon Avalanche Photodiode (SPAD) integrated with conventional CMOS circuits on the same substrate.

All SPADs (including their corresponding electronics) connected together
- to photon counter
- to TDC

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

**Digital SiPM**
- Each diode is a digital switch
- Digital sum of detected photons
- Data packet

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Advantages of D-SiPM for AX-PET:

- Intrinsically very fast photodetector (~ 50ps). => Great potential for TOF-PET.

- Small size. High level of integration.
- Compactness.
- Interesting concept of simplifying the readout chain. Bias supply included.

- Early digitization of the cell output; integrated electronics on chip => low noise.
- Digital => Temperature and gain stability is less critical than in analogue SiPM.
- Possibility to disable cells with high Dark Count.

- MRI compatible.

Technology Evaluation Kit (TEK):

- 4 tiles:
  - DLS_6400 (x2 tiles) ; 6400 cells/sensor
  - DLS_3200 (x2 tiles) ; 3200 cells/sensor
- each tile : 8x8 sensors
- 1 sensor : 3.9 x 3.3 mm²

received at CERN on Jan 12th, 2012
D-SiPM: first preliminary results

- 2 LYSO scintillator crystals
  - non AX-PET standard
  - (2x2x12) mm$^3$ and (2x2x15) mm$^3$
  - wrapped with teflon
  - coupling done with optical grease
- LYSO crystal placed in the center of the pixel (no precise mechanical alignment)

**time difference** between the two tiles for coincident events
(coincidence window = 2 ns)

PRELIMINARY !!!

DLS 3200
$T_{\text{Peltier}} = 5 \degree \text{C}$

Entries 10964
Constant $930.5 \pm 13.1$
Mean $0.2449 \pm 0.0011$
Sigma $0.08534 \pm 0.00123$
Time resolution = 200 ps FWHM

FWHM ~ 200 ps
(cutting on events at the photopeak)
D-SiPM: first preliminary results

Minimal AX-PET like set-up

- DLS_3200 (one pixel enabled)
- 22-Na source (~ 3 MBq)
- DLS_3200 (1/2 pixel enabled)
- WLS strip (3 x 0.9 x 40 mm³)
- LYSO crystal (3 x 3 x 100 mm³)

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**D-SiPM: first preliminary results**

**Raw LYSO spectrum, Na-22 source**

**LYSO light yield**

**Energy spectrum**
(calibrated, corrected for saturation)

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Chiara Casella, Genève 14/3/2012
D-SiPM: first preliminary results

- 2 tiles operated in coincidence

**Correlation**
LYSO / WLS response

Still to do:
- add more WLS strips
- full WLS cluster
- extract axial coordinate

Minimal AX-PET Setup

PRELIMINARY !!!
D-SiPM: Outlook

Questions to be answered:
- light yield and $\Delta E/E$ from LYSO crystals?
- axial coordinate reconstruction: does it work?
- axial resolution through WLS readout?
- time resolution (long crystals)?

coming soon...
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)

**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!

Currently under test:

**Digital SiPM as alternative for photodetector for AX-PET (TOF capabilities)**

- **calorimeter with tracking capabilities** (granularity)
- **novelty as a PET detector:**
  - geometry
  - WLS implementation
  - module sum / trigger
  - Compton scattering reconstruction
scintillator bars and WLS...

**AX-PET**

- photons, 511 keV
  - inorganic scintillator
    (high Z, high $\rho$, high light yield)
  - unwrapped scintillator bars
  - WLS strips (for axial coord.)
  - Si-PM

- pions, 170 MeV ($\mu$,e)
  - organic scintillator
    (fast)
  - WLS fibers embedded into scintillator bars
    (light collection and transport up to photodetectors)
  - MA-PMT
Conclusions
A. Braem, M. Heller, C. Joram, T. Schneider and J. Séguinot
CERN, PH Department, CH-1211 Geneva, Switzerland

V. Fanti
Università e Sezione INFN di Cagliari, Italy.

C. Casella, G. Dissertori, L. Djambazov, W. Lustermann, F. Nessi-Tedaldi, F. Pauss, D. Renker\(^1\), D. Schinzel\(^2\)
ETH Zurich, CH-8092 Zurich, Switzerland
\(^1\) Currently with Technical University München, D-80333 München, Germany
\(^2\) Currently with Massachusetts Institute of Technology, Cambridge 02139-4307, USA

J.E. Gillam, J. F. Oliver, M. Rafecas, P. Solevi
IFIC (CSIC / Universidad de Valencia), E-46071 Valencia, Spain

R. De Leo, E. Nappi
INFN, Sezione di Bari, I-70122 Bari, Italy

E. Chesi, A. Rudge, P. Weilhammer
Ohio State University, Columbus, Ohio 43210, USA

E. Bolle, S. Stapnes
University of Oslo, NO-0317 Oslo, Norway

U. Ruotsalainen, U. Tuna
Tampere University of Technology, FI-33100 Tampere, Finland