The AX-PET Demonstrator: Performance and first results

Chiara Casella
ETH Zurich
on behalf of the AX-PET Collaboration

12th Topical Seminar on Innovative Particle and Radiation Detector
June 7th, 2010 - Siena
AX-PET : AXial Positron Emission Tomography
A novel geometrical concept for a high resolution, high sensitivity PET scanner

• AX-PET
  • why axial ?
  • experimental concept
  • AX-PET ingredients

• AX-PET DEMONSTRATOR
  i.e. not a full scanner, only 2 PET modules

• AX-PET PERFORMANCE
  • assessed from dedicated test setups
  • spatial, energy, timing resolution

• VERY FIRST RECONSTRUCTED IMAGES
  of extended objects
The AX–PET camera modules – Design, Construction and Characterization

P. Beltrame\textsuperscript{a}, E. Bolle\textsuperscript{g}, A. Braem\textsuperscript{a}, C. Casella\textsuperscript{b}, E. Chesi\textsuperscript{e}, N. Clinthorne\textsuperscript{f}, R. De Leo\textsuperscript{d}, G. Dissertori\textsuperscript{b}, L. Djambazov\textsuperscript{b}, V. Fant\textsuperscript{a,1}, C. Joram\textsuperscript{a}, H. Kagan\textsuperscript{e}, W. Lustermann\textsuperscript{b}, F. Meddi\textsuperscript{h}, E. Nappi\textsuperscript{d}, F. Nessi-Tedaldi\textsuperscript{b}, J. F. Oliver\textsuperscript{c}, F. Pauss\textsuperscript{b}, M. Rafecas\textsuperscript{c}, D. Renker\textsuperscript{b,2}, A. Rudge\textsuperscript{e}, D. Schinzel\textsuperscript{b}, T. Schneider\textsuperscript{a}, J. Séguinot\textsuperscript{a}, P. Solevi\textsuperscript{c}, S. Stapnes\textsuperscript{g}, P. Weilhammer\textsuperscript{e}

\textsuperscript{a}CERN, PH Department, CH-1211 Geneva, Switzerland
\textsuperscript{b}Institute for Particle Physics, ETH Zurich, CH-8093 Zurich, Switzerland
\textsuperscript{c}IFIC, E-46071 Valencia, Spain
\textsuperscript{d}INFN, Sezione di Bari, I-70122 Bari, Italy
\textsuperscript{e}Ohio State University, Columbus, Ohio 43210, USA
\textsuperscript{f}University of Michigan, Ann Arbor, MI 48109, USA
\textsuperscript{g}University of Oslo, NO-0317 Oslo, Norway
\textsuperscript{h}University of Rome “La Sapienza”, I-00185 Rome, Italy
PET: Positron Emission Tomography

$p \rightarrow n + e^+ + \nu_e$

$e^+ e^- \rightarrow \gamma \gamma$

($E_\gamma = 511$ keV)

to be completed!
From standard (i.e. radial) to axial PET

conventional PET (radial arrangement)

parallax err.

to be completed!
3D localization of the photon interaction point without compromising between spatial resolution and sensitivity

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

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

- To increase spatial resolution \(\Rightarrow\) Reduce crystals size \((d)\)
- To increase sensitivity \(\Rightarrow\) Add additional layers
3D localization of the photon interaction point without compromising between spatial resolution and sensitivity

(1) TRANSAXIAL COORDINATE (x,y)
- Transaxial coordinate: from position of the hit crystal
- Transaxial resolution = \( \frac{d}{\sqrt{12}} \) FWHM
- To increase spatial resolution => Reduce crystals size (d)
- To increase sensitivity => Add additional layers

(2) AXIAL COORDINATE (z)
- Axial coordinate: from center of gravity method
- Axial resolution < w (goal: < mm)
**AX-PET MODULE**

**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 transmission
  - 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$^6$) ✓
    - insensitive to magnetic field ✓
    - compact size ✓
    - low bias voltages (~ 70V) ✓
    - temperature dependent ✓

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

- **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 ~
  - custom made units
**AX-PET MODULE**

**AX-PET MODULE SECTIONS:**
- MECHANICAL HOUSING
- LYSO + MPPC
- LYSO + MPPC + KAPTON
- WLS + MPPC + KAPTON
- MODULE ASSEMBLING

**Components:**
- BARE ASSEMBLED MODULE, including CONNECTIVITY CARDS
- LYSO
- WLS

**Features:**
- AX-PET MODULE construction and assembly details.
**Goal of the project**: Build and fully characterize a demonstrator for the AX-PET concept

- **not a full scanner, 2 modules only!!!**
- **to mimic the full scanner**: 2 mods coincidence + rotating source

  **a) small FOV coverage:**
  - 2 modules fixed, back to back position (180°)
  - rotating source in the center of FOV

  **b) extended FOV coverage:**
  - allow coincidences btw 2 modules not at 180°
  - 1st mod. fixed
  - 2nd mod. rotating (θ=180° +/- 60°)
  - rotating source

  - **dedicated simulations, 2 mods** + validation of the simulation from the data
  - **final performance of the full scanner**: assessed with dedicated simulations, full scanner

**“gantry” system / mechanics for the demonstrator**

2nd module support (θ = 180° +/- 60°)

source support (360°)

1st module support (fixed)
Demonstrator READOUT and TRIGGER

- 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 x 511 keV deposition

MPPC

OPA486

Bias

test

\[ \Sigma E \text{ (crystals only)} \]

VATAGP5 (128 ch.)

fast

'Slow'

S&H

Channels above threshold

Analog output: Light per crystal / WLS

to be completed
AXPET (2 modules, coinc.) is fully modeled by dedicated Monte Carlo simulations

GATE simulation package (G4 application for tomographic emission, including time-dependent phenomena e.g. detector movement)

AXPET challenges for realistic simulations:
- non conventional PET design
- WLS parameterization in the digitizer(*)
- Sorter for the coincidences
  
  (*) = implied major change in the simulation source code

Excellent agreement data / simulations:

Typical LYSO energy spectrum

LYSO multiplicity

One AXPET Module illuminated by a collimated 511 keV gamma beam:
Data and Simulations
AX-PET STORY: RECENT MILESTONES

- Module 1: assembled - July 2009
- Module 2: assembled - Sept 2009

- Single module characterization in a dedicated test setup (Aug ‘09 - Nov ‘09)
  - with $^{22}$Na point-like sources
  - at CERN

- Two modules in coincidence - dedicated test setup (Nov ‘09 - March ’10)
  - with $^{22}$Na point-like sources
  - at CERN

- Transition to the new gantry setup (Mar - Apr 2010)
  - at CERN, with point-like sources on rotating table

- Two modules in coincidence with phantoms filled with 18F-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute
  - 20th - 30th April 2010
• Module 1: assembled - July 2009
• Module 2: assembled - Sept 2009

• Single module characterization in a dedicated test setup (Aug ’09 - Nov ’09)
  - with $^{22}\text{Na}$ point-like sources
  - at CERN

• Transition to the new gantry setup (Mar - Apr 2010)
  - at CERN, with point-like sources on rotating table

• Two modules in coincidence with phantoms filled with $^{18}\text{F}$-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute - 20th - 30th April 2010
• Module 1: assembled - July 2009
• Module 2: assembled - Sept 2009

• Single module characterization in a dedicated test setup (Aug ’09 - Nov ’09)
  - with $^{22}$Na point-like sources
  - at CERN

• Two modules in coincidence - dedicated test setup (Nov ’09 - March ’10)
  - with point-like sources
  - at CERN
AX-PET STORY: RECENT MILESTONES

• Module 1: assembled - July 2009

• Module 2: assembled - Sept 2009

• Single module characterization in a dedicated test setup (Aug '09 - Nov '09) - with 22 Na point-like sources - at CERN

• Two modules in coincidence - dedicated test setup (Nov '09 - March '10) - with 22 Na point-like sources - at CERN

• Transition to the new gantry setup (Mar - Apr 2010) - at CERN, with point-like sources on rotating table

• Two modules in coincidence with phantoms filled with 18F-radiotracers - at ETH Zurich, Radiopharmaceutical Institute - 20th - 30th April 2010
• Two modules in coincidence with phantoms filled with 18F-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute (Animal PET Lab)
  - 20th - 30th April 2010
• Module 1 : assembled - **July 2009**

• Module 2 : assembled - **Sept 2009**

• Single module characterization in a dedicated test setup (**Aug ‘09 - Nov ‘09**)  
  - with $^{22}$Na point-like sources  
  - at CERN

• Two modules in coincidence - dedicated test setup (**Nov ‘09 - March ’10**)  
  - with point-like sources  
  - at CERN

• Transition to the new gantry setup (**Mar - Apr 2010**)  
  - at CERN, with point-like sources on rotating table

• Two modules in coincidence with phantoms filled with 18F-radiotracers  
  - at ETH Zurich, Radiopharmaceutical Institute  
  - **20th - 30th April 2010**
• Module 1: assembled - July 2009
• Module 2: assembled - Sept 2009

• Single module characterization in a dedicated test setup - with $^{22}$Na point-like sources - at CERN

• Two modules in coincidence - dedicated test setup (Nov ‘09 - March ’10) - with point-like sources - at CERN

• Transition to the new gantry setup (Mar - Apr 2010) - at CERN, with point-like sources on rotating table

• Two modules in coincidence with phantoms filled with 18F-radiotracers - at ETH Zurich, Radiopharmaceutical Institute - 20th - 30th April 2010

DETECTOR PERFORMANCE:
• energy resolution
• spatial (axial) resolution
• timing performance
• occupancy / multiplicities

• image reconstruction
• very first results
Chiara Casella     IPRD10 - June 7th, 2010

Single module characterization

For energy calibration, energy resolution

Collimated beam spot, spatial resolution

LYSO occupancy

LYSO occupancy

LYSO No. 44 - raw ADC

Single LYSO energy spectrum

WLS n.143 (W6.13)

Entries 21491
Mean 181
RMS 75.21

WLS n.143 (W6.13)

Entries 1176
Mean 98.06
RMS 71.33

W5.13

W5.18

Central WLS spectrum

Peripheral WLS spectrum
After ENERGY CALIBRATION (i.e. from raw ADC counts to keV units):

**LYSO Energy resolution**

\[
\text{R}_{\text{FWHM}} = 12.25 \% 
\]

@511 keV

(averaged on 48 LYSO crystals)

**LYSO Sum**

\[
\text{R}_{\text{FWHM}} = 12.25 \% 
\]

@511 keV

(averaged on summed distribution)
After ENERGY CALIBRATION (i.e. from raw ADC counts to keV units):

Typical LYSO MULTIPLICITIES (single module):
- Prob (1LYSO) ~ 64%
- Prob (2LYSO) ~ 30%

Typical LYSO MULTIPLICITIES - 2 MODS COINCIDENCES:
- Prob (1LYSO-1LYSO “1-1”) ~ 44%
- Prob (1LYSO-2LYSO “1-2” or “2-1”) ~ 38%
- Prob (2LYSO-2LYSO “2-2”) ~ 9%

R_FWHM_Sum ~ 12.25% at 511 keV
(on the summed distribution)

< R_FWHM > ~ 11.6% @511 keV
(averaged on 48 LYSO crystals)
TOP View - \(d(\text{Mod1, Mod2}) = 150\) mm

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

on scale!

[mm]
Intersection of LOR with central plane -- no tomographic reconstruction !!!

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

- intrinsic resolution
- positron range
- non collinearity
- (source dimensions ; \(\phi=250\mu m\))

\[\Rightarrow (R_{\text{intrinsic\_FWHM}})_z \sim 1.35 \text{ mm}\]

\[R_{\text{intr}} = \sqrt{R_{\text{meas}}^2 - R_{\rho}^2 - R_{180}^2}\]
• measure delay of coincidence wrt Mod2
• measurement from the scope [Lecroy Waverunner LT584 L 1GHz]

Measured time resolution : **FWHM ~ 1.9 ns**
MEASUREMENTS with PHANTOMS

• First measurements with extended objects filled with radio-tracers
• Apr 26th-30th 2010
• at ETH Zurich - Radiopharmaceutical Institute (Animal PET Lab)
• $^{18}$F - FDG ($t_{1/2} \sim 110$ mins)
• Phantoms used: mini-Derenzo, with and without inserts ($L = 1.5$ cm; $\varnothing = 2$ cm; $\varnothing_{rods} = [0.8, 1.3]$ mm)
  - mouse-like phantom ($L = 7$ cm; $\varnothing = 3$ cm)
  - capillaries ($L = 3$ cm; $\varnothing = 1.4$ mm)

• acquisition method: only source rotating - 2 modules fixed (i.e. center FOV)
• Dist_2mod2 = 15 cm

• for the moment only “golden events” are used for the reconstruction
  (1 LYSO per module, unambiguous definition of the z coordinate)

RECONSTRUCTION

• Statistical iterative reconstruction method
• MLEM (Max Likelihood Expectation Maximisation)
• System matrix
  - detailed description of the geometry
  - based on Siddon algorithm
• FOV : voxel dimension : 1 x 1 x 1 mm$^3$

MEASUREMENTS GOALS:
• test performance
• uniformity
  - Derenzo without inserts
  - mouse-like phantom
• resolution
  - Derenzo with inserts
  - Capillaries

PRELIMINARY RESULTS!
• phantom: 3 capillaries (∥ LYSO)
• capillaries (x3): $L = 3\text{cm}$; Diam = 1.4 mm; Pitch = 5 mm
• 17 positions of the phantom, $\theta$ in $[0^\circ, 170^\circ]$

• FOV: $30 \times 30 \times 83 \text{ vox}^3 = 30 \times 30 \times 83 \text{ mm}^3$
• 30 iterations

FWHM $\approx 1.73 \text{ mm}$
FWHM $\approx 1.96 \text{ mm}$
FWHM $\approx 1.96 \text{ mm}$
RECONSTRUCTED IMAGE : Capillaries (2)

- **phantom** : 8 capillaries (∥ WLS)
- **capillaries (x8)** : \( L = 3\text{ cm} ; \) \( \text{Diam} = 1.4 \text{ mm} ; \) \( \text{Pitch} = 5 \text{ mm} \)
- **17 positions** of the phantom, \( \theta \) in \([0°, 170°]\)

- **FOV** : \( 30 \times 30 \times 83 \text{ vox}^3 = 30 \times 30 \times 83 \text{ mm}^3 \)
- **30 iterations**

**Graphs**:
- FWHM \( \approx 1.69 \text{ mm} \), FWHM \( \approx 1.63 \text{ mm} \), FWHM \( \approx 1.71 \text{ mm} \)
- more statistics available (x2)
- no correction applied for the moment
CONCLUSIONS and OUTLOOK

Novelty of AX-PET

(1) as calorimeter
- “unconventional” use of WLS to collect escaping scintillation light / bare scintillators

(2) as PET
- new axial geometry
  • Sensitivity / resolution now decoupled and not competing
  • 3D reconstruction of photon interaction points
  • DOI (Depth Of Interaction) measurement => Parallax-free system
  • Resolution / Sensitivity tunable with granularity and nr. layers
- versatile concept, that can be scaled in size and nr layers to match specific needs (small animal PET, brain PET, PEM...)
- possible compatibility with MRI
- possibility to reconstruct the ICS (Inter Crystal Scattering) => Enhance sensitivity and resolution

Assessed performance

(1) as detector
In dedicated test benches, single module characterization & 2 mods coincidences
- good energy resolution
  \[ R_{FWHM} : 11.6 \% \text{ (@511 keV)} \]
- good time resolution:
  \[ \Delta t \sim 1.9 \text{ ns FWHM} \]
- good intrinsic spatial resolution:
  \[ R_{RWHM} \sim 1.35 \text{ mm} \]

(2) as imaging device
First measurements with extended objects, with \(^{18}\text{F-FDG}\) (phantoms)
- first reconstructed images
- image reconstr. sw successfully tested
- very promising (still preliminary) results
- competitive performance with state of the art PET scanners

Still to do...

- improve the quality of the reconstruction (system matrix / statistics / corrections ...)
- potentiality of Inter Crystal Scattering (ICS)
- large FOV coverage: new phantom measurements campaign (July 2010 ?)
- ...
BACKUP
LYSO intrinsic radioactivity

Lu decay:

\[ ^{176}\text{Lu} \rightarrow ^{176}\text{Hf} + \beta^- + \gamma \]

\[ ^{176}\text{Lu} \rightarrow ^{176}\text{Hf} + \beta^- + \gamma \]

\[ ^{176}\text{Lu} \rightarrow ^{176}\text{Hf} + \beta^- + \gamma \]

\[ ^{176}\text{Lu} \rightarrow ^{176}\text{Hf} + \beta^- + \gamma \]

from Saint Gobain Prelude 420 spec sheet:

1) Energy spectrum measured in a 1” diameter x 1” high LYSO crystal:

\[ \text{Counts/keV} \]

2) \[ A = 39 \text{ Bq/g} \ (\rho = 7.1 \text{ g/cm}^3) \Rightarrow \text{expected 250 Bq in 3x3x100mm3 LYSO} \]
**Why energy calibration** (i.e. ADC values => keV) ?
- equalized response from all channels
- correct for the MPPC’s non linearity (at 511 keV)

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

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

- deviation from linearity (~ 5% effect)
- parameterization: negative logarithmic fitting func.
Fundamental limitations in the spatial resolution of PET imaging come from the physics of the $e^+$ annihilation process.

1. Effective positron range

2. Non collinearity
Small animal PET comparison:

- SiliPET
- MicroPET Focus 120
- MicroPET Focus 220
- MicroPET-R4
- Explore-Vista
- ClearPET
- MicroPET II
- Quart-HIDAC
- YAP(S)-PET
- TierPET
- SHR-7700
- APD-PET
- A-PET
- MADPET
- ANIPET
- ratPET
- ANIPET

Sensitivity (%)
Spatial Resolution FWHM (mm)
Intrinsic resolution of commercial scanners
AX-PET components

The scintillator crystals are Ce doped LYSO (Lu$_{1.8}$Y$_2$SiO$_5$•Ce) single crystals, fabricated by Saint Gobain and commercialized under the trade name PreLude 420.

The main characteristics are:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm$^3$]</td>
<td>7.1</td>
</tr>
<tr>
<td>Attenuation length for 511 keV [cm]</td>
<td>1.2</td>
</tr>
<tr>
<td>Wavelength of maximum emission [nm]</td>
<td>420</td>
</tr>
<tr>
<td>Refractive index at W.L. of max. emission</td>
<td>1.81</td>
</tr>
<tr>
<td>Light yield [photons/keV]</td>
<td>32</td>
</tr>
<tr>
<td>Average temperature coefficient [%/K]</td>
<td>-0.28</td>
</tr>
<tr>
<td>Decay time [ns]</td>
<td>41</td>
</tr>
<tr>
<td>Intrinsic energy resolution [% FWHM]</td>
<td>~8</td>
</tr>
<tr>
<td>Natural radioactivity [Bq/cm$^3$]</td>
<td>~300</td>
</tr>
<tr>
<td>Effective optical absorption length [mm]</td>
<td>~420</td>
</tr>
</tbody>
</table>

Dimensions: 3 x 3 x 100 mm$^3$

One end is read out, the other end is mirror-coated (evaporated Al-film).
The WLS strips are of type EJ-280-10x from Eljen Technologies

- Shift light from blue to green
- Density: 1.023 g/cm³
- Absorption length for blue light: 0.4mm (10 x standard concentration)
- Index of reflection: 1.58
- Decay time: 8.5ns
- Size: 0.9x3x40mm³

One end is read out, the other end is mirror-coated (evaporated Al-film).
Extended pieces of detector \((L_{\text{lyso}} = 100 \text{ mm} ; L_{\text{wls}} = 40 \text{ mm})\)
- large FOV coverage
- dependence of the detector response on the position of the interaction point \(\lambda_{\text{attenuation}}\)

To achieve a good uniformity of the detector response:
- measure \(\lambda_{\text{attenuation}}\) (FULL SCAN measurements)
- correct offline (on a channel by channel basis)

<table>
<thead>
<tr>
<th>LYSO 3 Layer 6 - Ypos 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO 6,3 (ADC counts)</td>
</tr>
<tr>
<td>495</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>505</td>
</tr>
<tr>
<td>510</td>
</tr>
<tr>
<td>515</td>
</tr>
<tr>
<td>520</td>
</tr>
</tbody>
</table>

\[ \begin{array}{c}
\text{dZ (mm)} \\
10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
\end{array} \]

one LYSO example

FULL SCAN MODULE:
- 53(z) x 16(y) positions
- 848 runs
- few days acquisition
Summed LYSO signal, single module
Reconstructed z coordinate on each layer:

\[ z_{\text{reco}} = \sum_i \frac{z_i \times LY_i}{LY_i} \]

How to derive the intrinsic spatial resolution?

1. make hypothesis:

\[ \sigma_{i, \text{beam}} \propto d_i \]

\[ \sigma_i^2 = \sigma_{Z - \text{res}}^2 + \alpha d_i^2 \quad \alpha = \frac{\sigma_{\text{beam}}^2}{d^2} \]

2. extrapolate at zero distance

Spatial resolution

\[ \sigma^2 \sim 0.76 \text{ mm} \]

FWHM \sim 1.8 mm

It includes:

• intrinsic spatial resolution
• beam spot size on each layer

\[ \sigma_i^2 = \sigma_{i, \text{beam}}^2 + \sigma_{Z - \text{res}}^2 \]
AXIAL RESOLUTION

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

\[ (0.54 \text{ mm})^2 \]
\[ [0.0022 \times \text{Diam} = 0.33 \text{ mm}]^2 \]
two sources:
1) $A \sim 600$ MBq; in (0,0,0)
2) $A \sim 100$ kBq; in (0,0,$\Delta Z$)

$\Delta Z \sim 4.5 \div 5$ mm
1. Ter-Pogossian et al, 1978: pioneering original concept of NaI crystals axial arrangement

**2004**
- Proposed 5 years ago to use HPD (Hybrid Photon Detector) for the readout of long crystals in axial configuration. Pulse height ration was used to derive axial coordinate
- Best achievable axial resolution was 6mm for 100mm crystal → Not sufficient
- HPD were based on custom made in-house developments

**2007**
- New proposal:
  - Use interleaving WLS strips for the reconstruction of the axial coordinate
  - G-APD for crystal and WLS readout

**Publication:**
- A. Braem et al., Wave Length Shifter Strips and G-APD Arrays for the Read-Out of the z-Coordinate in Axial PET Modules (short version of Nim Paper), Conference Record IEEE Meeting 2007, Honolulu.

**2009:**
- Module constructions / performance assessment / single module characterization / 2 mods coincidence (with sources) [PAPER IN PREPARATION]
- Software progress: simulations / reconstruction [PAPER IN PREPARATION]

**2010:**
- Measurements with phantoms
Modified Siddon’s ray tracer approach

Simplistic approach: contribution to a voxel of the LOR is given by the intersection length.

The screening effect due to neighboring crystals attenuating the gamma is also considered.

Outline of SM computation without subsampling

- LYSO crystals are discretized in detector elements
- Lines of Response, LORs, joining centers are considered.
- Siddon algorithm. Intersection lengths between LOR and voxel are used to approximate the probability of a decay that takes place at that particular voxel gives a signal in that LOR.
- Crystal penetration effects were considered.
- Ignores effects due to the finite size of the crystals
Outline of SM computation without subsampling

- LYSO crystals are discretized in detector elements
- Lines of Response, LORs, joining centers are considered.
- Siddon algorithm. Intersection lengths between LOR and voxel are used to approximate the probability of a decay that takes place at that particular voxel gives a signal in that LOR.
- Crystal penetration effects were considered.
- Ignores effects due to the finite size of the crystals

Outline of SM computation with subsampling

- LYSO crystals are discretized in detector elements
- Instead of LORs each pair of detector elements define a Tube of Response, TOR.
- Each TOR is composed of several LORs defined by a grid of sampling points inside the detector element. All possible combinations
- Individual LOR contributions are computed as before, i.e. Siddon algorithm.
- Crystal penetration effects are properly considered. Each LOR has its own factor. No factorization.
- Effects due to the finite size of the crystals are partially considered.
Sensitivity Matrix

Transaxial slide sample  Axial slide sample

Without subsampling

LORs: 2.80 $10^7$
Elements: 7.57 $10^{11}$
non-zero elem.: 7.5 $10^8$
Size: 5.7 G
sampling: 1x1x1

With subsampling

LORs: 2.80 $10^7$
Elements: 7.57 $10^{11}$
non-zero elem.: 4.45 $10^9$
Size: 34 G (not optimized)
sampling: 2x2x2

FOV

Volume(vox): 30x30x30 vox
Volume(mm$^3$): 30x30x30 mm$^3$
voxel dimensions: 1x1x1 mm$^3$
voxels: 27000
GATE simulation of the full module

The AX-PET scanner is modeled by means of GATE. In order to correctly reproduce the achievable spatial resolution, the source code is modified to include the z coordinate parameterization according to WLS response.

- Intrinsic radioactivity
- Digitizer
  - energy and time blurring;
  - threshold at crystal level;
  - coincidence unit;
  - dead time in the acquisition;
  - rotation of the scanner.

- Geometry modeled
- Gamma source
- WLS parameterization
  \[ N_{pe,i,n} = N_{pe,i,n-1} + A(x_n, E_n) \cdot e^{\frac{(\bar{E}_n - E_n)^2}{2\sigma^2(x_n)}} \]

GATE simulation

Geant4 simulation

12/03/09
Simulation and image reconstruction for AX-PET

6
Investigate Inter-crystal scattering

Multiple events are accepted if $E_1 + E_2 \approx 511$ keV.

The use of ICS events implies:

- higher sensitivity;
- need of proper techniques to include ICS in the reconstruction algorithm to avoid spoiling the spatial resolution.

Different approaches:

- identify and reconstruct ICS and feed the image reconstruction algorithm with the “good” LOR;
- keep all LORs and adapt the system model.
ICS identification and reconstruction

Different identification algorithms are tested and their efficiency in ICS reconstruction is estimated on simulations.

- Klein-Nishina based on geometry or energy;
- Maximum Energy;
- Compton Kinematics (CK);
- Neural Network.

Simulation is performed by using 12% energy resolution at 511 keV, with point-like source in the centre of the FOV, back-to-back gamma emission, 2 modules at 85 mm distance.

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