The AX-PET Demonstrator: Performance and first results

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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 (not a full scanner, 2 PET modules)

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

• VERY FIRST RECONSTRUCTED IMAGES of extended objects
AX-PET COLLABORATION

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PET: Positron Emission Tomography

IDEAL PET SCANNER REQUIREMENTS:
- 2π full coverage
- maximum spatial resolution (up to the limits imposed by the physics of the β+ annihilation)
- maximum sensitivity
- good energy resolution
- good time performance
- ...

- **in-vivo functional imaging technique**
  - a biologically active compound labeled with a proton rich isotope (e.g. $^18$F, $^{11}$C, $^{15}$O, $^{13}$N...) is injected into the body
  - $p \rightarrow n + e^+ + \nu_e$
  - $e^+ e^- \rightarrow \gamma \gamma$
  - ($E_{\gamma} = 511$ keV)

- detection principle:
  - detection of the coincidence of two back to back photons (511 keV each)

- imaging reconstruction software => 3-dim image of the radiotracer concentration in the body
From standard (i.e. radial) to axial PET

**conventional PET**
(radial arrangement of scintillator detectors)

compromise btw **spatial resolution** ($R$) and **sensitivity** ($S$)

- long crystals (big $L$) $\Rightarrow$ high $S$, poor $R$
  - parallax error: $\delta_p = L \sin \theta$
  - no depth of interaction (DOI) information

- small crystals (small $L$) $\Rightarrow$ high $R$, poor $S$
  detection efficiency: $\varepsilon = 1 - e^{-L/\lambda}$
From standard (i.e. radial) to axial PET

conventional PET
(radial arrangement of scintillator detectors)

=> new geometry:

AXIAL PET

compromise btw spatial resolution \( R \) and sensitivity \( S \)

- long crystals (big \( L \)) \( \Rightarrow \) high \( S \), poor \( R \)
  - parallax error: \( \delta_p = L \sin\theta \)
  - no depth of interaction (DOI) information

- small crystals (small \( L \)) \( \Rightarrow \) high \( R \), poor \( S \)
  detection efficiency: \( \epsilon = 1 - e^{-L/\lambda} \)

• long crystals (\( L >> L_{\text{radial}} \))
• axially arranged around the body
3D localization of the photon interaction point without compromising between spacial resolution and sensitivity

(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
3D localization of the photon interaction point without compromising between spatial resolution and sensitivity

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(2) AXIAL COORDINATE \((z)\)

- Axial coordinate: center of gravity method
- Axial resolution < \(w\) (goal: < mm)
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 = d/√12 FWHM

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

from scintillator crystals: x, y, Energy deposition

(2) AXIAL COORDINATE (z)

- Axial coordinate: center of gravity method
- Axial resolution < w (goal: < mm)

from WLS strips: z
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 ($\rho = 7.1$ g/cm$^3$)
    - $\lambda$ @511 keV ~ 1.2 cm
    - quick decay time ($\tau = 41$ ns)
    - high light yield (32000 $\gamma$/MeV)
    - $3 \times 3 \times 100$ mm$^3$

- WAVE LENGTH SHIFTING STRIPS (WLS):
  - ELJEN EJ-280-10x
    - highly doped (x10 compared to standard) to optimize transmission
    - $0.9 \times 3 \times 40$ 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 ($\sim 50\%$)
    - high gain ($10^5$ to $10^6$)
    - insensitive to magnetic field
    - compact size
    - low bias voltages ($\sim 70V$)
    - temperature dependent
    - dark rate

- MPPC S10362-33-050C:
  - 3x3 mm$^2$ active area
  - 50 $\mu$m x 50 $\mu$m pixel
  - 3600 pixels
  - Gain $\sim 5.7 \times 10^5$

- MPPC 3.22$\times$1.19 Octagon-SMD:
  - 1.2 x 3.2 mm$^2$ active area
  - 70 $\mu$m x 70 $\mu$m pixel
  - 1200 pixels
  - Gain $\sim 4 \times 10^5$
  - custom made units
AX-PET MODULE

- MECHANICAL HOUSING
- LYSO + MPPC
- LYSO + MPPC + KAPTON
- WLS + MPPC + KAPTON

MODULE ASSEMBLING

- MECHANICAL HOUSING
- LYSO
- WLS

BARE ASSEMBLED MODULE, including CONNECTIVITY CARDS
**Goal of the project**: Build and fully characterize a demonstrator for the AX-PET concept

- **not a full scanner**, but **2 modules**
- **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

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

- 2nd module support (θ = 180° +/- 60°)
- source support (360°)
- 1st module support (fixed)

- **dedicated simulations, 2 mods** + validation of the simulation from the data
- **final performance of the full scanner**: assessed with dedicated simulations, full scanner
• Custom designed DAQ system - Individual analogue readout of MPPC output

• **Amplifiers** : OPA486 (Lyso) / OPA487 (WLS) - Fast energy sum of all the crystals module

• **VATA GP5 chip** : 128-ch charge sensitive integrating [AXPET : x4 VATA GP5 chips]
  - Fast (~40ns) / Slow (~250ns) branches
  - Sequential or Sparse readout mode
  - **Sparse** = the analogue signals of the flagged - i.e. above thr - channels only is multiplexed into the output

• **EXTERNAL TRIGGER** (NIM logic) :
  Coincidence of the two 511 keV annihilation photons (one per module), with high energy discrimination thr on the module energy sum
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
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• Two modules in coincidence with phantoms filled with $^{18}$F-radiotracers
  - at ETH Zurich, Radiopharmaceutical Institute
  - 20th - 30th April 2010
**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 point-like sources
  - at CERN

2-D moving station / later replaced by rotating motor

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AX-PET STORY: RECENT MILESTONES

• Module 1: assembled - July 2009
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• Single module characterization in a dedicated test setup (Aug ʻ09 - Nov ʻ09) - with 22Na point-like sources - at CERN
• Two modules in coincidence - dedicated test setup (Nov ʻ09 - March ʻ10) - with 22Na 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
AX-PET STORY: RECENT MILESTONES

- 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**)
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  - at CERN

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DETECTOR PERFORMANCE:
- energy resolution
- spatial (axial) resolution
- timing performance

• image reconstruction
• very first results
Single module characterization

for energy calibration, energy resolution

collimated beam spot, spatial resolution

LYSO occupancy

LYSO No. 44 - raw ADC

Single LYSO energy spectrum

central WLS spectrum

peripheral WLS spectrum

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

\[ \text{R}_{\text{FWHM}} \text{ Sum} \sim 12.25\% \text{ at } 511 \text{ keV} \]

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

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

N$_\text{coinc\_evts}$=100

on scale! [mm]

/home/daq/axpet/log/run02730.log INFO: Temperature is 20.89 in Mod1 21.05 in Mod2
/home/daq/axpet/log/run02730.log INFO: ***************************************
/home/daq/axpet/log/run02730.log INFO: Run Number: ********** 02730 **********
/home/daq/axpet/log/run02730.log INFO: ***************************************
/home/daq/axpet/log/run02730.log INFO: Run Type: SPARSE readout
/home/daq/axpet/log/run02730.log INFO: Comment: Test_Mod1_AND_Mod2 Temp. 20.89 M1 - 21.05 M2
Intersection of LOR with central plane
no tomographic reconstruction !!!

\[ R_{intr} = \sqrt{R_{meas}^2 - R_{\rho}^2 - R_{180}^2} \]

\( (R_{FWHM})_z \sim 1.5 \text{ mm} \)
- intrinsic resolution
- positron range
- non collinearity
- (source dimensions ; \( \phi = 250 \mu \text{m} \))

\( => (R_{intrinsic\_FWHM})_z \sim 1.35 \text{ mm} \)
- 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}\text{F} - \text{FDG} (t_{1/2} \sim 110 \text{ mins})
- Phantoms used: micro-Derenzo, with and without inserts \((L= 1.5 \text{ cm}; \varnothing = 2 \text{ cm}; \varnothing_{\text{rods}} = [0.8,1.3] \text{ mm})\)
  - mouse-like phantom \((L = 7 \text{ cm}; \varnothing = 3 \text{ cm})\)
  - capillaries \((L = 3 \text{ cm}; \varnothing = 1.4 \text{ mm})\)

- 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: \(1 \times 1 \times 1 \text{ mm}^3\)

MEASUREMENTS GOALS:

- test performance
- uniformity
  - Derenzo without inserts
  - mouse-like phantom
- resolution
  - Derenzo with inserts
  - Capillaries
• phantom : 3 capillaries (/ xy)
• capillaries (x3) : L = 3 cm ; Diam = 1.4 mm ; Pitch = 5 mm
• 17 positions of the phantom, θ in [0°, 170°]
• FOV : 30 x 30 x 83 vox³ = 30 x 30 x 83 mm³
• 30 iterations

FWHM ~ 1.73 mm
FWHM ~ 1.96 mm
FWHM ~ 1.96 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 \([0^\circ, 170^\circ]\)

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

Preliminary!!!
• phantom: micro Derenzo
• \( L = 1.5 \text{ cm}; \text{Diam} = 2 \text{ cm}; \text{Rods}_\text{Diam} = 0.8\div1.3 \text{ mm} \)
• 17 positions of the phantom, \( \theta \) in \([0^\circ,170^\circ]\)
• FOV: \( 30 \times 30 \times 30 \text{ vox}^3 = 30 \times 30 \times 30 \text{ mm}^3 \)
• 200 iterations

- more statistics available (x2)
- no correction applied for the moment
- possible refinements of system matrix
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 and Resolution decoupled
• DOI (Depth Of Interaction) direct measurement => parallax free system
• Resolution / Sensitivity tunable with granularity / Nr. layers
• Possibility to identify ICS (Inter Crystal Scattering) => Tag & discard ICS evts (Resolution fully maintained)
  OR Tag & reconstruct ICS evts (Sensitivity increased)
• Versatile concept, can be scaled in size and Nr. layers (small animal PET, brain PET, PEM...)
• Fully simulated detector

Status / Performance of AX-PET

• 2 modules (i.e. demonstrator) built and characterized (individually / in coincidence) with sources

• ASSESSED PERFORMANCE :
  - energy resolution: R_FWHM 11.6 % (@511 keV)
  - time resolution : Δt ~ 1.9 ns FWHM
  - intrinsic spatial resolution : R_FWHM ~ 1.35 mm

• First measurements campaign with phantoms filled with FDG radiotracer
• First reconstructed images (very preliminary, but encouraging...)

What’s next?

• 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 ?)
• ...

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