Development of a High Precision Axial 3-D PET for Brain Imaging

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On behalf of the AX-PET Collaboration

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Outline

- Basics of Positron Emission Tomography (PET);
- Principle of the AX-PET scanner;
- Recent progress towards a Two-Module Demonstrator:
  - LYSO Crystals;
  - Wave Length Shifter (WLS) Strips;
  - Photo Detectors (MPPC);
  - Axial coordinate Reconstruction;
- Outlook.
Positron Emission Tomography (PET)

- Images of functional processes in the body;
- Injection of biologically active molecules (FDG-FluoroDeoxyGlucose), tagged with radioactive ($\beta^+$) tracers -> $^{18}\text{F}$, $^{11}\text{C}$, $^{15}\text{O}$…;
- $\beta^+$ annihilation with $e^-$ from tissue, forming back-to-back 511 keV photon pair;
- Detection of the photon pair (Line of Response) by means of a set of detectors surrounding the patient;
- Display of areas with high metabolic activity by means of intersections of Lines of Response;
- Reconstruct 2D/3D images.
Standard (radial) PET scanners

Photon pair detection efficiency:

- Very important (related to the quantity of radioactive dose to inject to the patient);
- Depends on:
  - length of the crystals $L$;
  - attenuation length of the crystals $\lambda_a$.

$$\varepsilon_2 = \left(1 - e^{-L/\lambda_a}\right)^2$$

- Typical crystal attenuation length: 1-2 cm;

Recent PET scanner (HRRT, Knoxville, USA) efficiency for the detection of photon pairs is given to be 6.9%.

K. Wienhard et al., IEEE TNS 49 (2002) 104-110
**Standard (radial) PET scanners**

**Depth of Interaction (DOI):**

- Is not measured;
- Introduces a parallax error;
- The resolution degrades with $L$;
- The resolution in the off-center region degrades significantly;

**Solution:**

- Measure DOI, changing the geometry
  - Use of long crystals oriented parallel to the scanner axe;
  - Use wave length shifting strips (WLS) to read the third coordinate.

**HRRT PET volumetric resolution** is given as 20 mm$^3$ FWHM.

\[
\delta_p = L \cdot \sin \alpha
\]
Axial PET geometry
**Crystal + WLS**

- **The Principle:** Catch the scintillation light which is “lost” outside the angle of total reflection in the crystal to produce wave length shifted light in the WLS strip;

- X and Y coordinates (resolutions) are derived by the crystal (dimensions);

- Z coordinate (resolution) is derived by the (width of the) WLS strip;

- Read-out one end of WLS strips and crystals. Reflector on opposite side;

- Resolution in all three coordinates can be chosen, without compromising on the photon pair detection efficiency;

- Detection of Compton cascades is possible → increase of the total efficiency up to 13.6%-15.3%, depending on the recoil electron energy cut-off.
PET Detector Demonstrator

Two PET Modules under construction

- 6 layers of 8 LYSO crystal bars per module;
- Interleaved with 26 WLS strips oriented perpendicular to the crystal axe;
- Read-out with MPPC;
- Photon pair detection efficiency adjustable by selecting the number of layers;
- Evaluation of all aspects of the concept by mounting the 2 modules at 180° on a turntable gantry with a suitable phantom.
The LYSO crystals

- Produced by Saint-Gobain Crystals;
- Optical polishing on all sides;
- Dimension: 3x3x100 mm³;
- LYSO Specification:
  - Density: 7.1 g/cm³;
  - Light yield > 25 ph/keV;
  - Hygroscopic: no;
  - Attenuation length for 511 keV: 1.2 cm;
  - Refractive index: 1.81;
  - Light decay time: 41 ns;
  - Intrinsic energy resolution: 7-8% FWHM;
Experimental set-up for LYSO characterization

1. 1" PMT Photonis XP2978 + BaF$_2$
2. Pb collimator + $^{22}$Na source
3. LYSO Bar + 2 PMTs BURLE 8850
4. Linear translator M-511

PMTs coupled to the LYSO bar through optical grease (BC-630, $n_{\text{index}} = 1.47$)
To evaluate the effective light attenuation length ($\lambda_{\text{eff}}$) the $^{22}\text{Na}$ source is positioned at 7 positions:

- 96 samples measured:
  - $\lambda_{\text{eff}}$ at 511 keV: 
    \[(41.4 \pm 2.6) \text{ cm};\]
  - Energy resolution $\Delta E/E$ at 511 keV in the middle of the crystal: (11 ± 0.4)% FWHM;
  - $N_{\text{pe}}$ at 511 keV in the middle of the crystal: 1165 ± 64;
WLS Strips (ELJEN EJ-280)

- The fluorescent light is shifted from blue into the green range with a peak emission at 490 nm;
- The density of the plastic material is 1.02 g/cm$^3$;
- The quantum efficiency of the fluorescent dye is 0.86 and its decay time 8.5 ns;
- Dimension: 0.9x3x40 mm$^3$;
WLS Measurements

- Measured transmission coefficient for three thicknesses (0.7 mm, 1.1 mm and 1.5 mm);
- Verified absorption of blue light and emission of the green one;
- Measured WLS light output with a PMT at the end of a strip;
- For 61 samples light output: $(48 \pm 2) \text{N}_{pe}$ with a $\lambda_{eff}$: $(160 \pm 7)$ mm;
- On average a loss of 6 p.e. over 25 mm.
MPPC (Multi Pixel Photon Counter)

- Produced by Hamamatsu;
- High Gain \((10^5 @ HV=-70V)\);
- High PDE;
- Immune to B-field (NMR);
- LYSO readout:
  - 3 x 3 mm\(^2\) active area;
  - 3600 pixels (size 50 x 50 μm\(^2\));
  - Ceramic package;
  - First 50 samples have been recently delivered;
- WLS readout:
  - 1.19 x 3.22 mm\(^2\) active area;
  - 782 pixels (70 x 70 μm\(^2\) pixel size);
  - Plastic package;
  - 500 pieces delivered in July.
MPPC Measurements

- Samples of 3 x 3 mm² MPPC (for LYSO read out) have been tested;
- Not yet available measurements on 1.19 x 3.22 mm² MPPC (for WLS read out);
- Charge gain, dark count rate and optical cross-talk are plotted as function of the applied bias voltage;
- Relative detection efficiency to detect one or more photoelectrons, obtained from the 'zero' count rate, is plotted versus the bias voltage (plateau @ -71V).
Reconstruction of Axial Coordinate

- GEANT4 software package is used and developed;
- Optimize simulation based on measured data using an electron beam;
- Axial resolution using center of gravity (strip with highest signal ± 2 neighbors): ~1 mm FWHM → volumetric precision ~5 mm³ FWHM;

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\[ Z_{\text{rec}} - Z_{\text{true}} [\text{mm}] \]
Outlook

- Proof of concept looks very encouraging;
- All key components (LYSO Crystals, WLS strips and MPPC) tested (promising results);
- The projected spatial resolution will result in a volumetric precision of ~5 mm³ FWHM, close to the limits imposed by the physics of the positron decay (non-colinearity and path);
- A two module demonstrator with altogether 408 channels is under development:
  - Electronics is under development;
  - Mechanics is in production;
- Demonstration of the feasibility of the project, reconstructing the image of the phantom brain, expected in 2009.
Thanks for your attention!
Compton enhanced reconstruction

“unambiguous”

\[ \gamma \text{ reconstruction point} \]

“ambiguous”

\[ \gamma \]

- Select only events in which Compton scattering happens in forward hemisphere
- Restrict to Compton angle \(10^\circ \leq \theta \leq 60^\circ\)
- Ask for energy deposit in first interaction \(E \leq 170 \text{ keV}\)

Interactions <170 keV has to be primary

Interactions >170 keV can be Compton or photoabsorption
Small scale lab test setup

- MPPC, LYSO and WLS with AX-PET dimensions in same setup
- 2\textsuperscript{nd} scintillator to tag 511keV from Na-22
- Reading out 8 WLS
**Small scale lab test setup**

- **LYSO energy resolution:** 12% FWHM
- **WLS output:** 73 p.e. @ 511keV in 1 WLS
  - Good agreement with previous measurements and simulations!

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**Equation**

\[
y = a + bx + c(x - x_0)^2 + d(x - x_0)^3
\]

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**Wavelength Shifting Strip (Na-22, coincidence, collimated, May 13 [11-2])**

- **WLS signal strength [ADC counts]**

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**LYSO**

- **Counts**

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**energy/keV**

- **Entries**

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**Ignazio Vilardi**

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