The AX-PET Project: Progress and Recent Results

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INTRODUCTION
Medical Requirements for Optimal PET Scanning:

- Accurate observation of small structures, e.g. in Brain PET, is very important
- Precise location of tumors before Hadron Therapy treatment
- Small Animal PET preclinical studies
- Etc.....

**KEYWORDS**

- Very good spatial resolution close to physics limits
- Higher sensitivity at reduced radiation exposure
- Possibility of co-registration with other precise morphological modalities like X-Ray CT or MRI
Some of the important instrumentation limitations in present clinical PET scanners:

- Spatial resolution non uniform over FOV due to DOI uncertainty

- Relatively low efficiency of photon conversion: due to correlation between radial thickness of scintillator and “DOI smearing” of radial interaction point.

- Limited capability to recognize and reject Compton interactions in Crystals ➔ cascade events lead to smearing on interaction point.

- Physical limitations
  - Range of $e^+$
  - A-colinearity of 511 keV gammas
The Axial PET Concept
The idea of a PET scanner module with stacks of scintillation crystal bars arranged *axially* around the FOV is old (>20 years, patent awarded to Yamashita in 1989) but for some time good technical solutions for implementation have not been readily available.

History of this project (originally axially arranged LYSO crystal bars readout on both sides with Hybrid Photon Detectors based on silicon pad sensors and VATAGP5 readout ASIC) documented in two publications:


The Axial PET Concept with WLS Strips for axial Coordinate Measurement

Axially arranged long crystal bars

Interleaved WLS strip matrix

100 to 150 mm long

Radial Configuration

Modules

PET Scanner
The Principle: Catch the scintillation light which is “lost” outside the angle of total reflection in LYSO crystal to produce wave length shifted light in the WLS strip and readout signal at one end with fast photo detectors.

Main Issue:
Is there enough light produced in WLS strip for efficient detection of 511 keV and also Compton scatter events (at least down to 50 keV)?
Main Improvements expected from Axial Concept with WLS Strip Readout

- **3-D reconstruction** of 511 keV photo absorption and cascade events uniformly over the entire FOV.

- Spatial resolution in x, y and z in the detector module is determined by the choice of transverse dimensions of long scintillation crystals and WLS strips.

- Sensitivity and spatial resolution are uncorrelated.

- Full distinction of photo absorption and Compton cascade events

- With SiPM as an option for readout of LYSO bars and WLS strips opens the possibility of co-registration with MRI.
First Measurements to prove Feasibility

A Short Summary

Published:


**Prime Question:** Are there enough wavelength shifted photons at the end of the WLS strip to obtain good signal with MPPC photon detectors?

First tests with a low energy electron beam (covering equivalent photon energies from 50 keV to 511 keV) impinging on a LYSO crystal with two WLS strips placed on top and read on one end by MPPCs.

- **45 p.e. at 230 keV**
- **85 p.e. (extrapolated) can be observed at one end of the WLS strips using Hamamatsu MPPCs 3mm x 3mm, at 511 keV**

The Test Set-Up

**Pulsed low energy electron accelerator**

Vary energy deposition in LYSO bars and its position in an easy way: thus get a measurement both for the interesting energy range of Compton interactions and for photo absorption.

Also get a measurement of z coordinate resolution

EJ-280-10x, ELJEN Technology, Texas

MPPC 33-050 C, Hamamatsu

St. Gobain Crystals, France

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A recent measurement with one WLS strip on top of one LYSO strip. With 511 keV photons from $^{22}$Na impinging on LYSO bar in coincidence with another LYSO crystal read by PM.

The peak corresponds to 73 p.e. in 1 WLS strip, confirming previous measurement.
Recent Progress towards a Two-Module Axial PET Demonstrator

- The Demonstrator Project
- Component Evaluation: LYSO crystals, WLS strips, MPPC
- Readout Electronics and Trigger
- Mechanical Assembly
- Simulation and Image Reconstruction
The Demonstrator Project

Build two modules with 6 layers of 8 crystal bars interleaved with WLS strip matrices

Evaluates all aspects of the concept by mounting the 2 modules at 180° on a turntable gantry with suitable phantom.

Use specially designed Si PM (Hamamatsu MPPC) as photo detectors for readout of both LYSO bars and WLS strips
The LYSO Crystals

3mm x 3mm x100mm bars from St.Gobain

About 110 crystals available, now more than half of them characterized
LYSO 21 (10 cm)  
2.04.2008  

PMT Left: -2250V; PMT Right: -2160V  
Att: 15 db, Source: Na-22  

Na Source at 7 positions; 1 PM on each side of LYSO bar
N_{p.e.} measured on 47 samples: 1150 ± 80

Average attenuation
Length: 41.9 ± 3 cm

Energy Resolution: 11% ± 0.4 % FWHM
The WLS Strips

(ELJEN-EJ-280-10X)

~ 600 WLS strips of dimension 3mm x 0.9mm x 40mm available
Measured transmission coefficient for three sheets of high concentration WLS materials (0.7 mm, 1.1 mm and 1.5 mm thick). The data is corrected for the Fresnel reflections at the sheet/air interfaces. The corresponding absorption coefficient in the wavelength band 400 – 460 nm is around 2 mm$^{-1}$. 

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The test set-up allows to measure light output with a PM at the end of a strip scanning the LED in 5mm steps from 2.5 mm to 37.5 mm.

Light Output Positions 2 and 7; for 61 samples.

The number of p.e.’s in this plot is roughly what we expect from a 511 keV deposition in the LYSO.

Very satisfactory!
WLS Strip Width (45 samples)

Fulfills requirements for mechanical mounting

\(<\text{width}\> = 3.010 \text{ mm} \\
\sigma = 85 \mu\text{m} \\
<\text{Length}> = 39.9 \text{ mm}
Photo Detectors
MPPCs from Hamamatsu

For the readout of the LYSO crystals the rectangular 3 mm x 3 mm MPPC S10362-33-50-C in a ceramic rectangular package of 5.9mm x 6.5 mm was chosen. First 50 samples have just recently been delivered.

Expect characteristics as measured in first tests with devices from last year (shown below).

For the readout of the WLS Strips specifically tailor made devices from Hamamatsu have been ordered. Octagonal plastic package. 500 pieces are ordered and expected for delivery for the second part of July.

The sensitive area of the MPPC is 3.22 mm x 1.19 mm

Systematic bench tests for all devices will be performed
Properties of the Hamamatsu MPPC 33-050C.

**Left Figure:** Charge gain, dark count rate and optical cross-talk are plotted as function of the applied bias voltage.

**Right Figure:** Relative detection efficiency $\varepsilon$ for $\geq 1$ photoelectron, obtained from the ‘zero’ count rate, is plotted versus the bias voltage.

Plateau at ~ 71 V
Tailor made devices for readout of WLS strips:

Very thin (1.45 mm) plastic package; contact pads on the back of the package instead of pins; hard resin filling
Mechanical Support

High mechanical precision for the assembly is required to fully exploit the very good spatial resolution capability of the device.
Basic Layout of one module

LYSO Crystal Bars

WLS strips: every other one read out on opposite sides

Carbon fiber separators:
Upper surface diffuse reflector, lower surface light absorber
Support and alignment of crystals

High precision alignment of crystals; etched Cu-Be foil 200μm

Rectangular MPPC
3mm x 3mm
Exploded view of all components

Base serving as support for “patch panel”
Read Out Electronics and Trigger
Concept of the readout:

- Readout electronics separated from the detector module
- MPPC signals distributed to “patch panel” with kapton strip line cables (12 cm)
- MPPC signals into fast amplifier (<2 ns risetime) via 50 Ohm coax cables
- Individual bias to each MPPC (32 channel high voltage DAC)
- Output signals from Fast Amplifier into VATAGP5 chip with sparse read-out. Parallel output of signals from LYSO crystals via line drivers for trigger etc…..
- VME based DAQ and Control System
- External coincidence and reset trigger logic.
Schematics of one channel of readout

LYSO bar with MPPC glued

COAX Cable

Fast (rise time < 2 ns)
Voltage Amplifier
OPA846 (TI) Gain ~ 10

Twisted pair for each LYSO channel (test)

Sum of 48 Channels for trigger

128 channel VATAGP-5 Board
64 channels used

Twisted pair output

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Coincidence Trigger for 2 Modules

LYSO #1

Output PAs

Sum (Or)

Shaper 50 nS

Disc. (100 ns)
450 < E(keV) < 550

Busy DAQ

OR

Busy DAQ

OR

Start busy DAQ

Start Read-Out

GP5 Threshold ≥ 30 keV

U_{th} (VA) > U_{th} (trig.)

LYSO #2

Output PAs

Sum (Or)

Shaper 50 nS

Disc. Trig. (10 nS)
E_{th} ~ 20-30 keV

Busy DAQ

AND

Reset at end of the DAQ sequence

Reset GP5

J. Seguinot - E. Chesi

05/02/2008
Test of 2 channels of electronics coupled to two LYSO scintillator bars (100 mm, LYSO1 and LYSO2) in coincidence with a small LYSO crystal read with a PM.

Sparse readout of VATAGP5 (channel 94 and channel 116)

Trigger on external coincidence between LYSO1 crystal bar and PM

The second crystal bar sees only Compton scatters in the first crystal bar.

Readout Scheme works for **2 channels**: ➔ go to 2 x 48 channels

$$\Delta E/E = 10.6\% \text{ FWHM}$$

with VATAGP5 chip
It should be noted that the measured energy resolution of 10.6% FWHM is obtained in a setup where the coincidence with the LYSO crystal readout by a PM restricts the solid angle of 511 keV gammas impinging in the 100 mm long crystal such that the effective area of the crystal illuminated is only 25 mm. If the data are taken without coincidence the full length of the crystal is illuminated by the 22NA source. In this case we measure 15 % FWHM. Thus the quoted 10.6% FWHM are an upper limit of the energy resolution of an individual event.
Simulation and Reconstruction
Simulation software is developed to model the demonstrator and use model to predict performance of different geometries.

GEANT4 and GATE software packages are used and developed.
One results as an example: Spatial resolution from the WLS strips with a center of gravity algorithm using a highest signal WLS strip and its two neighbors: $\sigma = \sim 0.45$ mm

Within other topics Inter Crystal Scattering will be studied in detail

In close Collaboration with the simulation efforts Image Reconstruction Packages and algorithms for the demonstrator are developed
Development of Image Reconstruction Software

e.g. System Matrix for this Ax-PET geometry implemented
Effect of number of rotations on sensitivity matrix is studied

For $D = 85$ mm

$\text{FOV: } = 30 \times 30 \times 86 \text{ mm}^3$

2-step rotation

3-step rotation
Outlook:

• The axial PET concept has survived the first crucial feasibility tests.
• A two module demonstrator with altogether 408 channels is under development with first imaging tests to be expected early 2009.
• LYSO Crystals and WLS strips tested and satisfactory.
• MPPC (S10362-33-50C; vintage 2007) performance of adequate for demonstrator; 2008 delivery tested now
• Readout electronics tested successfully for two channels in coincidence.
• A long way to go
Energy resolution measured with $^{22}$Na source and a LYSO crystal with diameter 12 mm and height 18 mm. In coincidence with the 100 mm crystal bar.

$\sigma_E/E = 7.8\%$ from gaussian fit to distribution.
Photo Electron Yield Measured in the 2 WLS strips by moving Electron Beam across WLS Strips for converted energy $E_c = 200$ keV

Measured p.e yield in each strip  

<table>
<thead>
<tr>
<th>Mirror Position (mm)</th>
<th>Photoelectron Yield $N_{pe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15</td>
<td>30</td>
</tr>
<tr>
<td>-10</td>
<td>25</td>
</tr>
<tr>
<td>-5</td>
<td>20</td>
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<tr>
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<td>15</td>
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<td>10</td>
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<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
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Scan over WLS strips

- WLS strip 1
- WLS strip 2

p.e. yield: sum of both strips $\sim 42$ p.e. detected at 230 keV

<table>
<thead>
<tr>
<th>Mirror Position (mm)</th>
<th>Photoelectron Yield $N_{pe}$</th>
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</thead>
<tbody>
<tr>
<td>-15</td>
<td>60</td>
</tr>
<tr>
<td>-10</td>
<td>55</td>
</tr>
<tr>
<td>-5</td>
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<td>45</td>
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<td>5</td>
<td>40</td>
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<tr>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Scan over WLS strip (sum strip 1 + strip 2)

$E_c = 200 \pm 12$ keV

Linearity of p.e. yield with deposited energy

<table>
<thead>
<tr>
<th>Converted Energy $E_c$ (keV)</th>
<th>Photoelectron Yield $N_{pe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>50</td>
<td>5</td>
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<tr>
<td>100</td>
<td>10</td>
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<tr>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>250</td>
<td>25</td>
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WLS strip

The important number: equivalent to 85 p.e. (extrapolated) can be observed at one end of the WLS strips using Hamamatsu MPPC 3mm x 3mm, at 511 keV