AX-PET: A novel PET detector concept with full 3D reconstruction

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ABSTRACT

We describe the concept and first experimental tests of a novel 3D axial Positron Emission Tomography (PET) geometry. It allows for a new way of measuring the interaction point in the detector with very high precision. It is based on a matrix of long Lutetium-Yttrium OxyorthoSilicate (LYSO) crystals oriented in the axial direction, each coupled to one Geiger Mode Avalanche Photodiode (G-APD) array. To derive the axial coordinate, Wave Length Shifter (WLS) strips are mounted orthogonally and interleaved between the crystals. The light from the WLS strips is read by custom-made G-APDs. The weighted mean of the signals in the WLS strips has proven to give very precise axial resolution. The achievable resolution along the three axes is mainly driven by the dimensions of the LYSO crystals and WLS strips. This concept is inherently free of parallax errors. Furthermore, it will allow identification of Compton interactions in the detector and for reconstruction of a fraction of them, which is expected to enhance image quality and sensitivity. We present the results of proof-of-principle tests and qualification measurements of the various components prepared to build a larger scale demonstrator consisting of two matrices of 8 × 6 LYSO crystals and 312 WLS strips.

1. Introduction

Positron Emission Tomography (PET) has for several years been one of the most popular and highest quality imaging modalities to study and quantify metabolic processes in the human and animal body. There is a constant drive towards higher resolution to be able to detect for instance tumors at an earlier stage and better efficiency to reduce the total radioactive dose given to the patient. One of the most important instrumentation challenges to improve both resolution and efficiency is to be able to measure Depth of Interaction (DOI) in the detector. The lack of this information gives rise to parallax error with increased distance from the center of the Field of View (FOV) and leads to a non-uniform resolution over the FOV. It also imposes limits to the radial detector thickness and hence to the sensitivity of the camera. To solve this, new and better detection technology combined with novel detector designs is needed.

In this paper we report about a novel detector design offering a solution to the challenges described above. This design is based on Lutetium-Yttrium OxyorthoSilicate (LYSO) crystals and Wave Length Shifter (WLS) strips, read out by Geiger Mode Avalanche Photodiode (G-APD).[1] Results from preliminary feasibility studies and the currently ongoing production of a larger scale demonstrator are presented.

2. The 3D axial PET concept

The concept of a PET camera with axial readout is based on long scintillator crystals oriented in the axial direction, with WLS

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[1] Also known as SiPM and MPPC.
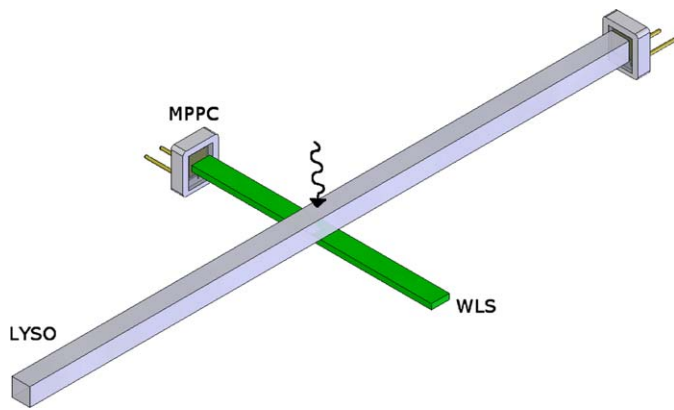
Fig. 1. Schematic illustrating the various components of a basic detection entity.

Fig. 2. Histogram of the photon yield for 62 evaluated LYSO crystals.

Fig. 3. Histogram of the LYSO attenuation length values for 62 evaluated LYSO crystals.

strips mounted orthogonally and interleaved with a small air gap between the crystals (see Fig. 1). Both the crystal and the WLS have a reflective coating at one end and a light detector on the opposite one. The detection of light from the crystals contains information about the energy deposited and its location. A center of gravity method for the light detected by the WLS strips gives the position along the crystals. This allows for a very good position resolution in three dimensions, which is in first order driven by the dimensions of the LYSO bars and the WLS strips. Light transport in the bars and strips relies on total internal reflection, putting high requirements on surface quality and cleanliness of the polished surfaces to maximize the amount of light collected.

The concept of a PET camera module with axially arranged scintillation crystals has been described in detail in previous publications [1,2].

3. Description and characterization of the main AX-PET sub-components

In the following we describe components used to validate the concept of an axial PET geometry and qualification results.

3.1. Geiger Mode APDs

To measure light both from the LYSO crystals and the WLS strips, G-APDs are used. We chose the so-called Multi-Pixel Photon Counter (MPPC) technology from Hamamatsu for their superior performance in terms of Photon Detection Efficiency (PDE) and dark noise. For the readout of the LYSO, model S10362-33-050C is employed, with an active area of $3 \times 3 \, mm^2$ divided in $50 \times 50 \, \mu m^2$ cells giving 3600 G-APD cells in total. Its high PDE in the blue range ($\approx 50\%$) makes it a perfect match to the LYSO crystals. For the readout of the WLS an MPPC with active area of $1.19 \times 3.22 \, mm^2$ and $70 \times 70 \, \mu m^2$ cell size is custom made. Compared to using the same MPPC as for the LYSO readout, the reduced size will give less dark counts and the fill factor is increased due to the larger pixel size. Since the light output from the WLS is relatively low it is important to optimize these parameters to maximize the signal to noise ratio. The MPPC also has a high PDE for green light ($\approx 40\%$) emitted from the WLS.

Measurements have been performed with the $3 \times 3 \, mm^2$ MPPC [3], showing very promising results for the AX-PET application. The $1.19 \times 3.22 \, mm^2$ MPPC have not been evaluated so far, since
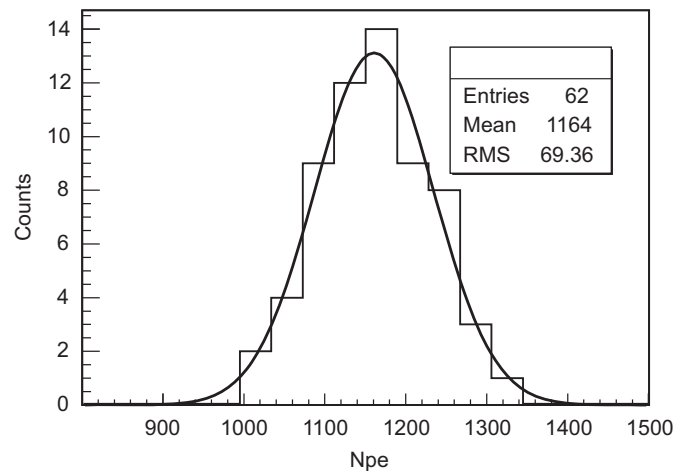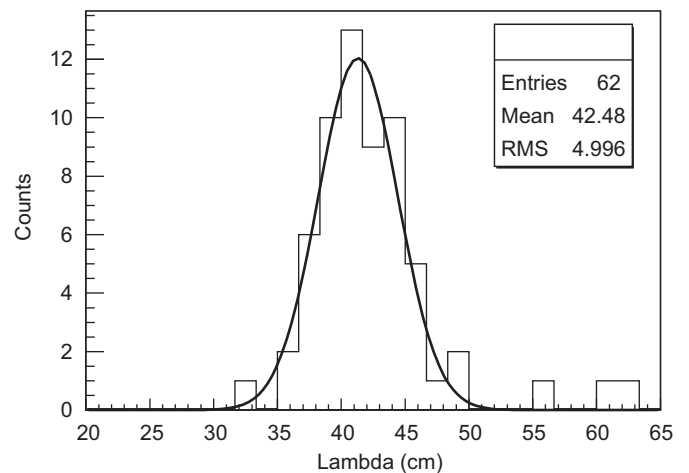
the delivery date is mid 2008. Similar characteristics are expected for both MPPCs.

3.2. LYSO crystals

LYSO crystals of dimensions $3 \times 3 \times 100 \, mm^3$ have been chosen for their high light yield and fast decay time in detecting annihilation photons. They emit their light in the visible blue spectrum. The crystals are produced by Saint-Gobain and have polished and crack-free surfaces to maximize light transport and collection. They are read out using an MPPC and only the opposite end of the crystal is coated (aluminized) with an Al specular reflector.

So far 62 LYSO crystals have been characterized in a dedicated test setup [4] to measure photon yield and attenuation length. Results for 511 keV photons from an Na-22 source show a mean number of photoelectrons of $N_{pe} = 1164$, measured with photomultipliers (PMTs) at both ends in the above-mentioned setup, (see Fig. 2) and mean effective light attenuation $\lambda_{att} = 42.48 \, cm$ (see Fig. 3). These values and their small fluctuations within the measured samples are perfectly suitable for our application.

The crystals have also been evaluated in a coincidence setup using an Na-22 source and the MPPCs, type S10362-33-050C, from Hamamatsu. The measurements show an energy resolution of 12.2% FWHM (see Fig. 4).

3.3. Wave Length Shifter strip

The axial coordinate from the interaction is derived from the light output of the WLS strips mounted orthogonally to the LYSO. The strips have the dimensions $0.9 \times 3 \times 40\,mm^3$. An interaction from a 511 keV gamma in the LYSO will lead to an isotropic emission of blue photons from the interaction point. Photons which are below the critical angle of total reflection escape the crystal. A large fraction of those is absorbed in the WLS strip mounted below and re-emitted as green light. Also the light transport in the WLS strip relies on internal reflection on its way to the readout end, where a G-APD registers the light. The opposite end of the WLS strip is coated (aluminized) with an Al specular reflector.

Laboratory measurements have been performed on WLS strips to determine their light absorption length, both for blue and for the shifted green light. The strips are produced by Eljen Technologies with a 10 times higher dopant concentration than standard WLS strips, in order to guarantee an absorption length for blue light of about 0.4 mm. Using a PMT and illuminating the top surface of the WLS with a collimated light spot of 1.5 mm at different distances from the PMT, gave a good measurement of the attenuation length for the wavelength shifted light. When the light output was measured with a step size of 5 mm along the
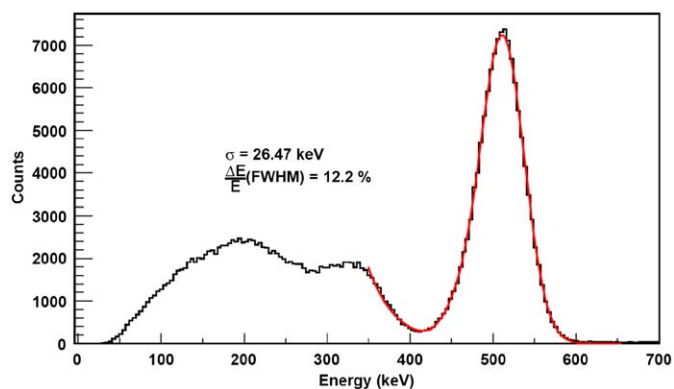
WLS and an exponential curve was fitted to the values, the attenuation length was calculated to be $\lambda_{att} = 160.3\,mm \pm 6.9$. This corresponds to an efficiency loss of 17% over 30 mm.

Sixty-one WLS samples have been measured so far with light injected at 7.5 and 32.5 mm from the PMT surface. The light intensity was adjusted to values similar to what is expected in normal operation. Fig. 5 shows that the 61 samples evaluated have a very low strip-to-strip fluctuation.

4. Detector resolution

The achievable resolution for the axial PET geometry is driven by the LYSO and WLS dimensions. The position resolution in the transverse plane is limited by the LYSO size. In the axial direction an interaction is registered by one or more WLS strips which allows for position interpolation to improve resolution. To understand the fundamental limit of the axial resolution a simulation in Geant4 [5] was done, using data from Ref. [2] for simulation verification. With a center of gravity technique taking the WLS with the highest signal and its two closest neighbors on each side, showed a maximum axial resolution of $\approx 1\,mm$ FWHM (see Fig. 6). For the AX-PET chosen dimensions the transverse resolution for photon pair detection is expected to be $\approx 2.2\,mm$, giving a volumetric resolution based on simulations of $\approx 5\,mm^3$ FWHM.

5. Demonstrator

Currently a PET demonstrator setup consisting of two modules, each with a 6×8 matrix of LYSO crystals, and a total of 312 WLS strips is under development (see Fig. 7). The modules will be mounted on a rotating gantry to allow data taken at different projections for tomographic reconstruction. The demonstrator is being built using $3 \times 3 \times 100\,mm^3$ LYSO crystals and $0.9 \times 3 \times 40\,mm^3$ WLS strips. The G-APDs have a photon sensitive area of $3 \times 3\,mm^2$ (LYSO crystals) and $1.19 \times 3.22\,mm^2$ (WLS strips), with a package size of $6.55 \times 5.9\,mm^2$ and $5.9 \times 5.9\,mm^2$ (octagonal package). They are arranged with an altering end readout.

The readout system for the demonstrator will comprise discrete and integrated electronics. Every MPPC output is connected to a commercial high bandwidth pre-amplifier [3]. To cope with the high channel density and to maintain the readout
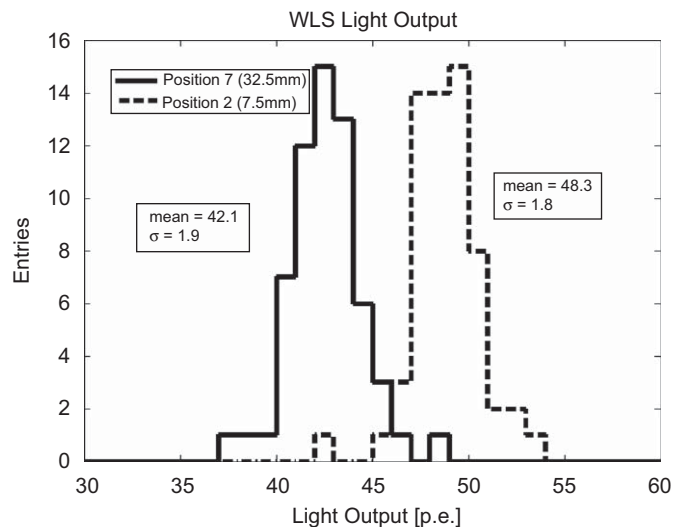

Fig. 4. Plot of the energy resolution for the center position of a 100 mm long LYSO crystals with an MPPC end-readout in coincidence with a small NaI crystal with PMT readout.

Fig. 5. Plot of light yield for 61 WLS samples at a distance of 7.5 and 32.5 mm from the PMT surface.
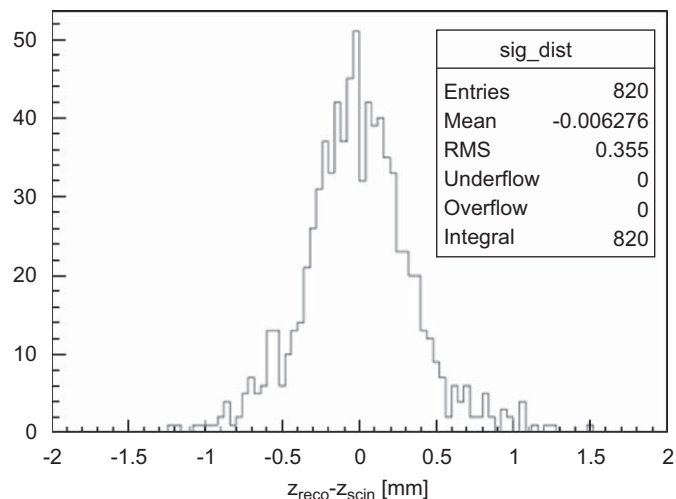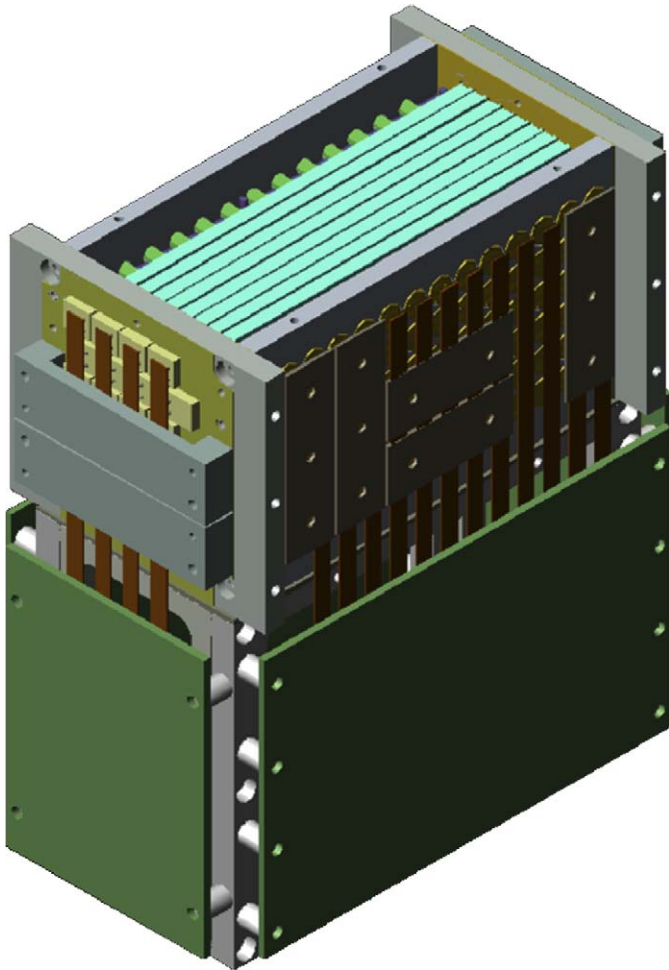

Fig. 6. Plot of the simulated axial position using a center of gravity technique taking the WLS with the highest signal ± 2 WLS neighbor strips.

Fig. 7. Screenshot of the axial PET demonstrator. The LYSO bars can be seen on top with the MPPC integrated in the aluminum frame. The readout electronics is at the bottom half of the assembly.

system compact, the amplified signals are fed into a 128 channel charge sensitive integrated circuit, VATAGP5 [6]. It is a low noise device with a 40 ns fast shaper and 250 ns slow shaper. It can be used in self-triggering mode or with an external trigger and has a special (sparse) readout architecture, which allows to read only those channels above a set threshold. The device will be read out through a digital interface and the data will be stored on a computer for off-line analysis. An external coincidence system will handle triggers from all modules with the possibility to apply module-specific energy thresholds.

To further improve the understanding of the concept and the system performance expectation, a simulation of the whole demonstrator is under development. This is mostly done in Geant4 and Gate [7]. In parallel, dedicated reconstruction software is under development in order to fully exploit the specific potential of the geometrical concept.

6. Conclusion

Measurements have been performed on the individual components specified for the AX-PET project. All components demonstrate a high yield and a performance perfectly suitable for the AX-PET detector concept. The results are very encouraging for the next step of building a larger scale demonstrator consisting of two matrices of 8×6 LYSO crystals and a total of 312 WLS strips, both read out by MPPCs.

Acknowledgments

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