The AX PET Project: Progress and Recent Results

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The AX–PET Project: Progress and Recent Results

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Abstract—We describe a novel concept to extract the axial coordinate from a matrix of long axially oriented crystals, which is based on wavelength shifting (WLS) plastic strips. The method allows building compact 3-D axial gamma detector modules for PET scanners with excellent 3-dimensional spatial, timing and energy resolution while keeping the number of readout channels reasonably low. One module consists of a stack of 100 mm long LYSO scintillation crystals interleaved with arrays of WLS strips which allow the determination of the axial coordinate. To detect the light from the Crystals and the WLS strips Silicon Photomultipliers (SiPM) are employed. A volumetric resolution of about 5 mm is expected. The feasibility of this concept has been demonstrated with a test set-up consisting of two long LYSO crystals and two WLS strips read out by SiPM’s. Results from these measurements have been published. Recent progress in building a demonstrator PET scanner prototype is reported in this paper.

I. INTRODUCTION

The performance of most commercial PET Scanners, both for preclinical studies and for clinical applications, which are presently in regular operation in laboratories and hospitals, are still limiting factors in image quality and thereby in the interpretation of the results and call for innovation and improvements. Important instrumentation limitations in most present day PET scanners are: Non uniform spatial resolution in the detector over the whole Field of View (FOV) due to Depth of Interaction (DOI) uncertainty in the scintillation detector. Relatively low efficiency of photon conversion due to the correlation between radial thickness of the scintillator and DOI smearing of radial interaction co-ordinate. Limited capability to recognize and reject Compton interaction (cascade events) in the scintillation crystals, which lead to smearing of the measurement of the interaction point. Medical requirements of optimal PET scanning are accurate observation and precise location of small structures e.g. in brain PET or precise location of the position of malignant tumors before hadron therapy treatment. Similarly small animal PET preclinical studies are more and more focused on detecting very small structures. This requires very good spatial resolution in the detector close to the limits given by positron range and non-collinearity of the two back to back photons. Another very important improvement could be obtained having higher sensitivity at lower total dose than obtained with present instruments. In small animal PET a longer survival of the rodent during an investigation is an important factor whereas in clinical PET low dose at increased sensitivity crucial to allow e.g. breast screening using PET. The other driving force in instrumentation innovation for PET is the possibility of co-registration with other precise morphological imaging modalities like X-Ray CT or MRI.
II. THE AXIAL PET CONCEPT WITH WAVE LENGTH SHIFTER (WLS) STRIPS FOR AXIAL CO-ORDINATE MEASUREMENT.

A. The Concept

The concept of using axially arranged long scintillation crystals with readout on both sides has been considered already more than 25 years ago. The project described in this article emanated from the idea to use 10 to 15 cm long LYSO crystal bars arranged in axial stacks and readout on both sides by Hybrid Photon Detectors (HPD) based on silicon pad sensor arrays read out by 128 channel VATAGP5 ASICs. The concept was to determine the axial co-ordinate measuring the difference of pulse heights on both sides [1][2]. Experimental studies showed that the axial coordinate resolution in this approach could at best be 5 mm FWHM. Moreover the production of the HPDs on a commercial basis would be difficult to implement. Another approach was proposed in this Collaboration to measure the axial co-ordinate by arrays of WLS strips placed orthogonally in between layers of LYSO crystal bars as shown in Fig. 1. Part of the photons produced by an interaction of a 511 keV photon in a LYSO crystal bar will be emitted within an angle of total reflection and travel to the ends of the LYSO bar where they are detected by a suitable photo detector. The part of the photons traveling in the opposite direction will be sent back to the photo detector by a reflector (Fig. 2). The photons which are emitted outside the cone of total reflection towards the side of the crystal bar where WLS strips are placed, will leave the crystal bar sideways and enter some of the WLS strips. Choosing adequately the optical properties of the WLS material these photons can be efficiently absorbed and wave length shifted into a wave length domain with little absorption in this material. Part of these wavelength shifted photons will be transported to the end of the WLS strips. Fast photo detectors mounted at the end of the LYSO crystal bars and the WLS strips will be employed to measure the amplitudes of the light pulses, and thereby the energy deposited in LYSO bars and WLS strips. The x and y coordinate of each hit LYSO crystal is given by its position in the stack with digital resolution \( \sigma_{x,y} = d/\sqrt{12} \) ( \( d \) is the transverse dimension of the crystal bar). The same applies for all WLS strips which absorb and re-emit photons from the gamma interaction in the LYSO crystal. Since it is expected that in general more than one WLS strip has a signal the z-coordinate measurement can be performed either by using just the strip with the highest signal or performing an analog interpolation using several strips. Finally using Silicon Photo Multipliers (SiPM) for the readout of the LYSO and WLS strips opens the opportunity of co-registration with MRI.

B. Main Performance Improvements Expected from the Axial PET Concept.

One big advantage of this concept is a full 3-D reconstruction of the impact of the interacting 511 keV gamma ray, both for full photo absorption and cascade interactions. The detector spatial resolution is independent of the origin of chord in the FOV. The spatial resolution in x, y and z in the detector module is simply determined by the choice of the transverse dimensions of the LYSO crystal bars and the WLS strips, and can be chosen to give the best results for a given application. Sensitivity and spatial resolution in the detector are uncorrelated. Photo absorption and Compton cascade events can be fully identified. Part of the cascade events can be used in the image reconstruction thus increasing the overall sensitivity. Finally using Silicon Photo Multipliers (SiPM) for the readout of the LYSO and WLS strips opens the opportunity of co-registration with MRI.

C. First Measurements to Prove Feasibility of Concept

In a previous experiment [3][4][5] it has been demonstrated that the light output from WLS strips is sufficiently big to allow observation of 511 keV photo absorption events and also recoil electrons from Compton interactions down to an energy of 50 keV. Very forward Compton interactions in a LYSO crystal can possibly be detected down to 10keV recoils electron energy. The measurements published in [3][4][5] used...
Fig. 3. Photo electron yield measured in a 40 mm long WLS strip. The light in the WLS strip was generated by photons from a 511 keV gamma impinging on a 100 mm long LYSO crystal on top of the WLS strip. A tunable electron beam to deposit adjustable energy in the LYSO crystals and demonstrated that around 85 p.e. can be observed (extrapolated to 511 keV) distributed over two strips. (only two strips we re employed in the experimental set-up). In this measurement the WLS strips were readout by 3mm × 3mm Hamamatsu MPPCs. A recent measurement using a 22Na source confirmed this result showing a signal in one WLS strip, placed under a LYSO crystal bar, of 73 p.e. (Fig. 3)

Based on these results a project was initiated to build two full modules containing 48 LYSO crystal bars and 156 WLS strips in each module in order to demonstrate the claimed advantages of the axial PET concept.

III. THE DEMONSTRATOR PROJECT AND PERFORMANCE OF MODULE COMPONENTS

A. The AX-PET Modules

The layout drawing of one module with 6 layers of 8 LYSO crystal bars (St. Gobain, PreLude 420) each, stacked vertically, was already shown in Fig. 1. The LYSO crystal bars are 100mm long with a cross section of 3mm × 3mm. Each crystal layer is placed on top of an orthogonally arranged WLS strips (ELJEN-EJ-2800-10X) consisting of 26 WLS strips of dimension 40mm × 3mm × 1mm. LYSO crystals and WLS strips are separated by a very small air gap. Below each WLS strip array a carbon fiber sheet separates optically this layer from the next one. The upper surface of the separator is fashioned as diffuse reflector and the lower surface is a light absorber. The layers of LYSO crystal bars are staggered by half a pitch (1.6mm). Mechanical precision mounting of the whole assembly will be achieved by a number of precisely machined support plates as shown in the blown-up view of the mechanical support.

Mounting two modules at 180 degrees on a suitable turntable gantry will enable us to study all aspects of the performance of an axial PET with point sources and suitable phantoms.

B. LYSO Crystal Bars

More than 100 LYSO crystals have been delivered and are at present characterized. A 22Na source is placed at 7 different positions along the crystal bars and spectra are taken with a photo multiplier tube on each side of the crystal recording the light pulses. The observed energy resolution is 11%±0.4% FWHM. Fig. 4 and Fig. 5 show the uniformity in light collection and the average attenuation length of 47 crystals measured so far.

C. The WLS Strips

The properties of the WLS material is very well adapted to efficiently absorb and transmit light produced in the LYSO crystals. The absorption coefficient in the wave length band 400 to 460 nm is ~2.5 mm and has nearly 100% transmission for wavelength larger than 480 nm (emission wavelength of material) All WLS strips for the two demonstrator modules are available. For 61 samples the light output has been measured scanning a LED in 5 mm steps along the strips read by a photomultiplier. Fig 6 shows the light output and its spread measured with the LED positioned at two different positions, 7.7 mm and 32.5 mm away from the PM tube window. The corresponding light absorption length, which can be derived from this measurement, is ~17 cm.

Again the optical quality of the strips is largely satisfactory for their application in the modules. Uniform width of the strips is important since they need to be mounted at a pitch of 3.2 mm. The average width of 45 samples has been measured to be 3.010 mm with a σ= 85 μm. Only a few percent of the strips are in the tails of the distribution and can be rejected.
be routed to a circuitry allowing to add signals from groups of channels to build a pulse height sum which can be used in the trigger selection; (iii) the signals of each channel will also be available on a parallel twisted output via a line driver for test purposes. The VATAGP5 chip has sparse readout option. Only for channels with a signal above a chosen threshold in the fast branch of the VATAGP5 chip the amplitude stored in the S/H of the slow branch will be readout. In the initial phase of the demonstrator set-up the output of the VATAGP5 chip will be sent to a VME based DAQ system. Single or sums of analog pulses from the slow amplifier will be used by an external coincidence trigger logic with appropriate reset facility. The whole chain (without Kapton strip lines) was tested with two LYSO crystal bars read out by MPPCs and a small LYSO crystal (diameter 12 mm, length 18 mm) read by a conventional PM to tag 511 keV photons. The LYSO crystals (LYSO1 and LYSO2) were readout by two channels of a VATAGP5 chip mounted on a PCB in the same way as planned for the full readout chain. The trigger was an external coincidence between LYSO1 and the small LYSO read by the PM, selecting an energy window around 511 keV. The result of a run with a $^{22}\text{Na}$ source placed between the two long LYSO crystals (side by side) and the trigger LYSO crystal is shown in Fig. 7.

LYSO1, which is in the trigger, shows the 511 keV peak with an energy resolution of 10.6% FWHM. In addition one observes a Compton continuum as expected. The LYSO2 spectrum shows only gammas Compton scattered in LYSO1. The small peak observed just below the photo absorption peak position is due to very forward Compton scatters in LYSO1, which is in the trigger, shows the 511 keV peak with an energy resolution of 10.6% FWHM. In addition one observes a Compton continuum as expected. The LYSO2 spectrum shows only gammas Compton scattered in LYSO1. The small peak observed just below the photo absorption peak position is due to very forward Compton scatters in LYSO1 which are then converted in LYSO2. This result validates the readout scheme for just two channels Full implementation of coincidences between all combinations of $2 \times 48$ channels is the next step in implementing the AX–PET demonstrator.

F. Simulation and Image Reconstruction

Work on a full simulation of the demonstrator set-up is in progress using GEANT4 [7] and GATE [8] software. One example is a simulation of the spatial resolution which can
be obtained by using analog information from 5 WLS strips with signals above threshold as shown in Figure 8. An axial resolution of better than 1 mm FWHM seems possible with this set-up in agreements with previous test results [4].

The goal of this work is to model the demonstrator and use the model to predict performance of different geometries by reconstructing images of phantoms with simulated data.

IV. CONCLUSION

The axial PET concept shows very promising performance features. First crucial feasibility measurements have been performed successfully. A two module demonstrator with altogether 408 channels is under development with first imaging tests to be expected within half a year. The components for this demonstrator set-up, long LYSO crystal bars, WLS strips, MPPCs and a readout chain, have all been successfully tested. Coincidence spectra with very good energy resolution of ~10% FWHM have been demonstrated with two 100 cm long crystal bars readout with MPPCs.

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