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 Wave Length Shifting (WLS) plastic strips. The method allows building compact 3-D axial gamma detector modules for Positron Emission Tomography (PET) scanners with excellent 3-dimensional spatial resolution, as well as good 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. This is achieved by collecting the wave length shifted light detected with suitable photo-detectors at the end of each WLS strip. 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. New results are reported using the final components which will be employed in the demonstrator set-up.

I. INTRODUCTION

The image resolution obtained in most commercial PET Scanners, both for preclinical studies and for clinical applications, which are in regular operation in laboratories and hospitals, are presently dominated by detector and system limitations [1] [2] [3]. This situation calls 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 a strong correlation between radial thickness of the scintillator and DOI smearing of radial interaction co-ordinate. Limited capability to recognize and/or reject Compton interaction (cascade events) in the scintillation crystals, which can lead to smearing of the measurement of the interaction point [4]. Medical requirements of optimal PET scanning are accurate observation and precise localisation of small structures e.g. in brain PET or precise determination 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. Examples of such challenges are the investigation of very small size organs such as thyroid (1 - 7 microlitres), adrenal (3 - 40 microliters) and small functional regions in the brain (400 - 800 microliters) [5] [6]. This requires very good spatial resolution in the detector close to the physical limits given by positron range and non-colinearity of the two back to back photons. Another very important improvement could be obtained by achieving higher sensitivity at lower total dose than obtained with present
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 is crucial to allow e.g. breast screening using PET. Another 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 [7]. In this paper the performance improvements expected from the new concept of an axial PET with WLS strip readout for the axial coordinate will be described. Results of prototype measurements using long LYSO scintillation crystals, WLS strips and Silicon Photo Multipliers (SiPM) as a fast photo-detector are reported. All results were obtained using the final components which will be implemented in a two module demonstrator unit, as described in section III.A.

II. THE AXIAL PET CONCEPT WITH WAVELENGTH SHIFTER (WLS) STRIPS FOR AXIAL CO-ORDINATE MEASUREMENT.

A. The Concept

The concept of using axially arranged long scintillation crystals has been proposed already more than 25 years ago [8]. The project described in this article emanated from the original idea to use 10 to 15 cm long LYSO crystal bars arranged in axial stacks and read out on both sides by Hybrid Photon Detectors (HPD) based on silicon pad sensor arrays read out by 128 channel VATAGP5 ASICs [9]. In this previous approach the axial co-ordinate was determined by measuring the difference of pulse heights on both sides of each crystal. 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 was considered to be difficult to implement.

As a consequence another method to determine the axial coordinate in an axial PET module with the potential of equal or better spatial resolution compared with the spatial resolution of the x- and y-coordinates was proposed. In this approach arrays of WLS strips are inserted orthogonally in between layers of the long LYSO crystal bars as shown in Fig. 1.

Both LYSO crystal bars and WLS strips are readout on one side only. To achieve a very compact module layout every second crystal bar in a layer and every second WLS strip in a layer are read out by specifically designed compact photon detectors (see section III.D) mounted alternately on opposite sides of the module. The end surfaces of crystal bars and WLS strips opposite to the photo detector are aluminized to reflect light back to the readout side. 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, which are close to the location of the 511 keV interaction as shown in Fig. 2. 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. 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 coming from the gamma interaction in the LYSO crystal. Since it is expected that in general more than one WLS strip produces a measurable signal, the z-coordinate measurement can be performed either by using just the strip with the highest signal (digital resolution) or performing an analog interpolation using several strips.

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

A significant advantage of this concept is a full 3-D reconstruction of the impact point 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 the Line Of Reference (LOR) 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. The total thickness of scintillation material in the path of the 511 keV gamma-
ray, and therefore the fraction of absorbed photons, and spatial resolution in the detector are uncorrelated. Photo absorption and Compton cascade events can be fully identified. The fraction of the cascade events, for which the first interaction in the cascade can be uniquely identified, 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 coregistration with MRI.

C. First Measurements to Prove Feasibility of Concept

In a previous experiment [9] [10] 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 ~20keV recoil electron energy. The measurements published in [9] [10] used a tunable electron beam to deposit adjustable energy (Photonis XP2978) selects 511 keV gammas from a 22Na source. Using a linear translation table 7 source positions along the crystal bars are selected. From these measurements we derive the photo electron yield, light attenuation length and energy resolution. Fig. 4 shows the distribution of number of photo electrons for 96 crystals. An average of 1165 p.e. can be observed (extrapolated to 511 keV) distributed over two strips. (only two strips were employed in the experimental set-up). In this measurement the WLS strips were readout by 3mm×3mm Hamamatsu MPPCs (see section III.D).

Having established the feasibility of the concept 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, interleaved with orthogonally arranged WLS strip arrays of 26 strips each, was already shown in Fig. 3. 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 strip array 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. A partially assembled module is shown in Fig. 3. 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. The measurements will be compared to a detailed simulation of the modules (see section III.F).

B. LYSO Crystal Bars

More than 100 LYSO crystals (St. Gobain, Prelude 420) have been delivered and have been characterized. The crystals are optically polished on all sides. Density is 7.1 g/cm³, refractive index n = 1.81 and the decay time of scintillation light is 41 ns. The experimental set-up for LYSO characterization consists of two Burle 8850 PMTs coupled to the LYSO bars with optical grease (BC-630) to read a LYSO crystal bar on both sides. A BaF2 scintillation counter coupled to a PMT (Photonis XP2978) selects 511 keV gammas from a 22Na source. Using a linear translation table 7 source positions along the crystal bars are selected. From these measurements we derive the photo electron yield, light attenuation length and energy resolution. Fig. 4 shows the distribution of number of photo electrons for 96 crystals. An average of 1165 p.e. are observed with relatively small spread (σ = 5.5%). The attenuation length distribution gives (41.6 ± .26) cm and the measured energy resolution was (11±0.4)%.

C. The WLS Strips

The properties of the WLS material (ELJEN Technology, ELJEN.EJ-2800-10X) is very well adapted to efficiently absorb light produced in the LYSO crystals. They are based on Polyvinyltoluene (PVT) and have a 10 times higher dye concentration than EJ–280. The absorption coefficient in the
wave length band 400 to 460 nm is ~2.5 mm$^{-1}$. The material exhibits good transmission for wavelength larger than 480 nm (emission wavelength of material). All WLS strips for the two demonstrator modules are available. The WLS material is polished and cut at the factory. The strips have dimensions of 1mm×3mm×40mm. Again to ensure the optical quality and the uniformity of the strips, samples were selected and characterized using a PMT for readout at one end of the strips. To monitor light absorption along the strips a LED (400 nm) was moved in 5 mm steps along the side of the strip. Fig. 5 shows an example of the light output distribution for 61 randomly selected samples measured with the LED at 7.5mm (position1) and 32.5 mm (position2) from the surface of the PMT window. The means and the width of the distributions are 42.1 p.e. with a $\sigma = 1.9$ p.e. (position 1) and 48.3 p.e. with a sigma = 1.8 p.e. (position 2). The observed spread in light output is sufficiently small to have little influence on the z-resolution. The light absorption length, measured with this sample, is $\sim(160 \pm 7)$ mm.

Again the optical quality of the strips is largely satisfactory for their application in the modules. Uniform mechanical 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 $\sigma = 85 \mu m$. Only a few percent of the strips are in the tails of the distribution and can be rejected before mounting.

### D. Photo Detectors

Silicon Photo Multipliers are an attractive possibility for the readout of the LYSO crystals and WLS strips. They combine high gain, high speed and allow operation in high magnetic fields. For this reason MPPCs from Hamamatsu have been chosen. For the readout of the LYSO crystals the MPPC S10362-11-050C has been chosen (3mm×3mm sensitive area with 50 $\mu$m pixel size). Charge gain, thermal dark count rate and optical cross talk have been measured [9] and fulfill all requirements in performance to be used in the demonstrator.

For the readout of the WLS strips tailor made MPPCs, fitting geometrically the cross section of the WLS strips, with a sensitive area of 3.22mm×1.19mm and a pixel size of 70 ×70, have been developed in collaboration with Hamamatsu (MPPC3.22x1.19-Octagon-SMD). A micrograph of the device is shown in Fig. 6. These devices are packaged in very thin plastic packages of octagonal shape with a flat hard protective resin cover over the whole surface. 500 devices have been delivered and samples have been tested. They show good performance similar to the MPPC S10362-11-050C (in a conventional ceramic package) used for the crystal readout, with higher gain as a function of voltage due to the bigger pixel size. The gain, measured at two temperatures, as a function of bias voltage is shown for one of the devices in Fig. 7. Recent measurements with WLS strips glued to the octagon MPPCs, tagging again 511 keV interaction in a LYSO crystal, confirm the earlier results on p.e. yield in the WLS strips.

### E. Read-Out Electronics

A short overview of the readout and trigger concept for the AX-PET demonstrator will be presented here. Very first results, which demonstrate the validity of the chosen readout scheme, will be shown in the following. In order to maintain a very compact size of the detector module (possibility of insertion in the bore of a high field MRI magnet) the readout electronics is separated from the detector module. The MPPC signals will be distributed to a patch panel via kapton strip line cables with six different length of 7cm to 9cm. From the patch panel the MPPC signals will be transmitted via bundles of thin coaxial cables to a master PCB equipped with fast amplifiers (OPA843 and OPA847). On the board the output of a fast
amplifier is threefold: (i) a direct short connection (line on the PCB) via a 100 k\(\Omega\) resistor, turning the voltage signal into a high impedance current signal, to the input of the VATAGP5 chip [9] which is mounted on a separate PCB; (ii) in parallel the signal will be routed to a circuitry allowing to add signals from groups of channels to build a pulse height sum which will be used in the trigger selection; (iii) the signals of each channel will also be available on the PCB on a parallel twisted output via a line driver for test purposes. The VATAGP5 chip has sparse readout option [9]. 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 (amplitude of hit and address) will be sent to a VME based DAQ system. The whole electronics chain was successfully tested with several LYSO crystal bars read out by MPPCs.

F. External Trigger

Single or sums of analog pulses from the slow amplifier will be used by an external coincidence trigger logic, providing also continuously reset signals to the VATAGP5 in case of invalid trigger conditions (mostly low energy hits in the crystals). To test the external trigger logic a small LYSO crystal (diameter 12 mm, length 18 mm) read by a conventional PM was used to to tag 511 keV photons. Two 100 mm long LYSO crystals (LYSO1 and LYSO2), equipped with ceramic 3mm×3mm MPPCs, 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 \(^{22}\)Na source placed between the two long LYSO crystals (side by side) and the trigger LYSO crystal is shown in Fig. 8.

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 in LYSO2 just below the photo absorption peak position is interpreted as 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 2×48 channels is the next step in implementing the AX–PET demonstrator.

G. Simulation and Image Reconstruction

The first AX-PET prototype, consisting of two modules, has been fully simulated by means of Geant4 [11] and GATE [12]. The light transport in the complex geometry was modeled by means of Geant4 and interfaced to the GATE simulation. The latter computes the entire system response, including a proper time management of the signals read-out. Based on such synthetic data, first studies are addressed towards Inter Crystal Scattering (ICS) in a 85 mm diameter scanner. To identify the original trajectory of the photons involved in a ICS event, various approaches were developed and tested [13] [14]. The identification efficiency was within 61\% and 78\%, depending on the used approach, for a point source located in the center of the FOV (CFOV). An MLEM image reconstruction algorithm has been implemented to estimate the spatial resolution. Simulating a point source located in the CFOV in a 3-steps acquisition, a spatial resolution for all 3 coordinates of 1.5 mm (FWHM) has been achieved.

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 early 2009. 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. In this measurement the final electronic chain, foreseen for the demonstrator set-up, has been used. Similar results have been obtained in a set-up with 16 LYSO crystals mounted in the final mechanical support structure [15].

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REFERENCES


