A Demonstrator for a new Axial PET Concept


AX-PET Collaboration

Abstract—In PET imaging, improving sensitivity while maintaining very good spatial resolution is crucial. To achieve this goal, we propose a novel concept of PET scanner, with axially arranged crystals, providing a high sensitivity and a 3D reconstruction of the gamma interaction point. The trans-axial coordinate is given by the crystal hit, while the z coordinate is reconstructed by the weighted distribution of light escaping the crystal and entering into an array of Wave Length Shifting (WLS) strips interleaving the crystal layers. This novel configuration allows full identification of Compton interactions in the crystals that can be included in image reconstruction thus enhancing the sensitivity. We present preliminary results obtained by a small prototype consisting of 4×4 crystals with orthogonally interleaved WLS strips. Experimental data are compared to simulated data.

Index Terms—PET, ICS, LYSO, WLS.

I. INTRODUCTION

PET (Positron Emission Tomography) is a powerful and versatile imaging tool. In particular when dealing with patients with brain tumors, imaging techniques are required at every step, from diagnosis, staging, treatment planning to follow-up of the patient. To fully exploit the potential added-value of PET, high spatial resolution and high sensitivity are both desirable to increase the detection capability of small lesions and the achievable image quality. The main limitation in increasing sensitivity by using longer radially oriented crystals, is due to the lack of information on the depth of interaction (DOI) of the gamma in the detector unit. A precise knowledge of DOI offers a more uniform resolution over the entire Field Of View (FOV) and, at the same time, the possibility to reconstruct and/or reject cascade events, i.e.

Compton interactions in the scintillation crystal [1]. The higher sensitivity has the advantage to reduce the dose to which the patient is exposed. The Axial PET scanner (AX-PET, [2][3]) provides several features capable to overcome most of the drawbacks of radial PET scanners. AX-PET consists of several layers of axially-oriented crystals, individually read-out by Geiger-mode Avalanche Photo-Diodes (G-APDs). The trans-axial coordinate is derived from the crystal hit and the axial coordinate is reconstructed from an array of Wave Length Shifting (WLS) strips orthogonally interleaving each axial crystal layer. Scintillation light which is not trapped inside the crystal escapes the LYSO and reaches the WLS strips, where it is absorbed and re-emitted with high efficiency, thus yielding the z coordinate. G-APDs represent an attractive detector solution also because, being insensitive to magnetic fields, they allow co-registration with other imaging modalities like MRI [4]. In the present work, preliminary results of a small scale prototype reflecting the final AX-PET demonstrator set-up are given. The study focused on:

- energy resolution;
- axial and impact point resolution;
- comparison between measurements and Monte Carlo simulations;
- study and quantification of Compton scattering events.

II. THE AX-PET DEMONSTRATOR

Two AX-PET demonstrator modules, each consisting of 6×8 crystals and 6×26 WLS strips, are currently under construction. Each AX-PET module consists of 6 layers of 8 LYSO crystals (St. Gobain, PreLude 420) with dimensions 3×3×100 mm³ (see Fig. 1). Each layer is interleaved by 26 WLS strips (ELJEN EJ-280-10X); each strip is 40×3×1 mm³ in size. Both crystals and WLS strips are readout by G-APDs of type Multi Pixel Photon Counter (MPPC, Hamamatsu), combining high gain, high speed and compactness. All crystals have been characterized in dedicated benches using PMT. The measured average light yield is (1162±53) photo-electrons. The effective light absorption length is (417±26) mm and the measured energy resolution σ_E is (11.1±0.2) %. The WLS strips have an absorption coefficient of ~2.5 mm⁻¹ in the wave length band from 400 to 460 nm. The effective absorption length in the re-emission band is (188±36) mm. One layer of crystals and WLS strips is optically separated from the next one by a white carbon fiber plate, in order to enhance the light collection efficiency.
crystal layers are staggered by half a pitch (i.e. 1.6 mm), improving the sampling capability of the device. The WLS strips, as well as the LYSO bars are Aluminum coated on the side opposite to the read-out one to increase the light collection efficiency. The LYSO crystals are readout by S10362-11-050C MPPC (3×3 mm$^2$, 3600 pixels, 50 μm cell size). For the WLS strips, Octagon-SMD MPPCs are used. They have a sensitive area of 3.22×1.19 mm$^2$ and a pixel size of 70 μm. MPPCs have been characterized with respect to gain, thermal dark count rate and optical cross-talk. They fully satisfy the performance conditions required by the demonstrator.

The readout electronics is separated from the detector module for practical reasons. The signals from the MPPCs are distributed to Fast Amplifiers (FA) having two linear outputs. The amplified signals are fed into a 128 channel charge sensitive integrated circuit, the VATAGP5 ASIC. VATAGP5 operates in sparse mode and is readout and interfaced to a PC through a VME Data Acquisition system (DAQ). The other outputs are first summed and then discriminated. The threshold of the discriminator is set to a value corresponding to 450 keV. The discriminated signal of the two demonstrator modules is fed into a coincidence unit providing the external event trigger. This allows rejecting events which underwent Compton scattering before detection.

III. SMALL SCALE PROTOTYPE

A. Experimental setup

The small scale prototype consists of 16 LYSO crystals of final dimensions arranged in a 4×4 matrix, and 3 WLS strips, assembled in the final mechanics as shown in Fig. 2. The 3 WLSs are orthogonally inserted after the first layer of 4 crystals. Optical contact is achieved by gluing (Dow Corning Silastic 3145 RTV, n=1.5) the crystals and the WLS strips to 3×3 mm$^2$ and 3.1×1.2 mm$^2$ MPPCs, respectively. A $^{22}$Na source of 195 kBq activity is located between the module and a tagging LYSO crystal read out by a PMT. Two tagging crystals of different dimensions (20×20×20 mm$^3$ and 2×2×12 mm$^3$) have been used for the measurements. The DAQ system consists of a charge sensitive ADC (CAEN QADC V792) housed in a VME crate. The tagging system consisting of the source, the small LYSO crystal and its PMT is located on an optical bench that allows moving the source and the tagging crystal with a precision of 0.1 mm, in order to scan the region covered by WLS strips. The signals of all crystals are split using a Linear Fan Out unit and are digitized in a QADC while the other outputs are fed into individual discriminators for which the threshold is set to a value corresponding to 50 keV. The coincidence of the tagger and the or-ed discriminators serves as trigger for the data acquisition system.

B. Simulation

The experimental setup has been simulated using GATE [5]. The geometrical arrangement, resolution and dimensions of the components reflect exactly the experimental setup. Co-linear gammas are geometrically collimated to mimic the trigger of the setup. The Aluminum housing (see Fig. 2) is taken into account in order to correctly reproduce sources of background that effect the measurements. The Monte Carlo simulation records the history of each gamma interaction in the module and therefore allows tracking cascade events in the crystal matrix.

IV. RESULTS

A. Compton contribution and reconstruction

The first measurements were performed using the larger tagging crystal (20×20×20 mm$^3$). The source/tagger distance was chosen such that all 16 crystals of the matrix were simultaneously irradiated with comparable rates. Using the setup described above single as well as multiple energy depositions in the crystals were recorded. Fig. 3 shows a typical measured (top) and simulated (bottom) spectrum for energy deposition in one single crystal. The measured energy resolution is 9.5% FWHM. Measurements and simulations agree well, also in the Compton region:

- the Back-scattering peak (~170 keV) is mainly due to gammas interacting in the Aluminum frame before entering the crystal;
the valley at \( \sim 250 \text{ keV} \) is due to \( 90^\circ \) Compton interactions where the secondary photon is detected within the same crystal.

The ratio of Compton scatters and the total number of events is 45\% and 41\% in experimental and simulated data, respectively. Fig. 4 shows experimental and simulated data for different thresholds for 1, 2 and \( \geq 3 \) hits, per trigger event. Events with \( \geq 2 \) hits are due to Inter Crystal Scattering (ICS). In this small scale prototype, for a summed energy of 450 keV, their fraction is 20\%. The discrepancy between experimental and simulated data is explained by imperfect energy calibration. Therefore also the quoted energy resolution has to be considered as a preliminary value. A linear conversion from ADC counts to energy is used, without taking into account possible saturation effects in the MPPCs. These effects are presently investigated.

B. Z coordinate reconstruction

The trigger used for the z coordinate determination consists of the or-ed signals from the first crystal layer in coincidence with the small tagging crystal. The tagging system collimates the gamma beam into a spot of \( \sim 1.3 \text{ mm} \) diameter on the first layer of crystals. The threshold of the trigger system is set such that only events in the photo-peak are accepted. The signal amplitude of each WLS strip is recorded in the QADC together with the signals of the first layer of crystals. Fig. 5 shows the number of photo-electrons on each strip plotted versus the optical bench position. A maximum light output of 70±5 photo-electrons is measured on single WLS, in good agreement with previous measurements [3].

Fig. 6 shows the resolution of the z coordinate for the central spot position. The z coordinate is computed by the centre of gravity of the signals on the 3 WLS strips with resolution of 1.1 mm FWHM.

V. CONCLUSION

First measurements with a small prototype reflecting the final AX-PET demonstrator module have validated the concept of the device. A FWHM energy resolution of 9.5\% has been measured. For a full energy deposition of at least 450 keV, 20\% of the events show ICS. These events, for which the fraction
is expected to increase by moving to the final 48 crystal module, can be properly reconstructed allowing a further gain in sensitivity, without affecting the spatial resolution. By measuring the light output on the 3 WLS strips, an average light output of $70 \pm 5$ photo-electrons has been measured at the photo-peak, and the $z$ coordinate was reconstructed with 1.1 mm FWHM resolution.

ACKNOWLEDGMENT

The authors would like to thank Mr. Thomas Krähenbühl, ETH Zurich, for his contribution to the project as part of his master thesis. The competent technical support by our technicians in the various labs was crucial for the achieved progress. Their contributions are highly appreciated.

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