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Development of a High Precision Axial 3-D PET for Brain Imaging

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We describe a PET device based on a novel method to extract the coordinates of the interaction point of the 511 keV γ rays from 100 mm long and thin LYSO (Lutetium Yttrium OxyorthoSilicate) scintillator bars, positioned axially in the tomograph. The coordinate along the hit crystal is measured by using a hodoscope of Wave Length Shifting (WLS) plastic strips mounted perpendicularly to each plane of scintillators. As photodetectors, new Geiger mode Avalanche PhotoDetectors (G-APDs) with integrated electronics are being used to detect both the hit crystal in a block (x and y coordinates) and the interaction point in the crystal (z coordinate) through the light escaping from the crystal and transmitted to the WLS strips. In this way, the γ interaction point can be determined with a spatial resolution of few cubic millimeters down to a minimum deposited energy of about 50 keV, resulting in a volumetric precision very close to the limits imposed by the physics of the positron annihilation. The method allows to increase the detection efficiency without affecting the spatial resolution by adding scintillator planes in the radial direction. A demonstrator scanner, based on two matrices of 8×6 LYSO crystals and 312 WLS strips, slotted in between the crystals, is under construction. Preliminary results from the feasibility studies of the various components will be presented.

1. Introduction

The potential of the coincidence technique in positron imaging was recognized by pilot experiments in the early '50s. In combination with tomographic techniques, it led to a new approach in medical diagnosis in the '70s: the Positron Emission Tomography (PET). Nowadays, functional imaging using PET has become one of the most powerful methods in medical imaging to study and quantify metabolic processes in the human and animal body. In particular, PET plays a crucial role in brain imaging.

Present generation PET scanners exploit a radial geometry with scintillation crystals either

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finely segmented or in block arrangement [1,2]. Their main limitations in acquiring images with a good spatial resolution and image contrast, while keeping reasonably high detector efficiency and low radiation dose to patients, are represented by:

- the parallax error due to limited knowledge of the Depth Of Interaction (DOI) of the 511 keV γ ray in the radial direction of the scintillators,
- the relatively low efficiency of γ conversion due to the anti-correlation between accurate knowledge of DOI and radial thickness (=length) of scintillation crystals,
- the limited capability to identify and reject in the scintillation material events with primary Compton interaction, which leads to smearing of the image.

Advances in brain PET imaging, where emphasis is put on accurate observation of small structures, rely on improving the spatial resolution and the sensitivity of actual PET scanners, possibly combined with a reduced radiation exposure for the patient. Further advance relies on improving the reconstruction algorithms in order to obtain better image quality and contrast and finally the possibility to combine a PET scanner with other precise morphological imaging devices like X-ray CT and MRI in co-registration mode.

In this paper, we report about an innovative PET design offering a solution to the challenges described above. The proposed approach envisages the extraction of the axial coordinate from a matrix of long and thin axially oriented crystals and WLS plastic strips, both coupled to G-APDs (Geiger mode Avalanche Photo Detectors). Results from characterization studies of the various detector components as well as the expected performance are being presented.

2. The 3D axial PET concept

The basic components of the novel design are 3 x 3 x 100 mm^3 LYSO, inorganic scintillators, positioned perpendicular to the direction of the 511 keV annihilation photons. The crystals features long attenuation length of the scintillation light, i.e. a high light yield and ultimately an

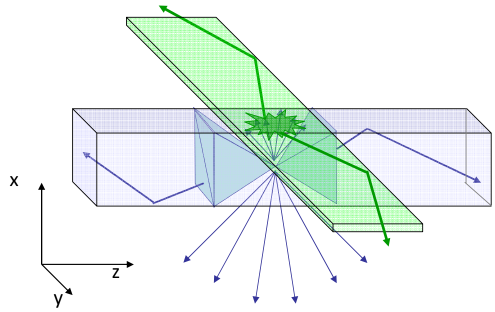

Figure 1. Details of scintillation and fluorescence light trapping. Only one crystal bar and one WLS strip are shown. The Figure is not in scale.

improved energy resolution [2]. The light collected from the crystal serves to measure the deposited energy and defines the (transverse) x and y coordinates. The (axial) z coordinate is obtained by introducing an orthogonal layer of thin WLS strips, placed in the 0.8 mm wide gaps between two crystal planes [3,4]. The WLS strips are excited by the scintillation light which is not trapped in the crystal by total internal reflection (Figure 1). Taking the signal from the WLS strip closest to the γ interaction in the LYSO crystal, one obtains a spatial resolution which can be tuned by varying the width of the WLS strips. In the case the conversion of the 511 keV γ in the LYSO crystal is detected by more than one WLS strip, the z resolution can be determined by a center of gravity algorithm, requiring in this case analogue readout.

We are in the process of building a demonstrator scanner based on two modules, each composed by a 8×6 matrix of LYSO crystals and six planes of 26 WLS strips, 3 mm wide, 0.9 mm thick and 40 mm long, slotted in between the crystals (Figure 2). One end face of LYSO crystals and WLS strips is mirror-coated reflecting the light to the opposite end, where it is detected by G-APDs.

Intrinsically this concept eliminates the parallax error in PET devices. The detection efficiency can be increased without any limit by adding scintillator planes in each module in the radial direc-

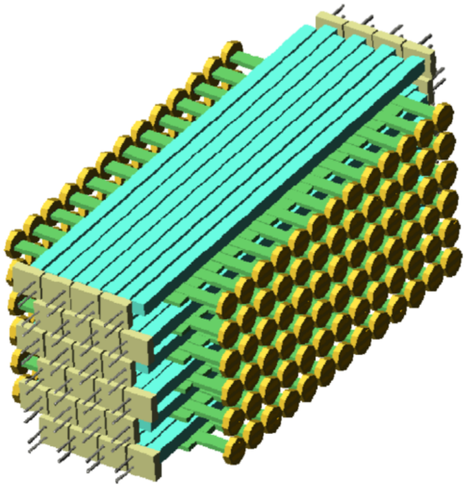

Figure 2. A demonstrator module with long LYSO scintillation crystal bars and WLS strips.

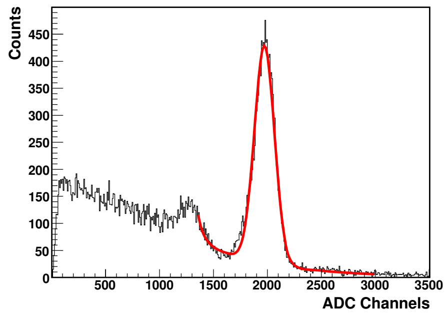

Figure 3. Energy spectrum for a LYSO crystal exposed to 511 keV γ's. The spectrum has been obtained by summing the two PMT signals.

tion and without affecting the spatial resolution. The device sensitivity can be improved by reconstructing part of events undergoing a Compton interaction in a crystal followed by a photoelectric interaction in another scintillator of the same block [2,3]. Mounting the two modules at 180° 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.

3. Description and performance of the components of the PET module

In the following we describe the key components used to validate our axial PET concept.

3.1. LYSO crystals

More than 100 LYSO crystals have been purchased and characterized. LYSO emits light in the visible blue spectrum. The crystals have been produced by Saint-Gobain and have polished surfaces to maximize light transport and collection. A dedicated test setup has been built in order to characterize the crystals (see Ref. [5] for detail). A ^{22}Na source is placed at 7 different positions along the crystal bars and spectra are taken with a Quantacon photomultiplier (PMT) from Burle/Photonis at each end of the crystal recording the light pulses. An example of the obtained spectra (sum of the two PMT signals), taken at the middle of the LYSO bar, is shown in Figure 3. Results for all the LYSO crystals show a mean number of photoelectrons $N_{pe} = 1162$ (see Figure 4, left panel) and a mean effective attenuation length of the scintillation light of $\lambda = 41.7$ cm (see Figure 4, right panel). These values and their fluctuations within the measured samples are perfectly suitable for our application. The observed mean energy resolution is $11\% \pm 0.4\%$ FWHM (see Figure 3).

3.2. The WLS strips

The properties of the chosen WLS material EJ-280-10x match well the need to efficiently absorb and transmit the light produced in the LYSO crystals. The WLS strips have been produced by ELJEN Technology [4]. Measurements of the transmission coefficient vs the wavelength have been performed [4] with a spectro-photometer, for three plastic sheet thicknesses: the absorption coefficient in the wavelength band 400 to 460 nm has been found to be $\sim$2.5 mm^{-1} and 100% transmission has been measured for wavelength larger than 480 nm (emission peak of material) [4].

The light output has been measured for 61 sam-

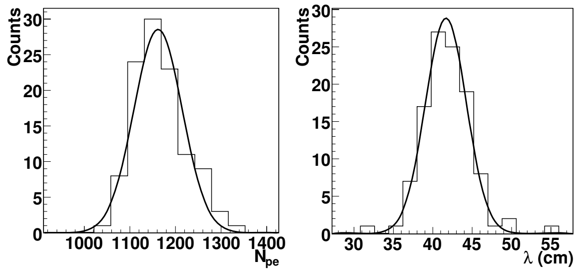

Figure 4. Distribution of number of photoelectrons N_{pe} (left panel) and light attenuation length λ (right panel) measured for LYSO bars.

ples by scanning with a LED in 5 mm steps along the strips readout by a PMT. The corresponding light attenuation length results to be ~160 mm. This corresponds to an efficiency loss of 17% over 30 mm. Figure 5 shows the light output and its spread measured with the LED positioned at two different positions, 7.5 mm and 32.5 mm away from the PMT window.

3.3. Geiger Mode APDs

G-APDs are used to measure light both from the LYSO crystals and the WLS strips. G-APDs are innovative photodetectors, particulary promising in the field of medical imaging applications. We have chosen the so-called MPPC (Multi Pixel Photon Counters) technology from Hamamatsu, which combines high gain, high speed and easy operation, also in high magnetic fields, and, thus, compatible with MRI. For the LYSO readout, G-APDs with an active area of 3×3 mm^2 divided in 50×50 μm^2 cells giving 3600 cells in total are employed. For the WLS readout a MPPC with active area of 1.19×3.22 mm^2 and 70×70 μm^2 cell size is used. They present a high photon detection efficiency ($> 35\%$) both in the blue emission peak of LYSO crystals and in the green one of WLS strips.

Charge gain, thermal dark count rate and optical cross talk have been measured with the MPPC devices [4], proving very promising for the AX-PET application.

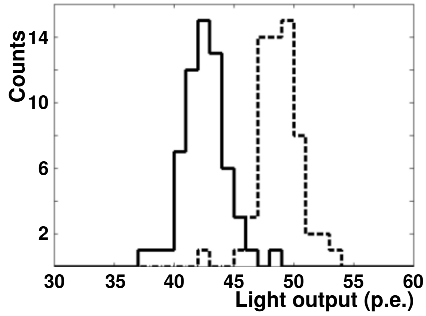

Figure 5. Light output measured on a sample of 61 WLS strips. The two distinct distributions are measured with a LED in two positions along the WLS strips 25 mm apart.

3.4. Readout electronics

The readout system for the demonstrator will comprise discrete and integrated electronics. In order to maintain a very compact size of the detector module the readout electronics is separated from the detector module. Every MPPC output is connected to a commercial high bandwidth pre-amplifier [4]. To cope with the high channel density and to maintain the readout system compact, the amplified signals are fed into a 128 channel charge sensitive integrated circuit, VATAGP5 chip [6]. It is a low noise device with a shaping time well adapted to the LYSO decay time constant. The chip features readout modes with external or self-triggering, with a sparse readout option (acquiring only the hit channels), besides serial (by multiplexing all channels), sparse with adjacent channels and sparse with reading any selection of channels, to optimize the data-taking rate in a high counting-rate environment. The device will be read out through a digital interface and the data will be stored on a computer for off-line analysis. All relevant features of custom designed readout chip VATAGP5 have been demonstrated [6]. The complete electronic chain was energy calibrated in an absolute way. The system has an appropriate dynamic range which allows detecting energy deposits from 30 to well above 511 keV in a LYSO crystal and shows very good linearity. In PET mode, an external trigger circuit will define the coincidence of the two detector modules. The analog sum of the crystals of one module can be used to discriminate photons which underwent Compton scattering in the patient.

4. The spatial resolution

The achievable resolution for the axial PET geometry is driven by the LYSO and WLS dimensions. In the transverse plane the LYSO size limits the position resolution $\sigma_{x,y} = \mathrm{d}/\sqrt{12}$ (d = 3 mm is the transverse dimension of the crystal bar). In the axial direction an interaction is recorded by one or more WLS strips which allow the center of gravity technique to improve resolution. 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 axial resolution which can be obtained by using analog information from 5 WLS strips with signals above threshold as shown in Figure 6. The expected axial resolution of 1 mm FWHM has been recently demonstrated in the lab. Therefore a volumetric resolution for photon pair detection of about 5 mm^3 FWHM appears reachable with the chosen dimensions of the AX-PET components.

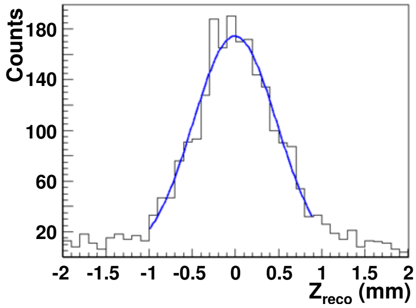

Figure 6. Reconstructed axial coordinate for the central spot position.

5. Conclusions and outlook

The AX-PET components (long LYSO crystal bars, WLS strips, G-APDs, readout electronics, and a dedicated light weight mechanical structure to assemble the module) have all been successfully tested, showing performance perfectly matching our goals. The volumetric spatial resolution which can be obtained with the concept is expected to result in a precision of 5 mm^3 FWHM, close to the limits imposed by the physics of the positron decay, given by the non-colinearity of the two 511 keV γ's and by the range of the positron for ^{18}F in the body before the annihilation point.

A demonstrator scanner will be assembled on a turntable gantry. It will be used in a typical PET configuration to record coincidences of two 511 keV γ's originating from positron annihilations in a phantom. This includes the three coordinates as well as energy of each γ. The performance of the device will be compared to detailed models based on the Geant4 and GATE codes. Dedicated reconstruction software tailored to the axial geometry is under development. The results should allows us to project the demonstrators performance to a full axial PET scanner and compare it with state-of-the-art devices like the HRRT scanner [1].

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