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COMPET – high resolution and high sensitivity PET scanner with novel readout concept: Setup and simulations

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ABSTRACT

COMPET is a MRI compatible preclinical PET scanner aiming towards a high sensitivity and a high point source resolution (PSR) by implementing a novel block detector geometry. Layers of matrices consisting of long LYSO crystals and wavelength shifter (WLS) fibers are used to determine the point of interaction (POI) of the γ-ray within the LYSO crystal. This reduces the parallax error to a minimum and allows for a high PSR and a high sensitivity, while keeping a low number of readout channels. Simulations show that the detector achieves a PSR below 1 mm in the transaxial plane and a sensitivity of up to 16%.

1. Introduction: the COMPET project

The main challenges in PET instrumentation is to achieve a higher image resolution, a higher sensitivity and building a PET as an insert for an Magnet Resonance Imaging (MRI). In COMPET, a MRI compatible, high resolution and high sensitivity preclinical PET scanner is designed and built, based on a novel block detector geometry. Each of the four blocks (displayed in Fig. 1) consists of each five layers of long $3\,\text{mm} \times 80\,\text{mm} \times 2\,\text{mm}$ LYSO crystals laying in the transaxial plane, where the incident γ-ray transfers its energy in subsequent processes to scintillation light. Some fraction of this light leaves the crystals and enters the $1\,\text{mm} \times 3\,\text{mm} \times 80\,\text{mm}$ wave length shifting fibers (WLS), which are arranged perpendicularly to the LYSO crystals in axial direction. Note that the WLS do not touch the crystals and thus only a small fraction of the scintillation light will enter the fibers. Within the WLS, the scintillation light has a certain probability to be absorbed and re-emitted, illustrated in Fig. 2. This allows for the point of interaction (POI) determination along the length of the LYSO crystal, as proposed in the AxPET project [1]. The energy deposit and the POIs in all three dimensions are reconstructed. Due to the fine pixelisation of the detector, the parallax error is small and uniform across the whole field of view (FOV), yielding a uniform PSR distribution. Thus, the detector can be placed close to the imaged object. Furthermore, not only photoelectric events, but also Compton scattered γs within the detector material can be reconstructed [2,3].

The FOV of the final scanner has an adjustable diameter between 30 and 90 mm, and an axial length of 72 mm. The light from both the LYSO and the WLS is read out with Geiger mode avalanche photodiodes (GAPD)[1] at one end. Each block consists of 150 LYSO crystals and 120 WLS strips, amounting to 1080 readout channels for the whole scanner.

2. Readout chain

The analog signals from the GAPDs are charge integrated and reset with a constant current such that they have a short rise time of a few nanoseconds and a linear decay proportional to the signal amplitude. Using a discriminator, the resulting digital signal has a length proportional to the number of photoelectrons (phe) measured with the GAPD and is fed into the deserialising input of one out of 12 FPGAs.[2] The full range for the light produced by γ-rays between 50 and 600 keV is between 0.1 and 1 μs. The deserialising input of the Virtex 5 allows for a digitization rate of 1 GHz, leading to a time resolution of 1 ns. With this time-over-threshold (TOT) approach, a cost and power efficient charge to digital converter/time to digital converter (QDC/TDC) system readout is realized. Inside the FPGA, the pulse parameters (start time, pulse length and channel number) are determined in real time, and a trigger number assigned to each event. The trigger is

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[1] Custom made multipixel photon counters (MPPC) from Hamamatsu.
[2] Xilinx Virtex 5.

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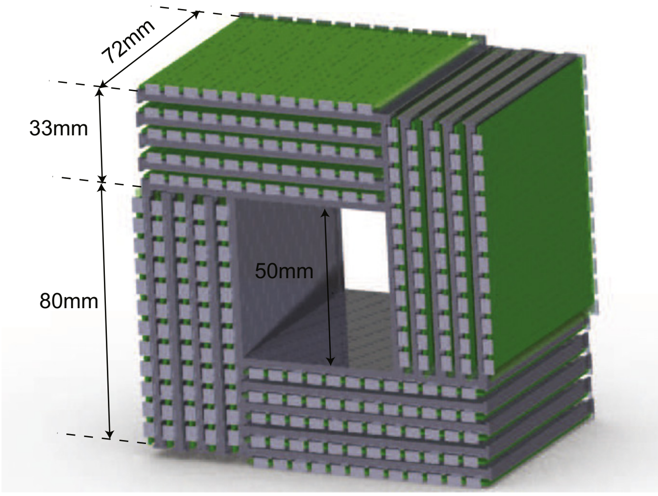

Fig. 1. This figure illustrates the arrangement of the four detector modules to ensure no intercrystal or intermodule gaps. In both Figs. 1 and 2, the WLS is drawn in green and the LYSO in gray color. The WLS is in axial direction, while the LYSO crystals lie in the transaxial plane. Each layer consists of 30 LYSO crystals and 24 WLSs. The adjustable bore diameter is between 30 and 90 mm, its length 72 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

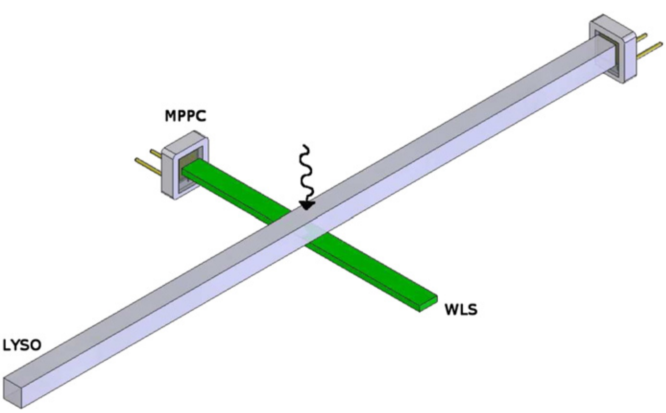

Fig. 2. This figure shows how the POI within the LYSO crystal is derived. Perpendicular to a layer of LYSO crystals, WLS is arranged. From the center of gravity of the light distribution measured in the WLS, the POI along the length of the LYSO crystal is determined.

generated synchronously with the system clock and distributed between the FPGA readout cards by a central trigger FPGA unit. The events are transferred through Gigabit Ethernet links to a farm of dedicated data acquisition computers. Depending on the trigger number, each event is assigned a different IP number and shipped to a corresponding computer. Such, a fanout can be achieved, which makes the readout system well scalable. For one single FPGA readout card, the full chain can handle an event rate of up to 10 Mevents/s.

3. Simulations

The PET detector was simulated within the framework of GATE [4]. The bore diameter was fixed at 50 mm. From these simulations, the internal PSR at different places in the detector and the detector sensitivity towards γ-ray coincidences was deduced. In all simulations, a back-to-back γ-ray source was used, emitting two 511 keV γ-rays at an intermediate angle of 180° degrees.

For the sensitivity simulation, this source was moved along the central axis. The following three cases where studied:

1. all interactions within the detector materials are assumed to be reconstructed,
2. only events, for which the energy of both γ particles is deposed in each one crystal in a photoelectric event can be reconstructed, and
3. events which have maximal one Compton interactions and exactly two photoelectric interaction are reconstructed.

The peak sensitivities for these three cases varies from 9% in case 2, over 14% in case 3 up to 16% in the optimistic case 1. We assume

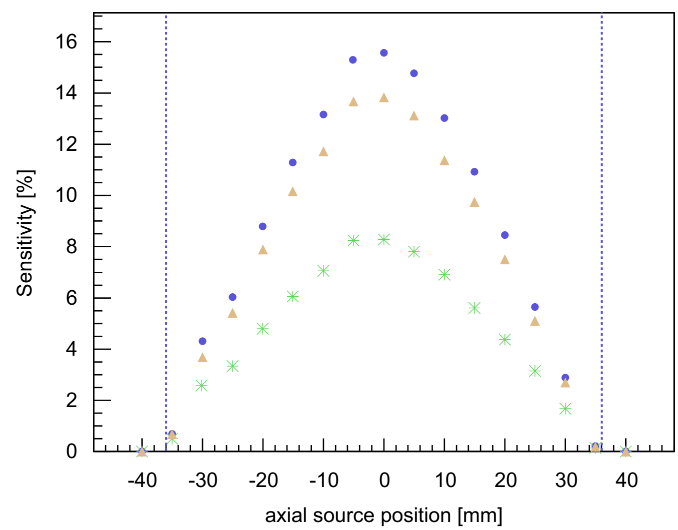

Fig. 3. The sensitivity for a point source moving along the central axis. The blue circles denote the sensitivity in case that the LOR can be reconstructed for every coincidence event, even if the γ-ray undergoes multiple scatter within the detector material. The red triangles denote the case when only single scatters are accepted. If one only accepts LORs where both end points are photoelectric absorption, one finds the sensitivity denoted with green stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

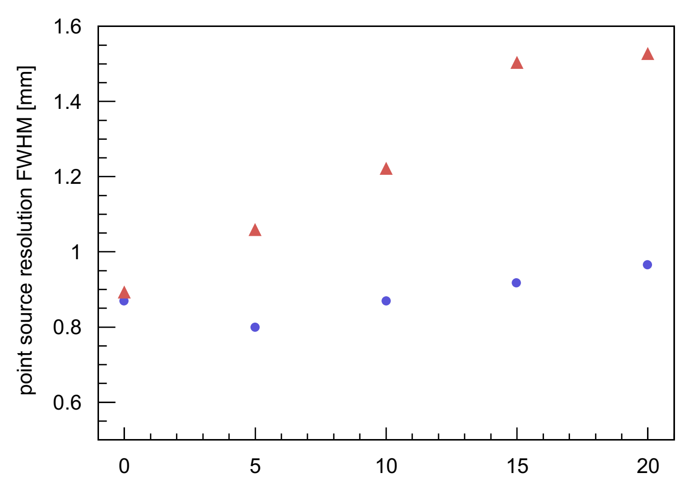

Fig. 4. The FWHM PSR is displayed for a source moved in the central transaxial plane. The x-axis describes the distance from the central axis, when moving on a horizontal line. The red triangles denote the PSR in the direction perpendicular to the x-axis, while the blue circles denote the PSR parallel to the x-axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

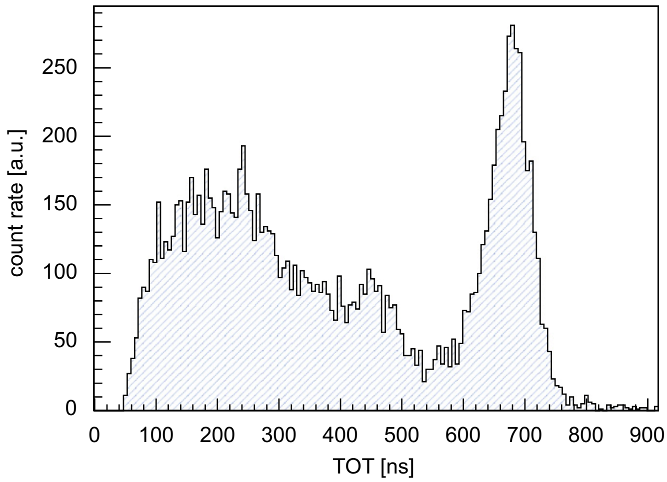

Fig. 5. Proof of principle: The γ-spectrum of a ^{68}Ge source, where the two emitted γs are measured in coincidence within a time window of 150 ns. Note that the time resolution of the readout system is 1 ns. For this measurement, however, we chose this large time window because the tagger signal was discriminated with a NIM constant fraction discriminator with an uncalibrated time delay. The spectrum was measured with the prototype COMPET readout system.

case 3 to be the most realistic one. The efficiencies for different positions along the axis are shown in Fig. 3.

The PSR was found by reconstructing the image using the exact FORE-J rebinning algorithm [5] and filtered back projection of the rebinned transaxial 2D sinograms. The point source was placed at a varying distance from the central axis in the transaxial plane. The central PSR is at 0.9 mm (full width half maximum) in both transaxial directions and 1.7 mm in the axial direction. The transaxial resolution degrades to 1.6 mm when moving the source towards the edge of the field of view, close to the first detector layer. In Fig. 4, the transaxial resolution as a function of the distance from the central axis is displayed.

4. First measurements

In a first test setup and as a proof of principle, we used one LYSO crystal and a small tagger crystal both connected to a GAPD and readout with a prototype DAQ system. The signals were shaped and discriminated with a TOT preamplifier board and processed with a single FPGA readout card. The events were transmitted through UDP to a readout computer. We installed a positron emitting ^{68}Ge source between the two crystals, allowing to measure the two 511 keV γ-ray in coincidence. In Fig. 5 the spectrum measured with the LYSO crystal is displayed for the γ-ray events measured in coincidence with the ones in the tagger crystal.

5. Outlook

Currently, each component is built and tested separately. As a next step we will build two modules, each one populated with two layers with LYSO and WLS. With this first prototype, we will be able to measure coincidences and to derive the POI resolution to confirm and update the simulations.

Acknowledgments

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