Novel high resolution detectors for Positron Emission Tomography (PET)

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In this paper we present some recent results we have obtained in the development of detectors for small animal PET and for PEM, based on the use of Position Sensitive PMTs or Hybrid Photo Diodes (HPDs) coupled to crystal matrices. New ideas and future developments are discussed.

1. INTRODUCTION

Clinical PET is a well established technology. However, the features of clinical scanners do not fulfil the requirements needed for specific high resolution applications such as small animal imaging and positron emission mammography (PEM). In particular, the relatively poor spatial resolution (about 4 - 8 mm FWHM) and the commonly used ring geometry, which limits the sensitivity for these specific applications, make the development of dedicated high performance scanners absolutely necessary.

Functional imaging of small animals, such as mice and rats, using high performance positron emission tomography (PET) is becoming a valuable tool for studying animal models of human disease [1–3]. Over the last decade, the use of mice as "laboratories" for genetic research has undergone a dramatic increase due to the ability of modifying the genotype of this animal rapidly. The mouse has long been used by molecular biologists to study fundamental cellular events in-vivo but the relatively small size of the mouse (weight 20 g) makes the use of imaging instruments developed for human subjects difficult. Despite the high complexity of current small animal PET scanners, the remarkable possibilities offered by this technique justify the growing interest of many research groups for the development of dedicated instruments. Most of the small animal

PET scanners have been built as research prototypes using various technologies [4] and some of them are now commercially available.

In recent years the scientific community has shown a growing interest in breast imaging performed by PET as a secondary screening technique for breast cancer, especially when X-ray mammography is not diagnostic. The conventional PET systems actually used in clinical scanning are characterized by a spatial resolution of about 4 - 8 mm FWHM and a geometric efficiency of about 2%. These performances do not fulfil the requirements for the detection of small (less than 1 cm diameter) tumors and for the staging of breast cancers. For this specific application an *ad-hoc* technique has been developed, called PEM (Positron Emission Mammography) [5–7]. PEM tries to overcome the limitations introduced by the complexity and the not adequate performance of PET systems, whilst still maintaining the advantage of this diagnostic method.

In this paper we present some recent results we have obtained in the development of detectors for small animal PET and for PEM, based on the use of Position Sensitive PMTs or Hybrid Photo Diodes (HPDs) coupled to crystal matrices. New ideas and future developments are discussed.

2. PHOTO-DETECTORS FOR HIGH RESOLUTION PET

Clinical PET detector elements usually consist of a matrix of scintillating crystals read by a position sensitive photo-detection system. The pixel identification is performed by using Anger-type methods: a system of four PMTs is employed for the readout of a large number of crystals. This allows an efficient packing and a reduced number of acquisition channels. The performances of this method, in terms of pixel identification, is good enough for the readout of relatively large crystals (down to 3-4 mm side) but do not scale very well for very small crystals such as those required for higher resolution scanners. The advent of novel high resolution Position Sensitive Photo-Detectors has dramatically expanded the possibilities for the construction of more simple and flexible systems with improved performances.

Many different combinations of scintillator pixellization and PS-PMTs are actually used, depending on the specific application and on the required field of view (FoV). A first solution is represented by a crystal matrix coupled to a single large area PS-PMT. This solution is very simple to implement, but it is limited by the dimension of the active area (up to 100 mm diameter) and by the usual circular shape of the photo-cathode that forbids the close packing of PMTs in a matrix configuration. Recently novel Multi Anode Photo-Multiplier Tubes (MA-PMTs) have been introduced by Hamamatsu[1]) These tubes offer, in a small package (22 mm × 22 mm square active area for the R8520-C12), performances similar to or even better than larger PS-PMTs and can be easily arranged in matrices so as to cover the whole area of larger scintillator matrices with a relatively low dead area. New flat panel MA-PMTs by Hamamatsu will be soon available. These latter devices will be characterized by a larger active area (49 mm × 49 mm) and by a very high packing fraction (up to 96% active area) for building very large cameras. Furthermore, the possibility to readout all of these tubes with a resistive chain makes the acquisition circuitry very

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[1]Hamamatsu Photonics K.K. 1126-1, Ichino-cho,Hamamatsu City, Shizuoka, Japan.

simple.

Solutions based on Hybrid PhotoDiodes (HPD) have been suggested as a valid alternative. The relatively small active area and rather high dead area of the commercially available devices make their use unpractical for direct coupling to large matrices. Multi-Pixel HPDs have been proposed in combination with Wavelength Shifting Fibers for the readout of matrices of scintillating crystals [8,9]. However, this method is limited in sensitivity due to the very low light yield that can be achieved at the end of the fiber [10]. Highly pixellated large area HPD are now being developed [11]; hybrid photodiodes can then become a realistic alternative to PS-PMT for the direct readout of matrices of crystals in the near future.

3. SMALL ANIMAL YAP-(S)PET SCANNER

At the University of Ferrara (Italy) there has been built a high resolution integrated PET-SPECT scanner (called YAP-(S)PET) dedicated to small animal imaging [12]. The YAP-(S)PET scanner is made up of four modules: each one is composed of 20×20 $YAlO_3$:Ce (Yttrium Aluminum Perovskite activated by Cerium or YAP:Ce) finger crystals ($2 \times 2 \times 30$ mm^3). The matrix is directly coupled to a 3" PS-PMT (Hamamatsu R2486-06). The system operates in 3-D data acquisition mode and an EM (Expectation Maximization) algorithm is used for image reconstruction [13]. The scanner has cylindrical FoV of 4 cm ×4 cm diameter. In PET mode, the spatial resolution is constant over the whole FoV and is better than 1.8 mm FWHM; the volume resolution at the center of the tomograph is 5.8 mm^3. The sensitivity at the center of the FoV is 17.3 cps/kBq (640 cps/μCi) with the detectors 15 cm apart [14]. YAP-(S)PET is not only suitable for PET imaging, but also for SPECT studies on small animals [15].

4. POSITRON EMISSION MAMMOGRAPHY PROTOTYPE

We are developing a dedicated device based on $YAlO_3$:Ce (Yttrium Aluminum Perovskite acti-

vated by Cerium or YAP:Ce) scintillator and PS-PMTs R8520-C12, to detect breast lesions, with dimension of 5.0 mm (and below) in diameter and a specific activity ratio of 10:1 between cancer and breast tissue [16]. The device will be composed of two opposite detectors (parallel plane geometry) whose technology derives from the YAP-(S)PET scanner. The proposed dimensions of crystals are 3 cm thick with a detection area of 6×6 cm^2; each detector has 30×30 finger crystals of $2 \times 2 \times 30$ mm^3, glued together with each element being optically isolated from an adjacent one by a 5 μm insulating layer. The distance between the detectors can range from 5 to 10 cm, depending on compression status.

To this end, we have studied three different solutions for the readout of the YAP:Ce matrix. In particular, the aim of the study is the optimization of the detection efficiency (in terms of fraction of the matrix successfully read-out), while keeping the spatial resolution good enough so as to allow an almost perfect coding (bi-unique pixel identification). The results for each of the methods used are reported in the following subsections.

4.1. R8520-C12 readout

R8520-C12 are position sensitive photomultiplier tubes produced by Hamamatsu. The position sensitive detection is performed with a special anode made of 6 (X) and 6 (Y) crossed plates. The active area of these tube is 22 mm $\times$ 22 mm with respect to an overall size of 25.7 mm $\times$ 25.7 mm, corresponding to a packing fraction of about 73%. We have used an array of four of these tubes for the readout of the YAP:Ce matrix.

In our configuration the 12 anode signals are weighted with a resistive chain and the four outputs of each tube are independently acquired. The YAP:Ce matrix we used is opened on both sides: front (where the PMT is coupled) and back. In order to recover the light from that which exits from the back side, we have tested different reflector materials. The results of these measurements are reported in table 1. Both Tyvek and PTFE are able to recover just over a quarter of the light that is lost with no reflector.

Table 1
Back reflector efficiency.

Material	Relative signal (Normalized to none)
None	1.00
Polystyrene	1.19
Tyvek[2]	1.27
Mg powder	1.26
PTFE	1.27
Paper	1.19
Aluminum	1.21
Aluminized Mylar	1.25

Either would be suitable for use with this detector, although Tyvek may be preferred for ease of handling.

Figure 1 shows the flood field image obtained with the uniform irradiation (flood field) of the YAP:Ce matrix with 511 keV photons from a ^{22}Na source. The array of tubes is directly coupled to the YAP:Ce matrix via optical grease. Annihilation events are selected by the coincidence detection of the second photon using a BGO scintillator coupled to a PMT. In this way only the crystals that are facing the active area of a tube can be identified (121 crystals for each tube), corresponding to a fraction of 53.8% of the whole matrix.

In order to recover the fraction of the matrix not directly coupled to the active area of any tube, we have used a 3 mm thick quartz window between the matrix and the PMTs as a light diffuser. In this way one can readout a total area of about 48 mm $\times$ 48 mm corresponding to 24 $\times$ 24 crystals. Figure 2 shows the flood field image obtained by using the quartz window. In this case one has to pay in terms of a reduced spatial resolution (especially in the region in between two tubes) that means a more difficult pixel identification. A comparison of the profiles of a single row of crystals extracted from the images obtained without (i.e. fig.1) and with (i.e. fig.2) quartz is shown in figure 3. Using the quartz windows the spatial resolution of the system is reduced to about 1.45 mm FWHM for each pixel (2 mm side) with respect to a value of about 0.79 mm FWHM
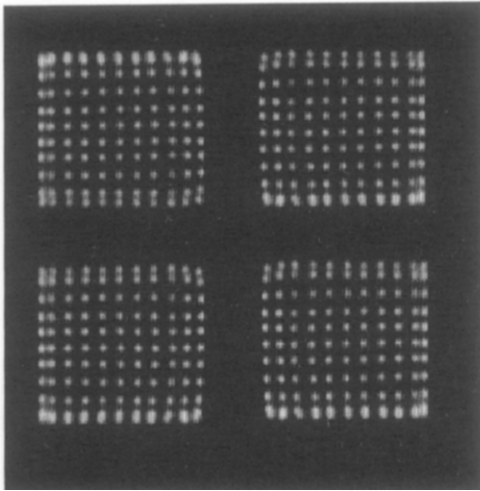
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[2]Tyvek is a DuPont registered trademark for its brand of protective material

Figure 1. Flood field image (511 keV irradiation) of the 24 × 24 YAP:Ce matrix read by an array of four PS-PMT R8520 by Hamamatsu. The PTFE tape (as light reflector) is used in this measurement.
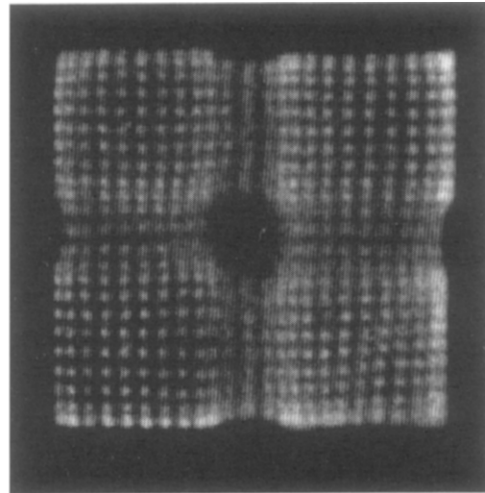

Figure 2. Flood field image (511 keV irradiation) of the 24 × 24 YAP:Ce matrix read by an array of four PS-PMT R8520 by Hamamatsu. A 3 mm thick quartz window (for light sharing) and PTFE tape are used in this measurement.

with the direct coupling.

4.2. Multi Pixel HPD readout

In order to evaluate the possibility to readout a matrix of scintillators by the direct coupling with a Multi-Pixel HPD we have assembled a small detector head using the 61 pixel HPD and a test 4 × 4 YAP:Ce (2 mm × 2 mm each crystal). This detector represents a small prototype of larger detectors that could be built by using large area HPDs. A photomultiplier tube (mod. R5900 by Hamamatsu) has been used to collect the light exiting from the other side of the matrix, so as to produce the trigger signal for the "sample-and-hold" of the HPD signals. The image obtained by the flood field irradiation of the 16 elements YAP:Ce matrix with a 122 keV [57]Co source is shown in figure 4. In this image all crystals can be clearly identified, thus demonstrating the good uniformity and spatial resolution of this Multi-Pixel HPD. The mean peak-to-valley ratio in the image is about 4.

5. CONCLUSIONS

A matrix of small scintillation crystals is a widely used technique for the gamma detection in high resolution PET. A high density / medium Z scintillator (such as YAP) could be very useful for both small animal PET scanner and PEM [17]. We have demonstrated that recently developed position sensitive photomultiplier tubes R8520-C12 by Hamamatsu could be successfully arranged so as to form a compact array for the readout of these matrices with an excellent spatial resolution that means a optimal pixel identification. However the dead area between adjacent tube can limit the efficiency of the instrument. The use of a quartz window between the matrix and the tube permits the recovery of the lost pixels that face the area between tubes, with the drawback of worsening the spatial resolution. In order to increase the light extraction from the crystals we have tested different reflectors. The

Figure 4. Flood field image (122 keV irradiation) of the 4 × 4 YAP:Ce matrix read by the 61 pixel HPD by DEP.
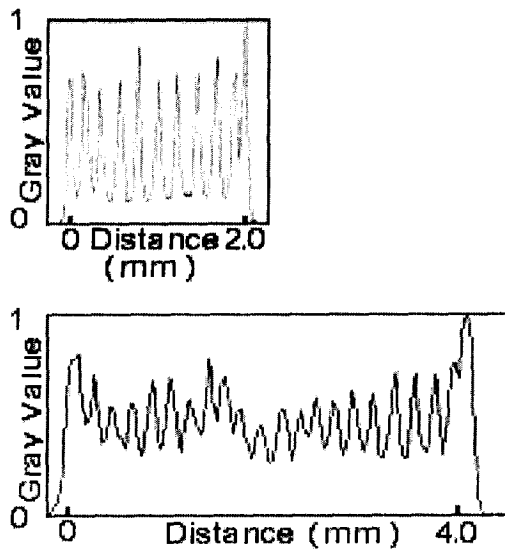
Figure 3. Top: profile of a single row of crystals (11 elements) in the flood field image obtained with the direct coupling of the tube to the matrix. Bottom: profile plot of a single row of crystals (24 elements) in the flood field image obtained with the quartz window.

best results have been obtained by using PTFE tape and Tyvek sheet with a net increase of almost 30% respect to no reflector. Tyvek sheet will likely be the final choice for ease of handling.

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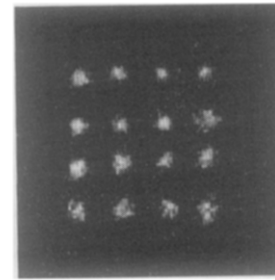7. R.R. Raylman et al. Med. Phys. 27 (2000) 1943-1954.
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