Abstract—We are developing a PEM detector head based on two planar detector heads each measuring 6×6 cm². Each head is composed of a 3×3 matrix of R8520-C12 phototubes from Hamamatsu and a YAP:Ce array of 2×2×30 mm³ pixels manufactured by Crytur. The R8520 is a compact 25.7×25.7 mm² square detector that has an active area of 22×22 mm². It has an excellent imaging performance and its square shape lends it well to PEM applications where a large active area is important to maximise sensitivity. However, even when tiled, the R8520-C12 only has an active area of 73%. Therefore, in an effort to recover the pixels lying on the detector boundaries that are not directly viewed by the active area, we have used a technique involving a quartz light diffuser between the crystal matrix and the PSPMT detectors. It is possible to recover virtually 100% of the area, but at the expense of a reduction in the system spatial resolution. Therefore, we have tested two versions of the detector head; one with the quartz diffuser which should provide a better sensitivity through maximised active area, and a second with no quartz that should have a superior imaging performance. Flood images are used to compare these two systems in terms of pixel identification and geometrical efficiency.

I. INTRODUCTION

POSITRON Emission Tomography using ¹⁸F-FDG could be a valid solution for the staging of breast cancer [1]. Whole body PETs are often used but their performances do not fulfill the requirements for the detection of small tumors (less than 1 cm in diameter). In recent years there has been increasing focus on PET systems designed for specific applications due to the limited performance and large cost of whole body systems. One such specific application is PEM (Positron Emission Mammography). One of the primary requirements for a PEM system is that it should provide the maximum sensitivity whilst also providing a spatial resolution that is an improvement on that of whole body scanners. Many research groups are working on the development of dedicated devices for PEM with high sensitivity and high spatial resolution [1-8].

The aim of this work is the evaluation of the performance, in terms of pixel identification resolution and effective active area of various solutions, based on an array of R8520-C12 position sensitive photomultiplier tube from Hamamatsu, to be used for the construction of a dual head PEM prototype.

II. YAP-PEM PROTOTYPE DESIGN

A prototype for positron emission mammography is under development within a collaboration of the Departments of Physics of the Universities of Pisa and Ferrara, which aims to provide a maximised sensitivity with an excellent spatial resolution. This device should be able to detect tumours of 5 mm diameter when there is a tumour/background specific activity ratio of 10:1 [9]. The system is composed of two planar detector heads, which will be attached to a standard mammography unit and used with compression. Each detector head is made up of a 6×6 cm² matrix of YAP:Ce pixels and an array of square compact R8520-C12 PSPMTs. A schematic of the layout of a single detector head is shown in figure 1.

YAP:Ce is a scintillator that produces a light yield of about 20,000 Ph/MeV, has a decay constant of 30 ns, a density of 5.4 g/cm³ and a emission maximum of 370 nm, so is well suited to PMT based readout. It is felt that YAP:Ce represents a good compromise between all of the features required for a...
scintillator employed in a PET system. One drawback is its low Z number which may, in certain situations, be an advantage, as described in [10]. The scintillator is 3 cm thick with a detection area of 6×6 cm$^2$; each of these crystals is composed of 30×30 pixel elements of 2×2×30 mm$^3$ each.

The R8520-C12 from Hamamatsu is a square, flangeless PSPMT with an outer dimension of 25.7×25.7 mm$^2$ and an active area of 22×22 mm$^2$. It has a metal channel dynode structure that minimises the charge spread during the multiplication stage which contributes towards its good resolution. The tube has 6X + 6Y crossed wire anodes which are readout using a resistive divider network to give just 4 readout signals for pre-amplification and processing. These signals undergo a centre of mass calculation to give the signal position. We have demonstrated that the R8520-C12 is well suited for this application [12] and now we have tested a configuration based on an array of nine (3×3) of these tubes for the readout of the YAP:Ce matrix described above. Each photodetector has been read-out by a specific resistive chain and a preamplifier board which contains 4 channels for the anode signals and an additional channel for fast timing of the last dynode. The data from each tube are independently acquired with two 32-channel peak-sensing VME based ADCs. The OR signal of the nine tubes is put in fast coincidence with its analogue from the other detector head. Dedicated software performs the center of gravity calculation of the light for pixel identification. Figure 2 shows the photographs of the YAP:Ce matrix of the array of 3×3 R8520-C12 used in our measurements.

In order to characterize the imaging performance of the R8520 tube, we have performed a study of the photocathode uniformity and the position linearity. Both studies have been performed by scanning the photocathode of the tube, across the center, with a blue LED. The led has been coupled to a clear fiber, 2 mm diameter, to guide the light to the photocathode with a reduced spot size. The position of the LED was controlled by a motorized, high precision translation stage. The measured signal is the sum of the four position signals ($X_A + X_B + Y_C + Y_D$) that is proportional to the number of photoelectron emitted by the photocathode.

Fig. 2. Left: photograph of the 6×6 cm$^2$ YAP:Ce matrix made up of 900 finger crystals 2 mm × 2 mm × 30 mm each. Right: photograph of the nine PSPMT (Hamamatsu mod. R8520-C12) arranged in a 3×3 array. The tubes are held together in a plastic frame.

Although the square shape of the tubes allows close packing of the detectors, the active area is only 73%. A method using a quartz light diffuser can recover pixels in the dead area between tubes, but with a consequent reduction in the achievable spatial resolution in the pixel identification and ultimately of the system as a whole.

III. EXPERIMENTAL MEASUREMENTS

A. R8520-C12 characterization

A plot of the detector uniformity has been produced by the position of the peak in the ADC channel scale (pulse height) as a function of the position of the illumination point across the photocathode (figure 4, top). The ratio between the lowest and the highest value in the uniformity plot is 1:1.6. We have measured just one profile rather than the whole area so the overall figure will likely be much larger.

Using the same data as above, the reconstructed position (pixel number in the image) has been plotted against the actual position of the light spot to give an indication of the position...
linearity of the tube (figure 4, bottom). This tube have a good linearity, only deviating significantly at the edges.

B. Detector head testing

Two different crystal-PMT coupling techniques have been explored: the first simple solution is the direct coupling of the array with a silicone-based optical grease. Figure 4 shows the image obtained with the uniform irradiation (flood field) of the YAP:Ce matrix with 511 keV photons from a $^{22}$Na source. 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 (676 out of 900 crystals), corresponding to a fraction of about 75% of the whole matrix. The measured mean Peak-to-Valley ratio (P/V) is 8.0 and the mean FWHM of the pixel image is 0.9 mm.

With regard the second configuration, we have evaluated the imaging performance of the detector head as a function of the thickness of the light-diffusing quartz window. This method of dead area recovery has been described previously [11]. It relies on a layer of quartz a few millimetres thick diffusing some of the light from the dead pixels (those lying between detector active areas) onto the photodetector either side of it. Tests were carried out to optimise the thickness of the quartz in terms of the most efficient recovery whilst not degrading the overall resolution too severely. Various quartz thickness, ranging between 1 mm and 3 mm, have been tested. The resulting P/V in the active area and the efficiency in recovering the events that occurred in pixels facing the non-active area are represented in figure 5.

As one might expect, as the quartz thickness increases, the P/V is reduced, due to the broader light spot on the photocathode, which ultimately reduces the spatial resolution on the reconstructed pixel position. In fact the the spatial resolution of a photon detector based on scintillating crystals and PS-PMTs depend on several parameters. The spread of the light spot due to the quartz window ($\sigma_w$) contributes to $\sigma_x^2$ (being $\sigma_x$ the spatial resolution along one axis) as $\sigma_w^2 / N$, where $N$ is the average number of photoelectrons produced by the light crossing the transparent window [13]. Thus, as the window thickness is increased, $\sigma_w$ become larger, while $N$ is reduced to the increased light attenuation, both degrading the intrinsic spatial resolution of the detector head. On the other hand, thicker quartz gives a better efficiency in the recovery of the dead area. This latter value has been measured by calculating the ratio between the counts in a chosen number of pixels (typically 6 or 8) facing the non-active area between two tubes ($\varepsilon_{\text{between two}}$) and the counts in an equivalent number of pixels facing the active area ($\varepsilon_{\text{active area}}$). Figure 6 shows flood field image (511 keV) obtained with a 3 mm quartz window, with only pixels facing the dead area between tubes open, while other pixels are covered with a black tape. This figure demonstrate that using the 3 mm quartz also the four pixels between four tubes can be recovered with a reasonable efficiency (about 72%).
An image of the 6×6 cm² YAP:Ce crystal matrix has been produced using the quartz window scheme, too. For this test we have chosen the 3 mm thick quartz, which represents the reverse condition (improved efficiency, degradation of pixel identification) with respect to the direct coupling technique. The resulting flood field image is shown in figure 7. In this case we have measured a mean P/V of 2.2 and a pixel FWHM of 1.4 mm.

![Image 1](image1.png)

**Fig. 7.** Flood field image (511keV) of the 6 cm × 6 cm YAP:Ce matrix obtained with the 3 mm thick quartz window coupled to nine R8520-C12. The plot below represents the profile of a single row.

### IV. CONCLUSIONS

We have successfully constructed a detector head to be used in a novel PEM prototype. A photograph of the prototype detector head used in these measurements is shown in figure 8. The use of a quartz window allows an array of nine R8520-C12 to read out the whole 6×6 cm² YAP:Ce matrix with a pixel P/V ranging between 2.06 and 3.48 and pixel recovery efficiency ranging between 78% and 94% a with respect the ideal readout. However, a final choice for the quartz thickness cannot be made at this stage. The optimal compromise between spatial resolution and efficiency, can only be obtained from a Signal-to-Noise ratio measurement of the entire PEM system with hot phantoms.

![Image 2](image2.png)

**Fig. 8.** Photograph of the test detector head: the YAP matrix is fixed in an aluminum frame; the tubes are kept together with a plastic holder (in this photograph only four electronics boards are in place).

### V. REFERENCES

[11] N. Belcari et al. “Novel high resolution detectors for positron emission tomography (PET)”, accepted for publication in NIM A