Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 550 (2005) 305–312
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Partially slotted crystals for a high-resolution γ-camera based on a position sensitive photomultiplier

N. Giokaris[a,b,*], G. Loudos[a], D. Maintas[a], A. Karabarbounis[a,b], M. Lembesi[a,b], V. Spanoudaki[a,b], E. Stiliaris[a,b], S. Boukis[a,b], A. Gektin[c], V. Pedash[c], V. Gayshan[d]

[a] *Institute of Accelerating Systems and Applications, P.O. Box 17214, 10024 Athens, Greece*
[b] *Physics Department, National Capodistrian University of Athens, Greece*
[c] *Institute for Scintillation Materials, Lenin Av.60, 310072 Kharkov, Ukraine*
[d] *Scintitech, 275 Concord Road, Wayland, MA 01778, USA*

Received 22 November 2004; received in revised form 25 April 2005; accepted 26 April 2005
Available online 7 July 2005

Abstract

Partially slotted crystals have been designed and constructed and have been used to evaluate the performance with respect to the spatial resolution of a γ-camera based on a position-sensitive photomultiplier. It is shown that the resolution obtained with such a crystal is only slightly worse than the one obtained with a fully pixelized one whose cost, however, is much higher.

Keywords: γ-camera; Crystal; Resolution; Efficiency; Cost

1. Introduction

Small field of view (FOV) high-resolution γ-cameras based on Position Sensitive Photomultipliers (PSPMTs) have been used widely for studies with small animals and for the development of new radiopharmaceuticals [1–5]. In the past 20 years several groups have demonstrated the ability of using such cameras for the early detection of small breast lesions in clinical applications and/or in experiments with phantoms [6–9].

The main components of such γ-cameras are the PSPMT, the collimator and the crystal and their choice, in the end, determines its main parameters, which are the spatial resolution, the efficiency in γ-ray detection and the cost.

*Corresponding author. Institute of Accelerating Systems and Applications, P.O. Box 17214, 10024 Athens, Greece. Tel.: +30 210 7257533; fax: +30 210 7295069.
E-mail address: ngiokar@cc.uoa.gr (N. Giokaris).

0168-9002/$ - see front matter
doi:10.1016/j.nima.2005.04.088

In this paper we describe the second part of a program whose purpose was to explore the possibility of building a γ-camera which has higher efficiency, good resolution and still costs less than the "base design" by the appropriate choice of its collimator and mainly its crystal. In Section 2 the "base design" of the γ-camera and the whole experimental setup are described. In Section 3 the design and the construction of the new, partially slotted, crystals are given. In Section 4 the results of the studies with these crystals are presented. In Section 5 the conclusions from these studies are drawn.

2. Experimental setup

The gamma camera in its "base design" consists of a PSPMT (Hamamatsu R2486), a parallel hole collimator and a pixelized CsI(Tl) scintillator. The thickness of the collimator is 2.75 cm, the holes are hexagonal ~1.1 mm in diameter, with a 0.25 mm septa. The pixelized crystal is 4.6 cm in diameter, 3 mm thick and the cells' size is $1.13 \times 1.13\,\mathrm{mm}^2$ with 0.25 mm septa. The anode consists of eight x- and y-crossed wires. The 16 anode signals are preamplified through 16 preamplifiers (LeCroy TRA1000) and then transferred to a CAMAC system, which hosts an ADC (LeCroy FERA 4300B), a memory (LeCroy FERA 4302), a driver (LeCroy FERA 4301) and a controller (Jorway 73A). The digital signals are transported to a G3 Power Mac via a SCSI bus. Acquisition software is written in $K_{\max}$ 6.4.5. (Sparrow Corporation) environment. Details about the system and its readout principles can be found elsewhere [10].

Along with the fully pixelized crystal one homogeneous and five partially slotted crystals have been tested, all 5 cm in diameter, 7 mm thick with slot depths of 0–5 mm. The cells' size was $2 \times 2\,\mathrm{mm}^2$ with 0.40 mm septa (white reflector with light reflection coefficient $>98\%$).

The spatial resolution of the "base" system has been measured and found to be ~1 mm in planar imaging and 2 mm in SPECT mode [4,10]. Energy resolution was found to be ~30% at 140 keV. This detector has been successfully used in small animal imaging and recently, in imaging of breast phantoms [9].

3. Design and construction of the partially slotted crystals

The idea of partial pixelization originates from the technique of surface forming [11]. Pixelization was made by slot milling with diamond mills. The thickness of the slot is 0.4 mm. To provide the light reflection from each semipixel the slot was filled with white reflecting material (MgO doped with silicone gel). The reflection coefficient is 98%. Fig. 1 demonstrates the scheme of the partially pixelized detector and the character of light output spread distribution.

It is seen that part of light divergent along the crystal volume and giving quite a "diffuse" distribution of the light coming from the crystal, due to reflection from the walls of slots may come out from the crystal. Thus there is a possibility of both, extraction of a greater quantity of light from the crystal and regulation of light spread function.

It is obvious that the peculiarities of light output regulation depend on the parameters of slot grid on the crystal surface. In this case variable parameters may be the distance between slots, their depth, the angle between elements of the grid and reflectivity of the material filling between the slits.

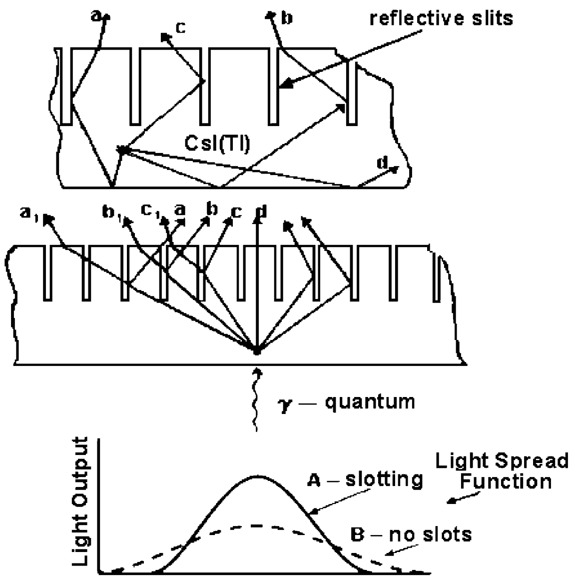

Fig. 1. Scheme of partially slotted crystals and light spread function.

4. Results

In the first phase of our study five CsI(Tl) homogeneous crystals with 1, 2, 3, 5, and 7 mm thicknesses and 5 cm in diameter all produced by the "Institute for Single Crystals, Alkali Halide Crystal Department" were tested and compared with the "base" 3 mm thick CsI(Tl) pixelized scintillator. The results have been reported in Refs. [12,13].

In order to study the effect of slot depth in partially slotted crystals the 7 mm thickness homogeneous crystal was selected as reference (slot depth 0 mm). The five partially slotted crystals were tested for crystal orientation, charge distribution, energy response, sensitivity, spatial resolution and capillary imaging.

4.1. Crystal orientation

As a first step we need to define the optimum side of the crystal where photons should strike on. Thus a ^{99m}Tc source, consisting of a 1.1 mm inner diameter capillary of 2 mm length (activity of the initial solution 1 m Ci/ml) and placed at 5 mm distance from the collimator surface, has been used. Data were collected with photons striking (a) at the slotted side and (b) at the homogeneous side. In Table 1 the measured sensitivities are given and compared.

Comparative raw images, in both crystal placements, of a similar capillary filled with ^{99m}Tc solution and placed in 5 mm distance from the collimator surface are shown in Fig. 2 for comparison. In this experiment the crystal with the 5 mm slot depth has been used.

The results indicate that sensitivity is significantly higher when photons strike the pixelized part. In addition, raw image quality is significantly improved, especially for thick pixelization. Edge artifacts are significant in the second image. Since sensitivity is a crucial parameter and all corrections are based on the raw image, all experiments have been carried out with this crystal orientation.

Table 1
Sensitivity of partially slotted crystals when a point ^{99m}Tc source is used

Pixelization depth (mm)	Measured sensitivity in cps/m Ci when photons strike at the	
	Pixelized side	Homogeneous side
0	426.76	387.39
1	412.78	246.71
2	346.85	37.88
3	282.60	24.52
4	289.29	24.57
5	236.96	26.50

Two possible crystal orientations have been evaluated. A 100% energy window has been used.

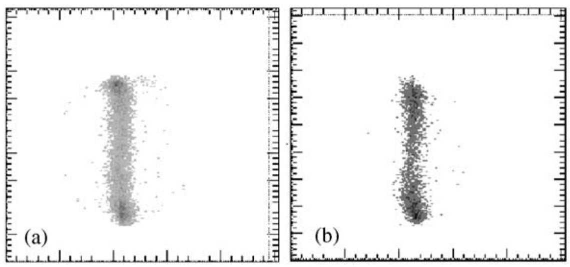

Fig. 2. Raw image of a 1.1 mm inner diameter capillary placed in 5 mm distance from collimator surface. A crystal with 5 mm pixelization depth has been used. (a) Photons strike the pixelized side and (b) photons strike the homogeneous side.

4.2. Charge distribution

In Fig. 3 the measured x-signals for photons detected at the center of the crystal are shown. The point source described in Section 4.1 has been used and the signal from 100 photons has been averaged. The experiment has been performed using the five partially slotted CsI(Tl) crystals and the results have been compared with similar data from the standard 3 mm thick CsI(Tl) pixelized crystal.

As it can be seen the deeper the slot is, the narrower is the distribution of the charge in the eight x-wires and slowly approaches the distribution of the pixelized crystal.

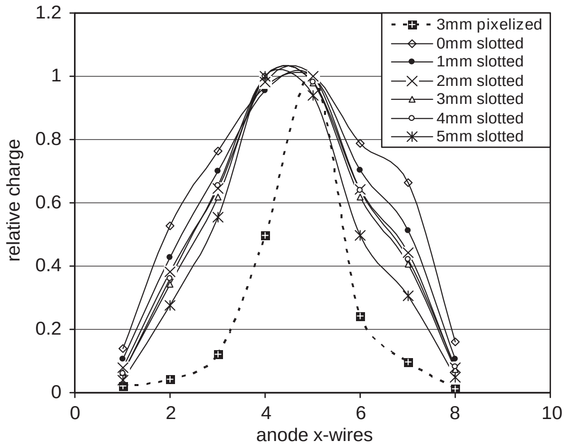

Fig. 3. Charge distribution in the eight x-wires for the standard 3 mm thick CsI(Tl) pixelized crystal and the six 7 mm thick partially slotted CsI(Tl) crystals with slot thicknesses of 0–5 mm. At this point the wire signals have not been corrected for preamplifier gain differences.

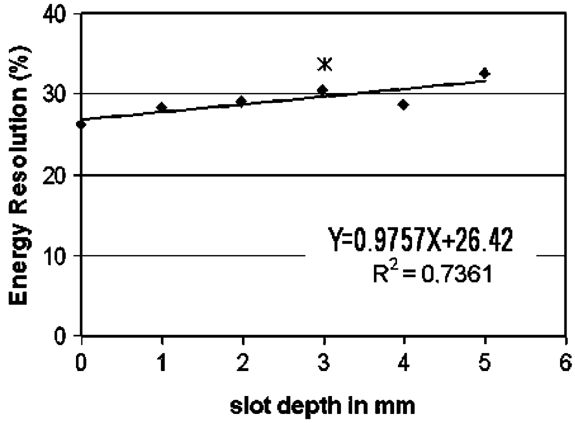

Fig. 5. Energy resolution (FWHM) as a function of slot depth. The energy resolution is measured using a point like source (initial ^{99m}Tc solution, 1 m Ci/ml) with the collimator removed. Only photons reconstructed in the center of the FOV have been used. The measured value for the 3 mm pixelized crystal is indicated with an asterisk (*).

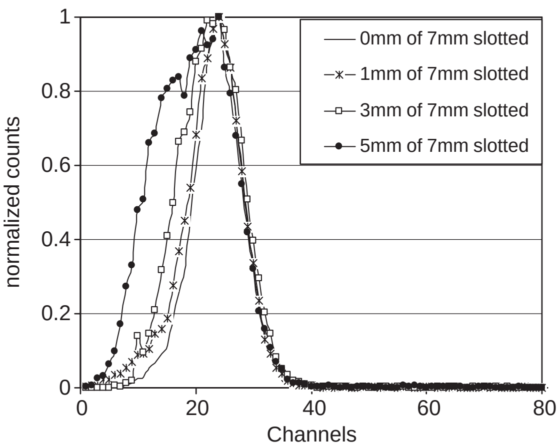

Fig. 4. Energy spectrums in the 0, 1, 3 and 5 mm partially slotted crystals using a ^{99m}Tc source.

4.3. Energy response

The energy spectrum is calculated by summing the signal in the 16 x- and y-wires. When a thin capillary filled with ^{99m}Tc solution and placed in the center of the FOV is used as a source, the calculated spectrum in the case of the 0, 1, 3 and 5 mm partially slotted crystals is shown in Fig. 4.

The thicker the pixelization is the more the spectrum's shape approaches the energy spectrum of a pixelized scintillator.

In Fig. 5 the energy resolution defined as the FWHM divided by the photopeak channel is plotted as a function of the slot depth. The line that fits best the experimental data is also shown. In order to calculate energy resolution only photons reconstructed in the center of the FOV have been used.

Using the same imaging conditions and the 3 mm pixelized scintillator, energy resolution was found to be ~35%.

4.4. Sensitivity

The sensitivity of the slotted crystals has been calculated using the capillary source of Section 4.3 placed in a 5 mm distance from the collimator. In Fig. 6 the measured sensitivities for each crystal and for both possible crystal positions are plotted. The data have been corrected for ^{99m}Tc decay. In all experiments a 100% energy window has been used in order to take into account all detected photons.

As it can be seen the sensitivity decreases with slot depth. In addition, as it was also stated in

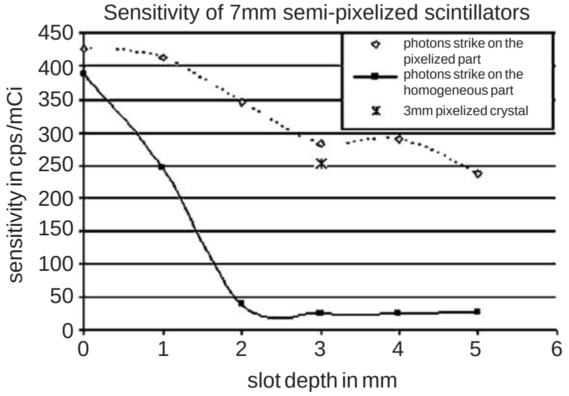

Fig. 6. Sensitivity as a function of slot depth. The measured value for the 3 mm fully pixelized crystal is indicated with an asterisk (*). A point-like ^{99m}Tc source has been used placed at an 8 cm distance from crystal surface with the collimator removed. The curves have been drawn just to guide the eye.

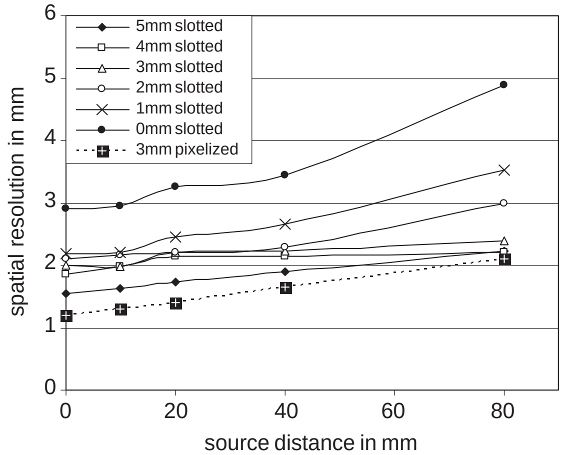

Fig. 7. Spatial resolution as a function of pixelization depth. The resolution of the fully pixelized crystal is also shown for comparison.

Section 4.1, the sensitivity is significantly lower when photons strike to the homogeneous part first. The comparison with the 3 mm fully pixelized scintillator shows that its sensitivity is almost equal with those corresponding to the partially slotted crystals with slot depths of 3, 4 and 5 mm.

4.5. Spatial resolution

The spatial resolution has been calculated using the capillary of Section 4.1, placed in several distances from the detector. Profiles have been drawn and the measured FWHM have been calculated. Spatial resolution as a function of pixelization depth is shown in Fig. 7. It is seen that the resolution of the 5 mm slot depth crystal is only slightly worse than that of the fully pixelized one.

4.6. Capillary imaging

In Fig. 8 raw images of the same capillary filled with ^{99m}Tc solution and placed in the center of the FOV are shown for each of the evaluated crystals. A simple COGA has been used for x and y position calculation.

It is seen that image quality improves as the pixelization becomes deeper.

5. Discussion

The main advantage of partially slotted crystals is that they are cheap and they can be easily constructed. The positioning of the crystal affects image quality and sensitivity. When photons strike the homogeneous part the produced light spreads but may be reflected at the slots. However, when photons strike the slotted part the produced light does not "stop" but is reflected inside the slots and then spread in the homogeneous part. The deeper the slotting is the stronger is this phenomenon and the greater is the sensitivity difference. The lower sensitivity and edge effects that cannot be easily corrected affect image quality in the second case.

Pixelized scintillators have been preferable in small FOV PSPMT detectors, since the position of each photon is calculated from the signal of one position-sensitive anode of a single PMT [14]. In the developed system, when a fully pixelized crystal is used, the 16 anode signals are collected and by applying a simple Center of Gravity Algorithm (COGA), the x and y coordinates of incident's photon position are computed. However, this method fails to provide accurate results when homogeneous crystals are used [12], since the light spreads in the crystal and COGA causes the reconstructed photon position to move towards the center of the image, especially for photons

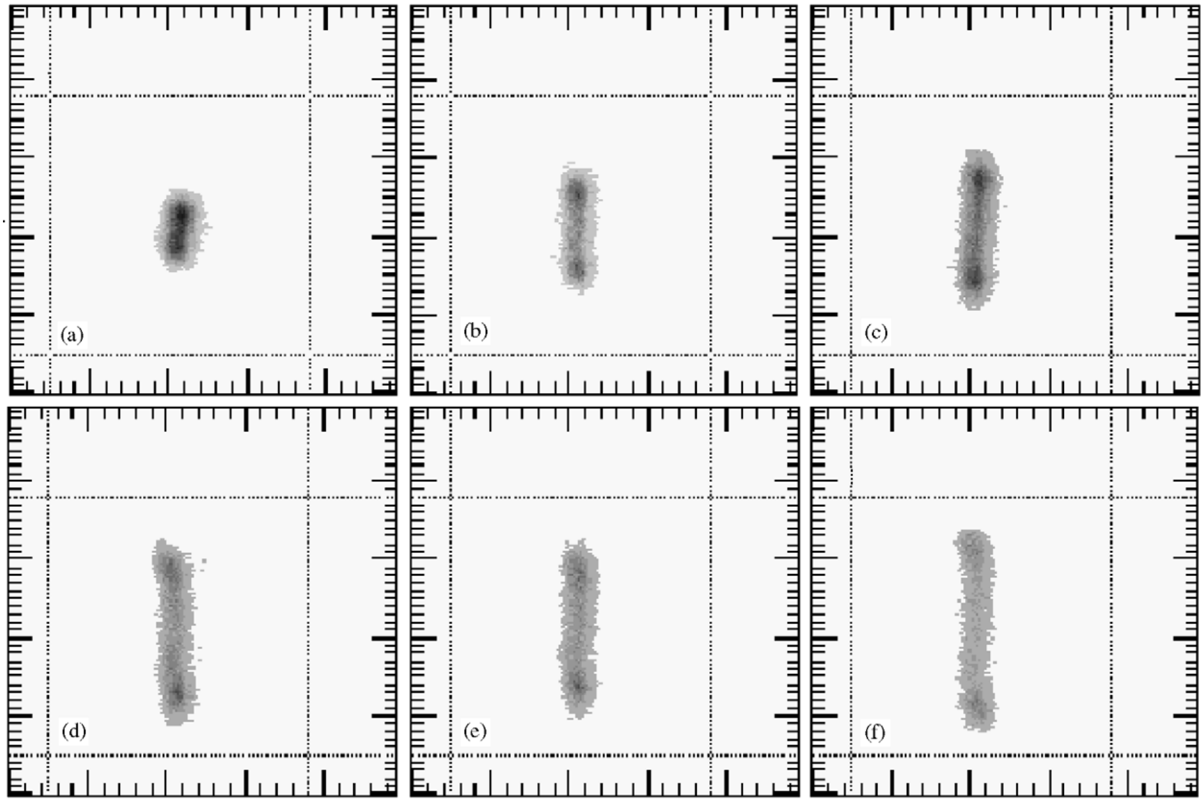

Fig. 8. Raw images of a 1.1 inner diameter capillary and 4 cm long, filled with ^{99m}Tc solution and placed in the center of the FOV for the (a) 0, (b) 1, (c) 2, (d) 3, (e) 4 and (f) 5 mm partially slotted crystal. The initial ^{99m}Tc solution was 1 m Ci/ml and the capillary to collimator distance is 5 mm. The more slotted is the crystal the better is the capillary image, when the standard Center of Gravity position reconstruction algorithm is used.

detected at the edges of the crystal. The study of charge distribution in x- and y-wires has shown that the deeper the slotting is the more focused is the charge distribution on the crossed-wired anode. Thus the simple COGA can be used in order to calculate the position of the interaction point between the photon and the crystal.

In addition special techniques, such as crystal mapping, have been proposed [15] in order to achieve accurate position calculation by using homogeneous crystals and this method has lead to very good results. If charge distribution is narrower it is expected that the accuracy of such crystal mapping will be improved. More reliable methods like fitting of two Gaussian curves, which works well in pixelized scintillators, are being tested and they show very encouraging results in the case of homogeneous crystals and we intend to apply them in position calculation in partially slotted crystals. Since spatial resolution is affected by the position calculation algorithm it is expected that the final spatial resolution will be comparable with the one obtained using pixelized scintillators.

Energy resolution in pixelized scintillators is relatively low, since the energy spectrum is the superimposition of the energy spectrum in each crystal cell. Moreover, nonuniformities of PSPMT significantly affect the measured energy response of these detectors. In partially slotted crystals a crystal cell cannot be defined since there is light spread in the homogeneous part of the scintillator. Corrections based on energy spectrum of each crystal cell cannot be performed. The energy resolution of the slotted crystals was found to be slightly better, since there is not such a strong energy dependency on the position of interaction. It should be noted that in Ref. [11] we had measured the energy resolution (FWHM) of the system and found it to be equal to 26.7%, using a 3 mm pixelized scintillator, 21% using the 3 mm homogeneous crystal and 23.5% using the 7 mm homogeneous crystal. In order to compare the results a 7 mm fully pixelized scintillator should be used, which was not available. If the results from Ref. [12] are taken into account we estimate that the partially slotted crystals will show significant improvement in energy resolution when compared with fully pixelized scintillators.

It is true that a direct comparison between the 3 mm thick fully pixelized scintillator with the 7 mm thick partially slotted is not possible. Thus we intend to further explore the performance of partially slotted crystals using Monte-Carlo simulation. We will use our own simulation code in order to study light transport in partially pixelized scintillators. Other possible geometries will be evaluated and the optimal parameters of the slotted crystals (material, slots depth, shape, wall thickness) will be determined. The results presented in this paper, as well as simulation results, will be used as a reference in order to proceed into a more detailed and quantitative study of partially pixelized crystals.

The use of such crystals in larger FOV systems (clinical cameras or dedicated cameras with four, nine or more small size PSPMTs) could provide promising results and needs to be investigated with simulation as a first step. In addition such crystals could be used in probe detectors providing approximate position information without significant cost and complex data processing.

6. Conclusions

This study has shown that partially slotted scintillators could be used as low cost alternative crystal in small FOV detectors since they provide improved sensitivity and with the appropriate data analysis good spatial resolution. Optimization of their characteristics and the position reconstruction algorithm will possibly allow the use of partially slotted crystals in such systems.

Acknowledgments

This work has been partly supported by the Greek General Secretariat for Research and Technology (GGET), by EEC RTN contract HPRN-CT-00292-2002 and by the Ministry of Education and Science of Ukraine, award 2M/182-2001. The authors would like to thank S. Majewski and A. Weisenberger of "Jefferson's lab" and R. Pani and F. Scopinaro of University of Rome "La Sapienza" for offering part of the used equipment.

References

[1] A.G. Weisenberger, E. Bradley, S. Majewski, M. Saha, IEEE Trans. Nucl. Sci. NS-145 (3) (1998) 1743.
[2] N. Schramm, A. Wirrwar, H. Halling, IEEE Trans. Nucl. Sci. NS-47 (3 (Part 3)) (2000) 1163.
[3] J.H. Kim, Y. Choi, K.S. Joo, B.S. Sihn, J.W. Chong, S.E. Kim, K.H. Lee, Y.S. Choe, B.T. Kim, Phys. Med. Biol. 45 (11) (2000) 3481.
[4] G.K. Loudos, K.S. Nikita, N.D. Giokaris, E. Styliaris, S.C. Archimandritis, A.D. Varvarigou, C.N. Papanicolas, S. Majewski, D. Weisenberger, R. Pani, F. Scopinaro, N.K. Uzunoglu, D. Maintas, K. Stefanis, Appl. Radiat. Isot. 58 (4) (2003) 501.
[5] R. Pani, R. Pellegrini, A. Soluri, G. De Vincentis, R. Scafe, A. Pergola, Nucl. Instr. and Meth. A 409 (1–3) (1998) 524.
[6] R. Pani, R. Pellegrini, F. Scopinaro, et al., Nucl. Instr. and Meth. A 392 (1987) 295.
[7] A. Weisenberger, M. Williams, R. Wojcik, S. Majewski, F. Farzanpay, A. Goode, B. Kross, D. Steinbach, Nucl. Instr. and Meth. A 409 (1998) 520.
[8] S. Majewski, E. Curran, C. Keppel, D. Kieper, B. Kross, A. Pulumbo, V. Popov, A.G. Weisenberger, B. Welch, R. Wojcik, M.B. Williams, A.R. Goode, M. More, G. Zang, IEEE Trans. Nucl. Sci. NS-48 (3) (2001) 822.
[9] N.D. Giokaris, G.K. Loudos, D. Maintas, D. Papapanagiotou, K.S. Nikita, N.K. Uzunoglu, A. Karabarbounis, C.N. Papanicolas, E. Stiliaris, S.C. Archimandritis, A.D. Varvarigou, C.N. Stefanis, S. Majewski, R. Pani, F. Scopinaro, Nucl. Instr. and Meth. A 497 (1) (2003) 141.
[10] G.K. Loudos, K.S. Nikita, N.K. Uzunoglu, N.D. Giokaris, C.N. Papanicolas, S.C. Archimandritis, A.D. Varvarigou, D. Maintas, Comput. Med. Imaging Graphics 27 (4) (2003) 307.
[11] Patent France #2,237,206.
[12] N. Giokaris, G. Loudos, D. Maintas, A. Karabarbounis, V. Spanoudaki, E. Stiliaris, S. Boukis, A. Getkin, A.

Boyarintev, V. Pedash, V. Gayshan, Nucl. Instr. and Meth. A 527 (2004) 134.
[13] Gektin, V. Gavryluk, A. Boyarintsev, V. Gayshan, Invited talk, second ITBS Conference, Milos, 26–30 May, 2003.
[14] R. Pani, R. Pellegrini, M.N. Cinti, M. Mattioli, C. Trotta, L. Montani, G. Iurlaro, G. Trotta, L. D'Addio, S. Ridolfi, G.De. Vincentis, I.N. Weinberg, Nucl. Instr. and Meth. B 213 (2004) 197.
[15] M.M. Fernández, J.M. Benlloch, J. Cerdá, B. Escat, E.N. Giménez, M. Giménez, Ch.W. Lerche, J. Martínez, N. Pavón, F. Sánchez, A. Sebastià, Nucl. Instr. and Meth. A 527 (1–2) (2004) 92.