Development of TlBr arrays for hard X- and gamma-ray spectroscopy

A. Owens¹, M. Bavdaz¹, V. Gostilo², R. den Hartog¹, A. Kozorezov³, I. Lisjutin²,
A. Peacock¹, S. Zatoloka²

¹*Science Payload & Technology Division, Research and Scientific Support Department,
ESA/ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands*

²*Baltic Scientific Instruments, 26 Ganību dambis, P.O. Box 33, Riga LV-1005, Latvia*

³*Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom*

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Alan Owens^{*1}, M. Bavdaz¹, V. Gostilo²,
R. den Hartog¹, A. Kozorezov³, I. Lisjutin², A. Peacock¹, S. Zatoloka²

¹Science Payloads Technology Division, ESA/ESTEC, Postbus 299, 2200AG, Noordwijk,
The Netherlands

²Baltic Scientific Instruments, 26 Ganību dambis, PO Box 33, Riga LV-1005, Latvia

³Department of Physics, University of Lancaster, Lancaster LA1 4YB, England

ABSTRACT

TlBr is relatively unique amongst semiconductors, in view of its very high density coupled with its large band-gap. In fact, its density (7.5 g cm^{-3}) is comparable to bismuth germanate and thus it has excellent absorbing power for hard X- and gamma rays. For example, a 1 mm thick detector, has a usable efficiency of $\sim 10\%$ at 500 keV. Its lowest energy of operation is set by leakage currents at typically 1 keV. Such a wide dynamic range is ideally suited for a range of applications, such as gamma-ray astronomy, isotopic measurements for environmental redemption and particularly nuclear medicine, where small size and large stopping power are highly desirable attributes. Additionally, its band-gap energy of 2.7 eV is large enough to ensure low noise performance at room or even elevated temperatures. In this paper we assess the suitability of using TlBr arrays for X- and gamma-spectroscopy and specifically for nuclear medicine applications. For example, it is shown that the attributes of TlBr make it an ideal material for the production of intra-operative, radio-guided surgical probes, which operate in the hard X- and low energy gamma-ray regions. By using a segmented or pixelated anode design and tailoring the geometry to promote the near-field effect, most of the negative material attributes normally associated with TlBr (*e.g.* poor hole transport) can be largely negated.

Keywords: X-ray detectors, compound semiconductors, TlBr, spectroscopy

1. INTRODUCTION

Thallium bromide (TlBr) has attracted attention as an exceptional radiation detector material. Due to its high atomic number (81 for Tl, 35 for Br) it has excellent stopping power for hard X-ray and gamma rays and due to its high band-gap (2.7 eV) its operation requires no or only modest cooling. At room temperature, promising energy resolutions have been demonstrated with detectors fabricated from high-purity samples (3.3 keV FWHM at 60 keV incident energy [1]). Potentially, these properties make TlBr the material of choice for hard X- and γ -ray imaging spectrometers in applications where small weight and/or size is important (*e.g.* space astrophysics, nuclear medicine and environmental redemption). Although, our primary research is targeted towards future space missions, there are several spin-off applications that can already benefit from this research. In particular a good application is as the detection element in radio-guided surgical probes, used to locate a sentinel node of the lymphatic system invaded by breast cancer metastasis cells. To date, such probes generally use monolithic detectors fabricated from CdTe or CdZnTe. Whilst these are compact and spectroscopic, they become inefficient at higher energies because of the finite thickness of the crystals, which, in turn, is imposed by the poor transport properties of the material. They also lack directional sensitivity and the ability to effectively isolate “hot” spots in the presence of a non-uniform background. Much higher sensitivities could be achieved if *a)* a denser medium is used and *b)* the detection plane is pixelated and imaging techniques are employed. For the former, we propose using TlBr, which is $\sim 30\%$ denser than CdTe or CdZnTe. While the detection properties of monolithic detectors are dominated by the transport properties of the material, the charge response and spectroscopic

*aowens@rssd.esa.int; phone 31-71-565-5326; fax 31-71-565-4690; <http://astro.esa.int/ST-general/index.html>

performance of a semiconductor imaging array depends not only on its material properties but also on the pixel geometry. For instance, it has been demonstrated, that the ratio of pixel size to the thickness of the detector is an important factor for its charge response. This is known as the small pixel or near-field effect [2].

Figure 1. Schematic of the array showing pixel layout and dimensions.

In this paper, we evaluate the performance of a small pixelated 3×3 TlBr array of pixel size $350 \mu\text{m}$ and thickness 1.0 mm and investigate the optimization of pixel properties in a broader context, taking into account material properties (electron and hole mobility and diffusion, trapping / detrapping), fabrication details and the specific energy (-range) of interest. The overall goal is optimise both its response and energy resolution to hard X- and low energy γ -ray photons.

TlBr was originally demonstrated as a radiation detector material by Hofstadter in 1949 [3] - albeit with limited success due to purity and fabrication problems. Since this time, relatively little work has been carried out [4-10]. Recently, Owens *et al.* [1] have produced a series of monolithic planar detectors of area $\sim 3.1 \text{ mm}^2$ and thickness $\sim 800 \mu\text{m}$ with demonstrated room temperature performances of 1.8 keV FWHM at 5.9 keV and 3.3 keV FWHM at 59.54 keV . With only modest cooling (-30°C), these fall to 800 eV and 2.6 keV FWHM , respectively. The focus of this research has been to address the material, electronic and technological issues that need to be solved in order to develop practical, hard X- and γ -ray detectors. While these resolutions are the best yet reported, the line spectra show the classical hole tailing associated with TlBr. Following on from this work, we have now produced the first small-format array to explore array design and operation and particularly possible improvements in spectral acuity using the small pixel effect. The pixel size was chosen primarily by *a)* the ease with which they could be instrumented, *b)* the ability to carry out detailed and spatially resolved metrology at the pixel level and *c)* to satisfy the small pixel criteria as elucidated in Eskin, Barrett and Barber [11].

Figure 2. Photograph of the completed detector/preamp assembly. The insert in the upper left shows an internal view of the array directly under the Be window (see text).

2. EXPERIMENTAL

A TlBr array was fabricated from a boule, grown by the Bridgeman-Stockbarger method. The boule was sawn into several 1 and 2 mm thick wafers using a wire saw. These were lapped with diamond paste, followed by mechanical and

chemical polishing to an optically smooth and transparent finish. A crystal of dimensions $2.7 \times 2.7 \times 1.0 \text{ mm}^3$ was diced out of the most optically clear wafer and gold contacts evaporated onto its planar surfaces through a shadow mask. The contacts consist of a plane cathode covering the whole of one crystal surface and a 3×3 pixel structure, surrounded by a guard ring on the other surface. The device is illuminated through the cathode. A schematic of the detector is shown in fig. 1. The pixel dimensions were $350 \times 350 \mu\text{m}^2$, with an inter-pixel gap of $100 \mu\text{m}$. The typical leakage currents at a bias of 50 V were $\sim 24 \text{ pA}$ at room temperature and $\sim 2 \text{ pA}$ at -10°C . The pixel resistivities were found to be in the range $(6 - 10) \times 10^{10} \Omega \text{ cm}$ and the inter-pixel resistance $\sim 500 \text{ G}\Omega$ with 50V differential between pixels. The array was mounted to a dielectric substrate, which in turn, is coupled to a three-stage Peltier cooler, capable of cooling the device to $\sim -40^\circ\text{C}$. Each pixel was instrumented with its own resistive feedback preamplifier whose front-end components are also mounted on the substrate, close to the array. Contacting is achieved *via* wire-bonding. Initial tests showed that biasing the detector to preferentially collect holes from the illuminated electrode gave significantly better spectral resolution than collecting electrons. This reflects the poor $\mu\tau$ product for holes in TlBr, which is more than a factor of 20 lower than that for electrons [1]. The rest of the analog chain is mounted externally on an outer vacuum vessel. This vessel has a thin Be window to facilitate the efficient transmission of soft photons to the detector. In fig. 2 we show the completed detector assembly. The preamplifier outputs are fed to spectroscopy amplifiers and then to a linear fan-in whose output is digitized by an Amptek MCA8000 12-bit ADC and stored on a PC.

Figure 3. Energy-loss spectra of a) ^{241}Am , b) ^{109}Cd , c) ^{57}Co and d) ^{137}Cs measured by the center pixel. The bias voltage was -400V and the detector temperature -30°C . Note that the lines are clearly resolved with little evidence of the hole tailing, normally observed in planar TlBr detectors.

Figure 4. The energy resolution of the center pixel measured from soft X-ray to γ -ray energies. The array temperature was -30°C . The solid line shows the best-fit resolution function to the combined data set (see text). The individual components to the FWHM are also shown (see text).

The X-ray characterization of the array was carried out using ^{55}Fe , ^{109}Cd , ^{57}Co , ^{137}Cs and ^{241}Am radioactive sources. In Fig. 3 we show the response of the center pixel to the latter four sources at a bias of 400 V and an amplifier shaping time of $6\mu\text{s}$. These sources were used because they have lines, which encompass the energies of the radionuclides commonly used in nuclear medicine, *i.e.*, ^{125}I (35 keV), $^{99\text{m}}\text{Tc}$ (140 keV), ^{111}In (171 keV and 247 keV), ^{131}I (356 keV). The acuity of the spectra shown in fig. 3 are clearly enhanced, with little evidence of the strong hole tailing component normally observed in planar TlBr detectors (*e.g.*, see Owens *et al.* [1]). The FWHM resolutions ΔE , under full-area illumination, range from 1.8 keV at 5.9 keV to 29 keV at 662 keV. The measured resolutions, ΔE , were found to be well-fit by a semi-empirical function of the form,

$$\Delta E = 2.355 \sqrt{F \varepsilon E + \left(\Delta e / 2.355 \right)^2 + a_1 E^{a_2}}, \quad (1)$$

where the first term in the square root represents the component due to Fano noise, the second, the electronic noise of the system and the third term, noise due to incomplete charge collection caused by charge trapping. Here, F is the Fano factor (assumed to be 0.14), E is the incident energy, ε is the electron-hole pair creation energy (6.5 eV [12]), Δe is the FWHM electronic noise width as measured with a precision pulser (1.7 keV FWHM) and a_1 and a_2 are semi-empirical constants determined by best-fitting. The solid line in fig. 4 shows the best-fit resolution function and the broken lines its individual components. From this figure, we see that electronic noise dominates the response below 60 keV, while trapping noise dominates above. Lastly, the overall response of the array was found to vary significantly from pixel to pixel. For example, the energy resolutions of the other pixels can be up to a factor of three worse than those shown in fig. 4. We attribute this to material damage introduced during the fabrication process.

The spatial uniformity of the array was evaluated at the HASYLAB synchrotron radiation research facility [13] by raster scanning a 20 keV monochromatic pencil beam of size $50 \times 50 \mu\text{m}^2$, across the entire array with a spatial

resolution of 30 μm . Spectra were accumulated for fixed time intervals (3.5 s) at each position on a 52×52 spatial grid which covered the array. The total count rate above a 3 keV threshold, the peak centroid position and the FWHM energy resolution at each position were determined by best-fitting. The measured distribution of the centroid, or gain of the array is shown in fig. 5 as a surface plot. From the figure, we can see that except at the corners, the gain is reasonably uniform over the surface of each pixel and over the entire array. In fact, the average non-uniformity seen in each distribution is consistent with the expected statistical variations, *i.e.*, 0.3%. The spatial distribution also reflects the uniformity of the electron $\mu\tau$ product throughout the array.

Figure 5. The spatial response (*i.e.*, the gain) of the array, mapped at HASYLAB using a $50 \times 50 \mu\text{m}^2$, 20 keV X-ray beam. These data were derived from individual spectra accumulated at 2704 positions across the array.

3. THEORY

3.1 Small-pixel or near-field effect

Recently, Barrett, Eskin and Barber [1] have shown that the deleterious effects of hole trapping are greatly reduced if the pixel dimension, w , is made small relative to the detector thickness, L . This is generally referred to as the small-pixel, or near-field effect. It can be understood within the context of Ramo-Shockley's theorem by the presence of highly non-uniform weighting potentials $\Phi_w(\mathbf{x})$ induced in detectors with a small pixel geometry [11]. An illustration of this effect is given in Fig. 6. If an electron moves inside the volume of the detector, in the electrical field between the (negatively biased) electrode and the (grounded) pixel, from position $\mathbf{x}_1$ to $\mathbf{x}_2$, the charge induced on an integrating capacitor connected to the pixel will be $Q = e[\Phi_w(\mathbf{x}_2) - \Phi_w(\mathbf{x}_1)]$ (and $-Q$ in the case of a hole). If no charge gets lost underway, and the integration time on the capacitor is taken longer than the drift time from photon absorption site to pixel and electrode, all the charge generated by the photon absorption is collected and the pixelated geometry does not have an advantage over a planar (or 'single pixel') geometry other than facilitating imaging. However, if one of the charge carriers is easily trapped (such as the holes in TlBr), the near field effect provides a clear advantage over the planar geometry. In the latter case the charge Q_e induced by an electron created at position z_0 and making it to the pixel is simply $Q_e = ez_0/L$. A hole would travel in the opposite direction and would it reach the electrode, the contributed charge is $Q_h = e(L - z_0)/L$, so that $Q_e + Q_h = e$. In this idealized case, one would detect for monochromatic photons a delta peak at eN_0 (with $N_0 = E/\epsilon$ the initial number of electron-hole pairs), convoluted with an exponential photon absorption probability distribution for thick detectors. On the other hand, if the hole is trapped very quickly, the total integrated

Figure 6 *a, b*. Illustration of the weighting potentials $\Phi_w(x)$ for two different ratios of pixel size to detector thickness. Contour lines are equivalent with the fraction of the total charge generated at $z=1$ that is so far detected, when the electrons are drawn towards the pixel at $z=0$ mm, and all holes are lost. Thick black lines indicate the location of the pixels. *c*. The fraction of the generated charge that is actually measured as a function of the absorption depth of the photon, for different pixel geometries, characterized by the ratio of the pixel size w to the detector thickness L .

charge is just Q_e , which thus depends on photon absorption position. In that case, the detected charge is smeared over the entire range from 0 to eE/ϵ . Above a pixel of finite size, the electrons contribute little to the induced charge during most of their journey through the pixel. Only when they move near the pixel the major fraction of the induced charge is generated. This is illustrated in Fig. 6c where the accumulation of induced charge is plotted as a function of height above the pixel, for different pixel geometries. Consequently, there is a considerable range of absorption heights z_0 away from the pixel, starting from which an electron will induce (almost) the full charge e on the pixel. Electrons created in this range will contribute to a sharp peak in the measured spectrum. This range will be larger, and hence the peak sharper, for smaller pixels.

3.2 Experimental verification

The small pixel effect is experimentally demonstrated in Fig. 7a, in which we have over-plotted one of the ^{241}Am spectra shown in Fig. 3a ($w/L = 0.35$; broken line), with a spectrum obtained with a $2.7 \times 2.7 \times 0.8 \text{ mm}^3$ planar detector ($w/L = 3.4$; solid line) fabricated from the same wafer material and using the same contacting technology. The energy scale and event counts of the spectrum obtained with the planar detector have been renormalized to those of the pixel detector for the Np $L\alpha$ line at 13.64 keV. At this energy, it is assumed that X-rays interact so close to the cathode that both devices are 100% efficient. From the figure, it is clear that the gains of the planar and pixel detectors and therefore their charge collection efficiencies (CCEs) are different, since the apparent measured energy-losses become increasingly divergent at higher energies. At 59.54 keV, the CCE of the pixel detector is 22 % larger than the planar device. Clearly, the tailing due to hole trapping is greatly reduced and the amplitude of the nuclear line is increased. Note that the bias applied to the planar detector was considerably larger than that applied to the pixel detectors (250 V as opposed to 170 V), which accounts for its better spectral resolution at low energies.

In Fig. 7b we show simulated spectra based on a refinement of the calculations of Eskin, Barratt and Barber [11] which include diffusion and the material properties of our TlBr. The detector and pixel geometries, bias voltages, and operation temperatures were chosen identical to the experimental values. The photo-absorption sites are distributed according to the expected absorption characteristics of TlBr. The values for the mobility and lifetimes of electrons and holes used in these simulations are $\mu_e = 20 \text{ cm}^2/\text{Vs}$; $\tau_e = 30 \text{ }\mu\text{s}$; $\mu_h = 1 \text{ cm}^2/\text{Vs}$; $\tau_h = 1 \text{ }\mu\text{s}$. These values do reflect the measured $\mu\tau$ products for electrons and holes. Both spectra were convolved with a Gaussian shaped pulser of FWHM 690 eV to account for the additional line broadening due to electronic noise. Although we did not attempt to model the neptunium X-ray lines, nor the difference in gain between the two detectors it is clear that the simulated spectra bear great similarity to the experimental spectra.

Figure 7 *a.* Demonstration of the small pixel effect in TlBr, in which its spectral properties are greatly influenced by pixel geometry and specifically the ratio of the pixel dimension, w , to its thickness L . We show two ^{241}Am spectra - one recorded by pixel 2-2 ($w/L = 0.35$, broken line) and the other by a $2.7 \times 2.7 \times 0.8 \text{ mm}^3$ planar detector ($w/L = 3.4$, solid line). *b.* Two modelled 60 keV spectra, with matching properties. The spectra have been convolved with a Gaussian pulser with a FWHM of 690 eV.

4. APPLICATION TO NUCLEAR MEDICINE

For sentinel node detection, the present array is too small in area, although its thickness is comparable to commercial products. Since the size of the sentinel node can be of the order of several tens of mm^2 , an active area of about 100 mm^2 would seem prudent. The minimum number of pixels considered should be 4 in a 2×2 array because 1) the tumor itself can extend over the area of the probe and 2) subdividing the active area in this way will allow a more accurate location of the peak activity using bi-directional gradient techniques [15]. These methods have the added advantage of improving the signal to noise for very small lesions, by making the probe less sensitive to “take-up” radiation from the rest of the body or “shine-through” radiation from the primary injection site. In fact, hot-spots, of volumes of a few tens of cubic mm^3 or less, could be detected. However, the goal should be not only to locate the node but also to image the surrounding area. Therefore, the number of pixels should be large enough to locate the sentinel node with good sensitivity and have good enough spatial resolution to map the distribution of possible carcinomas.

4.1 Optimum detector thickness

In Fig. 8 we show the calculated efficiency for the present array, from which we can see that it still has a usable efficiency of 10% at 500 keV. For comparison, we also show efficiency curves for 2.5 mm, 5 mm and 10 mm thick TlBr as well as the efficiency for a 3 mm thick CdTe detector. This is the thickest material available in surgical probes currently available [14]. For nuclear medicine applications we should consider an efficiency of, say, 30% as the lowest acceptable, because of patient dose issues. Therefore, the current detector has an effective upper energy range of $\sim 250 \text{ keV}$. We note that below 200 keV, 1 mm of TlBr is equivalent to 3 mm of CdTe. From Fig. 8 we find that to properly detect the 5 most common radionuclides used in nuclear medicine, a thickness of at least 2.5 mm of TlBr should be considered a requirement. In particular since even with 2.5 mm TlBr the efficiency for detecting 356 keV γ -rays from ^{131}I is only $\sim 30\%$. Currently CdTe and CdZnTe probes do not exceed 3 mm and so at the present time, this energy range is covered by using more than one probe, with the highest energies monitored using a scintillator/photodiode combination.

Figure 8. Calculated efficiency of the array. For comparison, we also show efficiency curves for 2.5 mm, 5 mm and 10 mm thick TlBr and well as the efficiency for a 3 mm thick CdTe detector. This is the thickest material available in surgical probes currently available [14]. The line energies of the 5 most common radionuclides used in nuclear medicine are also shown.

4.2 Pixel size

The charge transport is governed by combination of drift and diffusion. In the simplest case, when the drift velocity is sufficiently large, diffusion will not significantly change the (vertical) charge drift motion, so we only consider diffusion in the two lateral directions. Then the diffusion of the induced charge distribution in the direction perpendicular to the drift motion sets a natural limit to the smallest size of the pixel and therefore the maximum number of pixels in the probe. Obviously, the smallest pixel size should be sufficiently large to collect all of the liberated charge. The minimum pixel size is now defined by the diameter of the region over which the charge carriers will diffuse laterally during $t_{\max}$, given by:

$$w_{\min} = 2\sqrt{4Dt_{\max}} = 4L\sqrt{\frac{k_B T}{eV_b}} \quad (2)$$

Here the diffusion constant D is given by the familiar Einstein relation, $D = \mu k_B T / e$, where μ is the mobility, k_B is Boltzmann's constant, T is the temperature, V_b is the applied bias voltage and e is the electronic charge. The maximum time the charge carriers will diffuse is equal to the maximum drift time, $t_{\max} = L / v_{\text{drift}} = L^2 / \mu V_b$, which occurs when the charge carrier is created opposite to the electrode it drifts towards, and crosses the entire detector thickness L . Interestingly, the mobility of the charge carriers or any other material parameter does not enter; the minimum pixel size is determined by the thickness of the detector and two operational parameters, temperature and bias voltage. Making pixel sizes smaller than $w_{\min}$ will not improve spatial resolution because charge divergence will cause a response in neighbouring pixels as well. If we now consider a detector thickness, L , of 2.5 mm (which will give an efficiency of ~30% for the highest energy photons from ^{131}I), then the minimum pixel size would be 50 μm , assuming $T = 300\text{ K}$ and $V_b = 200\text{ V}$. In this case, the number of pixels would be over 10^4 (!) and the ratio of w/L would be ~0.02.

There are however other aspects that need to be taken into consideration for pixels this small. As Eskin *et al.* point out the escape of K-shell X-rays, straggling of energetic electrons and Compton scattering will also cause a spread in the charge distribution. Also, the smallest pixel size is unlikely to be optimal when considering charge collection. The most uniform distribution of pulse heights with absorption depth, and thus the lowest FWHM for a spectral line, was obtained for a w/L ratio of 0.25 [11]. Applying this ratio to our case, the pixel size would be 625 μm . Now assuming an inter-pixel gap of 100 microns and a 200 μm guard-ring surrounding the array, the array would be of size 13×13 pixels. Such an array could be instrumented by flip-chip bonding to an ASIC, for example, one based on the MEDIPIX design [16]. From section 3.1, we can conservatively estimate at least a 10-fold improvement in peak to tail ratio with this geometry over a conventional monolithic design.

5. SUMMARY

In summary, the attributes of TlBr make it an ideal material for the production of intra-operative probes. By using a segmented or pixelated anode design and tailoring the geometry to promote near-field effects, most of the negative material attributes normally associated with TlBr (*e.g.* poor hole transport) can be largely negated.

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REFERENCES

- [1] A. Owens, M. Bavdaz, G. Brammertz, V. Gostilo, H. Graafsma, A. Kozorezov, M. Krumrey, I. Lisjutin, A. Peacock, A. Puig, H. Sipila, S. Zatoloka, Nucl. Instr. and Meth., in press.
- [2] H. Barrett, J. Eskin, H. Barber, Phys. Rev. Letts., **75**, 156, 1995.
- [3] R. Hofstadter, Nucleonics, April, 1949.
- [4] I.U. Rahman, W.A. Fisher, R. Hofstadter, J. Shen, Nucl. Instr. and Meth., **A261**, 427, 1987.
- [5] K.S. Shah, F. Olschner, L.P. Moy, J.C. Lund, W.R. Squillante, Nucl. Instr. and Meth., **A299**, 57, 1990.
- [6] F. Olscher *et al.*, Nucl. Instr. and Meth., **A322**, 504, 1992.
- [7] K. Shah, J. Lund, F. Olschner, L. Moy and M. Squillante, IEEE Trans. Nucl. Sci., **36**, 199, 1989.
- [8] K. Hitomi, O. Muroi, T. Shoji, T. Suehiro, and Y. Hiratate, Nucl. Instr. and Meth., **A436**, 160, 1999.
- [9] K. Hitomi, T. Murayama, T. Shoji, T. Suehiro, and Y. Hiratate, Nucl. Instr. and Meth., **A428**, 372, 1999.
- [10] A. Owens, M. Bavdaz, I. Lisjutin, A. Peacock, S. Zatoloka, Nucl. Instr. and Meth., **A538**, 123, 2001.
- [11] J. Eskin, H. Barrett, H. Barber, J. Appl. Phys., **85**, 647, 1999.
- [12] C.A. Klein, J. Appl. Phys., **4**, 2029, 1968.
- [13] http://www-hasylab.desy.de/facility/experimental_stations/stations/X1.1_ROEMO_II.htm
- [14] M. Ricard, Nucl. Instr. and Meth., **A458**, 26, 2001.
- [15] W. Dusi, D. Bollini, C. Moroni, M. Ricard, Proc. IEEE Trans. Nuc. Sci., **2**, 754, 1998.
- [16] S.R. Amendolia *et al.*, Nucl. Instr. and Meth., **A422**, 201, 2001.