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A PSPMT based auroral X-ray imager

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Abstract

A pinhole camera based on the use of a 3 in. square position-sensitive photomultiplier (PSPMT) to view a two-dimensional segmented CsI(Tl) scintillation crystal has been designed to operate in the range 2 to 200 keV. It has also been used to generate extended test images by rotating two radioactive sources of different energies in the the field of view. The optical characteristics of the system have been simulated using a Monte-Carlo package in order to optimise the detector crystal geometry. The detector performance has also been investigated experimentally as a function of crystal dimensions, and measurements made using different readout techniques are presented. Also outlined is a design for an auroral imager based on the use of an array detector modules which will form part of the Auroral Imaging Observatory (AURIO), selected for inclusion within the payload complement of ENVISAT II. This will be located on a polar orbiting platform at an altitude of 800 km.

1. Introduction

Previous studies have shown that the auroral X-ray spectrum extends from a few keV to more than 200 keV. The current proposal for the Auroral Imaging Observatory (AURIO), envisages the use of two complementary instruments in order to provide efficient coverage for this wide range of energies [1]. The first of these detectors, AURIX-L, is a position-sensitive multiwire gas-proportional counter designed to detect X-rays below 10 keV. The second detector, AURIX-H, comprises several position-sensitive scintillation counters based upon the position-sensitive photomultiplier tube (PSPMT) from Hamamatsu, whose imaging characteristics have been demonstrated in previous works [2–4].

We have investigated the possibility of reducing the low-energy detection threshold of AURIX-H through the careful design of the scintillator crystal and the application of a different readout electronics technique. Previous tests made using a single small crystal and multiwire readout suggested that the low energy threshold could be reduced to significantly below 6 keV [2]. Such a development could avoid the need for two separate AURIX instruments with a corresponding increase in the sensitivity at all energies within the existing payload allocation.

2. Experimental setup

This paper describes the results obtained with an adjustable aperture pinhole collimator and a 676-element two-dimensional segmented CsI(Tl) crystal array viewed by a Hamamatsu R2487, 3 in. square PSPMT. Test images are presented which illustrate the detector performance at 122 keV (^{57}Co), and at 60 keV (^{241}Am). The effectiveness of readout techniques based upon conventional resistive charge-division, as well as the multi-channel readout method which uses Gaussian-fitting and centroiding algorithms to interpolate the data and hence determine the event location will be compared. A suitably extended test source was generated by rotating two 5 mm diameter radioactive sources in the field of view of the pinhole camera (see Fig. 1). This provided a test scene similar to that which might be expected from an auroral arc.

3. Detector crystal design

Since the auroral X-ray spectrum is very steep at low energies (see Fig. 2), it is particularly important to arrive at an optimum detector crystal design in order to be able to use a scintillation counter for imaging at these unusually low energies. This objective can only be achieved if one can localize the spread of the scintillation photons within the detector crystal, thus reducing the width of the PSF and increasing the SNR of the photodetector response. This

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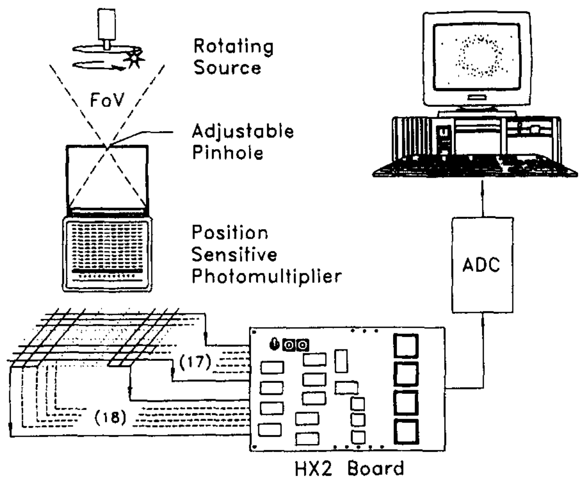

Fig. 1. Arrangement of rotating X-ray source and imager.

subsequent increase in the photon flux density incident upon the photocathode is expected to yield improved Poisson statistics and correspondingly superior spatial resolution.

Monte-Carlo simulations were used to compare the optical characteristics of both thin continuous and segmented scintillator crystals. These indicated that the spread in the spatial distribution of scintillation photons incident upon the photocathode, and hence the size of the emerging photoelectron cloud might be much better constrained with the use of optically isolated segmented detector crystals (see Fig. 3a and 3b).

Previous measurements made using arrays of small CsI(Tl) scintillator crystals that are optically isolated using white TiO_2 loaded epoxy have shown significant advantages over the use of continuous crystals, especially when optimum light collection is required for low energy X-ray detection and a broad band of incident energies is envisaged [2,5].

4. Readout system

The method used to read out the charge from the crossed-wire anodes of the PSPMT is also important in optimising the performance of the PSPMT for use at low energies. In order to determine the most suitable readout we have compared both the conventional resistive charge-

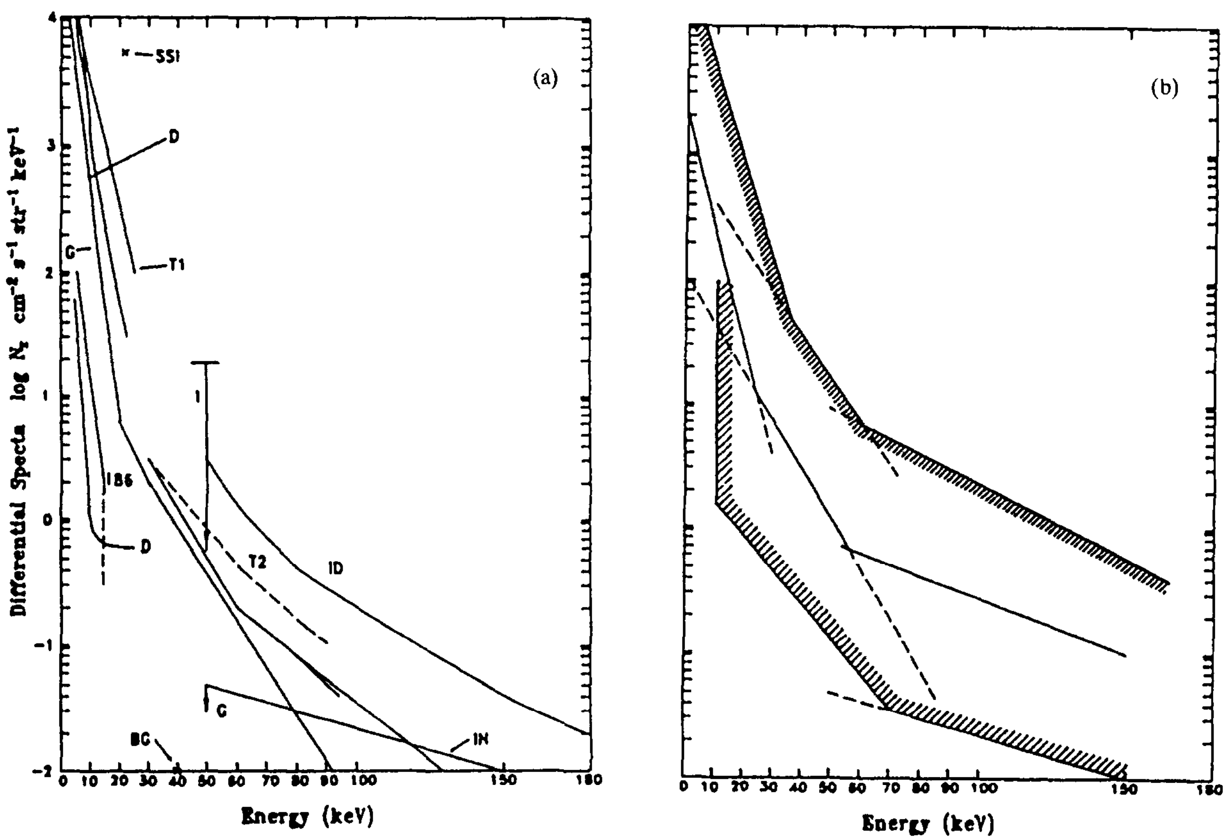

Fig. 2. A compilation of available auroral X-ray spectra.

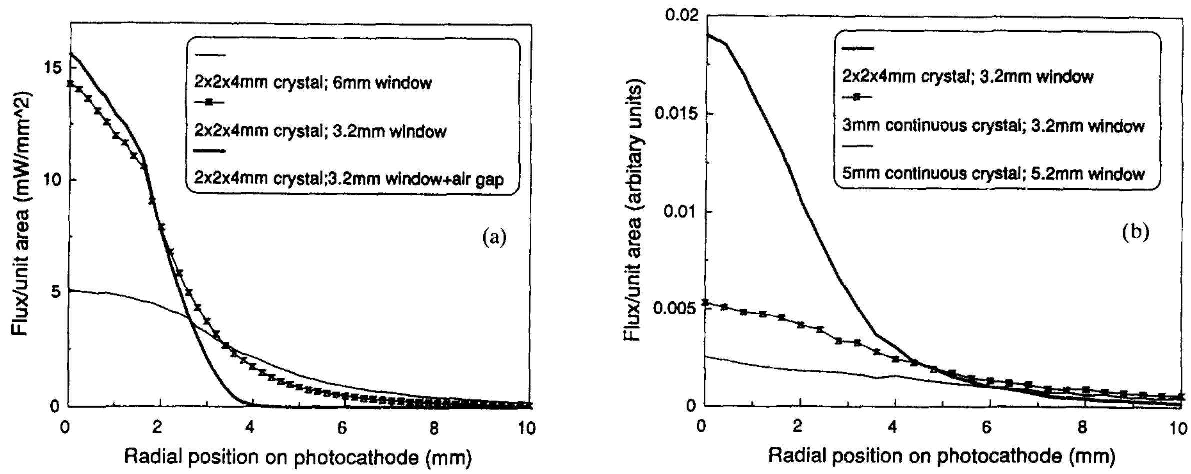

Fig. 3. (a) Optical Monte-Carlo simulations illustrating the effect of glass window thickness on light spread. (b) Optical Monte-Carlo simulations illustrating the effect of crystal dimensions on light spread.

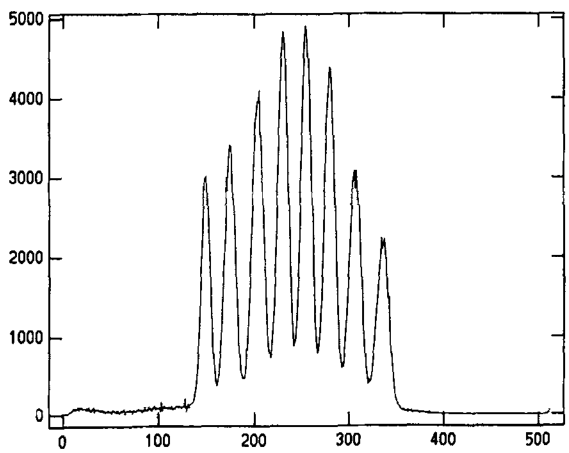

Fig. 4. 3 mm crystals illuminated by 122 keV (^{57}Co) with conventional readout. Detector response is 2.1 mm FWHM.

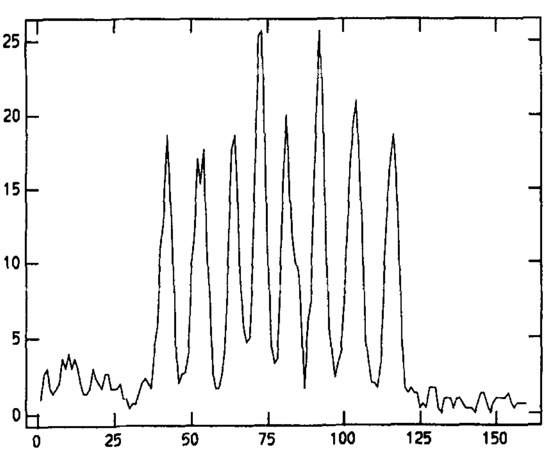

Fig. 5. 3 mm crystals illuminated by 122 keV (^{57}Co) with multi-wire readout. Detector response is 1.5 mm FWHM.

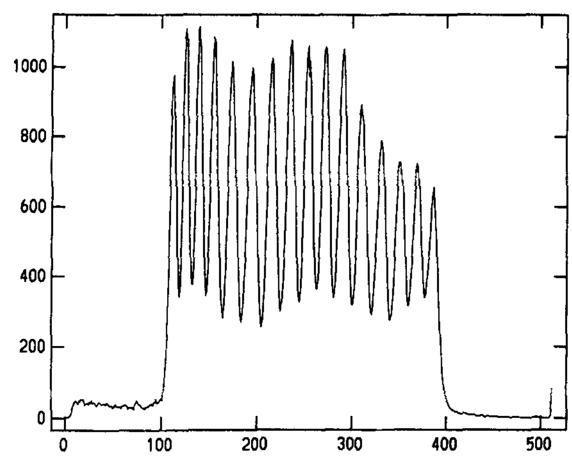

Fig. 6. 2 mm crystals illuminated by 122 keV (^{57}Co) with conventional readout. Detector response is 1.5 mm FWHM.

division method, with a VLSI multi-channel charge readout technique.

4.1. Conventional readout

Conventional readout methods use a resistor chain to divide the charge collected by each anode wire and a simple interpolating algorithm is then used to reconstruct the position of the interaction in the detector [2–4]. One problem associated with this readout technique is that the crossed-wire anodes accept the dark current from the whole of the photocathode. This causes the lowest energy deposit in the scintillator which can be detected by the photodetector to increase, and we believe causes a disproportionate weighting of uncertainty in the reconstructed position towards the edge of the tube's sensitive area.

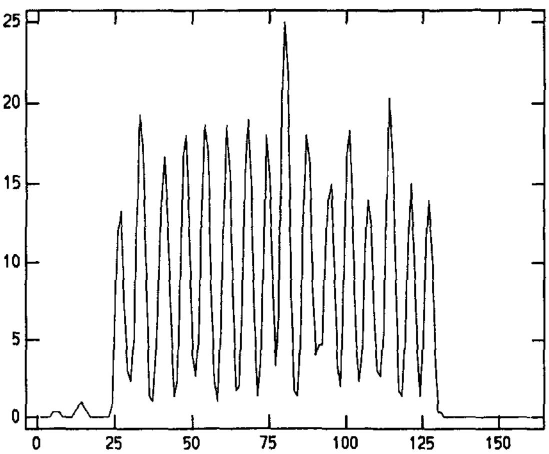

Fig. 7. 2 mm crystals illuminated by 122 keV (^{57}Co) with multi-wire readout. Detector response is 1.2 mm FWHM.

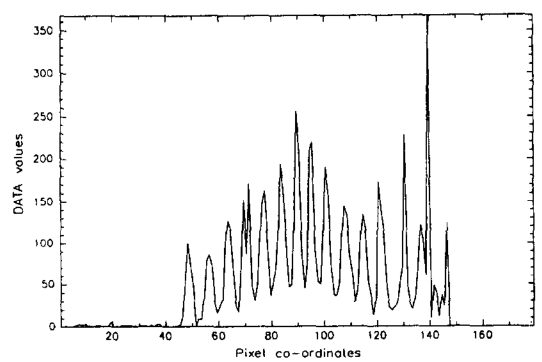

Fig. 8. Response function of CsI(Tl) ladder illuminated with 22 keV -rays.

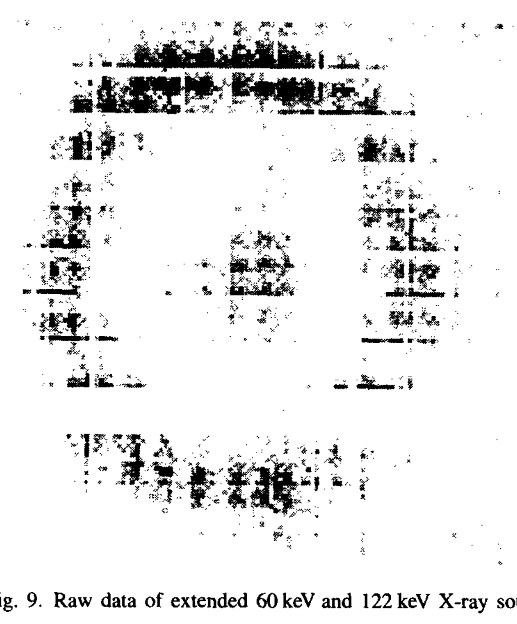

Fig. 9. Raw data of extended 60 keV and 122 keV X-ray source.

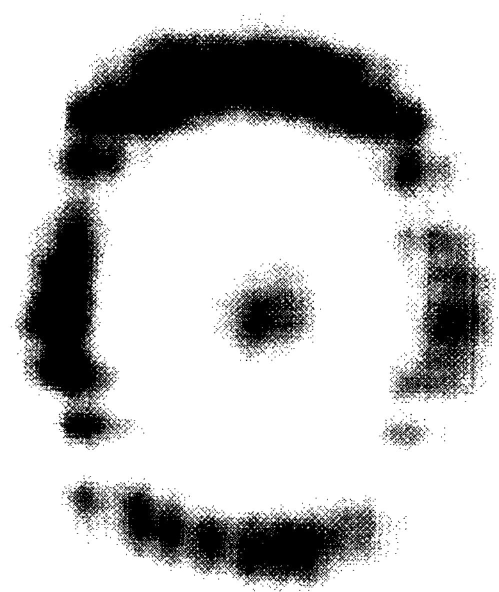

Fig. 10. Extended 60 keV and 122 keV X-ray source after smoothing.

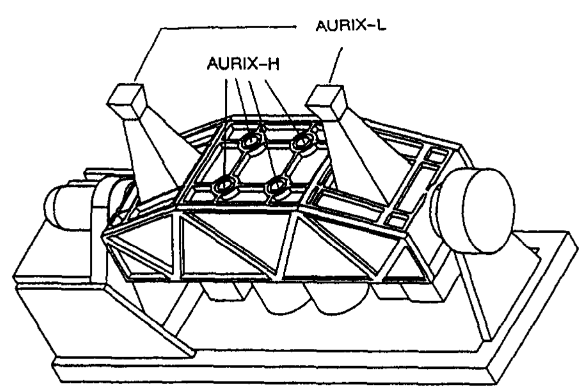

Fig. 11. A proposed imager for auroral X-rays.

4.2. HX2 readout

Earlier work has suggested that by directly sampling the charge collected upon individual anode wires, the charge contribution due to dark current would approximate to the line integral of the dark current from a smaller region of the photocathode which corresponds to the wire being sampled. Indeed, preliminary tests with such a readout system indicated the low energy threshold to be below 6 keV whilst at the same time providing better position linearity across an extended sensitive area of the tube [2].

The tests reported here were made using the HX2 VLSI multi-channel charge-integrating amplifier designed by DRAL. For this evaluation phase, a simple system comprising four HX2 16 channel amplifier chips, together with the timing circuitry and decoding logic, were mounted on a prototype test board. The integration period is determined by a presetable counter generating a number of clock cycles between two pulses which reset the inputs of all 64 channels. Thus the synchronous integration of the deposited charge is assured, with the integrated charge being read out from each chip sequentially.

Whilst the range of integration times possible with these chips extends from 5 μs to 100 ms, for these tests the minimum integration time was restricted to 40 μs due to the speed of our existing data acquisition system. This is much longer than the 15 μs used in earlier work in which 5.9 keV (^{55}Fe) has been successfully detected [2], and has naturally led to a higher, low energy threshold of about 15 keV in these tests. Such a readout system is by no means ideal, but was used for convenience. However, the present system does serve as a valid test of the principles involved.

5. Results

5.1. The optical Monte Carlo

Monte-Carlo simulations of the optical characteristics of a variety of detector crystal designs have been made using GUERAP V. In each case, the FWHM of the light pool reaching the photocathode has been estimated. By running simulations which include the crystal, optical coupling layer, and the glass window of the PSPMT, we have been able to directly compare both the 3 in. square (R2487), and the 5 in. diameter circular (R3292) tubes from the Hamamatsu family of position-sensitive photomultipliers. Simulations suggest that the light spread in the 6.0 mm thick glass window of the R3292 tube accounts for an increase in the FWHM value of the radial photon distribution of approaching 100% and a reduction in the peak photon flux of 60% compared with the thinner 3.2 mm entrance window of the R2487 tube (see Fig. 3a). Demonstrated also is the effect of introducing a 50 μm air gap between crystal and glass window. This has the effect of cutting off the long tail of the PSF and slightly increases the density of the photon flux at the centre of the crystal. For imaging auroral X-rays, where very accurate event location is desired, this technique could prove useful, but could equally well be applied to nuclear medicine or to the monitoring of contaminated areas within the nuclear industry [7]. Subsequent measurements of a range of segmented detector crystals have demonstrated good agreement with these simulated data, and we found that when viewing even the largest array having 3.5 mm pitch, adjacent crystals could not be spatially resolved with the R3292 PSPMT.

We have also compared both continuous and segmented crystals, and the effect of crystal dimensions upon light spread. From these simulations it is evident that small, segmented crystals exhibit markedly superior spatial performance when compared with continuous crystals of equal and smaller thickness (see Fig. 3b).

5.2. Detector response

Recent measurements, together with earlier work, have used a variety of incident photon energies to illuminate one-dimensional detector of crystals having different sizes and crystal pitches [5]. These arrays, viewed in turn by the 3 in. square PSPMT, have been read out using both resistive-charge division, and multi-wire readout methods, comparing the response function for each detector at each energy. The results of these measurements for 3 mm and 2 mm crystals, having a crystal separation of 500 μm, when uniformly illuminated by 122 keV photons (^{57}Co), are presented in Fig. 4–7. It is clear from these results that for arrays of small crystals in particular, the peak-to-valley ratio is improved by individually sampling the charge from each anode wire. This in turn improves the accuracy of event location in the reconstructed image.

The problem associated with segmented detector crystals is all too apparent from these measurements. Because the response function of the detector is far from flat with uniform illumination even at low energies and it becomes necessary to rebin the image so that events located within each scintillator crystal are uniformly redistributed over the whole area of each crystal. Thus each scintillator crystal effectively becomes one image pixel, resulting in a contiguous image which represents the true resolution of the imager. Also, a smoother image can be achieved if the scintillator crystal geometry is chosen such that the photon PSF of each crystal overlaps sufficiently with that of its neighbours that the peak-to-valley ratio approaches zero for a uniformly illuminated crystal. This might occur if the crystal pitch and the crystals themselves were much smaller than the uncertainty of the reconstructed event. Alternatively this can be achieved after the image has been formed by simply convolving each data point in turn with a Gaussian having the same FWHM as the pitch of the array. We have performed this simple convolution in Fig. 10 using a subroutine called GAUSS.

5.3. Low energy threshold

The low energy detection threshold of the detector in its current configuration is limited by the use of a much longer integration time than is desirable because of the limitations of our present data acquisition system. The level of charge due to the dark current is typically ~100 times more than expected with flight electronics. Nevertheless, a 22 keV (Ag) X-ray fluoresence source has been used to illuminate a one-dimensional CsI(Tl) detector crystal array and the signal from the PSPMT subsequently read out using the HX2 prototype test system. The response function of this detector for 22 keV incident photons is presented in Fig. 8.

The theoretical 5σ threshold achievable with the present system is limited to about 15 keV, although with the implementation of the faster data acquisition system, a 5σ threshold of 2.4 keV should be possible.

5.4. Imager performance

Test images have been obtained by rotating 122 keV (^{57}Co) and 60 keV (^{241}Am) sources in the field of view of the detector where the outer ring represents 60 keV and the centre spot 122 keV. Using the centroiding interpolating algorithm, the uncertainty in the reconstructed image yields a profile of the PSF which resembles a delta function convolved with a Gaussian. The PSF is sharper at higher energies due to Poisson statistics which subsequently leads to events being preferentially reconstructed towards the centre of each crystal in the array, with the consequence that the image takes on a very pixellated appearance (see Fig. 9). This figure also shows some other artifacts in the image (gaps) which correlate well with previously observed dynode support structures within the PSPMT itself.

Clearly one could rebin the data in such a way that events within each crystal are uniformly redistributed within each pixel and corrected to give a contiguous appearance to the image.

6. A proposed auroral imager

It has been proposed that several imaging detectors of the type we have discussed will be mounted beneath a platform placed in an 800 km polar orbit. Illustrated in Fig. 11 is a line representation of the present proposal for such an arrangement comprising two AURIX-L and four AURIX-H detectors. The AURIX-H detectors have adjustable aperture pinhole collimators and the instruments themselves are mounted on a tilt-table which is all controllable via a telemetry link from the ground. Obviously the mass and space currently occupied by the AURIX-L detectors would accommodate several more of the detectors that we have described.

7. Conclusions

Using Monte-Carlo simulations we have designed a scintillation counter which is suitable for imaging the aurora at low energies. These simulations suggest that event localization can be further improved through the use of segmented detector arrays and the possible addition of a small air gap between the detector crystal and the tube. Despite the limitations of the data acquisition system employed, we have shown that for imaging applications, where accurate event location is of critical importance, the HX2 multi-wire readout offers significant performance advantages over the conventional resistive charge-division technique. Using this configuration we have successfully obtained images of similar morphology to an auroral arc, and have discussed the resulting uneven response function of this type of detector, suggesting that a smoother image can be achieved with some post-processing of the data. Work soon to be reported has concentrated upon the development of a dedicated HX2 readout system with very little dead time that is capable of integrating at 5 μs which is the limit of the specification of the HX2. This development will be of interest for any application requiring dedicated signal processing electronics to read out individual wires of the PSPMT.

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