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Thin Scintillators and Position Sensitive Photomultiplier Tubes for Hard X-ray Imaging in Space[1]

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Abstract

Monolithic and segmented CsI(Tl) scintillators coupled to a position sensitive photomultiplier tube (PSPMT) have been tested for imaging and environmental performance necessary for hard X-ray astrophysics missions. Using a crossed-wire PSPMT and individual anode-wire readout, spatial resolution of 1-2 mm rms at 60 keV over the entire photo-cathode imaging surface is obtained out to near the edges of the scintillator. A PSPMT mapping correction was used to obtain energy resolution close to what is expected from CsI(Tl) scintillators.

I. INTRODUCTION

Many concepts for future instruments in hard X-ray astrophysics demand large area detectors that provide good spatial resolution and modest energy resolution. Collecting areas as large as 1–2 m^2 are necessary to obtain high sensitivity and to surpass the performance of instruments now in operation such as HEXTE on the XTE spacecraft, or the recently approved IBIS on the European Integral mission. Along with high sensitivity, imaging is necessary to resolve closely spaced sources, observe large areas of the sky at once, and determine positions of previously unidentified sources. With a coded aperture imaging technique, position resolution on the order of 1–2 mm rms will be necessary to provide arc minute spatial resolution (centroiding) and a large field of view (~50^o).

Position-sensitive photomultiplier tubes (PSPMT) coupled to a thin scintillator such as CsI(Tl) or NaI(Tl) are an attractive approach achieving good spatial and energy resolution. We have been developing these detectors to support the "Burst Locations with an Arc Second Telescope" (BLAST) mission which will enable gamma-ray burst locations to be determined with arc-second accuracy over a wide field of view, and to provide a hard X-ray sky survey [1]. In the BLAST concept a coded aperture is used to provide a wide field of view (~1 steradian) with position resolution (centroid) better than 1 arc minute for most bursts. The BLAST focal plane consists of 384 PSPMTs that provide a collecting area of 1.4 m^2 with position resolution ~1–2 mm rms. The coded aperture is 2 m from the detector plane with 6 mm occulting elements. In addition to the coded aperture, a pair of checker-board phase-modulation grids produce an interference pattern on the focal plane that permit burst locations to be determined to ~1 arc second accuracy.

We report on the imaging characteristics and spaceflight qualification of PSPMTs proposed for the BLAST mission. To meet our requirements, individual readout of the anode wires is required. Key developments include imaging over the full photocathode area, an algorithm to efficiently compute the interaction position from the signals on the anode wires, and ruggedness testing of commercial grade PSPMTs for survival of launch vibration loads.

II. EXPERIMENT

A variety of tests using both monolithic and segmented CsI(Tl) scintillators coupled to a Hamamatsu 3-inch R2487 position-sensitive photomultiplier tube (PSPMT) have been conducted. The PSPMT has 18 x- and 16 y-anodes spaced on 3.75 and 3.70 mm pitch respectively. The useful photocathode imaging area is 67×59 mm. A readout approach using a charge division network that requires only four channels was rejected due to the poor position resolution at low energies near the edge of the detector [2]. Instead, all 34 anode wires were individually read out to optimize position resolution over the entire imaging area. One of the dynodes (the 10th) was also read out to provide a simple measure of the total energy. Total energy may also be computed by summing either the x- or the y-anode wires.

For these tests, a 65 × 65 × 4 mm CsI(Tl) scintillator was coupled to the PSPMT. The crystal thickness was selected to meet the detection efficiency requirements of BLAST yet minimize the background. Tests were conducted with polished and lightly sanded crystal surfaces. The light sanding diffused the reflected light, thus improving position resolution [3]. In our tests we sanded only the upper surface of the crystal. Edges of the crystal were polished with no reflector.

Gain of a R2487 PSPMT varies significantly over the photocathode area. Gain variations over the face of the PSPMTs we tested have been mapped using an led flasher on a fine grid of positions over the face of the tube. Factors of ~2 variation in gain above and below the mean value are observed. The gain map of a typical PSPMT is shown in Figure 1. Typically the extremes in gain are found near edges of the useful photocathode area. In principle this gain map can

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be used to correct for gain variations over the surface area of the PSPMT. However, to do this some assumption about the distribution of scintillation light from an event is needed.

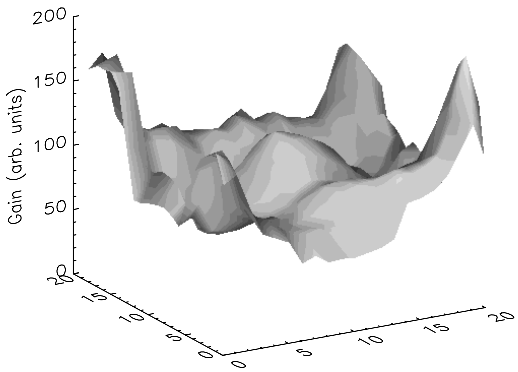

Figure 1. Map of gain variations of a R2487 PSPMT measured using an LED flasher.

Instead, a simple calibration was developed for this work based on the average signal in each wire from a uniform (flood) illumination of the scintillator with a monoenergetic gamma-ray source for the purpose of position reconstruction. The energy calibration for the detector is applied as a separate step later. A simple calibration technique is required since, for a space mission, positions must be computed in real-time with fast computing hardware (Digital Signal Processors). Calibration coefficients are derived so that the average pulse height in each wire rolls off from the center to the outer wires to correct for effects such as reflection off the edges. The roll-off function (calibration curve) is determined empirically to provide the best event reconstruction using a simple, fast, fitting algorithm, discussed next. The calibration curve depends on crystal size, edge and surface treatments, thus a different choice may prove superior for another detector. Figure 2 shows a plot of the calibration curve used with our detector and crystal. The pattern of gain variations is not a simple product of variations in the x- and y-directions; thus the best x-wire calibration is a function of the y coordinate of that wire and *vice versa*.

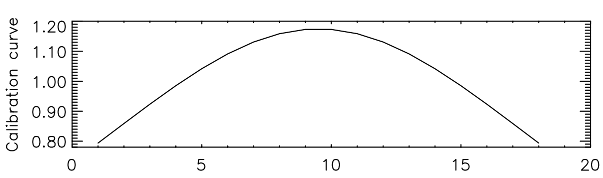

Figure 2. Calibration curve for x-anode wires. The average pulse height from a uniform illumination is adjusted to fall on this curve.

The wire calibration is achieved using crude positions derived for each event from weighted averages of the x- and y- signals. The calibration coefficient for each wire is selected so that the average pulse height for that wire falls on the calibration curve shown in Figure 2. The calibration coefficient is a function of position along the wire. In this work, the PSPMT is divided into 10 bands in the x-direction and 10 bands in the y-direction for wire calibration.

The light distribution amongst the anode wires is a function of several factors: Surface treatment of the scintillator, edge treatment, and thickness of the scintillator. Figure 3 shows the measured light distribution on the x-anode wires for gamma-rays collimated to a narrow spot (0.5 mm diameter) on the scintillator. Superimposed on the light distribution is a Lorentzian curve fit to the data, with the Lorentzian defined as,

$$y = \frac{Aw}{2\pi\left[\left(x - x_0\right)^2 + \left(\frac{w}{2}\right)^2\right]} \tag{1}$$

where y is pulse height on each wire, A is area, x_0 is the peak value, and w is the Full Width at Half Maximum (FWHM). With the calibration curve described above, the Lorentzian function is a good fit to the data. Most importantly, it provides a good fit for events interacting anywhere in the crystal. Selection of a Lorentzian has the advantage of being easy to cast in a form to fit the data with a simple algorithm. Edge effects are easily handled by the calibration curve. By use of the calibration curve in Figure 2 and Lorentzian fits, the imaging area has been made to extend to near the edge of the scintillator. Better spatial resolution has been obtained using slower, more complex fitting procedures. The advantage of the Lorentzian fits used here is that it provides comparable resolution with a fraction of the computing requirements. Hence, it is amenable to high data rates.

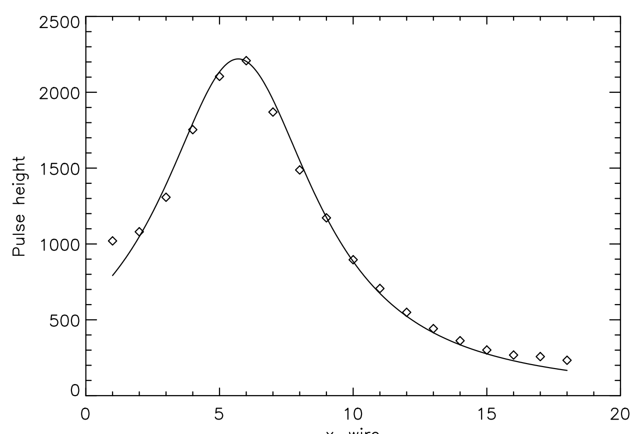

Figure 3. Distribution of light on x-anode wires from a point source illumination between wire 6 and 7. The superimposed smooth curve is a Lorentzian function fit to the light distribution. The crystal is 4 mm thick and the wires are spaced 3.75- mm.

The Lorentzian fit is similar to the technique employed by the GIS instrument on the Japanese ASCA spacecraft [4]. We linearize the Lorentzian curve by taking its inverse and fitting

1/*y*, thus the fit is a simple quadratic function. The data are fit using a weighting function that is proportional to a power of the best fit Lorentzian curve. The data weighting function places emphasis on the peak of the light pool in determining the best fit and reduces the effects of the wings. An alternative approach is to restrict the fit to the wires with the largest signals. An efficient implementation of the fit algorithm has ~700 multiplications and additions. Real-time positions can be computed for events at rates on the order of 25 kHz using a digital signal processor (e.g. TMS320C50).

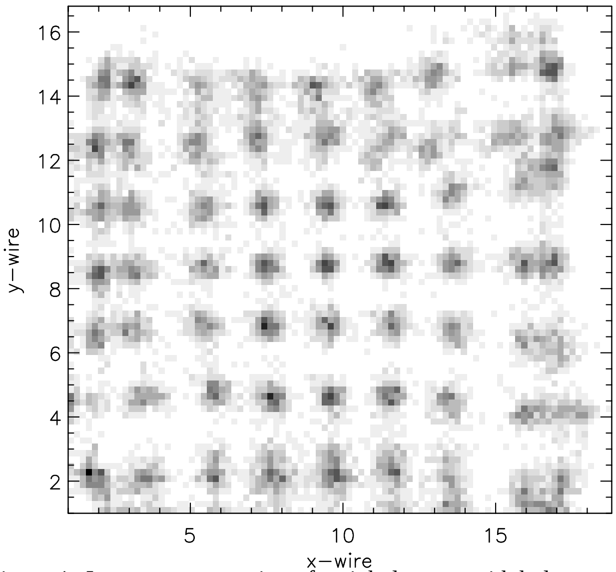

Figure 4. Image reconstruction of a pinhole array with holes spaced on 8 mm centers. This image shows the fit positions of the Lorentzian peak. No mapping corrections have been applied to correct for distortion near the edges of the PSPMT. CsI(Tl) and 122 keV gamma rays were used.

Position resolution was measured using an aperture with a two dimensional array of pinholes spaced every 8 mm exposed to a 60 keV γ-ray source. A 2-dimensional plot of the reconstructed positions is shown in Figure 4. We obtained good performance over most of the active area of the PSPMT using the simple wire-gain calibration described above. However, regions near the edge of the PSPMT photocathode with the most extreme gain variations did not image as well.

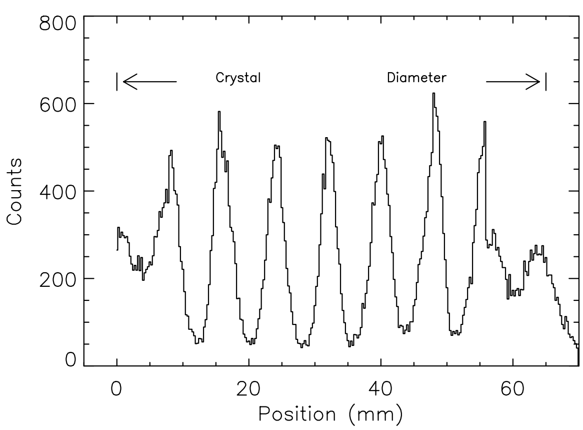

Figure 5. Position resolution demonstrated using pinholes spaced 8 mm apart for a slice through the center of the PSPMT. CsI(Tl) and 122 keV gamma rays were used.

The reconstruction algorithm determines good positions for about 90% of all events. The remaining 10% reconstruct to obviously incorrect positions generally outside the imaging area. Figure 5 shows the spatial resolution that is achieved using the fast Lorentzian imaging routine. A simple piece-wise linear mapping correction has been applied to correct for spatial distortion. Spatial resolution demonstrated here is 1.9 mm rms at 8 mm from the edge of the crystal, improving to 1.1 mm rms in the central region of the crystal using the weighted Lorentzian approach.

Good energy resolution was also achieved using a two-dimensional gain correction map. Resolution at 60 keV is ~25% FWHM over the full crystal area using CsI(Tl). Pixellated CsI arrays have also been tested. We found that one common commercial pixellated scintillator array using unpolished CsI crystals in a white epoxy matrix had little energy resolving power and thus was not suitable for most applications in astrophysics. However, we do not rule out that another crystal array with different crystal preparation may perform better.

III. Spaceflight packaging

Packaging of the PSPMT for spaceflight is shown in Figure 6. Axial loading of the PSPMT with wave springs (60 lbs) provides a vacuum seal around the tube face and holds the tube to withstand launch vibrations. The bleeder string is potted behind the tube to provide protection from coronal discharge. The scintillator is glued directly to the PSPMT front face and is covered by a thin window, transparent down to 5 keV. The detector module electronics consist of CMOS Application Specific Integrated Circuits (ASICs) to read out the anode wires and one dynode.

A series of vibration tests were performed on two non-ruggedized Hamamatsu R2487 position sensitive PMTs to determine whether the standard non-ruggedized devices could survive the MIDEX vibration environment. Note that Hamamatsu Corporation has produced a ruggedized version of this PSPMT.

The maximum expected random vibration spectrum increases from 0.005 G^2/Hz at 20 Hz to 0.08 G^2/Hz at 100 Hz, is constant at 0.08 G^2/Hz from 100 to 1000 Hz, then decreases to 0.04 G^2/Hz at 2000 Hz, with no input above 2000 Hz or below 20 Hz; this has an overall level of 11.5 G rms. The qualification (maximum) level test used was 6 dB above this flight level, or 23 G rms.

Each tube was mounted in a flight-like configuration comprising compressed rubber mounts at the perimeter of the faceplate supporting the tube (both axially and radially) and a

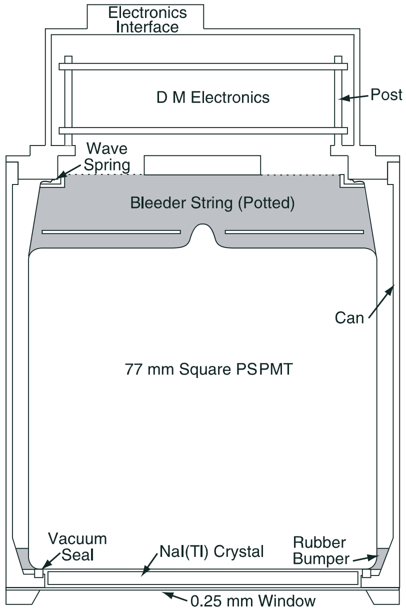

Figure 6. Detector module.

spring load from the bleeder string end. A known preload was applied to the rubber mounts through a wave spring pressing on a plate mounted on the rear of the bleeder string potting material. This "three-point" mounting system permitted a small amount of rocking of the tube under axial loading, and was thus not ideal. Tests were done for one minute per axis at the flight level, then repeated at +3 dB , and at +6 dB (the qualification level) for each tube.

Each tube's energy resolution was measured before and after each of the test levels. Neither tube suffered significant performance or mechanical degradation as a result of the tests. However, during the qualification level random vibration test, the dynode structure could be heard chattering against the PMT glass envelope, suggesting that the level was approaching the limit for these non-ruggedized tubes. The ruggedized versions of these tubes employ stiffened lateral supports which will prevent this sort of chattering.

IV. CONCLUSION

We conclude that the position and energy resolution required for many hard X-ray imaging applications in astrophysics can be achieved with a thin CsI(Tl) scintillator and a PSPMT. A large imaging area is possible as a result of fitting the signals on individual anode wires. Although not discussed in this summary, using CsI(Na) or NaI(Tl) for the scintillator will further improve the performance, and extend good imaging properties to lower energies.

Conclusions from vibration testing support the use of non-ruggedized versions of these tubes in space instruments. Acceptance screening for ruggedness of each tube would be done with vibration tests performed at the flight level, thus eliminating the higher cost of specially ruggedized tubes.

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