

AN IMAGING PROPORTIONAL COUNTER FOR A 0.1 to 10 keV X-RAY TELESCOPE

Paul Gorenstein and Daniel Fabricant

Harvard/Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138Abstract

A xenon multi-wire position sensitive proportional counter with a high degree of differential spatial linearity (better than $50\mu\text{m}$) and long-term stability has been constructed and tested in detail. It is suitable for a 0.1 to 10 keV X-ray telescope such as AXAF, which it would share with detectors having better spatial and spectral resolution. Compared to other detectors, the larger format, higher quantum efficiency, and lower background of the PSPC makes it generally the most useful instrument for observations of diffuse cosmic X-ray sources and associations of sources more extended than a few tenths of a degree in diameter. Given the good spatial linearity the systematic uncertainty for source locations is finer than an arcsecond. The spatial resolution varies as $0.3 \text{ mm/E}^{0.5} \text{ (keV)}$ over the range 0.2-4 keV in accordance with theoretical limits determined by the size and the number of electrons in the primary charge cloud.

Introduction

A position sensitive X-ray proportional counter (PSPC) known as the Imaging Proportional Counter¹ was the most highly utilized instrument in the focal plane of the Einstein Observatory. It operated throughout the two and one-half year life of the mission without deterioration. Second generation X-ray astronomy observatories such as AXAF will benefit from significant advances in the technology of other types of imaging X-ray detectors. These include high spatial resolution channel plate multiplier arrays with greatly improved quantum efficiency and charged coupled devices (CCDs) which provide simultaneous spatial and spectral resolution that are superior to those of a PSPC. The advent of these new devices underscores certain properties of the PSPC which remain critically important in an observatory where a variety of detectors are available. We describe those properties as exemplified by the performance of a PSPC that we have constructed and tested.

The properties of the PSPC which remain superior to those of other imaging detectors are: broad bandwidth and high quantum efficiency to 10 keV (the practical upper limit of reflecting telescopes), large format, and rejection of signals from particles and gamma rays. Although the usable field of an X-ray telescope is about one degree in diameter, the high angular resolution portion is confined to the center. At an angle depending on the focal plane scale of the telescope the angular resolution of the telescope becomes the limiting factor rather than the linear spatial resolution of the detector. This would occur at 8 arcminutes when the PSPC that we have developed is used with a telescope of 10 m focal length such as AXAF (1mm is equivalent to 20 arcseconds). Therefore with sources more extended than 24 arcminutes diameter the mean angular resolution of the PSPC over the object is essentially as good as that of any other detector. Furthermore, given the superior performance of a PSPC with regard to reduction of non X-ray background it becomes the prime detector for studying features of low surface brightness. Therefore the PSPC will be very useful in observations of extended sources especially those with low surface brightness such as clusters of galaxies, as well as source

complexes such as stellar associations, and of relatively close galaxies.

The PSPC is also important in measurements of the broad band spectral properties and temporal variability of individual point sources, because its high quantum efficiency and broad energy coverage provide high throughput. Given that the angular resolution of all the imaging detectors is good enough to eliminate confusion the high collection efficiency of the PSPC makes it optimum from the standpoint of studying variability on all time scales. On the other hand, in the context of a multi-detector observatory, the PSPC will not be used for high resolution imaging or high resolution spectroscopy. Thus a modest improvement of the spatial or spectral resolution that is achieved at the expense of either quantum efficiency, bandwidth, low background or reliability is not a desirable tradeoff.

Since the PSPC will be used extensively for the mapping of surface brightness and temperature profiles of extended sources and providing positions for sources detected serendipitously in the field, spatial linearity on a fine scale and gain uniformity are very important properties. The accuracy in determining the centroid of an image becomes the predominant factor in obtaining celestial positions. Good differential spatial linearity, i.e., $50\mu\text{m}$, permits the detector to provide the 1 arcsecond positions necessary for optical identifications.

Performance

We have constructed a prototype PSPC that operates with an 830 torr mixture of 90% xenon and 10% CH₄. The use of xenon is not only essential to achieving good quantum efficiency at 10 keV but also to optimizing the angular resolution above 2 keV by absorbing, in a small depth, the converging-diverging cone of radiation focused by the telescope. The method of position readout is essentially the same as the center of mass method of detecting induced cathode signals that was developed by the CERN group². It seems to demand the least gas gain from the detector. Lower gas gain is conducive to longer lifetime in orbit where the detector is subjected to occasional very large energy deposits from cosmic ray showers and trapped radiation. Lower gain also results in better linearity of the pulse height versus photon energy response, particularly for xenon which is prone to saturation at higher gain. The gain of the detector was measured to be about 10^4 , which is substantially less than that of the Einstein Observatory's Imaging Proportional Counter.

Stability and long life of a comparatively large area detector (20 cm x 20 cm) is best achieved with an anode plane of discrete wires rather than a continuous anode. In a discrete wire anode the avalanche is confined to a small volume around individual wires and tends to be self-limiting if the gain is not too large. On the other hand, in a continuous anode the region in which an avalanche may occur is essentially the entire volume between the anode and the cathode. Therefore signals from occasional cosmic ray events that deposit very large energy over an extended volume are liable to be more destructive to a continuous anode detector. This is important to the problem of long-term stability and survival in orbit. Operational experience on satellites is consistent with this hypothesis.

The requirement on spatial linearity, gain uniformity, and stability set a practical lower limit of about one millimeter on the spacing between wires. Given a minimum absolute error in the ability to locate anode wires a smaller spacing would result in a larger percentage variation in wire spacing and hence greater differential non-linearity and larger gain variations. The voltage would also have to be increased to maintain the same gain. Smaller spacing increases the tendency for the anode to discharge erratically and also results in greater mutually repulsive electrostatic stress upon adjacent anode wires. In a detector of 20 cm or larger, the force between wires spaced less than 1 mm is near the threshold of forcing the wires to bow alternately above and below the plane.

We spaced the 10 μ m anode wires by using two precisely machined large screws as templates at either end of the anode frame. The anode wires were bonded with conductive epoxy to a macor ceramic frame. Measurements of the anode wires (as shown in Figure 1) showed a rms deviation from the mean spacing of 4.6 μ m. This is about a factor of five smaller than the wire spacing variation of the Einstein Observatory's IPC. The macor frame also contained separate gold-plated copper layers to provide electrical continuity and collect leakage currents.

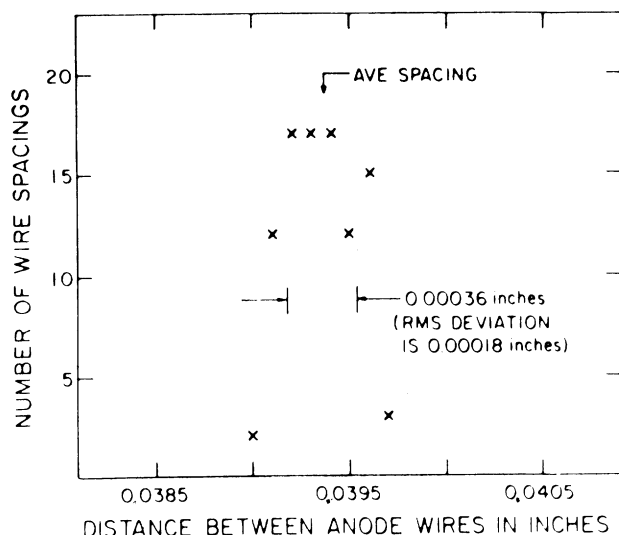


Figure 1. Spacing between adjacent anode wires.

The 1 mm wire spacing effectively determines the spatial resolution of the detector across the 0.2-10 keV band. To avoid spatial non-linearity at a periodicity equal to the anode wire spacing, the primary charge cloud should grow to 2 mm or more by the time it drifts to the anode. The depth of the absorption and drift region was made equal to 2 cm to satisfy this condition. The spatial resolution is measured by fitting a two dimensional gaussian function to the image of a pinhole. It is defined as 2.35 times the standard deviation, in each dimension, of the best fit to the count distribution. This has the same value in both dimensions and is equivalent to the full width at half maximum in each dimension of a slit image. It varies as $0.3 \text{ mm}/E^{0.5} \text{ (keV)}$ from 0.28 to 4 keV in accord with theory. The improvement in spatial resolution with energy slows above 4 keV. Measurements are shown in Figure 2 along with an angular scale corresponding to its angular resolution in the focal plane of a telescope with a 10m focal length like that of AXAF. The effect of the finite absorption depth is seen as a degradation in angular resolution below the L absorption edge of Xenon. When observed on axis a typical cosmic X-ray source would have a FWHM angular resolution of six seconds of arc averaged over its spectrum.

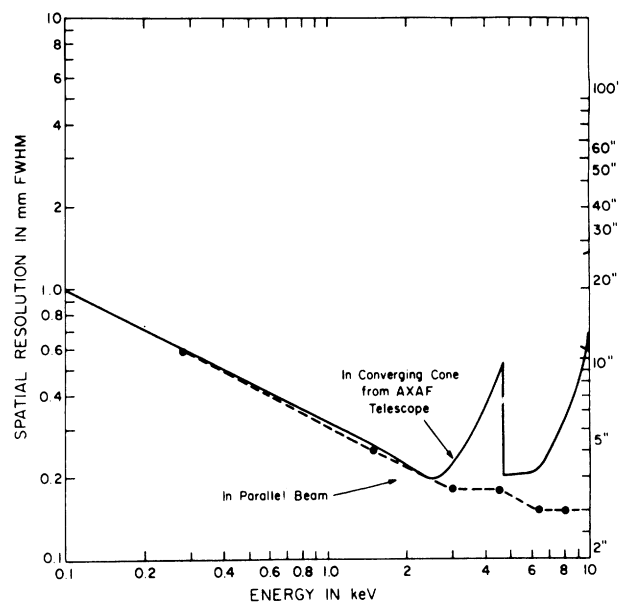


Figure 2 Dashed curved (left-hand scale) is linear spatial resolution as measured by fitting gaussian functions to images of pinholes in parallel X-ray beam. Solid curve (right scale) is computed angular resolution at focus of 10M telescope taking into account the conical geometry of the focused image and absorption characteristics of xenon.

The detector was subjected to a variety of tests involving scanning slits and pinholes. As shown in Figure 3 the small scale (<1 cm) variation in gain was within $\pm 2\%$. However, we observed a larger scale variation in gain across the detector of about 1.2% per centimeter (Figure 4), which we attributed to the anode and cathode planes not being perfectly parallel when placed in the detector. This should be correctable by more careful assembly. As shown in Figure 5, the differential spatial non-linearity is nearly always less than 2 mils (50 μ m) across the detector. In the focal plane of a 10m telescope, 50 μ m corresponds to a systematic error in the centroid of an image of one arcsecond. With an image diameter of only about 6 arcseconds from a typical cosmic X-ray source, the detection of about sixty photons provides sufficient statistical precision to obtain the limiting accuracy of one arcsecond. This is nearly always good enough to make optical identifications. More than 8 arcminutes off axis, the mirror becomes the limiting factor.

The detector was also examined for flat field response to uniform illumination. The results are shown in Table 1 for the axis which would suffer modulation due to quantization on individual anode wires.

Table 1

Response to Uniform 3 keV Illumination

(Figures refer to a 2.4 x 4.8 cm region)

Pixel Size (0.1 mm = 2 arcsec)	RMS Dev. Divided By Mean	Statistical Error	Residual Error
0.10 mm	5.2%	4.3%	2.9%
0.24 mm	3.4%	2.7%	2.0%
0.48 mm	2.1%	1.9%	0.9%
0.95 mm	1.7%	1.4%	1.0%
2.38 mm	1.5%	0.9%	1.2%

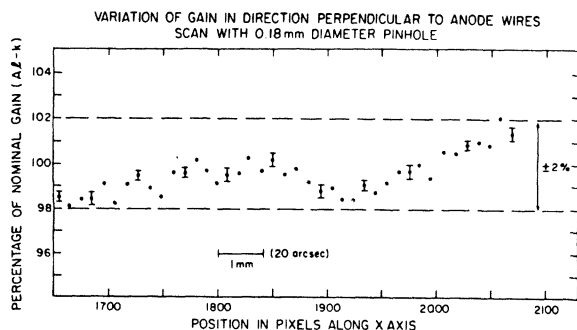
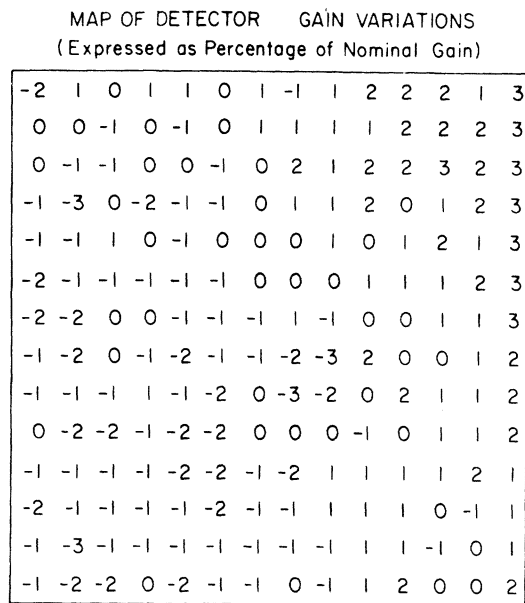


Figure 3. Variation in mean pulse amplitude distribution of 1.5 keV X-rays across 10 anode wires as a function of position.



Each Cell is 2x2mm (40x40 arcsec on AXAF)
A 2.8x2.8cm Region is Displayed (9.3x9.3 arcmin on AXAF)

Figure 4. Two dimensional map of mean pulse amplitude of 1.5 keV X-rays in a parallel beam expressed as a percentage variation from the overall mean value. One millimeter on the detector would correspond to 20 arcseconds in the focal plane of the AXAF telescope.

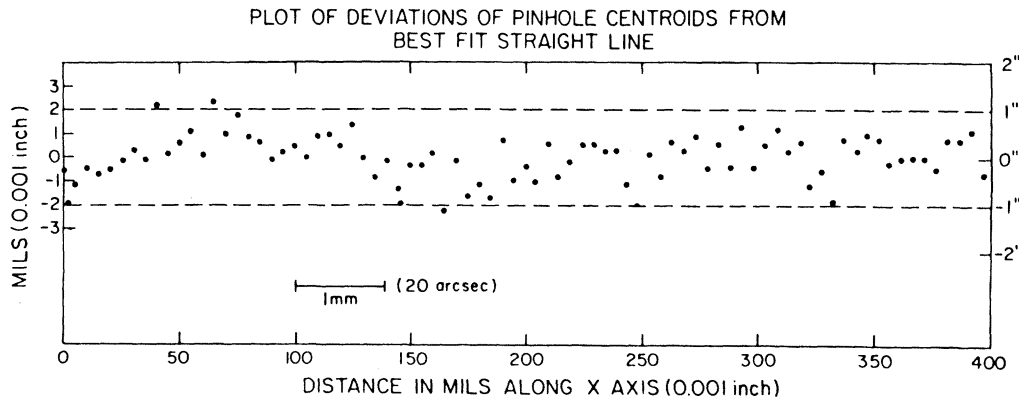


Figure 5. A uniform matrix of pinholes in front of the detector was exposed to a parallel beam of 1.5 keV X-rays. The left-hand scale shows the linear deviations from a fit of a straight line across 10 anode wires. The right-hand side is the equivalent angular scale in the focal plane of a 10 M telescope.

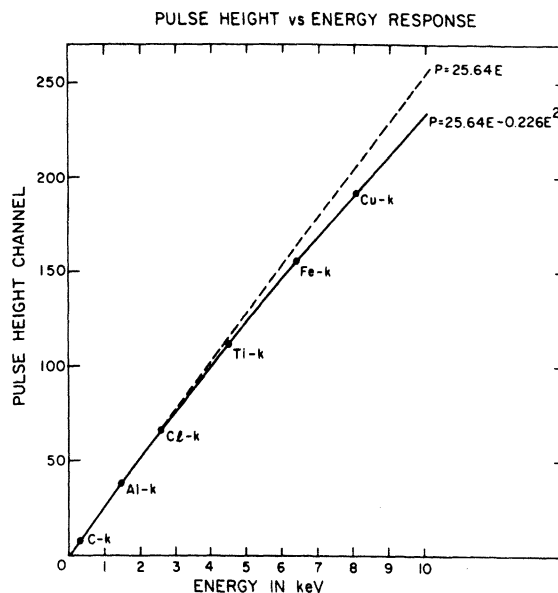


Figure 6. Pulse height versus X-ray energy from 0.28 to 8.3 keV. The curve becomes somewhat non-linear above 4.5 keV. The gas filling is 1.1 atm of Xe (90%) and CH₄(10%). The gain is about 10000.

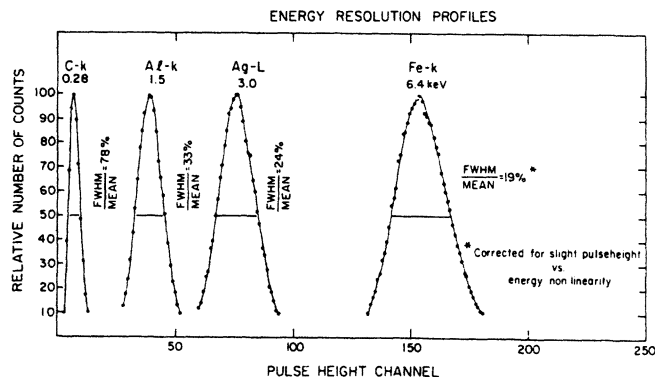


Figure 7. Pulse height spectra of several X-ray lines from 0.28 to 6.4 keV.

The energy linearity and resolution of the detector are similar to that of a conventional xenon proportional counter. There is an indication of a small nonlinear effect at the upper end of the energy range (Figure 6) but it is readily calibrated. The pulse height resolution is shown at several X-ray energies in Figure 7.

Conclusion

The new PSPC is a factor 3 to 5 superior to the IPC of the Einstein Observatory with respect to spatial resolution, pulse height resolution, gain uniformity, and spatial linearity. With the 3X increase in focal plane scale from Einstein to AXAF the solid angle of the minimum size pixel is reduced by over a factor of 100. A PSPC continues to provide uniquely important capabilities to an advanced x-ray observatory that also contains state of the art CCD's and channel plate detectors that surpass it in spatial and energy resolution. These are large format, broad bandwidth, high quantum efficiency, and low non x-ray background. By spacing the anode wires with high precision and utilizing low noise electronics that permit the detector to operate at no more than moderate gain a PSPC can be a very uniform and stable instrument. It will generally be the optimum device for studying low surface brightness sources such as clusters of galaxies as well as all extended sources and associations of sources that are larger than a few tenths of a degree in diameter.

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References

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- [2] G. Charpak, I.E.E.E. Transactions On Nuclear Science, Vol. NS-21, 38, 1974.