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A Polarimeter for Studying Hard X-Rays from Solar Flares

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Abstract

We present a modular design for a Compton scatter polarimeter that will be used for studying the polarization of hard X-rays (50-300 keV) from solar flares. A complete polarimeter module fits on the front end of a 5-inch position-sensitive photomultiplier tube (PSPMT). The PSPMT is used to determine the Compton interaction location within an annular array of small plastic scintillator elements. Some of the photons that scatter within the plastic scintillator are subsequently absorbed by a small centrally-located array of CsI crystals that is read out by an independent multi-anode PMT. The independence of the two PMT readout schemes provides appropriate timing information. Monte Carlo simulations indicate that one such module, with a scintillator thickness of 12.7 cm, has a peak effective area of almost 3.5 cm^2 at 200 keV and a polarization modulation factor in excess of 50% from 50 keV up to 250 keV. A small array of such detectors would be capable of measuring polarization levels of less than 1% in X-class solar flares. We are currently testing a fully-functional science model based on this design concept. These tests are designed to evaluate the performance characteristics of the design and to more fully validate our Monte Carlo simulation code. Here we shall review the characteristics of this modular design and report on the status of the laboratory testing. We will also outline the potential of this design for performing polarization measurements of solar flares, including the possibility of incorporating such detectors into an imaging polarimeter.

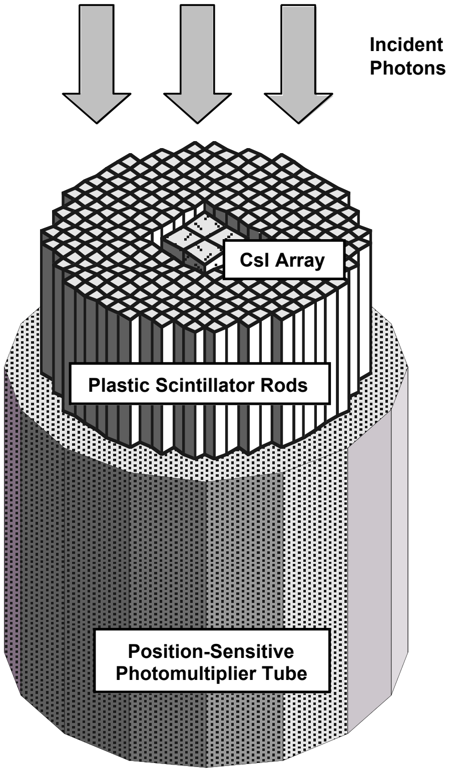

Figure 1: The modular design showing the layout of the plastic scintillator elements and CsI elements on the front surface of a PSPMT. As shown here, the depth of the detector elements is 5.08 cm. Not shown is the MAPMT used to readout the CsI elements.

1 Introduction:

The basic physical process used to measure linear polarization of hard X-rays (50–300 keV) is Compton scattering. The successful design of a polarimeter at these energies hinges on the ability to reconstruct the kinematics of each Compton scatter event. In this context, we can consider: 1) the ability to measure the energies of both the scattered photon and the scattered electron; and 2) the ability to measure the scattering geometry.

A Compton scatter polarimeter consists of two detectors that are used to measure the energies of both the scattered photon and the scattered electron (e.g., Novick 1975; Lei, Dean & Hills 1997). These measurements also serve to define the scattering geometry. One detector (the *scattering detector*) provides the medium for the Compton interaction to take place. This detector must be designed to maximize the probability of a single Compton interaction with a subsequent escape of the scattered photon. The second detector (the *calorimeter*) absorbs the remaining energy of the scattered photon. The accuracy with which the scattering geometry can be measured determines the ability to define the modulation pattern and has a direct impact on the polarization sensitivity.

The spatial resolution can easily be improved by using arrays of smaller detector elements, where the element size determines the spatial resolution. Using a large number of detection elements typically requires a correspondingly large number of electrical channels.

2 A Modular Polarimeter Design:

We have developed a modular polarimeter design that places an entire device on the front end of a single 5-inch diameter PSPMT, as shown in Figure 1 (McConnell et al., 1998a, 1999). This approach provides high spatial resolution, but significantly reduces the number of readout channels. This design, which we call SOLPOL (for SOLar POLarimeter) incorporates an array of 5 mm × 5 mm optically-isolated plastic scintillator elements arranged in the form of an annulus having an outside diameter of 10 cm (corresponding to the sensitive area of the Hammatsu R3292 5-inch PSPMT). The central portion of the annulus is large enough to insert a 2 × 2 array of optically-isolated 1 cm CsI scintillators. The CsI array is coupled to an independent 4-anode MAPMT (Hamamatsu R5900-04) for energy measurement and signal timing.

An ideal event is one in which the incident photon Compton scatters in one plastic element, with the remaining photon energy subsequently absorbed in the central CsI array. The small cross-sectional area of each scintillator element ensures that practically all multiple scatter events are rejected.

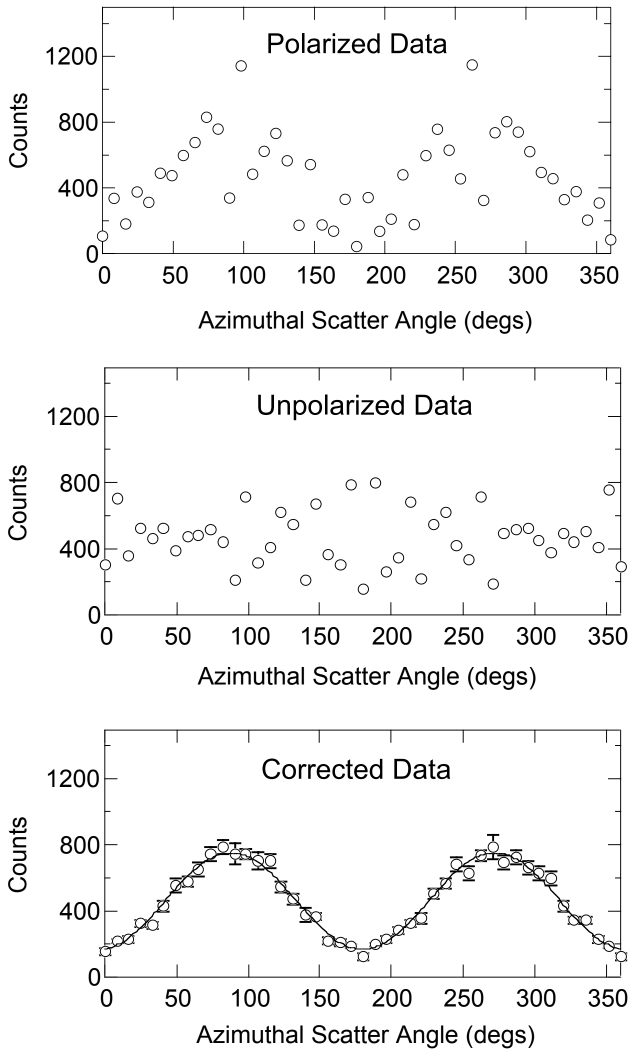

Figure 2: Simulated polarimeter data showing how the measured data is corrected for intrinsic geometric effects to extract the true modulation pattern. These data correspond to the response of the baseline SOLPOL design to a monoenergetic beam of polarized 150 keV photons incident at 0°.

A series of Monte Carlo simulations have been used to determine the charcteristics of the SOLPOL design. The energy threshold levels, particularly in the scattering elements, have a significant influence on the performance of the polarimeter at low energies. These simulations assume threshold energies of 15 keV in the plastic and 50 keV in the CsI. Figure 2 illustrates the nature of the simulated data. The first panel shows the polarization response to a fully polarized monoenergetic beam of 150 keV photons vertically incident on the front surface of the polarimeter. This distribution includes not only the intrinsic modulation pattern due to the Compton scattering process, but also the geometric effects related to the specific layout of the detector elements within the polarimeter and the associated quantization of possible scatter angles. The geometric effects can be more clearly seen in the case of an incident beam that is completely unpolarized, as shown in the second panel of Figure 2. To extract the true distribution of polarized events, we divide the polarized distribution by the unpolarized distribution (as determined either by simulations or direct measurement) and normalize by the average of the unpolarized distribution, yielding the expected cos 2θ modulation pattern (the third panel of Figure 2).

Figures 3 and 4 show the characteristics of the SOLPOL design, in terms of the effective area and modulation factor, respectively, as a function of incident photon energy. In both cases, we show the results for two different detector depths. The deeper detector presents an advantage in terms of effective area, while having little influence on the modulation factor. In practice, the advantage of increased effective area for the deeper detector must be offset by the decrease in light collection efficiency and the increase in detector background.

One potentially useful aspect of the SOLPOL design is that there exists a significant polarization response at large off-axis angles. This can be seen in Figure 5, which is based on simulations with a detector depth of 5.08 cm. The effective area remains relatively constant at large angles, a result of the fact that the exposed geometric area of the detector remains relatively constant. Although there is a decrease in the modulation factor at large angles, there is still significant polarization response even at 60° incidence angle. The off-axis response of this design would be especially useful, for example, in studies of γ-ray bursts.

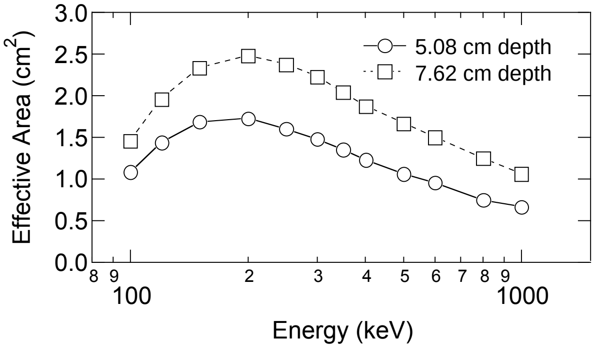

Figure 3: The effective area as a function of energy.

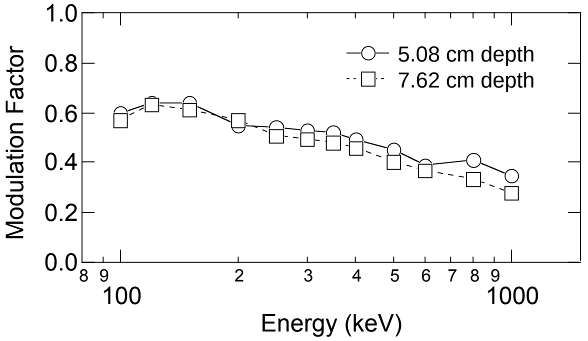

Figure 4: The modulation factor as a function of energy.

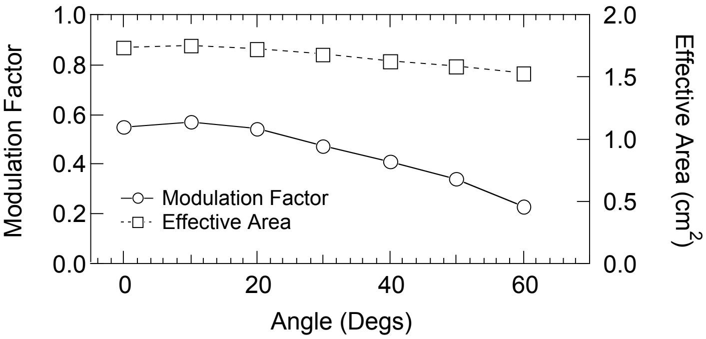

Figure 5: The modulation factor and effective area at 200 keV for various incidence angles. The polarimeter maintains good response out to 60° incidence angles.

3 Recent Laboratory Testing:

We have very recently completed the fabrication of a science model based on the modular SOLPOL design. The initial tests make use of a charge division network for the PSPMT (Hammamatsu R3292) that provides a weighted average of the spatial distribution of the measured light output using only four anode signals. In the future, we will gain more precise information regarding the distribution of energy deposits within the plastic by using the 56 (28-x plus 28-y) anode signals from the PSPMT. Given the mean free path of photons in plastic (6 cm at 100 keV), we expect that a high level of multiple scatter event rejection can be achieved using a readout scheme that relies on only a fraction of the 56 anode signals, thus minimizing the required number of electrical channels.

Figure 6 shows the spatial distribution of events within the plastic array. Photons from a ^{137}Cs source were used to uniformly illuminate the front surface of the polarimeter. Only those events that were coincident in both the plastic and the CsI are registered. The individual 5 mm plastic elements are clearly resolved by the PSPMT. These data suggest that even smaller elements could be used with this PSPMT. We are still in the process of completing the setup and energy calibration of this science model, after which we will proceed with tests using polarized photons

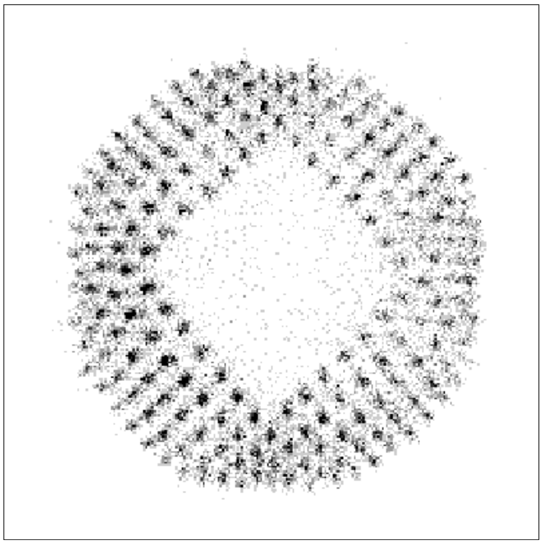

Figure 6: Distribution of measured polarimeter events within the plastic array. These are events (from ^{137}Cs) which scatter between the plastic elements and the central calorimeter. The spatial resolution of the PSPMT clearly distinguishes individual 5mm plastic elements.

4 Solar Flare Polarimetry:

The measurement of hard X-ray polarization in solar flares would be useful in studying the directivity of flare-accelerated electrons (e.g., Chanan, Emslie & Novick 1988). We anticipate that this design may be used in the context of an array of polarimeter modules. An array of 4 modules, for example, would be capable of measuring sensitivity levels in the 50-300 keV range of less than 1% in X-class flares. A larger array of 16 modules would also be capable of measuring polarization levels down to ~5% in some of the largest γ-ray bursts (McConnell et al. 1998b).

The SOLPOL design might also be useful in the context of an imaging polarimeter. For example, a SOLPOL element or array of elements could be used with a rotation modulation collimator to achieve arc-second angular resolution. Such an approach is the same as that employed for hard X-ray imaging in the upcoming HESSI mission. Imaging polarimetry with arc-second spatial resolution would open up the possibility of measuring polarization at various locations within the flare region, providing detailed information about the geometry of the accelerated electron beam.

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