Development of a Hard X-Ray Polarimeter for Solar Flares and Gamma-Ray Bursts

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Polarization in Hard X-Ray Astronomy

☞ Can be used to study the geometry of the emission region, especially if the emission region geometry is well-defined by magnetic fields.

☞ Might also provide information on the emission mechansim (e.g., bremsstrahlung vs. synchrotron).

☞ Polarization measurements have traditionally been considered difficult to perform, especially at hard X-ray energies.

☞ To date, polarization measurements of astrophysical sources have all been made at energies below ~30 keV.

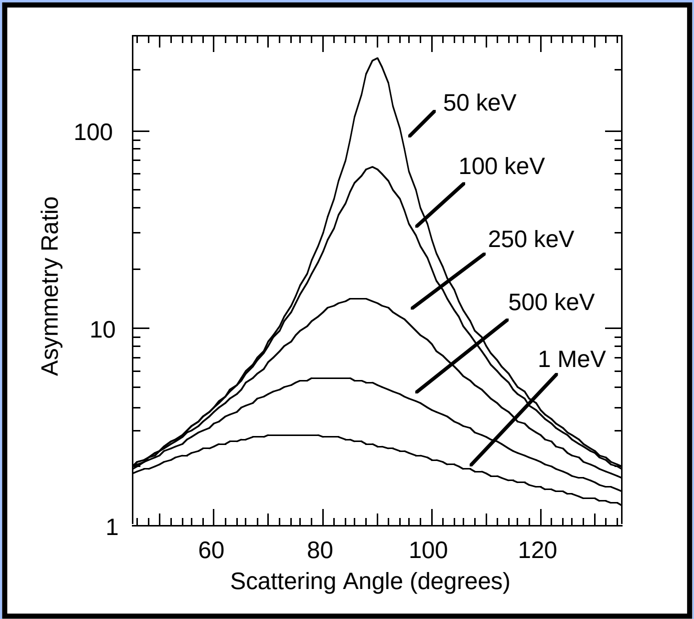
☞ Solar flare polarization measurements (E > 100 keV) should tell us something about the directivity (beaming) of the accelerated electrons.

☞ A <u>direct</u> measurement of the polarization of a γ-ray burst has not yet been attempted, but may provide useful clues as to their nature.

Compton Scatter Polarimetry

At hard X-ray energies (100 – 300 keV), a Compton-scattered photon tends to be ejected at right angles to the incident polarization vector.

A Compton scatter polarimeter measures the angular distribution of the scattered photons in a plane which is perpendicular to the incident photon direction. The asymmetry of this *azimuthal scatter angle distribution* can be exploited to measure the linear polarization of the incident flux.



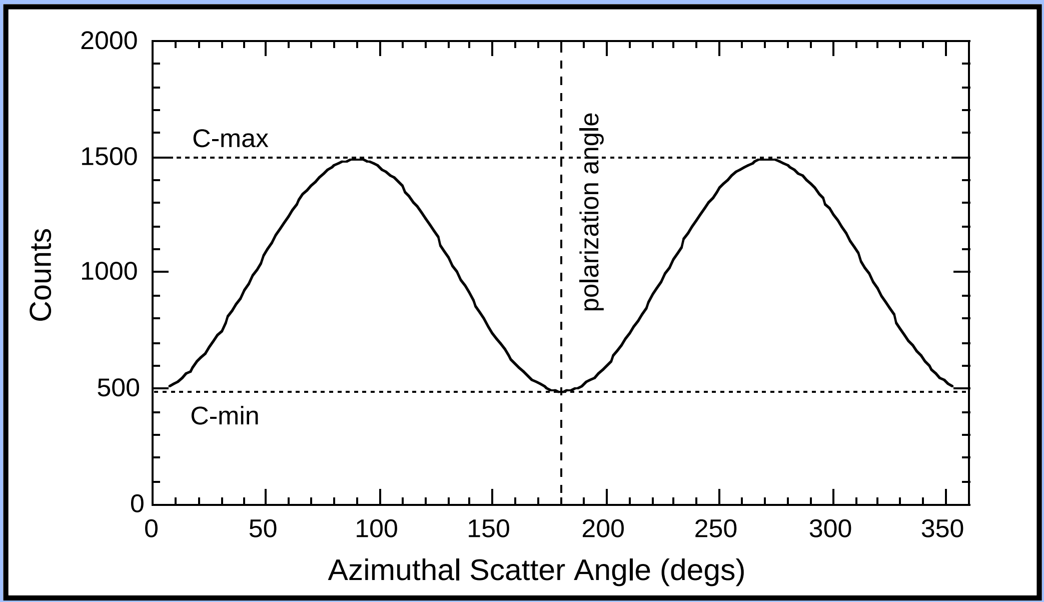
A Compton scatter polarimeter consists of two basic components:
1) low-Z scattering detector(s) to provide Compton scattering medium
2) high-Z calorimeter detector(s) to absorb the scattered photon

The Polarization Signal

An important figure-of-merit for a polarimeter is the polarization modulation factor. For 100% polarization, we define (via simulations),

$$\mu_{100} = \frac{C_{max}(100\%) - C_{min}(100\%)}{C_{max}(100\%) + C_{min}(100\%)}$$

The polarization angle corresponds to the minimum in the scatter angle distribution, as shown in the schematic below.



The Polarization Measurement

In a real measurement, we compute the polarization (P) by comparing the measured scatter angle distribution with that expected for 100% polarization. In particular,

$$P = \frac{\mu_P}{\mu_{100}} = \left(\frac{1}{\mu_{100}}\right)\left(\frac{C_{max}(P) - C_{min}(P)}{C_{max}(P) + C_{min}(P)}\right)$$

where μ_{100} represents the modulation for the 100% polarization case and μ_P represents that of the measurement.

Polarization sensitivity (for a 3σ measurement) is given by,

$$P(3\sigma) = \left(\frac{3}{\mu_{100}\, S}\right)\left[\frac{2(S+B)}{T}\right]^{1/2}$$

where *S* and *B* refer to the source and background counting rates, respectively, and *T* is the observation time.

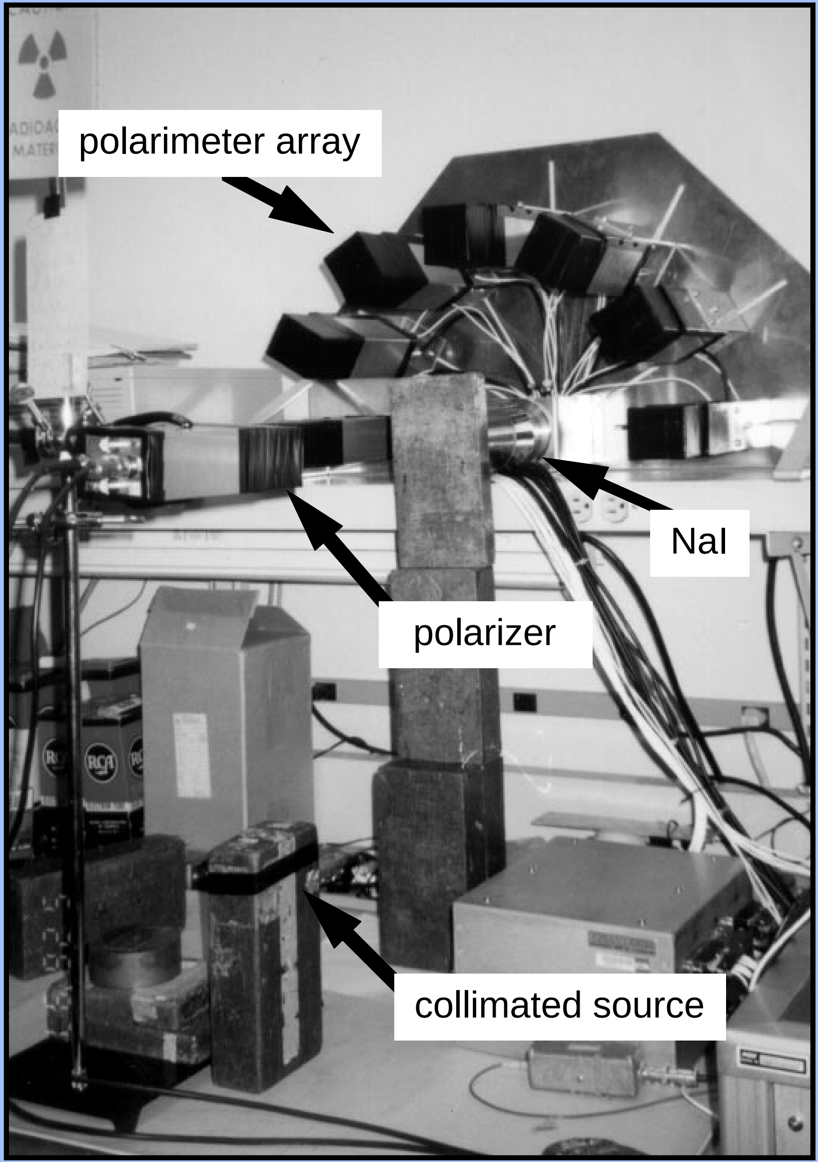
Laboratory Prototype

A prototype has been set up at UNH to demonstrate the basic principles and to validate our (GEANT-based) Monte Carlo simulations.

The prototype uses a semicircular array of 7 plastic scintillators arranged around a central NaI(Tl) detector.

Each plastic scintillator block is 5.5 $\times$ 5.5 $\times$ 7.0 cm in size. The cylindrical NaI(Tl) detector is 7.6 $\times$ 7.6 cm.

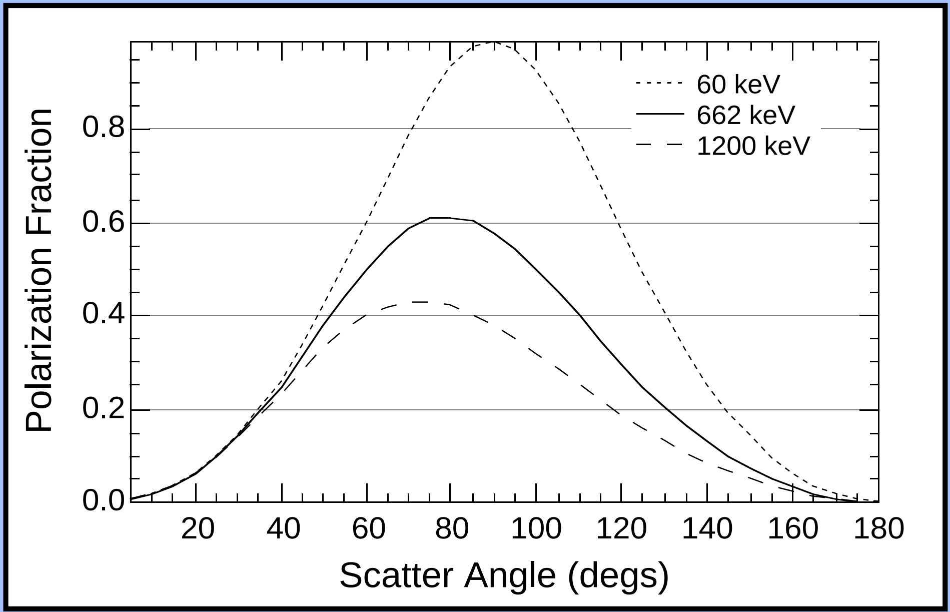
For the data reported here, the plastic detectors were positioned at a radius of 15 cm from the NaI detector.



Generating a Polarized Beam

A polarized beam of hard X-rays can be generated in the lab by Compton scattering photons from a γ-ray calibration source.

Our principle calibration source is a ^{137}Cs source, whose photons are Compton scattered within a block of plastic scintillator. A signal from the scintillator provides an electronic tag for each scattered photon, which can be used as a coincidence signal with the polarimeter.



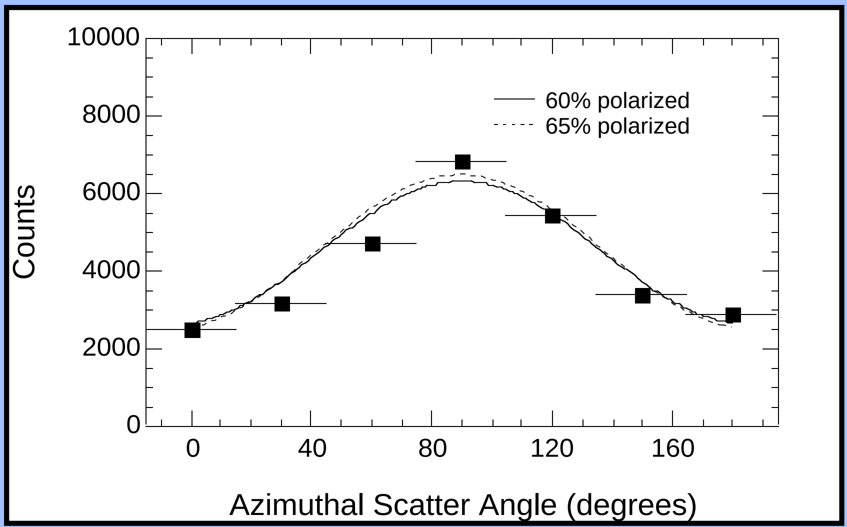
This graph shows the level of polarization that can be achieved for various <u>input</u> photon energies (corresponing to ^{241}Am, ^{137}Cs and ^{60}Co) and various scatter angles.

A 662 keV photon beam, scattered at 90°, is ~60% polarized; the scattered energy is 288 keV.

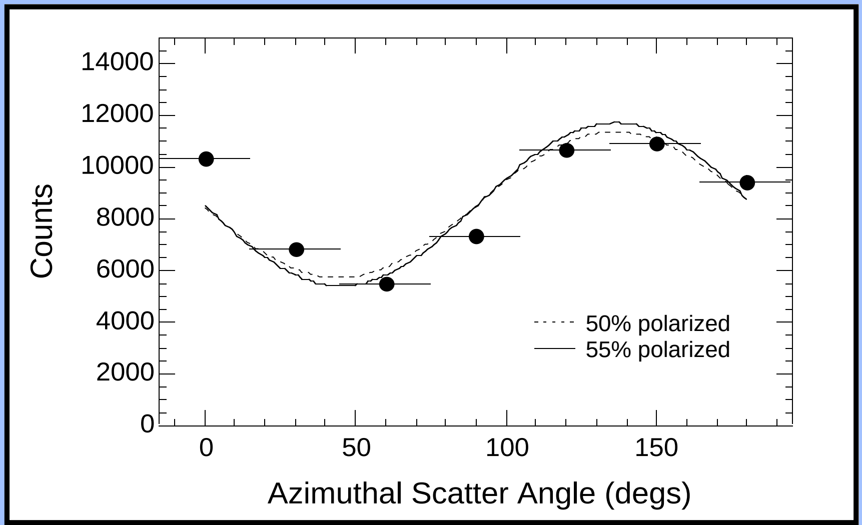
Results from Lab Prototype

These data show a comparison between the laboratory data and Monte Carlo simulations for two different polarization angles and an incident photon energy of 288 keV.

Not only do these data demonstrate a consistency with the simulations, they also show how the polarimeter response changes with the polarization angle of the incident beam.



polarization angle = 0°



polarization angle = 45°

Design Considerations

We can define at least three important design criteria :

<u>Identification of Valid Polarimeter Events</u> -
A valid event involves a photon which scatters only once in the plastic scattering elements. Rejecting multiple scatter events will improve the modulation factor (and the polarization sensitivity).

<u>Determination of the Scatter Geometry</u> -
The ability to determine the location of the energy deposits in the plastic and in the calorimeter detectors directly defines the ability to determine the scatter angle. A more precise determination of the scatter angle will improve the modulation factor (and the polarization sensitivity).

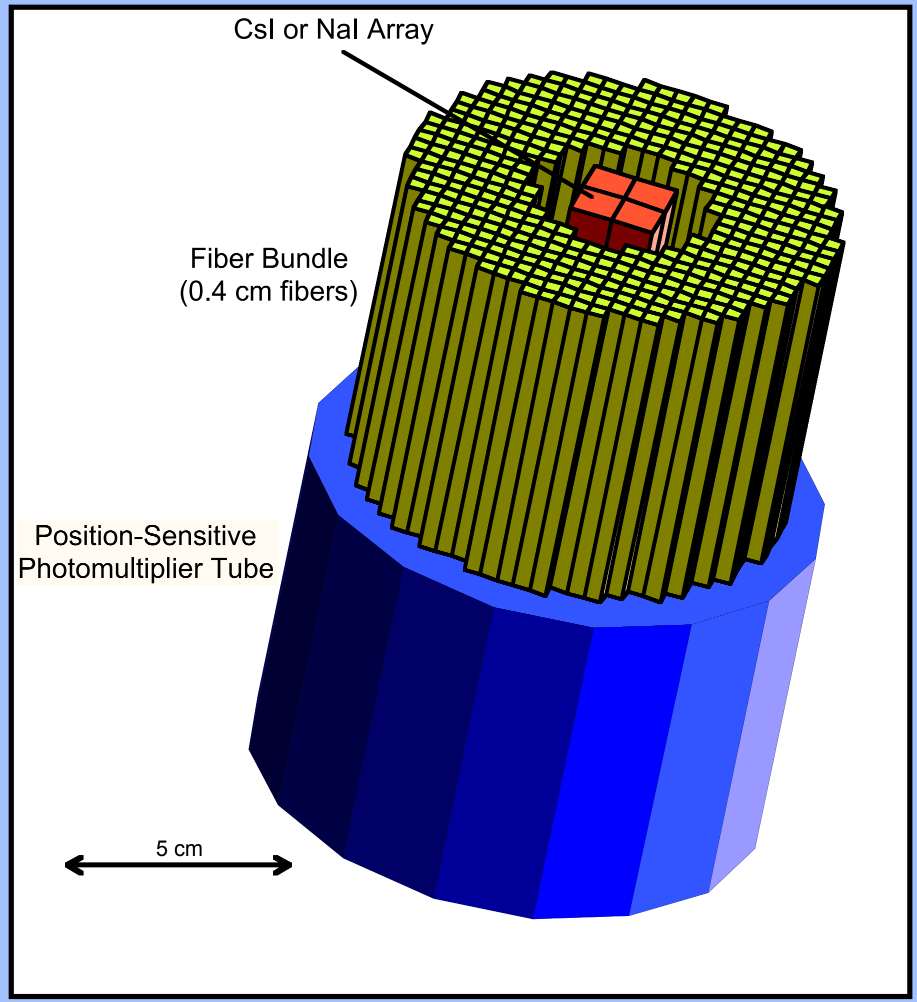
<u>Measurement of Energy Deposits</u> -
Our principle motivation so far has been a polarization measurement of solar flare continuum emission. Energy resolution has not been an important factor. It may be a more critical factor, for example, if we are interested in the cyclotron lines observed in γ-ray bursts.

A Compact Polarimeter Design

Our latest design provides for a complete polarimeter module placed on the front end of a 5” position-sensitive PMT.

The plastic scattering elements are a bundle of 4mm plastic scintillating fibers (7.6 cm long). Readout is provided by the PSPMT

The calorimeter detectors are an array of 1cm CsI (or NaI) scintillators (7.6 cm long). Readout is provided by independent compact PMTs.

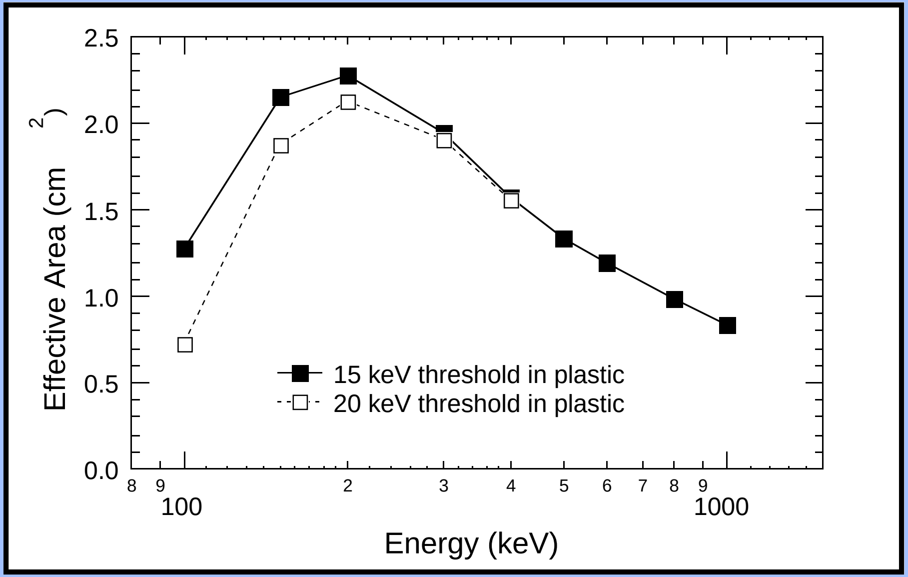


schematic of our latest design concept

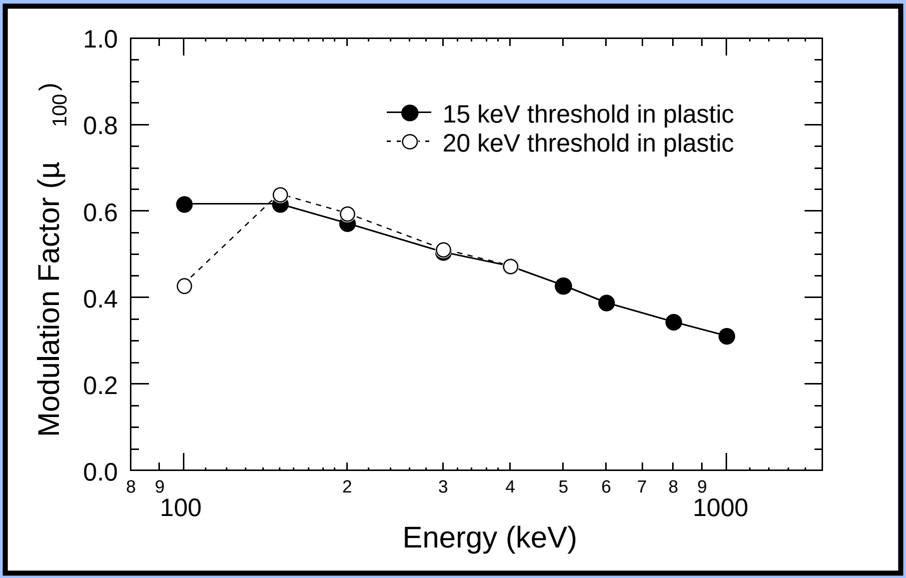
Predicted Performance - On-Axis

These data show the performance of this design based on a series of simulations using a monoenergetic photon beam.

In both cases, we show the results for two different values of the plastic fiber energy threshold. A lower threshold leads to an improvement in the low energy characteristics.



Effective Area

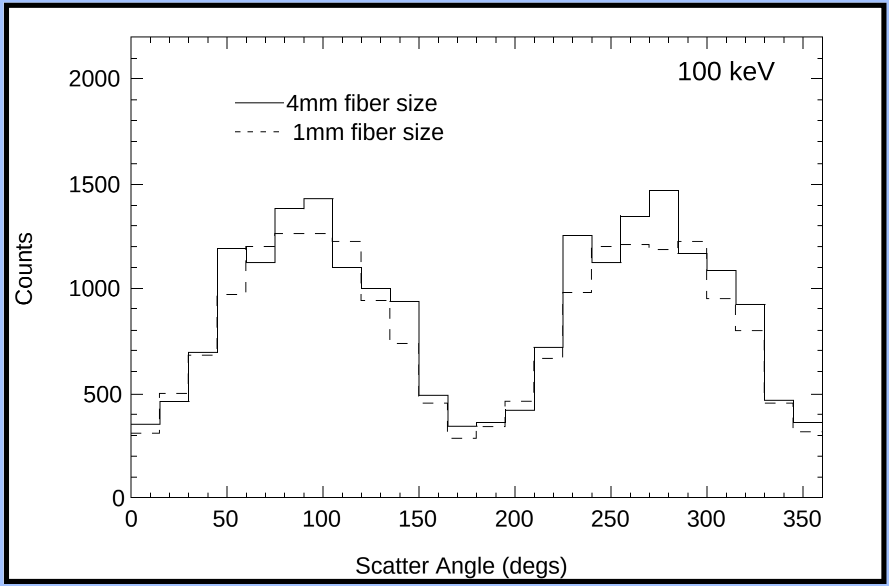


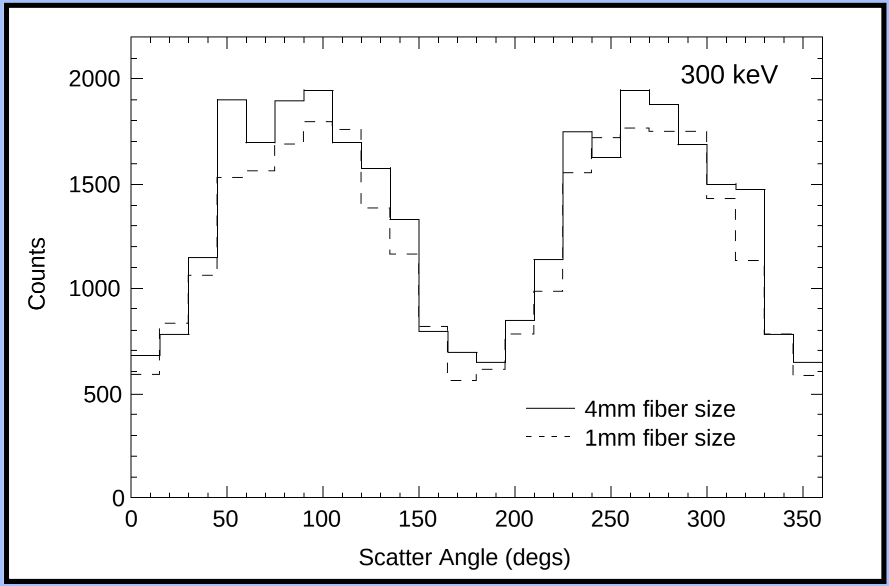
Modulation Factor

Predicted Performance vs. Fiber Size

Simulations show that a smaller fiber size of 1mm offers no significant improvement over the results obtained with a fiber size of 4mm.

Shown below are results for two different energies (100 keV and 300 keV). In both cases, the use of 1mm fibers provided no significant improvement in the polarization modulation factor.





modulation factor 60%

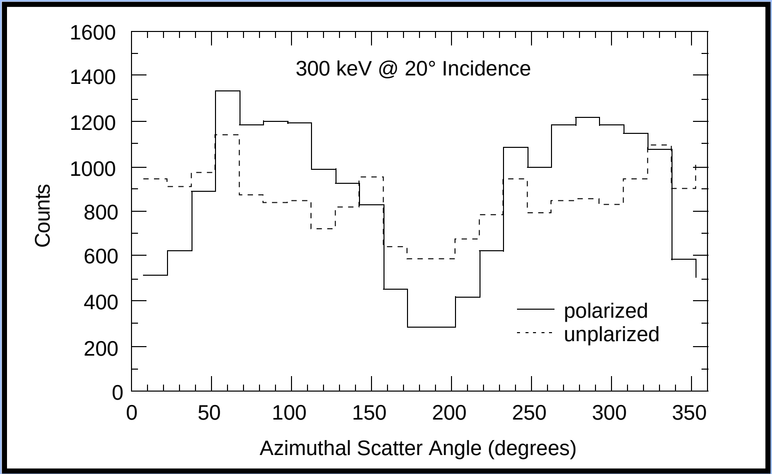
modulation factor 50%

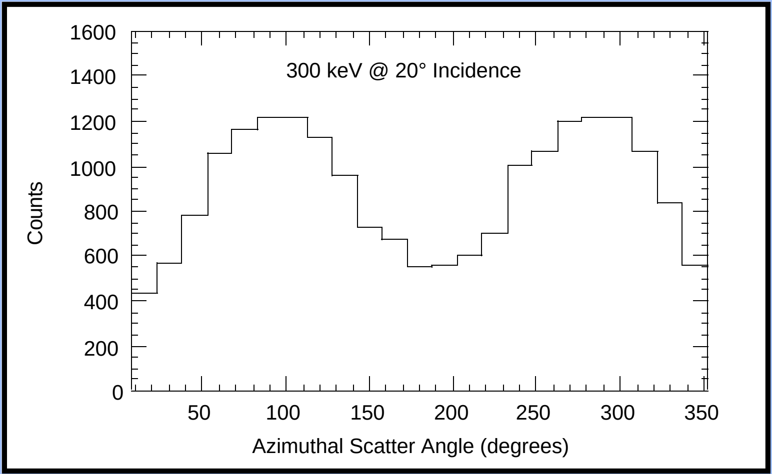
Predicted Performance - Off-Axis

For off-axis angles, even unpolarized sources exhibit a modulated scatter angle distribution. This source data must be compared with that expected for an unpolarized source in order to extract the polarization signal.

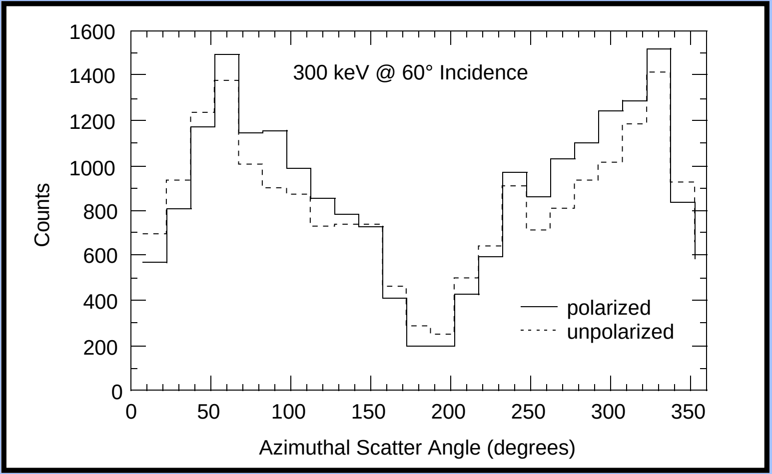
'Raw' Data

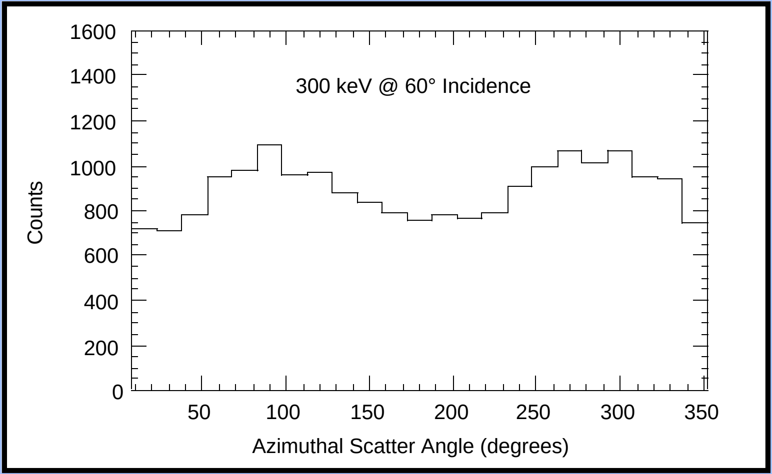
'Difference' Data





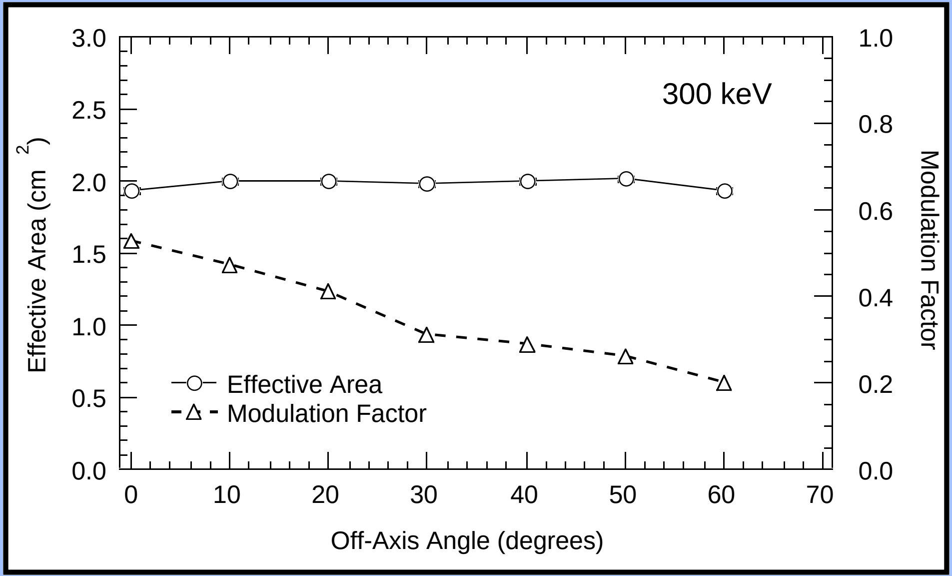
20° off-axis

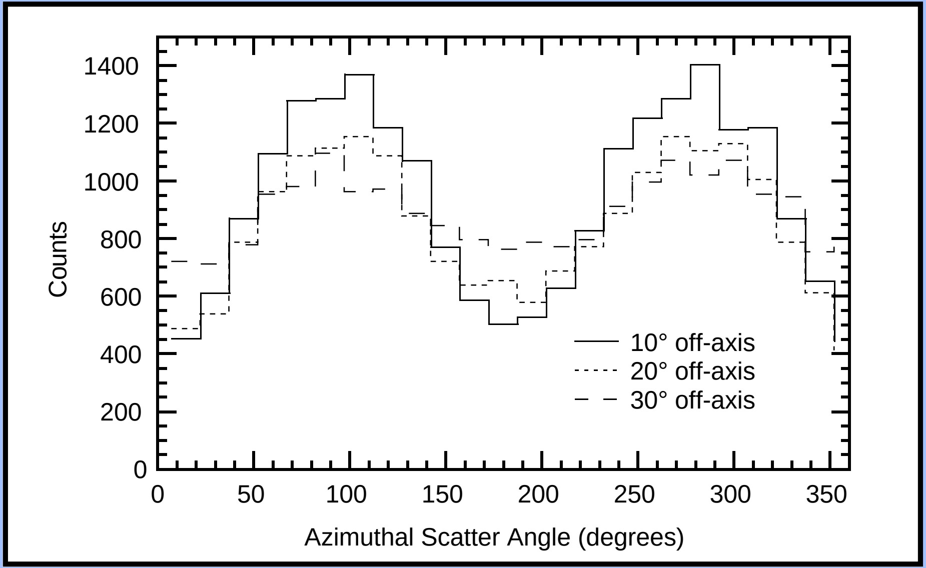




60° off-axis

Predicted Performance - Off-Axis



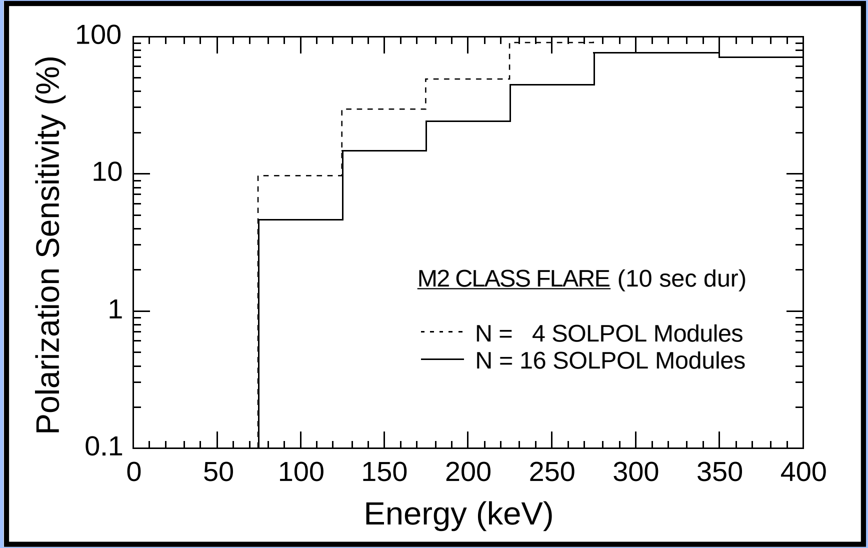


The total effective area as a function of incidence angle remains relatively constant due to the roughly constant exposed area of the fiber bundle.

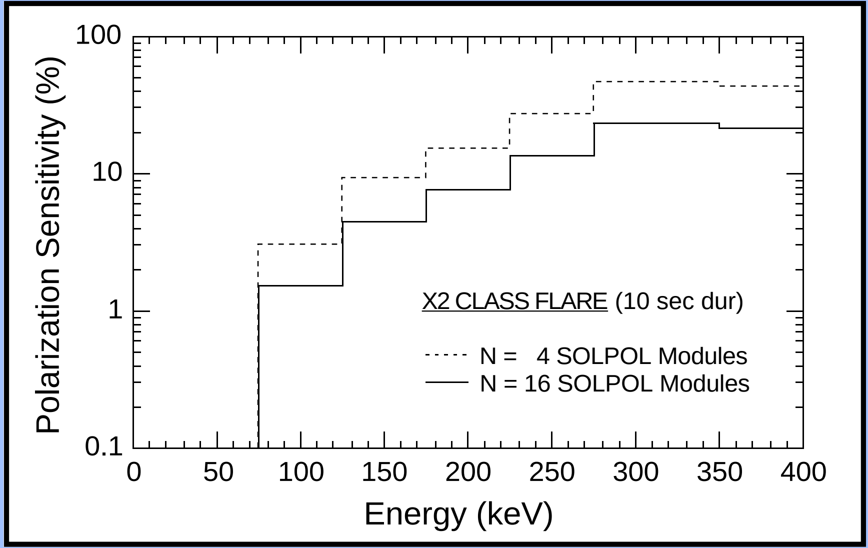
The modulation factor varies dramatically as a function of the off-axis angle.

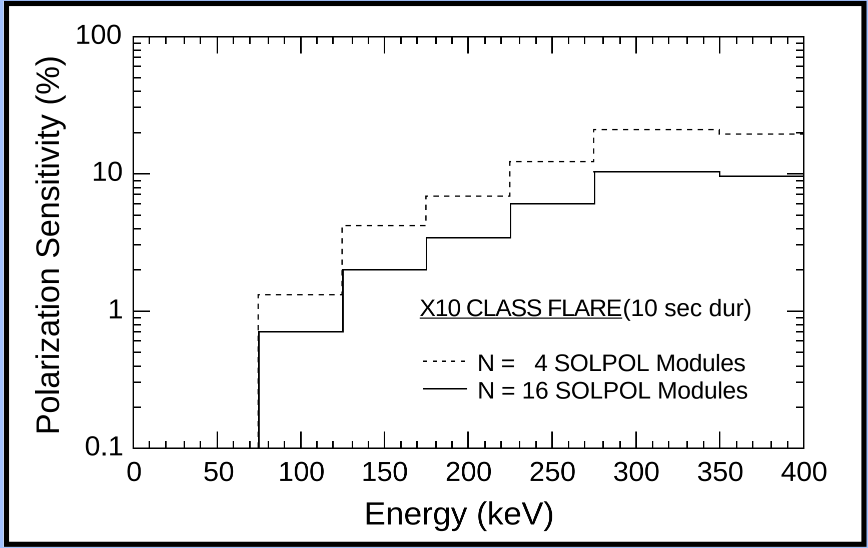
Nonetheless, there remains significant polarization sensitivity even at angles as large as 60°.

Solar Flare Polarization Sensitivity



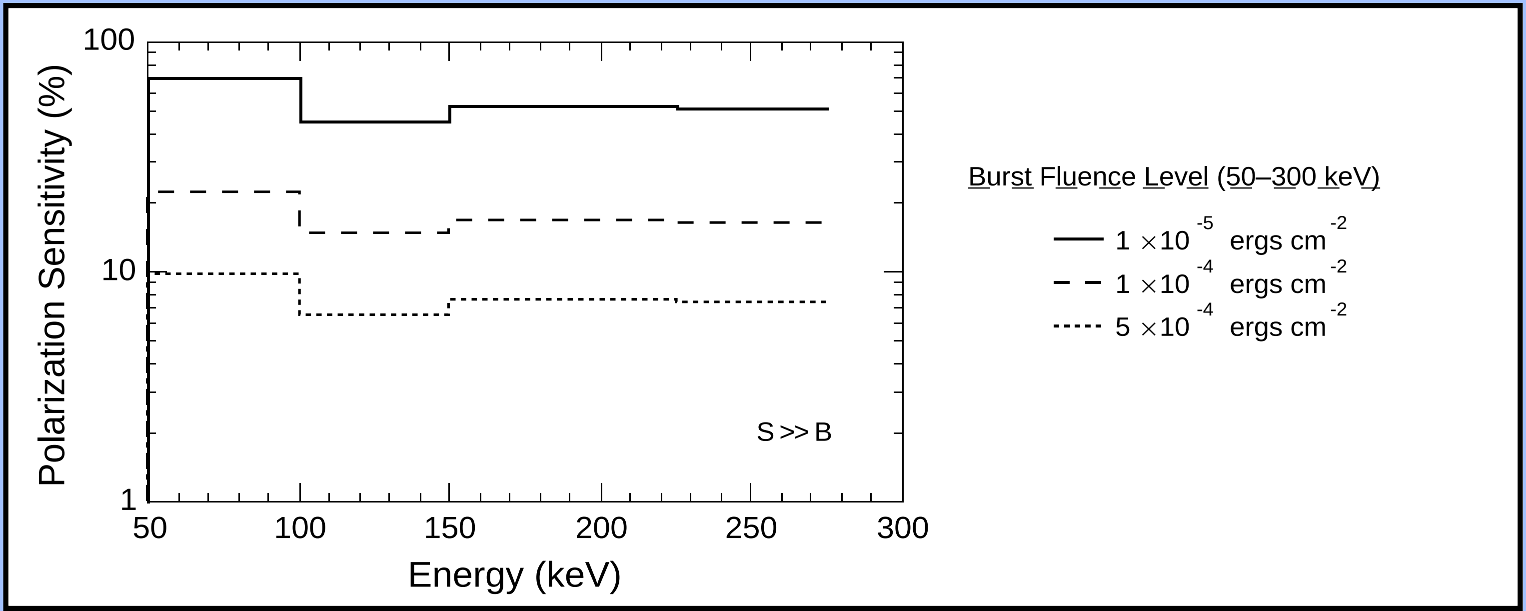
These plots show the expected sensitivity of a polarimeter array based on this design. In each case, the sensitivities are shown for an array of 4 modules and an array of 16 modules. Array sensitivity goes as sqrt(N).





Burst Polarization Sensitivity

An array of these polarimeter modules may have sufficient sensitivity to study polarization in γ-ray bursts. As shown below, polarization sensitivities approaching 10–20% can be achieved in individual energy intervals for the strongest events with an array of 16 modules.



The sensitivity integrated over the full 50–300 keV interval is about 10% at a fluence level of 7×10^{-5} ergs cm^{-2}. This corresponds to the fluence level of some of the strongest BATSE events.

Project Status

- ✔ We have successfully demonstrated a prototype polarimeter in the laboratory.
- ✔ We have developed a design for a compact polarimeter module that could be adapted to a variety of configurations.
- ✔ We have extensively modeled our new design using Monte Carlo simulations to evaluate its performance characteristics.
- ✔ We have begun testing a PSPMT/fiber bundle detector module to precisely evaluate its performance in the lab.
- ✔ Although our developments are primarily directed towards the study of solar flares (with support from Space Physics SR&T funding), we are investigating the use of this design in the context of γ-ray bursts and other non-solar (e.g., collimated) applications.