Laboratory Testing of a Hard X-Ray Solar Flare Polarimeter

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Polarization of Solar Flare Hard X-Rays

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

☞ To date, polarization measurements of solar flares have all been made at energies below ~30 keV, but with generally inconsistent results.

☞ Measurements at higher energies will be required to avoid contamination by thermal X-rays.

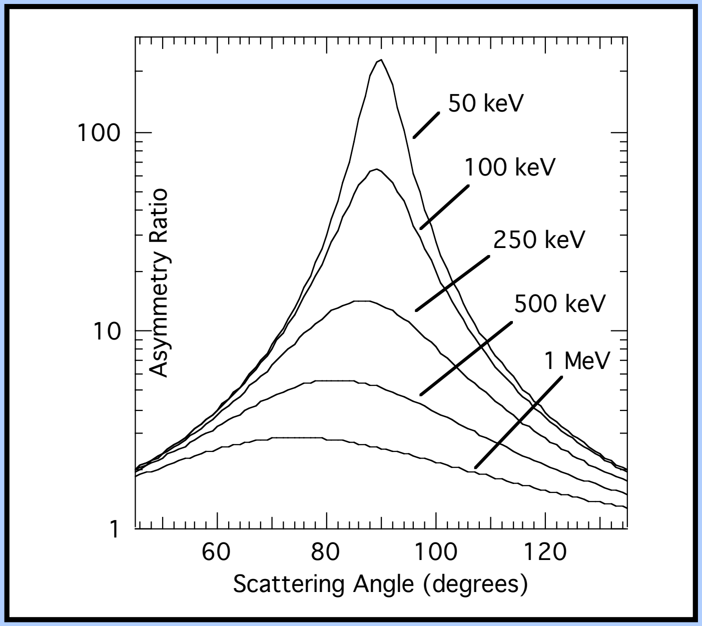
☞ Solar flare polarization measurements (E > 100 keV) should tell us something about the directivity (beaming) of the accelerated electrons.

☞ Models for solar flares typically predict polarization levels of up to ~10% at hard X-ray energies.

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.



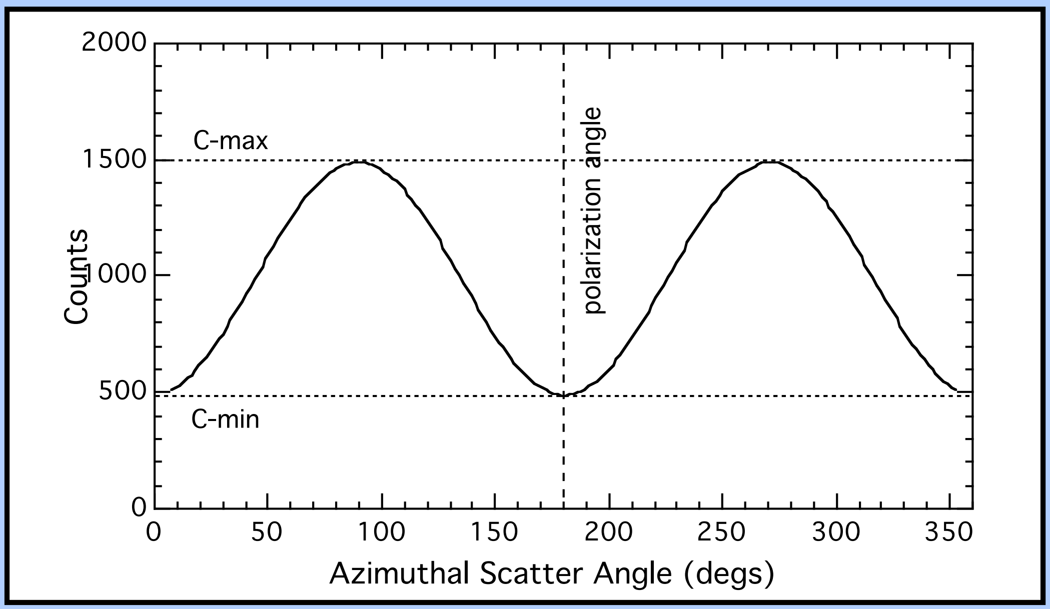
A Compton scatter polarimeter consists of two basic components:
1) low-Z scattering detector(s) to provide Compton scattering medium
2) high-Z calorimeter detector(s) to absorb the scattered photon

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.

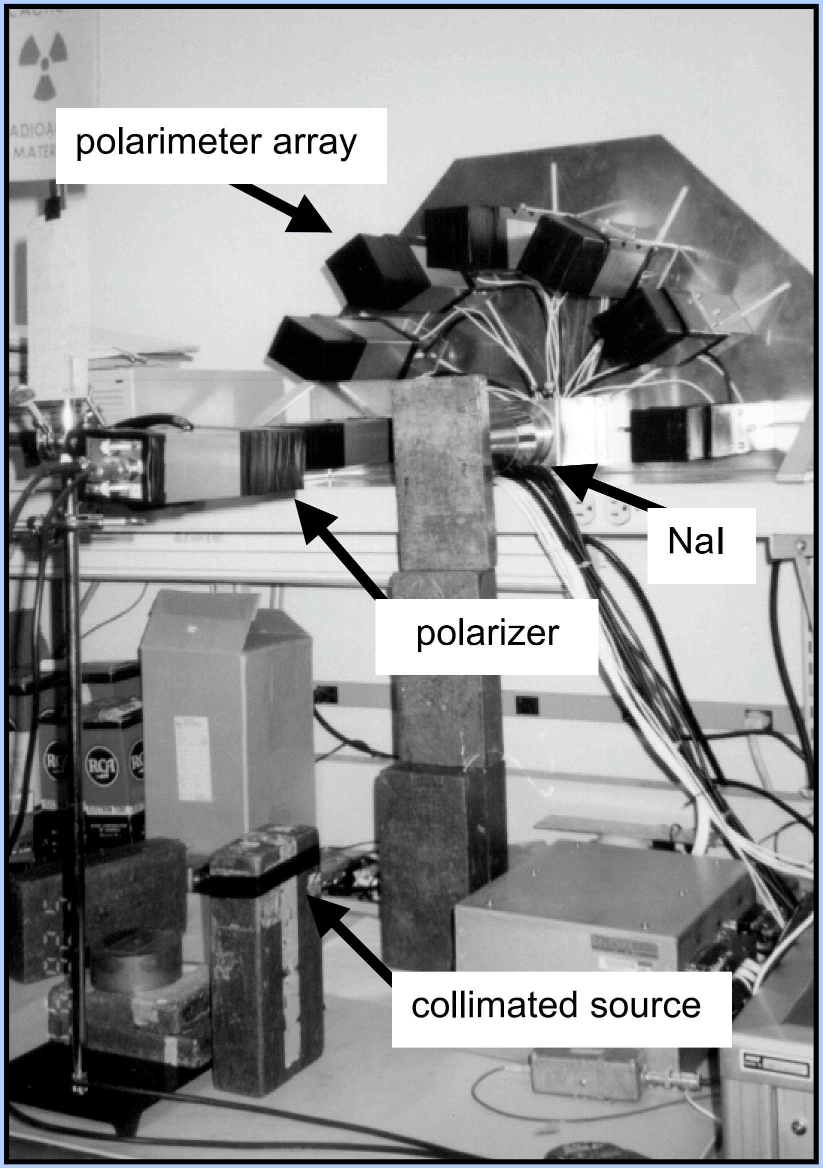
Laboratory Prototype

A laboratory prototype was used to demonstrate the basic principles and to validate our (GEANT-based) Monte Carlo simulations.

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

Each plastic scintillator block was 5.5 × 5.5 × 7.0 cm in size. The cylindrical NaI(TI) detector is 7.6 × 7.6 cm.

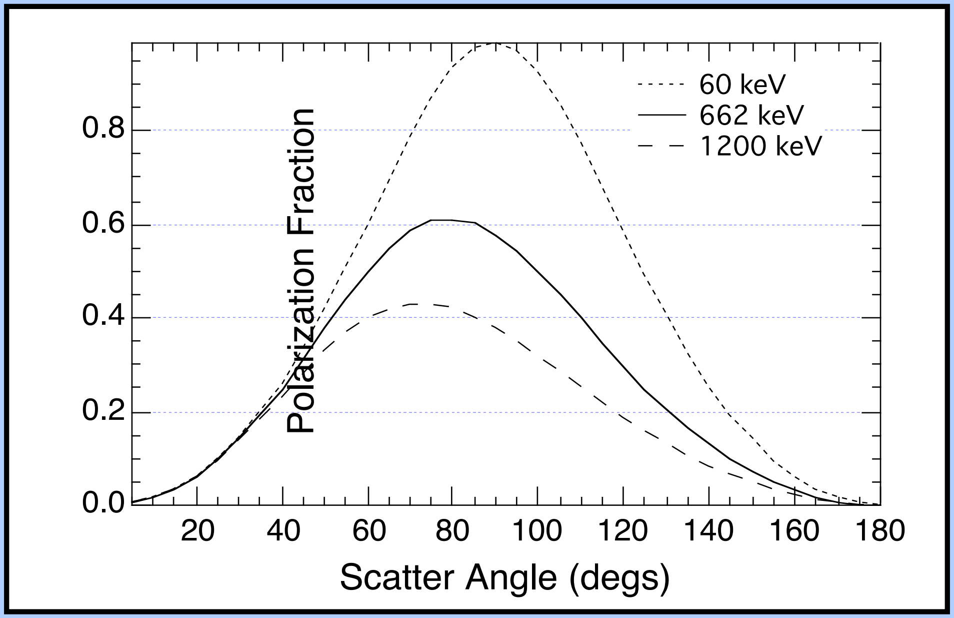
The plastic detectors were positioned at a radius of 15 cm from the NaI detector.



Generating a Polarized Beam

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



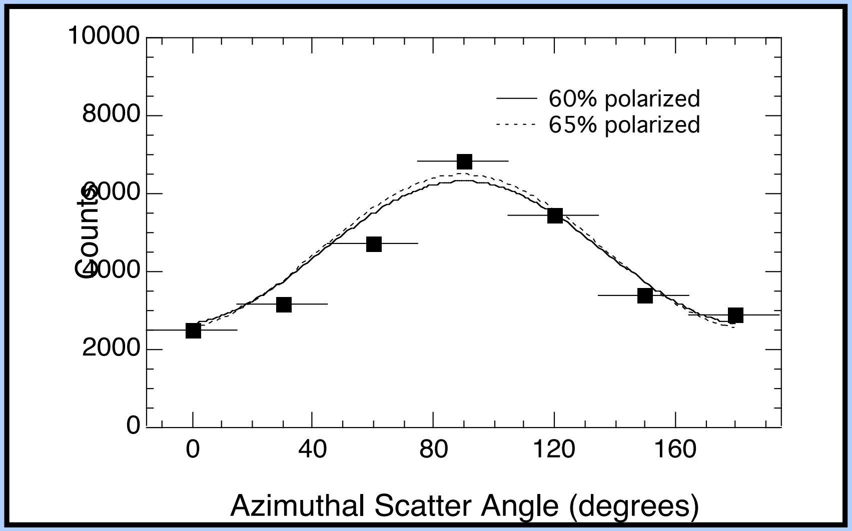
This graph shows the level of polarization that can be achieved for various <u>input</u> photon energies (corresponing to ^{241}Am, ^{137}Cs and ^{60}Co) and various scatter angles.

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

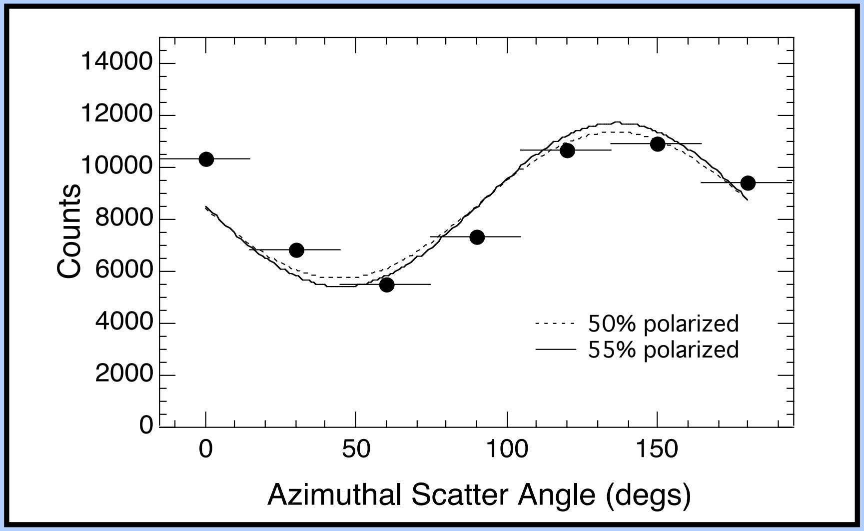
Results from Lab Prototype

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 looking at line features.

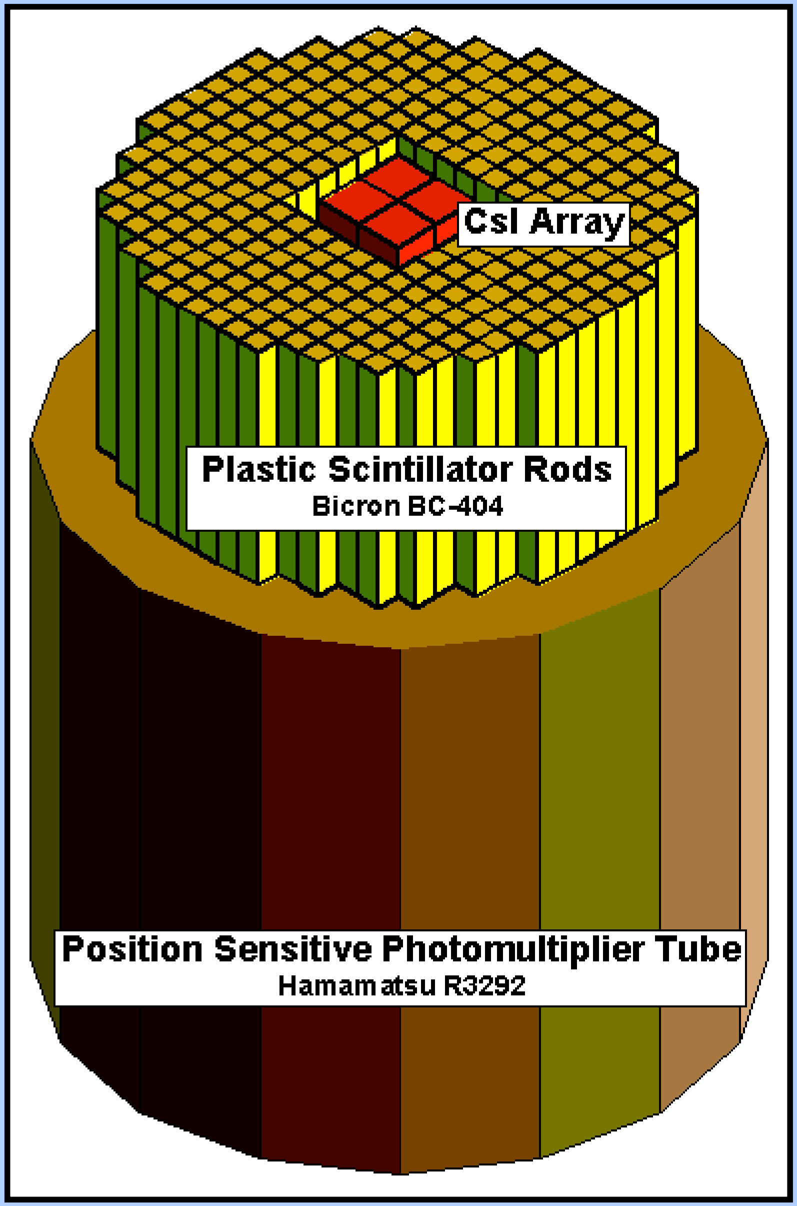
SOLPOL Science Model

SOLPOL
SOLar POLarimeter for Hard X-Rays

The plastic scattering elements are a bundle of 5mm square plastic scintillators (each 2-inches long). Readout is provided a 5-inch PSPMT

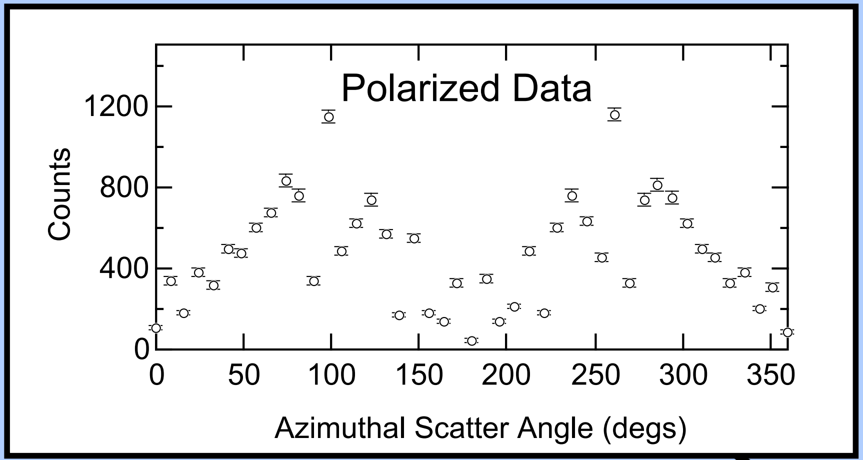
The calorimeter detectors are an array of 1cm square CsI scintillators (each 2-inches long). Readout is provided by a 4-channel multi-anode PMT (Hamamatsu R5900).

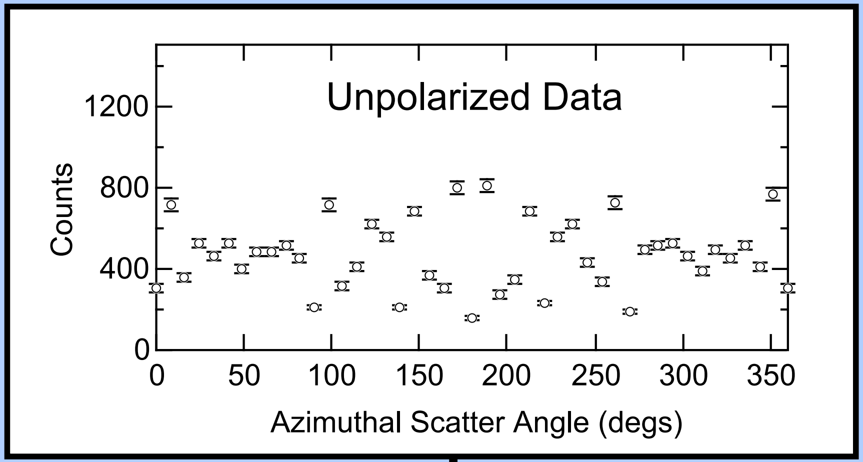
We are currently testing a laboratory science model of the SOLPOL design.



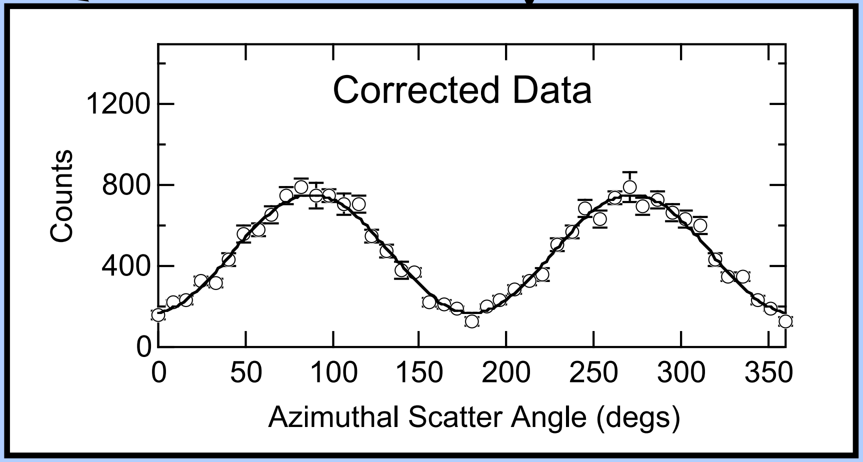
SOLPOL Polarimetric Response

Simulated Results for Monoenergetic On-Axis Beam at 150 keV





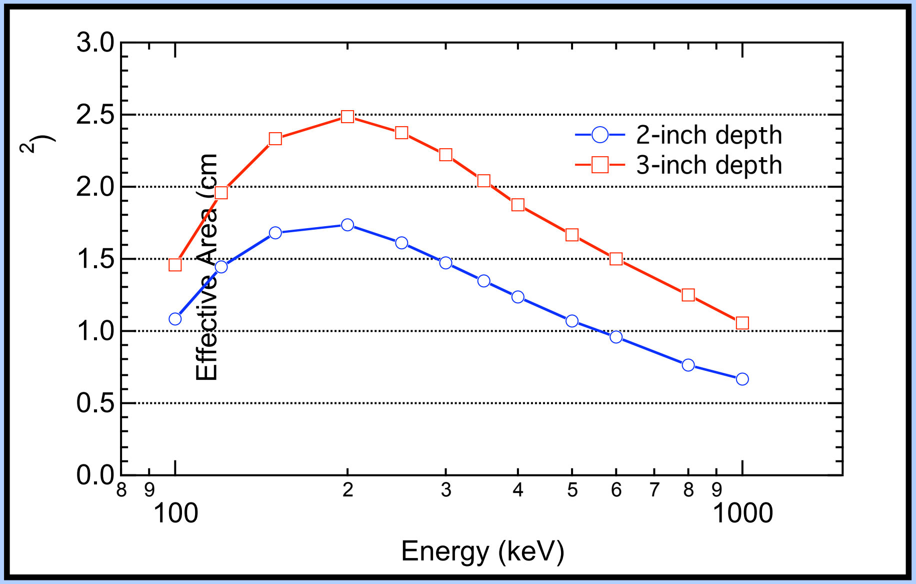
The simulated data for an unpolarized beam are used to correct for geometric effects and to extract the true modulation pattern from the data.



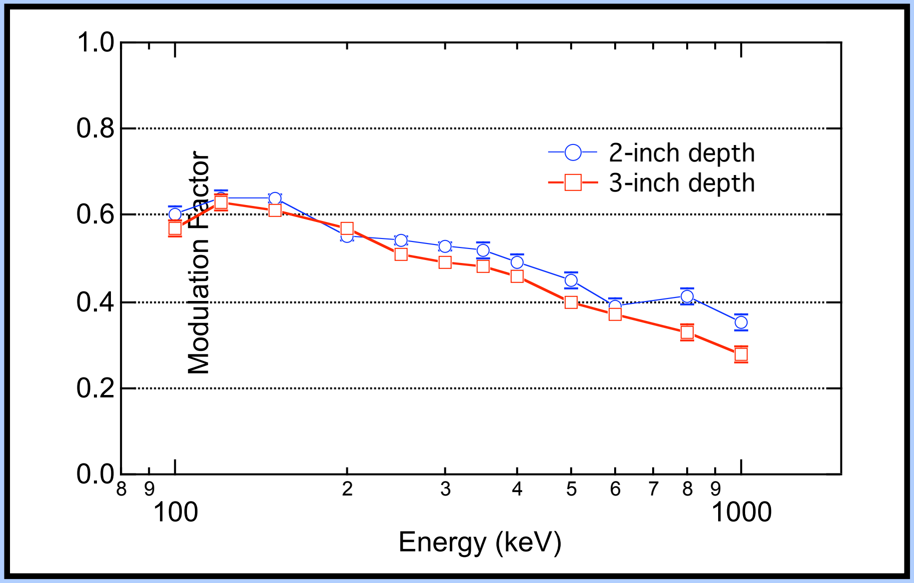
SOLPOL Performance - On-Axis

These data show the performance of the SOLPOL design (for two different detector depths) based on a series of simulations using a monoenergetic photon beam.

The drop-off in effective area at low energies results from the energy threshold of the detectors, especially the plastic scattering elements. In this case, the threshold energies were assumed to be 15 keV for both detectors.



Effective Area



Modulation Factor

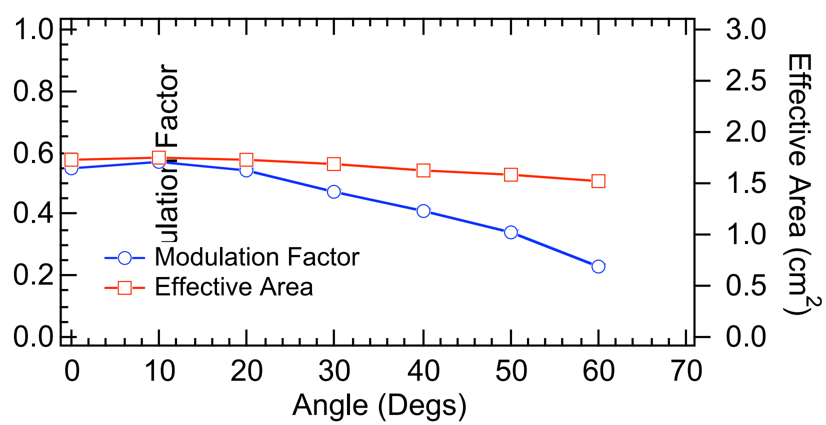
SOLPOL Performance - Off-Axis

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

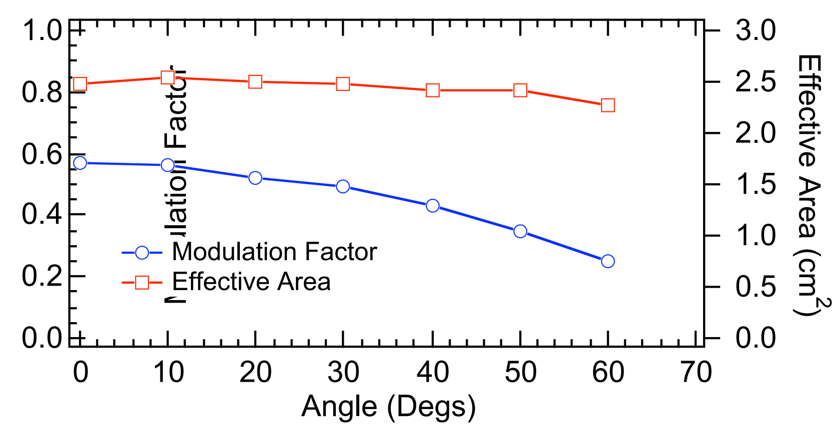
The modulation factor varies dramatically as a function of the off-axis angle.

There remains significant polarization sensitivity even at 60°.

5.08 cm depth @ 200 keV



7.62 cm depth @ 200 keV



SOLPOL Sensitivity to Solar Flare Emissions

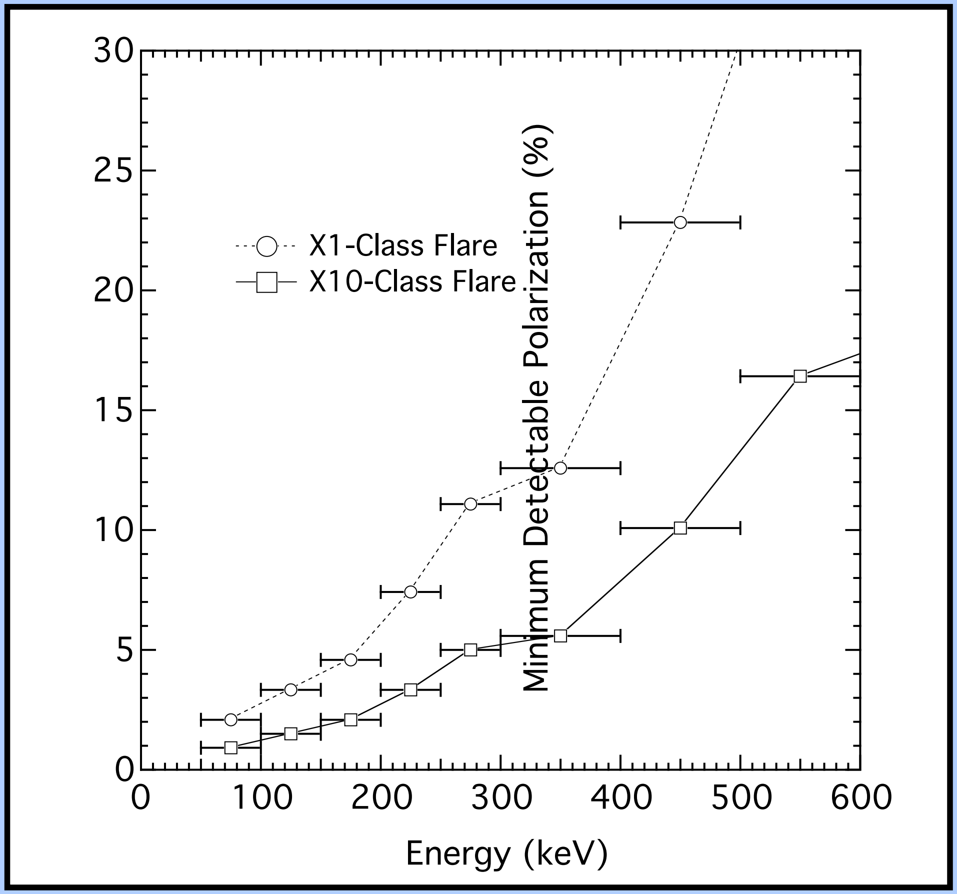
In practice, the SOLPOL design would be used in the context of an array of modules.

An array of sixteen modules would be provide a Minimum Detectable Polarization (MDP) of less than 1% in the 50-300 keV energy range for some M-class flares and all X-class flares.

An array of four modules would be provide a Minimum Detectable Polarization (MDP) of 1% or better in the 50-300 keV energy range for all X-class flares.

The modular nature of this design would also support an imaging polarimeter based on rotating modulation collimators. This could provide arc-second spatial resolution for spatially resolved polarization measurements.

SOLPOL Differential Sensitivity to Solar Flare Emissons

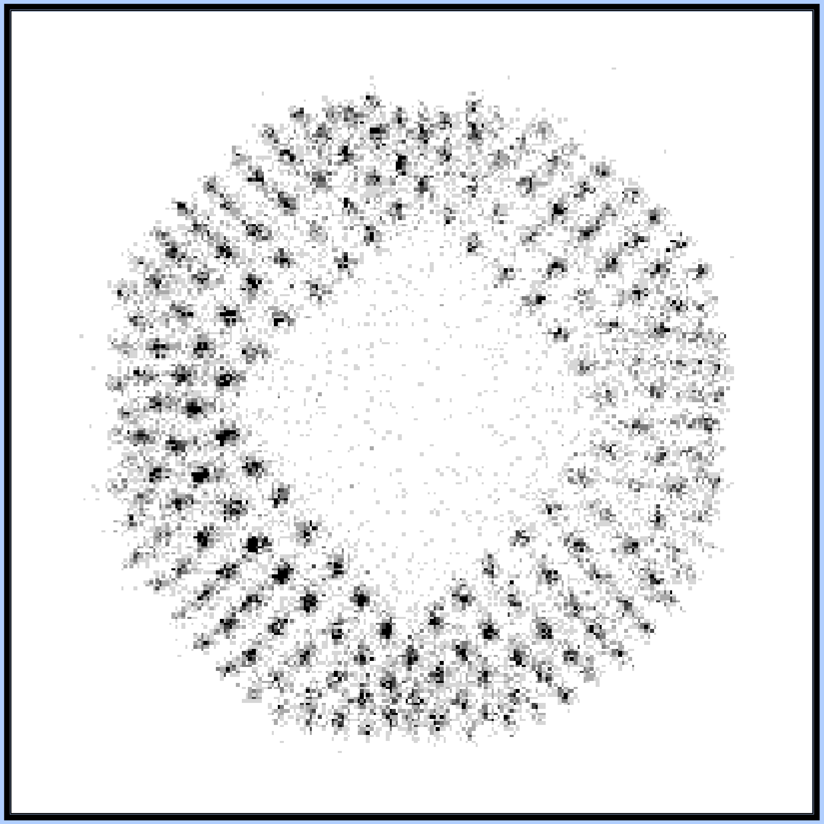


This plot shows the sensitivity of a 16-element SOLPOL array, in terms of the minimum detectable polarization (MDP), for several different energy bands.

Shown are the sensitivity data for both an X1 and an X10 solar flare.

Initial Results from Science Model

Recent tests with the assembled science model demonstrate a spatial resolution that is sufficient to resolve the individual 5 mm plastic scattering elements.



Distribution of ^{137}Cs Events

This figure shows the spatial distribution of events in the array of plastic scintillator elements. These are coincident events, representing photons that have scattered from one of the plastic elements into the central CsI array. The individual plastic elements are clearly resolved, as is the square well for the central CsI array.

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.
- ✔ Initial testing of the new polarimeter design has so far yielded encouraging results.
- ✔ More complete testing of the science model will be performed this summer.