Development of a Dedicated Hard X-Ray Polarimeter

Mark L. McConnell, James R. Ledoux, John R. Macri, and James M. Ryan

Space Science Center
University of New Hampshire
Durham, NH

Hard X-Ray Polarimetry

Gamma-Ray Bursts

- **In the context of fireball models of classical GRBs, polarimetry provides useful constraints on the extent to which the flow is beamed.**
- **Energy-dependent polarization measurements can also distinguish between synchrotron and inverse-Compton emissions.**
- **Polarimetry can test the importance of photon splitting in SGRs.**

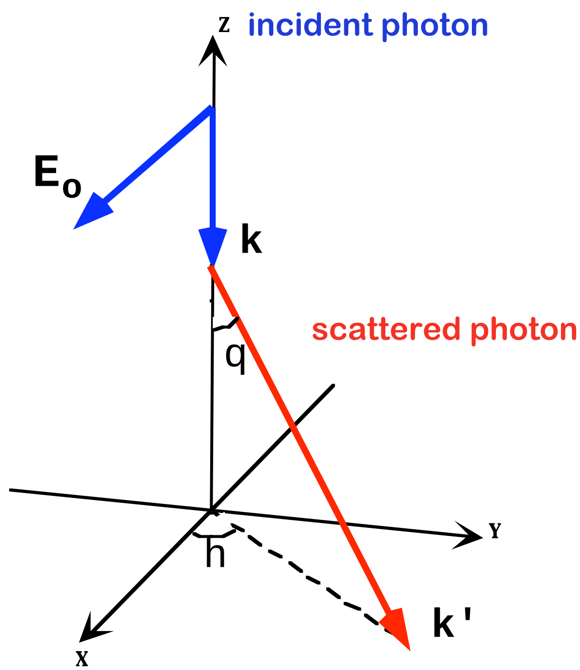
Solar Flares

- **Polarimetry provides a means to determine the extent to which the energetic electrons are beamed.**

Basic Principles of Compton Polarimetry

Polarimetry relies on the fact that…

photons tend to Compton scatter at right angles to the incident polarization vector



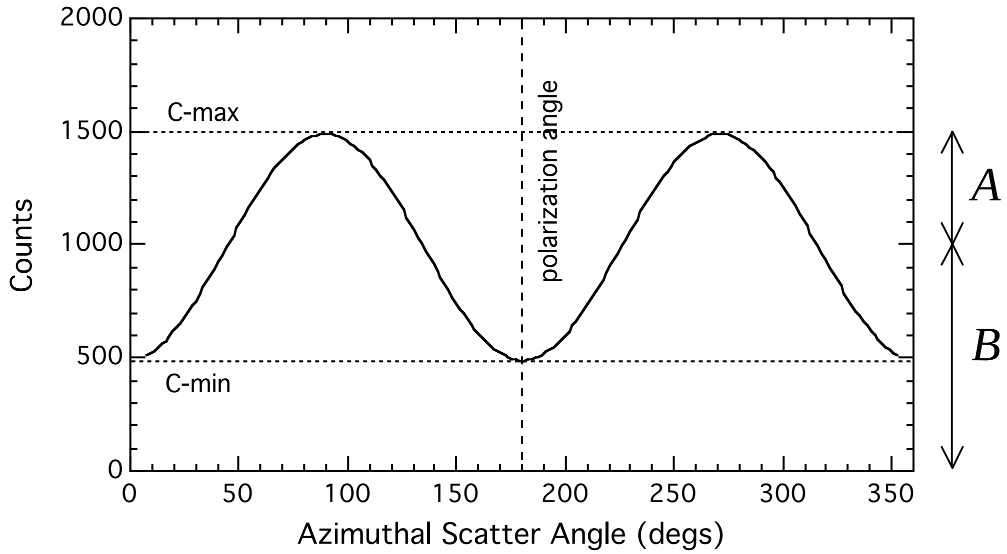
$$d\sigma = \frac{r_o^2}{2} d\Omega \left(\frac{E'}{E_o}\right)^2 \left(\frac{E_o}{E'} + \frac{E'}{E_o} - 2\sin^2\theta\cos^2\eta\right)$$

$$E' = \frac{E_o}{1 + \frac{E_o}{mc^2}(1 - \cos\theta)}$$

θ is the Compton Scatter Angle, η is the Azimuthal Scatter Angle

The Polarization Signature

For a fixed Compton scatter angle (q), the azimuthal distribution of scattered photons contains the polarization signature.



$$C(h) = A \cos 2(h - j) + B$$

Modulation Factor for a 100% polarized beam represents a figure-of-merit for the polarimeter

$$Q = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} = \frac{A}{B}$$

The *amplitude* of the modulation defines the *level of polarization*.

The scattering angle corresponding to the *minimum* of the distribution defines the *plane of polarization*.

Minimum Detectable Polarization (MDP)

$$MDP = \frac{n_s}{Q_{100} S}\sqrt{\frac{2(S+B)}{T}}$$

S =	source counting rate
B =	background counting rate
T =	observation time
Q_{100} =	modulation factor for 100% polarization

Sensitivity can be improved by :

1) Increasing S (efficiency or geometric area)

2) Decreasing B

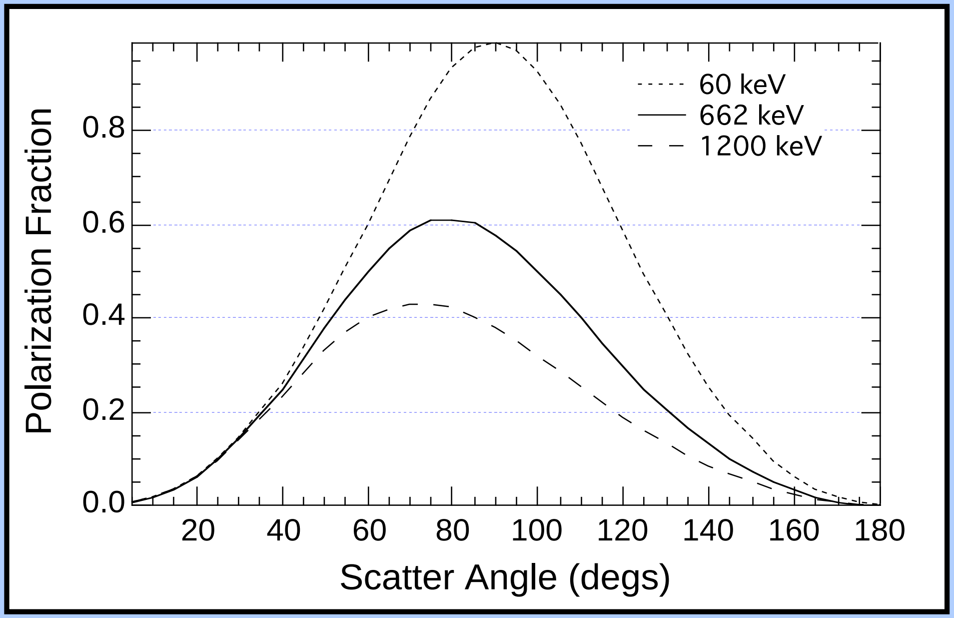
3) Increasing T

4) Increasing Q_{100} (optimizing geometry)

Generating a Polarized Beam

Polarized X-rays can be generated in the lab by Compton scattering photons from a g-ray calibration source 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 input photon energies (corresponding 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.

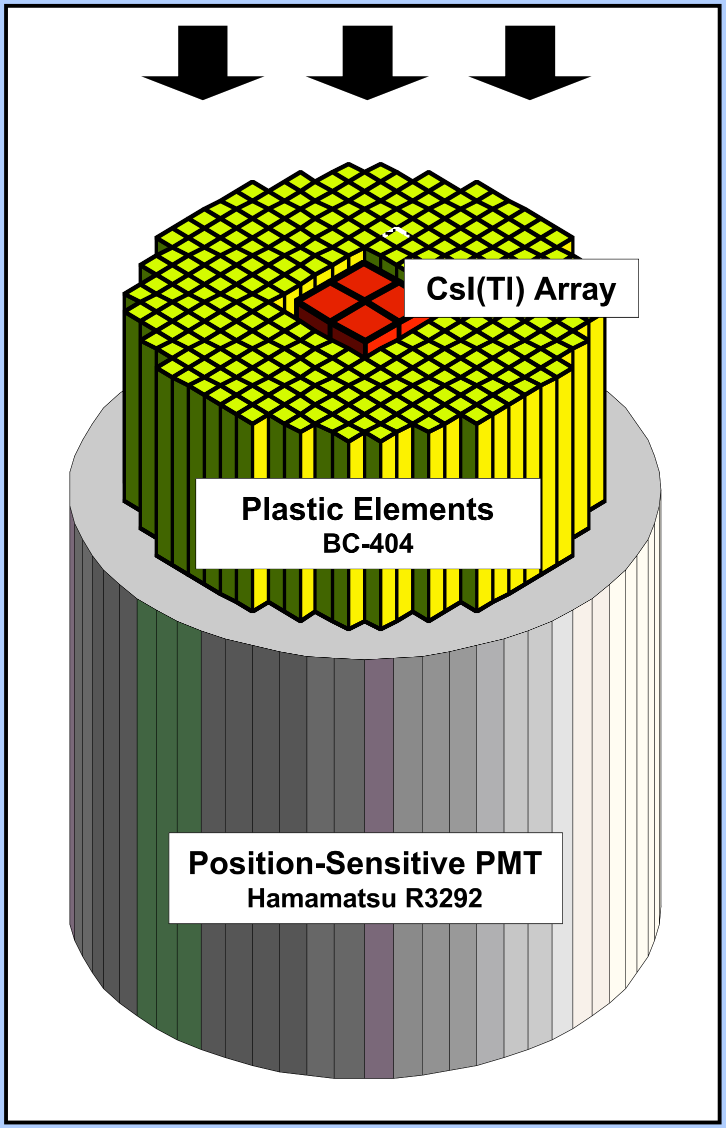
The GRAPE Science Model

Gamma-RAy Polarimeter Experiment

Plastic Scattering Elements :
- 280 element array of BC-404
- Each element optically isolated
- Wrapped in Tyvek® and Kapton® tape
- Each 5 mm square by 5 cm long
- Readout provided a 5-inch PSPMT
- Hamamatsu R3292 PSMT

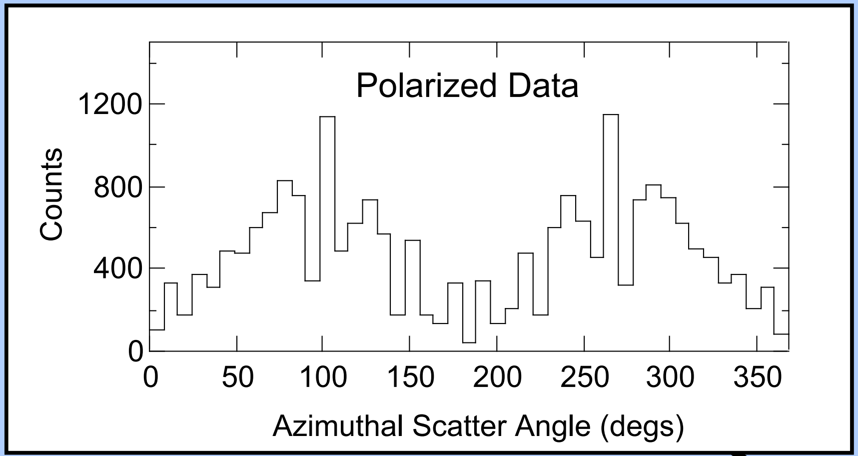
Calorimeter Elements :
- 4 element array of CsI(TI)
- Each 1cm square by 5 cm long
- Readout provided by a MAPMT
- Hamamatsu R5900 MAPMT

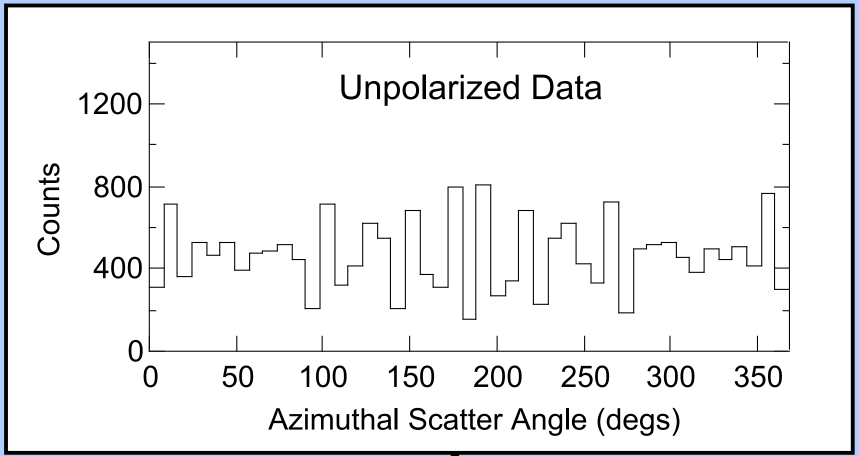
PSPMT / Plastic Array Housing :
- 1mm thick aluminum
- Optically isolated from CsI/MAPMT



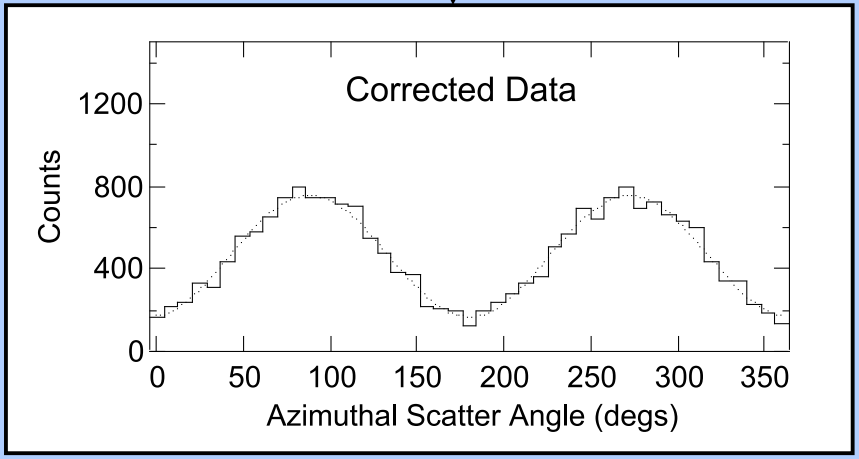
GRAPE Polarimetric Response

Simulated Results for Monoenergetic On-Axis Beam at 150 keV

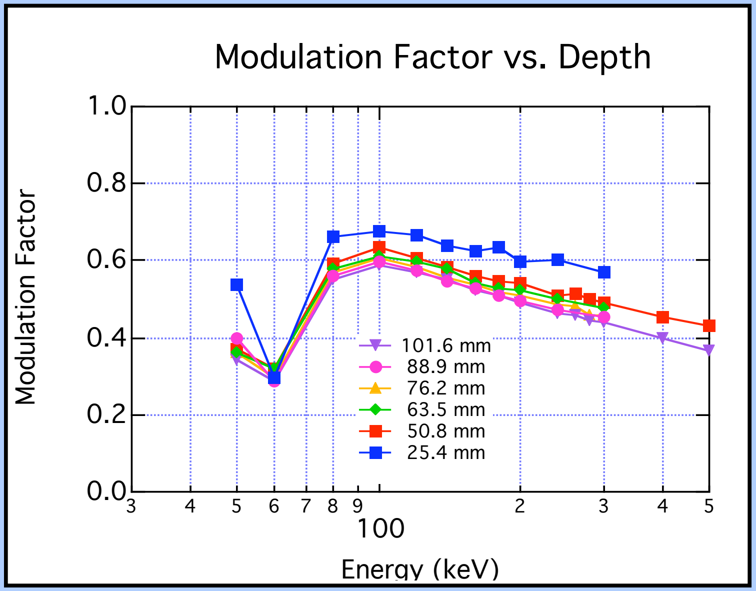


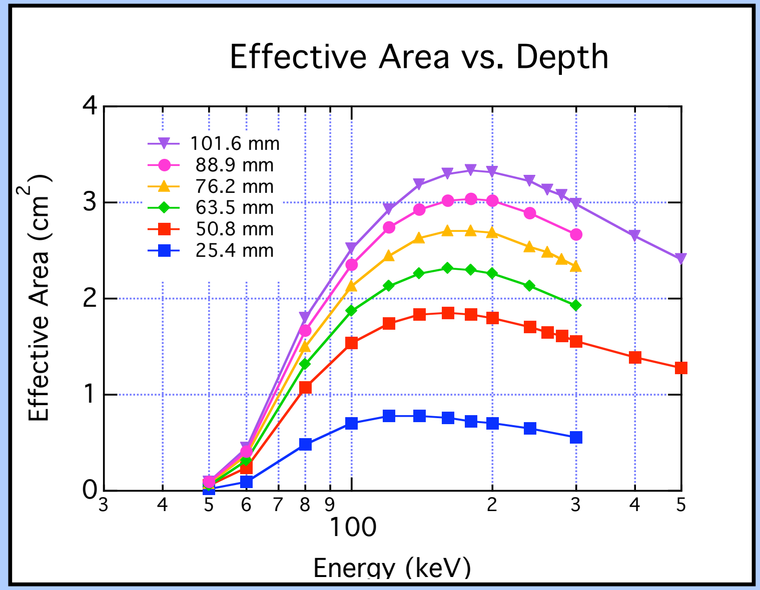


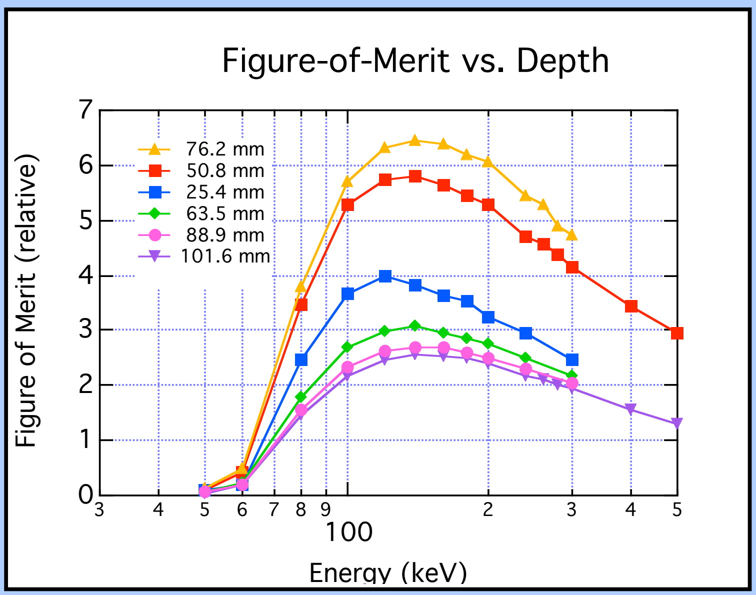
The simulated data for an unpolarized beam are used to correct for geometric effects and to extract the true modulation pattern from the data.



Simulated Performance: On-Axis





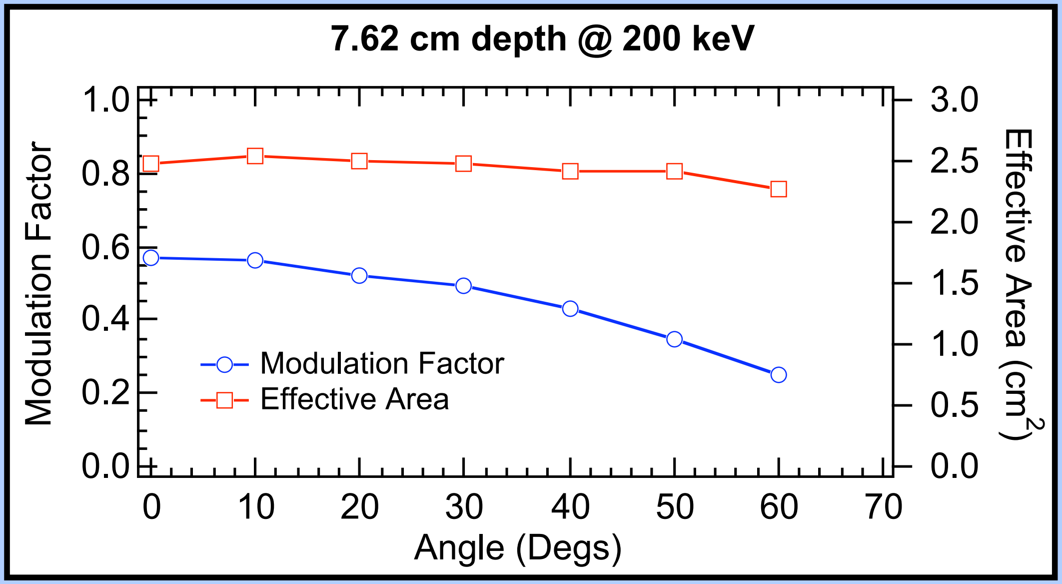


The figure-of-merit incorporates an estimate of the increased background as a function of detector volume.

$$FoM = \frac{\mu_{100}\, \epsilon A}{\sqrt{V_{\text{det}}}}$$

Optimum Depth for this design is ~3 inches

Simulated Performance: Off-Axis

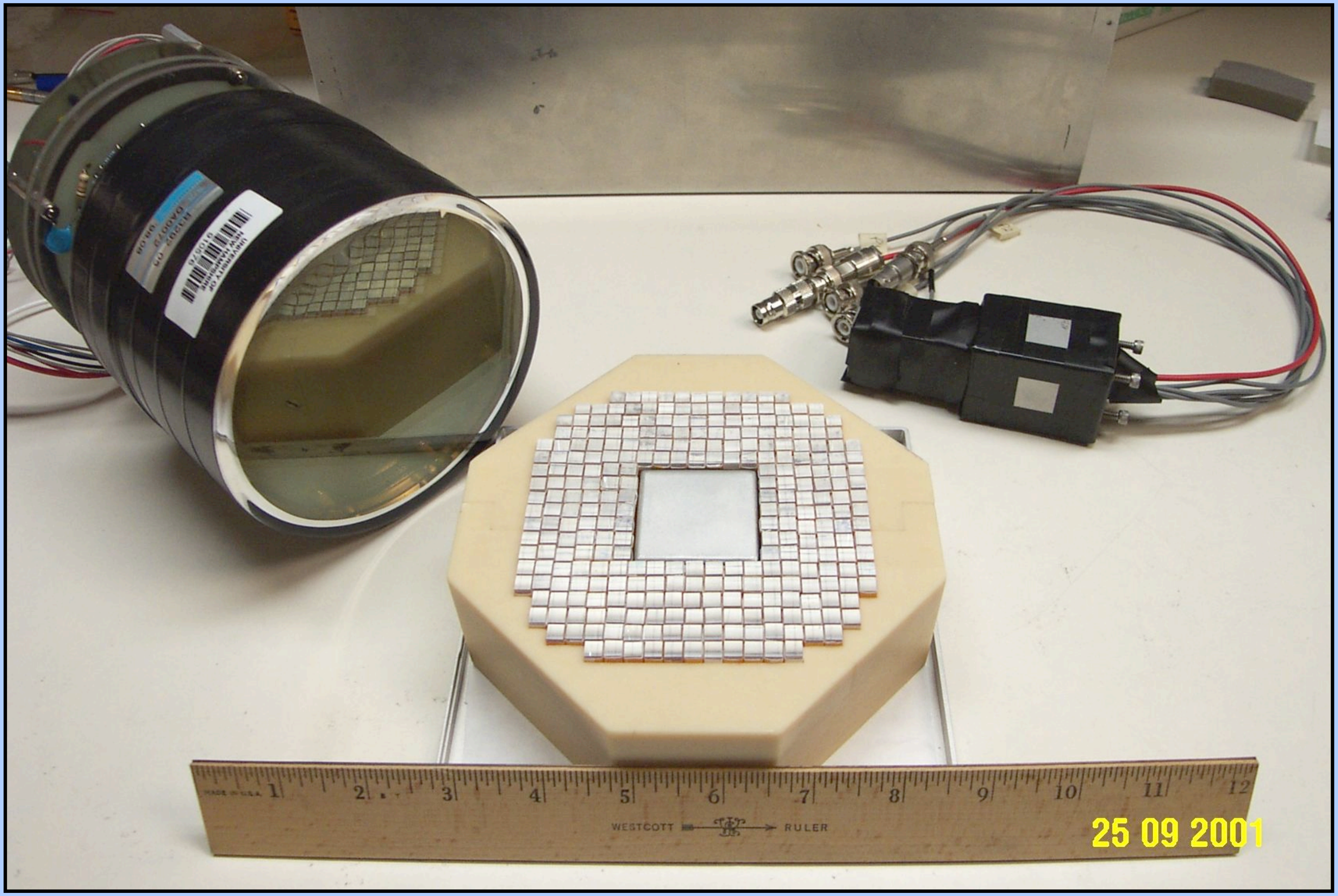


The GRAPE design offers significant response even at large off-axis angles.

This makes GRAPE an attractive design for polarization studies of transient sources (Gamma-Ray Bursts).

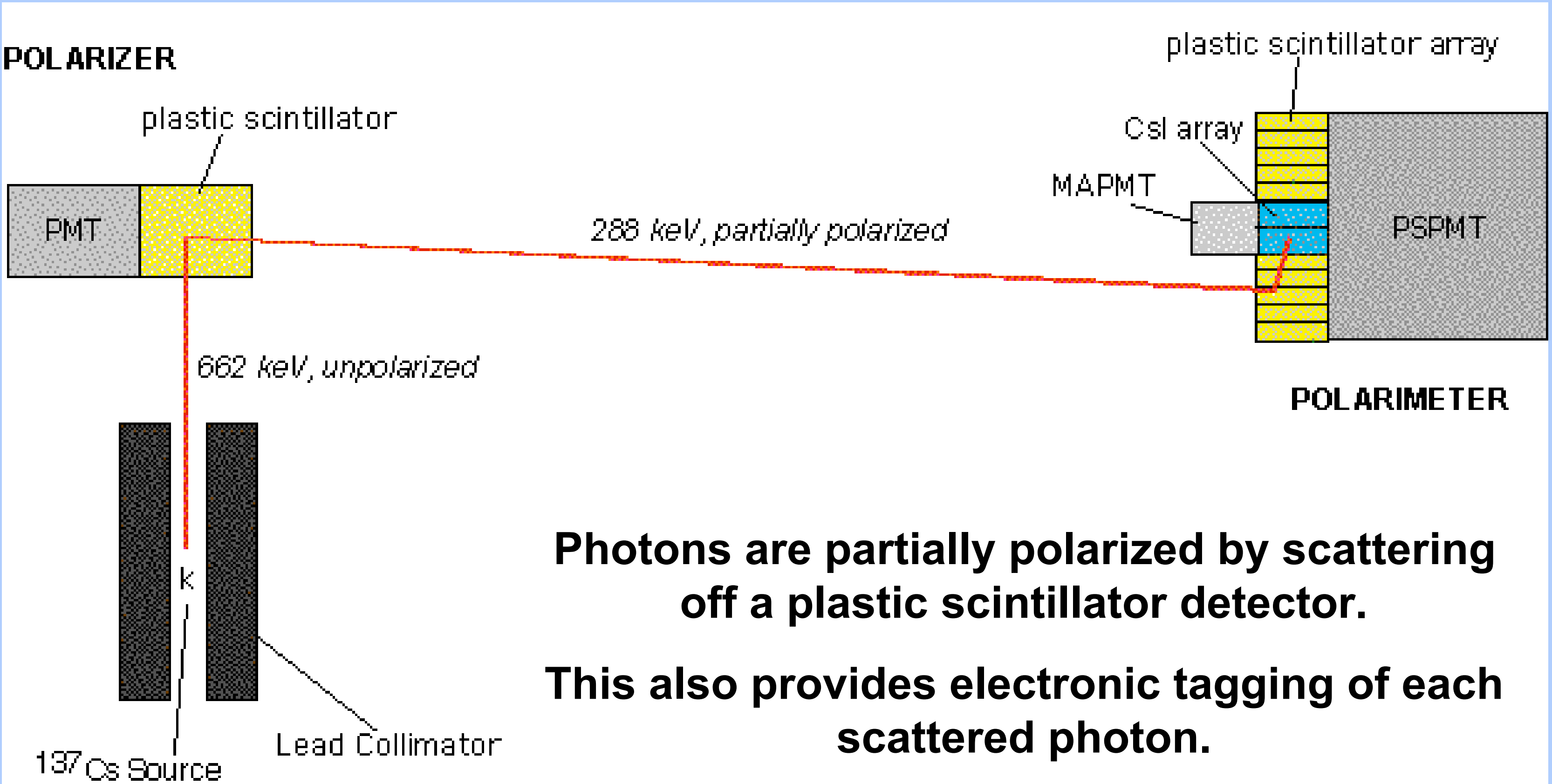
Science Model Components

This photo shows the 5-inch PSPMT, the array of plastic scattering elements and the MAPMT/CsI assembly.



GRAPE Science Model Lab Set-Up

(drawing not to scale)

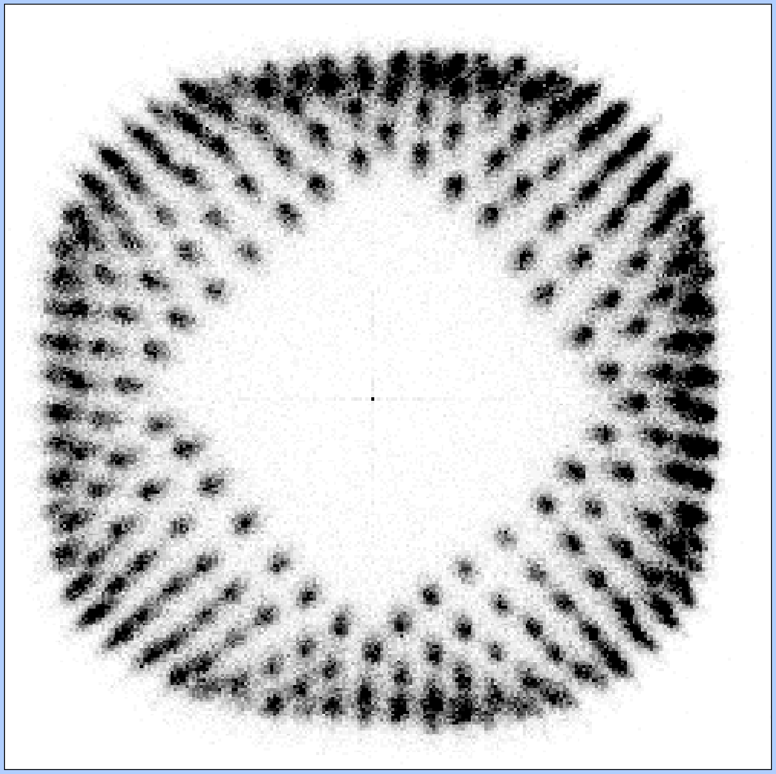


Photons are partially polarized by scattering off a plastic scintillator detector.

This also provides electronic tagging of each scattered photon.

PSPMT Response to Plastic Array

The spatial resolution in the PSPMT is sufficient to resolve the individual 5 mm plastic scattering elements.



Distribution of ^{137}Cs Events

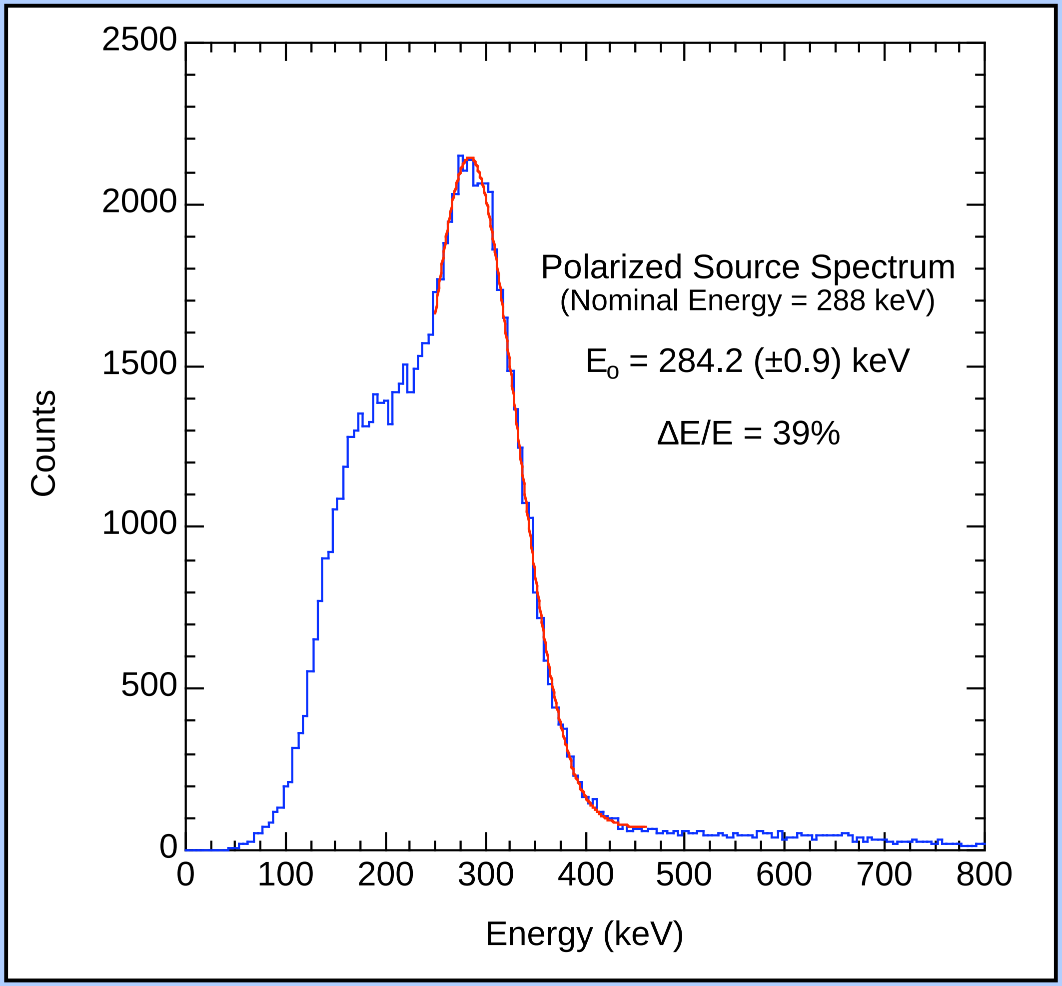
This figure shows the spatial distribution of events in the plastic scintillator array.

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.

Distortions near the edge of the PSPMT are also evident in these raw data.

Results from Science Model



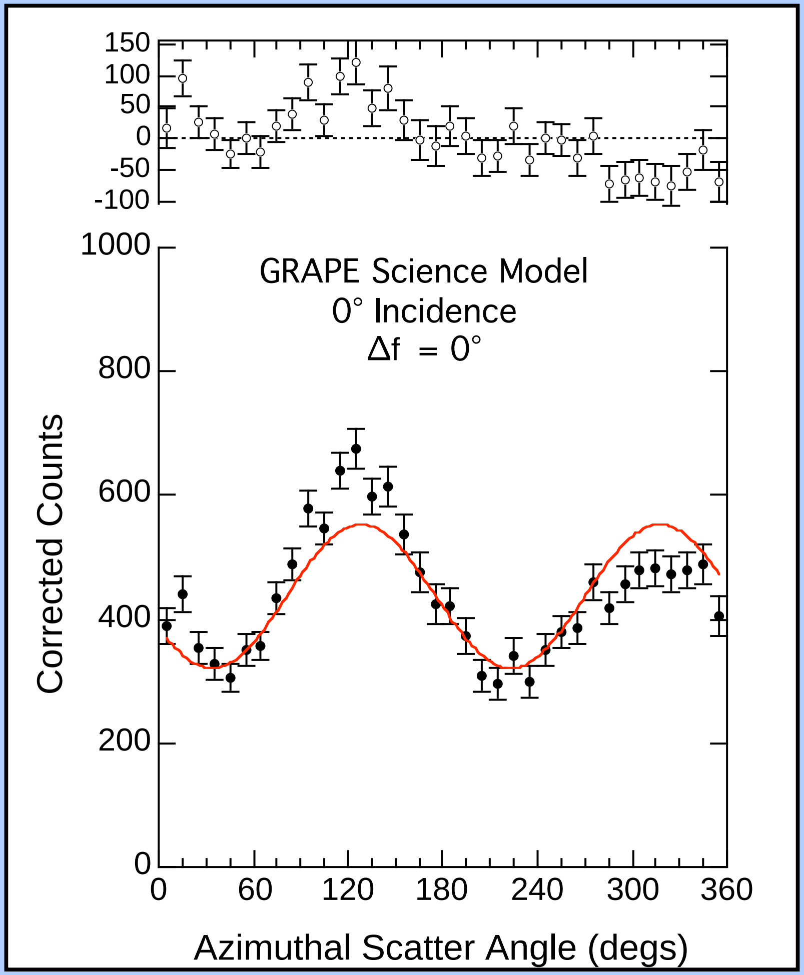
The incident energy spectrum is reconstructed by combining the energy loss in both the CsI and in the plastic array.

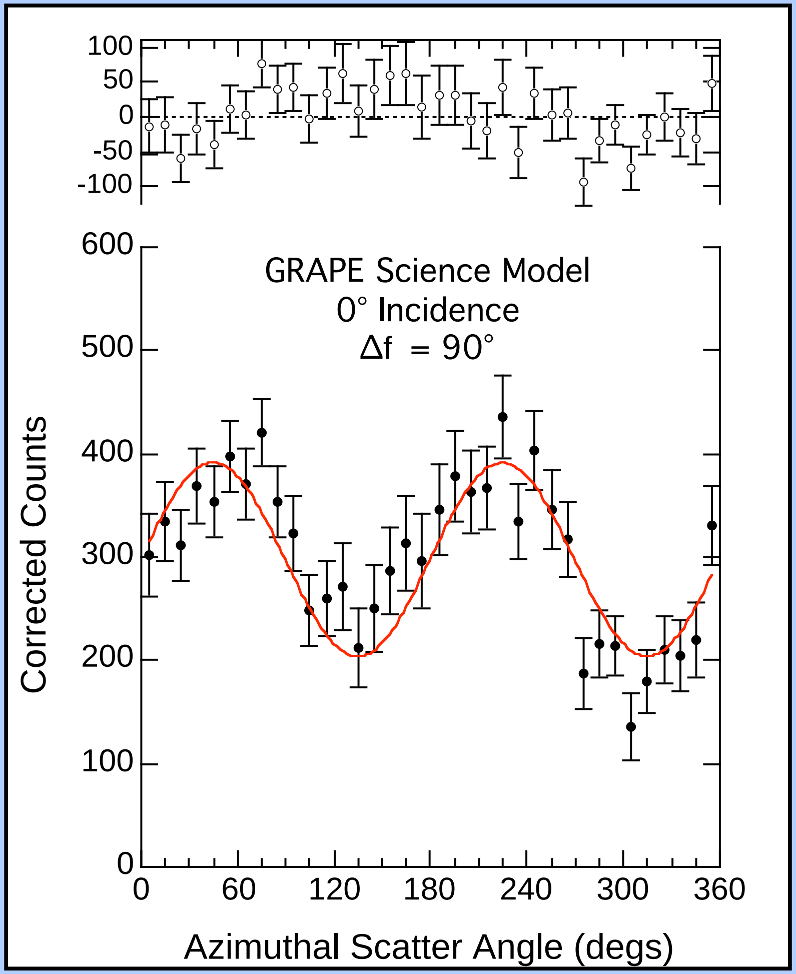
This energy spectrum is that of a 662 keV beam that has been scattered once.

The variable scattering geometry results in an incident beam that covers a broad range of energies, thus accounting for the broad nature of this spectrum.

Lab Results from Science Model

Runs taken with the incident beam having a polarization angle that differs by ~90°.





measured polarization = 61(±3)%
polarization angle = 49(±1)°

measured polarization = 73(±7)%
polarization angle = 135(±3)°

GRB Sensitivity

We have estimated the polarization sensitivity of a long-duration balloon payload consisting of a planar array of 36 GRAPE modules. Such an array would have a FoV of ~2π steradian and cover less than 1 m^2 of area.

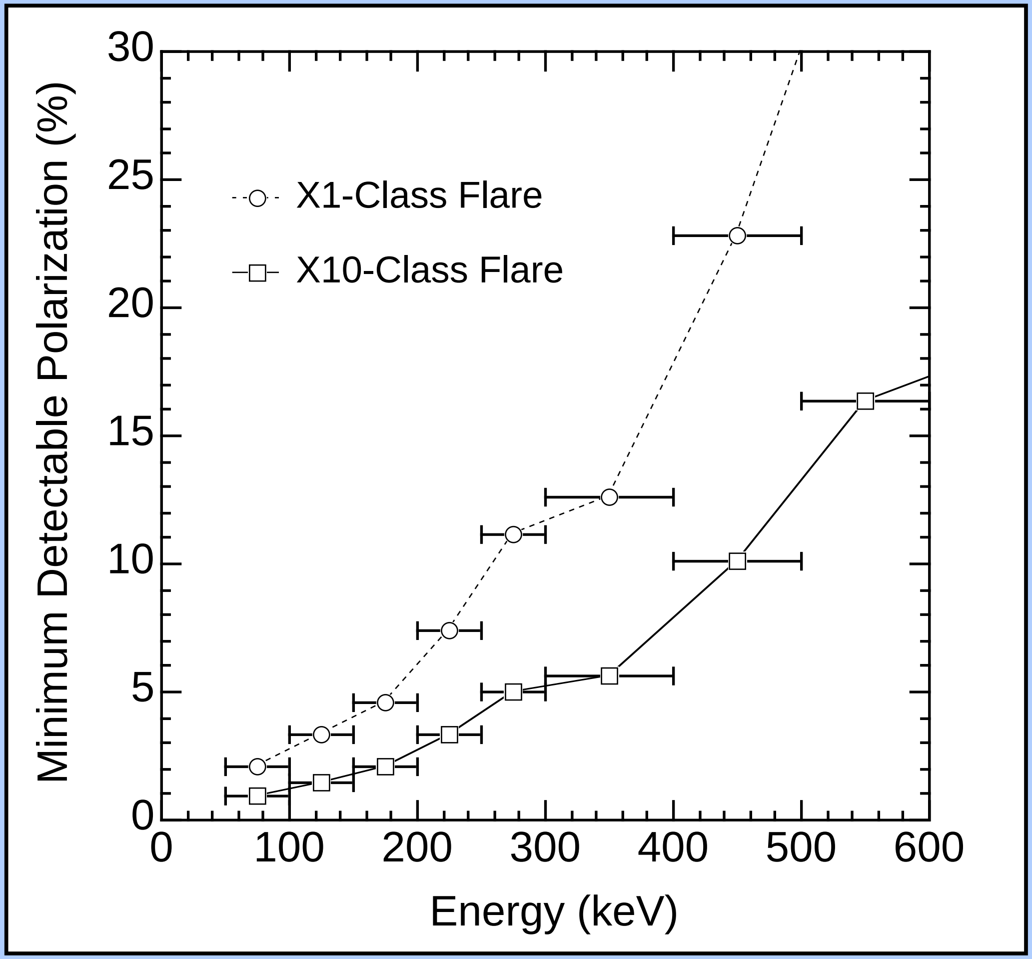
The table below gives the polarization sensitivity over the full energy range (50-300 keV) and the expected frequency of observed events (based on the fluence distribution of the 4B catalog).

GRB Polarization Sensitivity
50-300 keV energy band

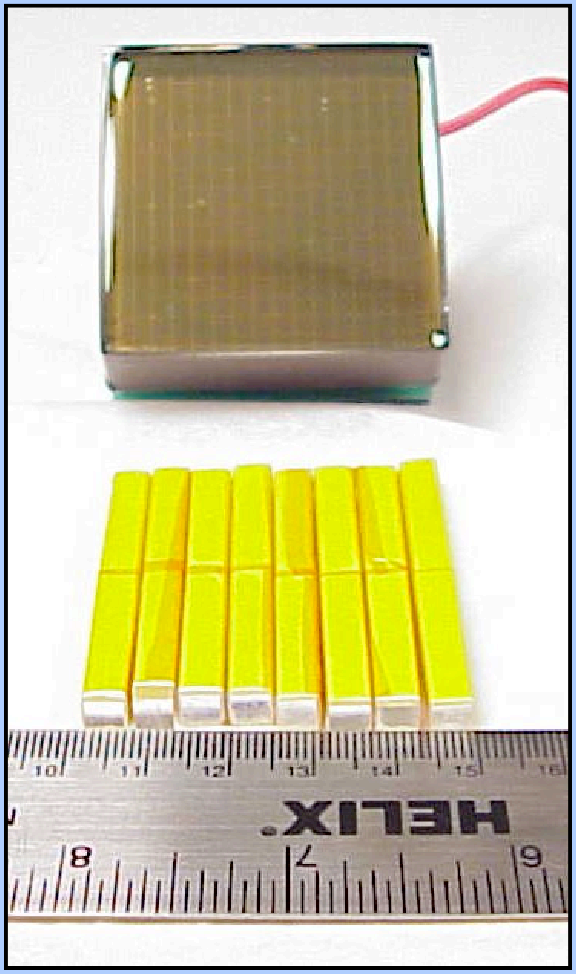
Fluence (ergs cm^{-2})	*MDP T = 10 sec*	*MDP T= 100 sec*	*Observed Rate (N > Fluence)*
1 ¥ 10^{-4}	2.8%	2.9%	1 every 320 days
5 ¥ 10^{-5}	3.9%	4.4%	1 every 80 days
1 ¥ 10^{-5}	9.3%	13.7%	1 every 10 days
5 ¥ 10^{-6}	14.0%	24.4%	1 every 6 days
3 ¥ 10^{-6}	19.4%	38.6%	1 every 4 days
1 ¥ 10^{-6}	43.2%	——	1 every 2 days

Solar Flare Sensitivity

The solar flare polarization sensitivity for various energy bands.
These data assume a balloon-borne array of 16 GRAPE modules.



A New Design



We are currently preparing to conduct lab tests with a more compact design based on Hamamatsu's new flat-panel MAPMT.

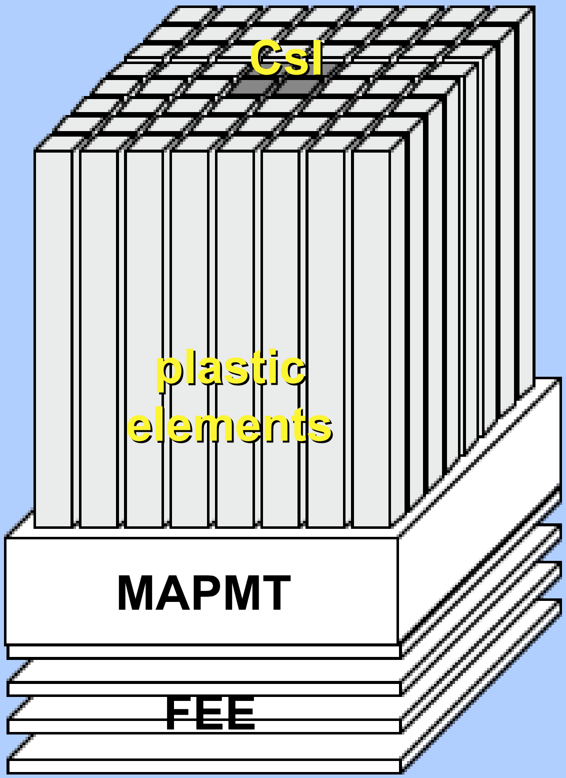
This new PMT design (Hamamatsu H8500) provides an 8 x 8 array of anodes.

The anode size of 5.6 mm (on a 6 mm pitch) is an excellent match to the 5 mm plastic elements that we are currently using.

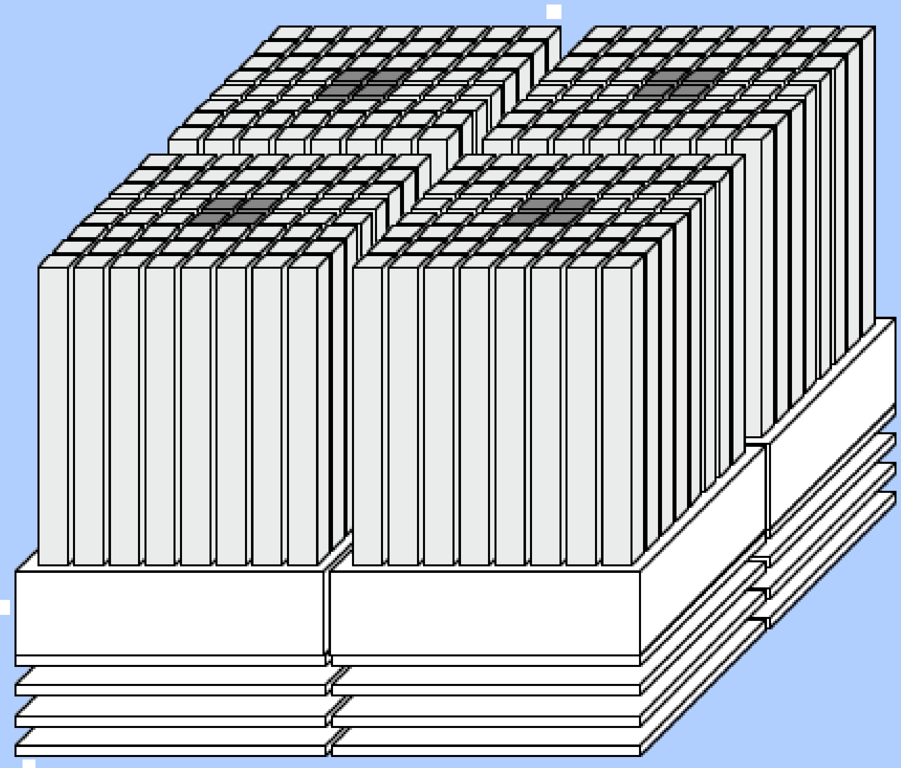
The MAPMT can be used to read out both the plastic scattering elements and the CsI calorimeter elements.

This also eliminates a significant amount of mass in front of the detector array.

Polarimeter Design Based on MAPMT



Single module with MAPMT and FEE electronics.



Array of modules suitable for use as a coded aperture imaging plane.

Development Status

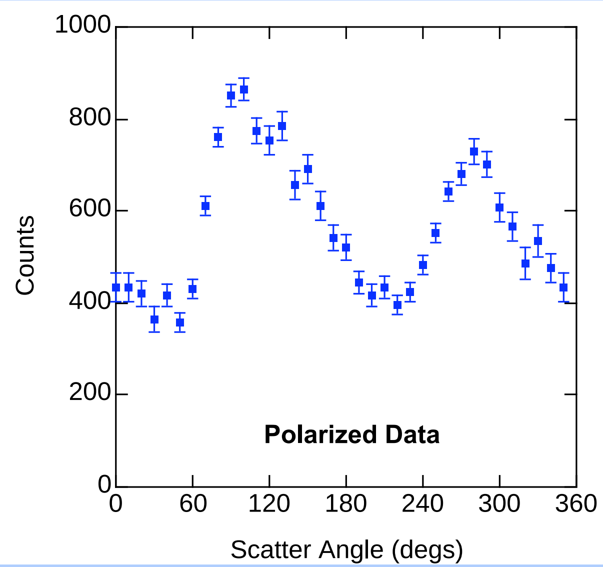
- We have developed a design for a compact polarimeter module that could be adapted to a variety of configurations.
- Testing of a science model based on the design has so far yielded encouraging results.
- Further testing of the science model will be completed in the coming months.
- We will soon be testing a new design based on the use a flat panel multi-anode PMT.
- Long-term goal will be to develop a dedicated balloon payload.
- An array of GRAPE modules (a “bunch of GRAPEs”) will provide sufficient sensitivity to constrain models GRBs and solar flares.

Results from Science Model

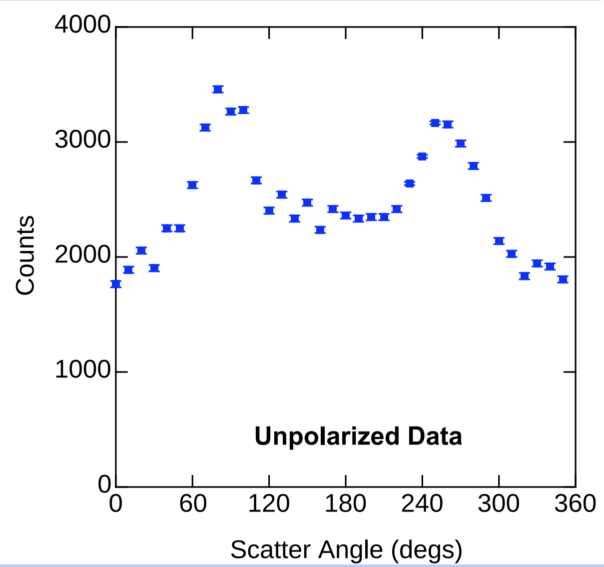
Data from the science model are shown below. These are energy selected data from both a polarized beam (left) and an unpolarized beam (middle). The corrected data is on the right.

Measured Polarization = 53(±3)%

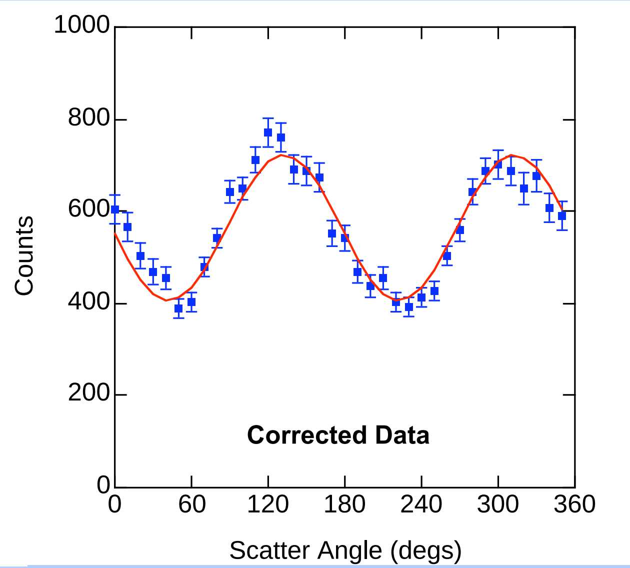
Polarization Angle = 48 (±1)°



288 keV



356 keV

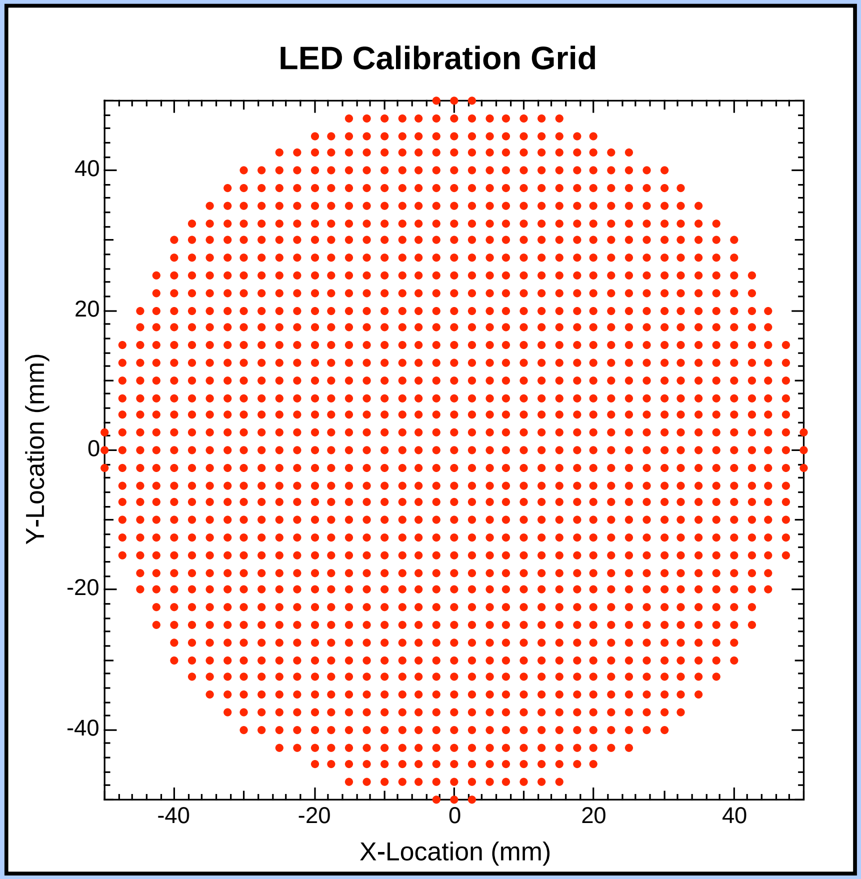


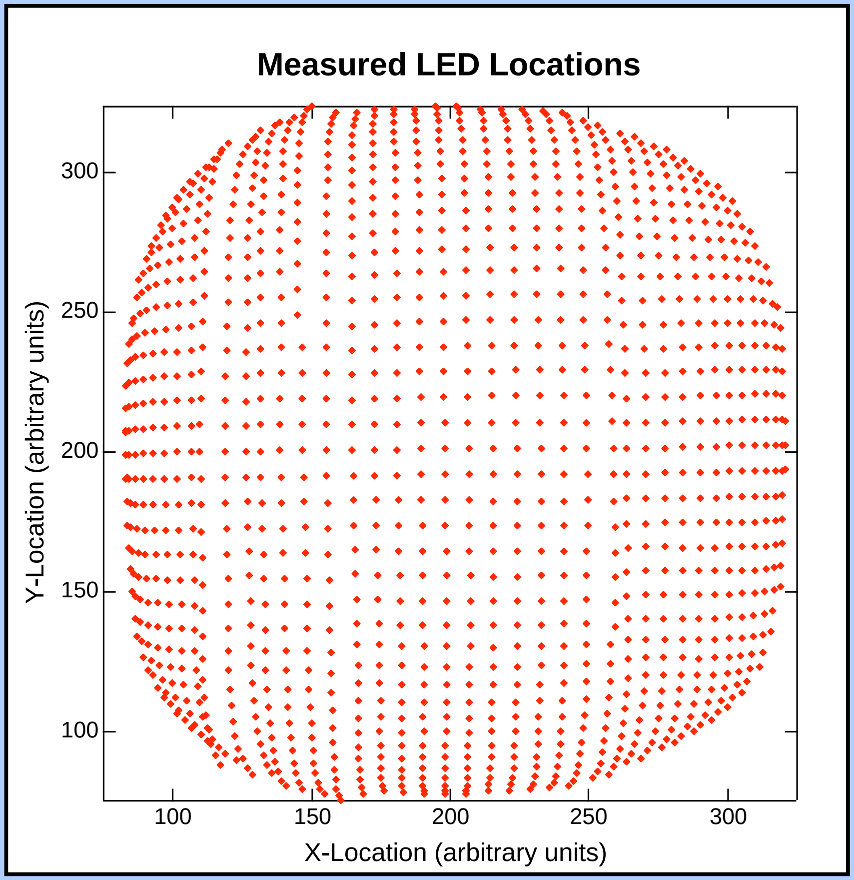
288 keV

PSPMT Calibration

The PSPMT response was calibrated during the summer of 2001.

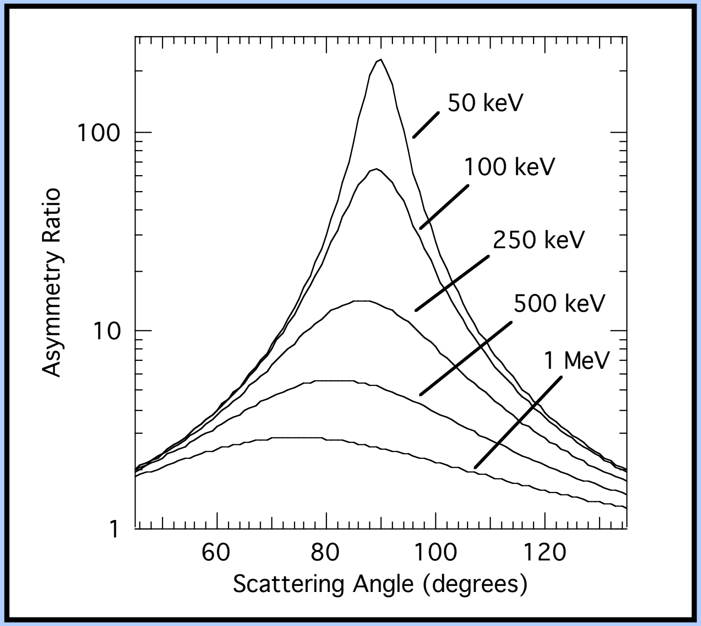
These data show both the calibration grid (2.5 mm spacing) and the reproduced locations. Distortions near the edge of the PSPMT are evident.





Compton Scatter Polarimetry

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