POLAR, an instrument to measure GRB polarization. Design and laboratory tests.

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Abstract: Reliable polarization measurements of photons from Gamma Ray Bursts (GRB) would make the understanding of the GRB phenomenon progress enormously. POLAR is a concept for an instrument that would enable such a measurement. We report about performances predicted by Monte Carlo and on laboratory tests to validate some critical aspects of the design

Introduction

Gamma Ray Bursts (GRB) are one of the most fascinating mysteries of modern astronomy. These short bursts of non-thermal radiation hundreds of times brighter than a typical supernova were until recently very hard to apprehend and even harder to understand. The information we get from the prompt signal of GRB is scarce. For each of the hundred to thousand detected gamma-ray photons we can get four numbers at best: its detection time, its direction, its energy and its polarization. Up to now, detectors in space were blind to the polarization information.
A measure of the polarization will allow researchers to discriminate the emission mechanisms at the origin of the prompt emission: 80% polarization favors the cannonball model; 30-40% polarization favors electromagnetic models; less than 10% could be accommodated by all other models. Hydrodynamical models are not able to create higher polarization than 10%, so a large amount would permanently exclude these models.

The POLAR detector

The POLAR detector [2] is an active target of outer dimensions 240X240X200mm^3. The target material is plastic scintillator, i.e. doped polystyrene, chemically and mechanically stable and supporting high total radiation doses with little degradation. The target is segmented into 1600 elements (scintillation bars) of dimension 6X6X200mm^3, with their long axis facing the preferred photon entry direction. The target elements are optically insulated from each other. On the back, a flat panel metal mesh photo detector is directly coupled to the scintillator elements. With the associated power distribution and front-end electronics, the photo detector is thick enough to shield the detector from photons entering from the back.

Working principles

POLAR is designed to determine the polarization of photons in the energy range from keV to several MeV which covers well the peak energy flux of the prompt GRB emission. It is based on large angle Compton scattering which has a strong modulation pattern in the azimuth angle around the photon polarization direction. The polarization direction can be reconstructed by observing the recoil electron from the Compton scattering and then observing the scattered photon by a subsequent process depositing sufficient energy (second Compton scattering or photoelectric effect). In addition, the cross section is symmetric with period π such that it is not necessary to know the order in time of the two observations.

The observation consists of recording all pair of bars that show a coincident energy deposition $>$ 5 keV. A pair is accepted if the total energy deposition is $>$ 50 keV and lower than 300 keV. The 300 keV cut efficiently remove all cosmic ray induced events. A histogram of the angle defined by the line joining the two bars and an arbitrary chosen reference direction is accumulated for all photons during a GRB. Information about GRB polarization degree and direction of the polarization is extracted from this histogram by simulating effect of a 100% polarized signal coming from the same direction. Prediction of the background contribution in the histogram can be achieved with data collected before and after the GRB or by simulation. This instrument cannot predict by itself precisely the localization and spectrum of a GRB and has to rely on another detector to provide this information. Without this information, the measurement of polarization is still possible but suffers more systematic uncertainties.

Monte Carlo simulation

The interactions of signal and background photons with the detector has been simulated using GEANT 4. The target is simulated as a solid block of C_8H_8 material with appropriate density and radiation length. The back end of the target was grossly approximated as a 10 cm deep block of aluminum with reduced density (0.9 gcm^{-3}) , The front and side shield are taken as 1 mm of carbon of density 2.265 gcm^{-3}. The simulation of physics processes includes the polarization dependence of Compton scattering, and takes into account the electromagnetic processes which are all implemented in GEANT 4, even those at very low energy. As expected, the photon interactions are dominated in number by low energy Compton scattering with small energy transfer to the electron.

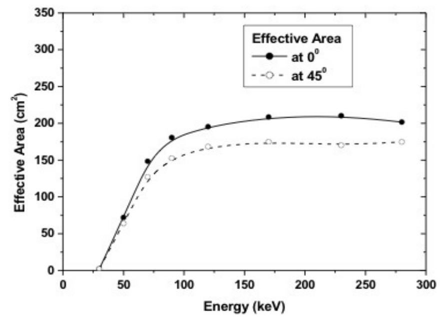

Figure 1: Detector effective area as a function of energy for photons coming at two different polar angles θ=0^o and θ=45^o (azimuth angle ϕ=0^o).

The performance predicted are summarized in figure 1 and 2. The two parameters of importance for characterizing performance of the polarimeter are the effective area (see Figure 1) of the detector that predicts how many photon can participate in the measurement once the fluency of a GRB is known and the modulation factor (see Figure 2) that says how much each photon brings information about the real polarization (for an exact definition of this two parameters see [2]).

Laboratory tests

The laboratory developments aimed to address several critical issues for the definition of the detector design.

1) Threshold energy: In the Monte Carlo study we assumed being able to detect single bar energy deposition as low as 5 keV. It approximately corresponds to the lowest energy threshold of the detector taking into account the scintillation efficiency, light collection efficiency and quantum efficiency of the anode. In order to verify such a low energy threshold, individual plastic bars were exposed to X-rays of different energies. For this purpose we used the portable X-ray fluorescence source (various energies between 8 and 44 keV) as well as standard ^{55}Fe and ^{241}Am sources. Ability to achieve the 5 keV value of the low energy threshold was demonstrated when the source of irradiation was

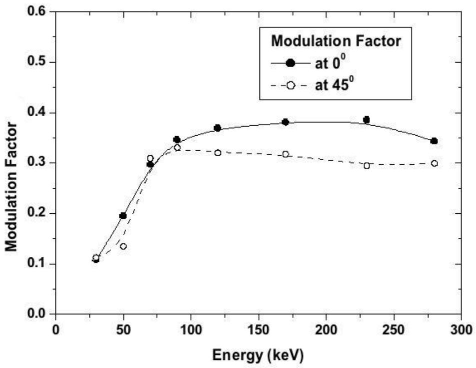

Figure 2: Detector modulation factor as a function of energy for photons coming at two different polar angles θ=0^o and θ=45^o (azimuth angle ϕ=0^o).

closer to the photomultiplier. Due to some light collection inefficiency higher threshold was measured further along the bar length.

2) Light collection: Dedicated light collection tests were conducted to examine variations in the light output intensity for plastic scintillators irradiated at different distances from the photo-cathode. Guided by Monte Carlo, the two most promising wrapping solutions were investigated: Aluminum foil plus air gap and Teflon foil plus air gap. Two radioactive sources: ^{241}Am (E$_\gamma$=59 keV) and ^{57}Co (E$_\gamma$=122 keV, 86% emission probability) were used. The sources were located 5 mm from either the top or the bottom and also at the middle of the plastic bar. The performance achieved with both solutions were comparable within 10% differences and any residual inhomogeneity was measured under 15% when using high quality surface polished bars.

3) Surface quality: All these tests were demonstrating the critical role of the surface quality of scintillator bars. A method of measuring the surface quality of a bar is to measure the coordinate of the surface point along the length of the detector. The distribution of the derivative of this function tells how much the local perpendicular is tilted versus the nominal one. This distribution is also appropriate to characterize the surface quality in GEANT Monte Carlo. A commercial bar of

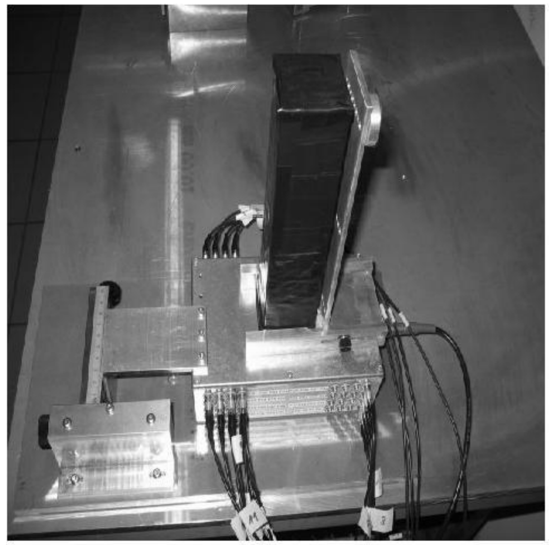

Figure 3: Single POLAR laboratory module with the 8x8 MAPM H8500 coupled to 6x6x200 mm3 plastic scintillators.

very good quality was measured (see Figure 4). We find that two surfaces are of extremely good quality and two other surfaces are of lower quality but still very good. This is in fact to be expected by the way those bars are produced: two surfaces are determined by the mould quality, the two others are achieved by cutting and polishing.

With this quality control, we are now able to achieve performances that are reproducible and predictable by Monte Carlo.

4) A full proof of concept of the detector requires a measurement of a modulation to be compared to the simulation. An 8X8 scintillator bars detector (Figure 3) has been tested for modulation measurements in a dedicated simplified facility of polarized gamma rays. This facility has been described elsewhere [1]. It provides a collimated beam of 290 keV photons that are 60% polarized. The facility provides also for each photon a synchronous tag in form of an electronic signal. The asymmetry was determined by measuring the rate of coincidence between the bar where the beam enters (A), a second bar (B) and the tag signal. Then the detector is turned by 90 degree and the rate is measured again using the same bars A and B. The asymmetry is computed from those two rates and compared with

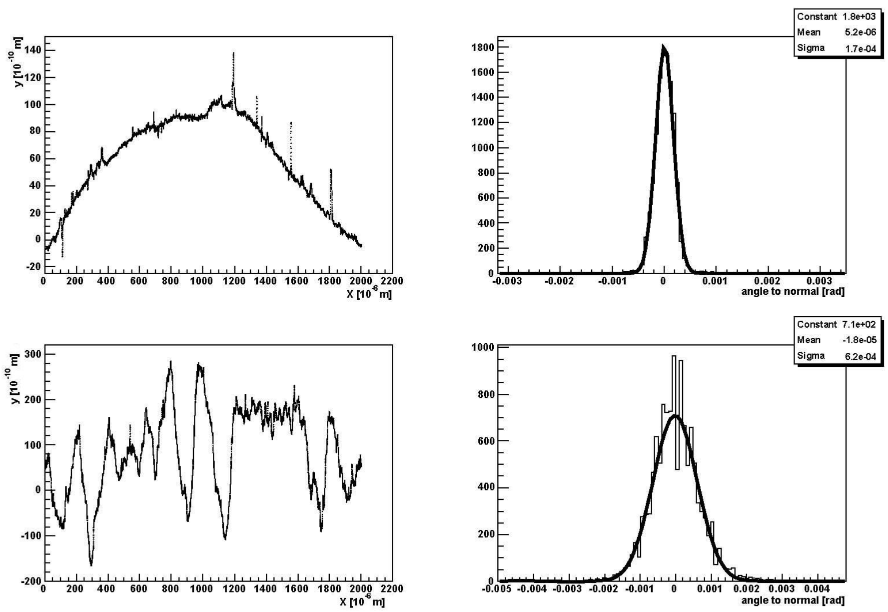

Figure 4: Scintillator bar roughness scanning measurements (left panel) and distribution of the derivatives (right panel), respectively for higher (top) and lower (bottom) quality surface

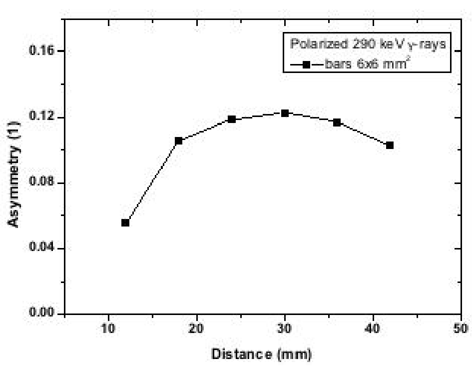

Figure 5: Measured level of asymmetry up to 12%, as a function of distance between bars triggering coincident hits.

Monte Carlo. Figure 5 summarizes the resulting asymmetry as a function of the distance between bars A and B.

Conclusion

Preliminary feasibility simulations and tests of the POLAR instrument are completed. A first prototype is being constructed and will be tested in a polarized beam of photons before end of the year. We plan to have a fully space qualified instrument in 2010.

References

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