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A crosstalk and non-uniformity correction method for the space-borne Compton polarimeter POLAR

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ABSTRACT

In spite of extensive observations and numerous theoretical studies in the past decades several key questions related with Gamma-Ray Bursts (GRB) emission mechanisms are still to be answered. Precise detection of the GRB polarization carried out by dedicated instruments can provide new data and be an ultimate tool to unveil their real nature. A novel space-borne Compton polarimeter POLAR onboard the Chinese space station TG2 is designed to measure linear polarization of gamma-rays arriving from GRB prompt emissions. POLAR uses plastics scintillator bars (PS) as gamma-ray detectors and multi-anode photomultipliers (MAPMTs) for readout of the scintillation light. Inherent properties of such detection systems are crosstalk and non-uniformity. The crosstalk smears recorded energy over multiple channels making both non-uniformity corrections and energy calibration more difficult. Rigorous extraction of polarization observables requires to take such effects properly into account. We studied influence of the crosstalk on energy depositions during laboratory measurements with X-ray beams. A relation between genuine and recorded energy was deduced using an introduced model of data analysis. It postulates that both the crosstalk and non-uniformities can be described with a single matrix obtained in calibrations with mono-energetic X- and gamma-rays. Necessary corrections are introduced using matrix based equations allowing for proper evaluation of the measured GRB spectra. Validity of the method was established during dedicated experimental tests. The same approach can be also applied in space utilizing POLAR internal calibration sources. The introduced model is general and with some adjustments well suitable for data analysis from other MAPMT-based instruments.

1. Introduction

Gamma-ray bursts (GRBs) are observed as short flashes of gamma-rays appearing randomly in the sky. In a few seconds they release energy between 10^{42} J and 10^{48} J making them the most energetic explosions in the Universe. They are frequently associate with either a collapse of the massive stars or a violent merge of compact binaries [1]. In spite of numerous observations and theoretical efforts in the past decades many key questions such as GRB emission mechanisms or origin and structure of their magnetic field are not answered yet (for recent reviews, see Refs. e.g. [1–3]). Direct measurements of the GRB polarization in the prompt emission phase should be able to shed light on the whole system and constrain the energy emission mechanisms [4,5].

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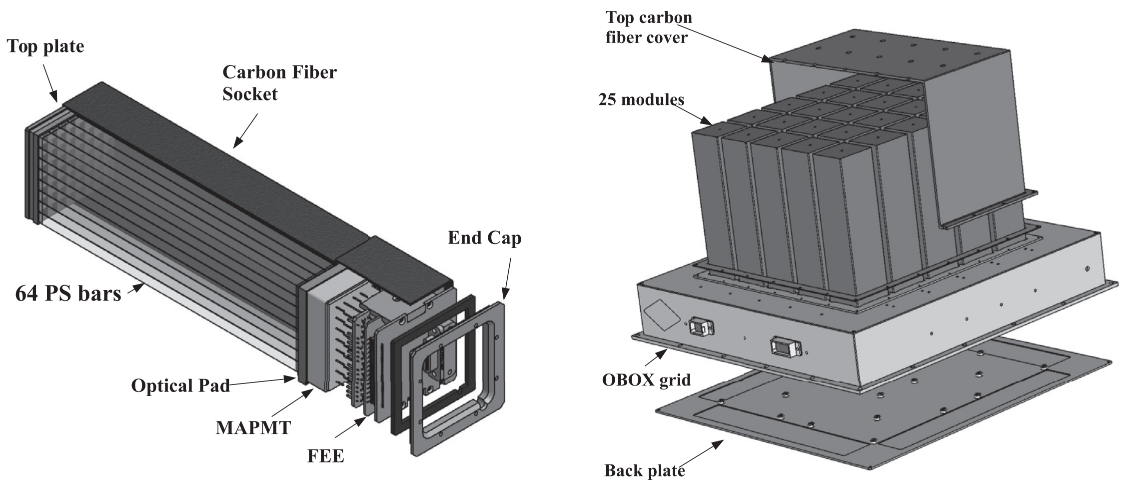

Fig. 1. Exploded view a POLAR detector module (left) and the full POLAR instrument (right). Each module has 64 PS bars ($5.9 \times 5.9 \times 176\,mm^3$ each) coupled to a 64 channel MAPMT (Hamamatsu H8500) and a front-end electronics. The full instrument consists of 25 identical modules.

To achieve this goal, several dedicated instruments are currently under development [6–10]. They are specially designed and optimized for polarization measurement with support by precise on-ground calibrations as well as rigorous performance modeling and verification. POLAR is one of such new hard X-ray polarimeters for studying the GRB prompt emissions. It utilizes Compton scattering to measure linear polarization of gamma-rays in the energy range from 50 keV to 500 keV. Plastic scintillator (PS) bars are chosen as gamma-ray detecting medium and 8×8 channels multi-anode photomultipliers (MAPMTs) serve for readout of the scintillation photons.

It is an inherent property of MAPMT-based detectors that a signal from a certain channel can, through crosstalk effects induce signals in the neighboring channels. In addition, the response non-uniformity of the MAPMT modifies initially deposited energy altering the signal amplitudes. Together with the crosstalk effect that spreads the initial energy deposition, it makes the energy calibration and spectral unfolding more difficult. Thus, the precise knowledge of both effects is necessary to properly extract polarization observables in the detected GRBs.

Based on laboratory calibration data we constructed a model describing both the crosstalk and response non-uniformities for all 64 channels of each POLAR module. The relation between genuine and recorded energy deposition can be described by a single matrix. In the following chapters we describe methods applied to determine matrix elements and present results from laboratory tests used for their verification.

2. POLAR instrument

The main goal of POLAR to measure linear photon polarization is realized using Compton scattering. Polarized gamma-rays undergoing Compton process tend to scatter perpendicularly to their incident polarization vector according to the Klein–Nishina equation:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E} + \frac{E'}{E} - 2\sin\theta^2\cos\eta^2\right), \tag{1}$$

where r_e is the classical radius of the electron, E and E' are the energy of the incident photon and the scattered photon, respectively, θ is the scattering angle between initial and final photon direction, and η is the azimuthal scattering angle between the initial polarization vector and the direction of the scattered photon.

POLAR has both, a large effective detection area (~80 cm^2) and a wide field of view (~1/3 of full sky). They are needed for efficient and precise measurements of the azimuthal distribution of gamma-rays undergoing Compton scattering in its scintillator bars. After being hit by a gamma-ray the instrument records energy depositions in its 1600 channels. POLAR uses an array of 40 (row) × 40 (column) plastic scintillator (PS) bars as gamma-ray detection target. The azimuth angle of the scattered gamma-ray is determined from positions of two bars with the highest energy depositions. Polarization degree as well as polarization angle of the detected GRB can be retrieved in the off-line reconstruction of all recorded gamma-ray events.

The scintillating material EJ-248 was chosen because of its fast response and high value of the softening temperature (90 °C). Each PS bar has dimensions of $5.9 \times 5.9 \times 176\,mm^3$. In order to reduce optical crosstalk all bars have narrower bottom-end cross-sections resembling a pyramid-like shape. The procedure used for bar selection involved several strict criteria. Firstly, all of them were carefully inspected to reject macroscopic defects. Secondly, the dimension of each bar was precisely measured and only bars with dimension deviations smaller than 0.1 mm were accepted. Afterwards, the light output difference between the top and the bottom of each bar was measured with a dedicated setup. It consisted of a photomultiplier and an Aluminum-made bar holder lined with the Enhanced Specular Reflector (ESR) films. The test used a collimated Am-241 source placed at the bottom and the top of the bar. Only bars with the light output difference smaller than 10% were accepted. Finally, to increase the light collection, all selected bars were wrapped in the 65 μm thick ESR film.

The 1600 selected bars were assigned to 25 identical modules. Each module consists of 8×8 PS bars, a soft optical coupling pad made of transparent silicon (Dow Corning DC93-500), a 64 channel flat panel MAPMT (Hamamatsu H8500) and a front-end electronics (FEE). This structure was enclosed in a 1 mm thick carbon fiber sockets (see the left panel of Fig. 1). The top and the bottom of each PS were fixed and aligned with two plastic frames. They enhance resistance to vibrations and further reduce the optical crosstalk. The dimension of the optical coupling pad is $50 \times 50 \times 0.5\,mm^3$. It can partially absorb vibrations and also protects the MAPMT glass window. The channel numbering convention and MAPMT dimensioning are shown in Fig. 2.

The front-end electronics consists of three stacked Printed Circuit Boards (PCBs). The boards contain low voltage power supply circuits, a dedicated voltage divider for the MAPMT, a