# POLAR – space-borne Gamma Ray Burst polarimeter

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***Abstract.*** **A compact detector dedicated to the measurement of GRB gamma-ray photon polarization is presented.**

**The gamma-ray space detector consists of an array of light, plastic scintillator bars. Contrary to classical spectrometers, a light scintillator is chosen as a detection medium to guarantee the prevalence of Compton scattering in the gamma-ray interactions. Using the Compton effect is a standard method of determining the polarization of incoming gamma-rays in the 10-1000 keV energy range. A segmented detector connected to segmented light sensors and dedicated electronics capable of recognizing time coincidences, gives a unique chance of measuring the polarization of gamma-rays coming from strong, transient sources like GRBs and the strongest persistent sources.**

**POLAR is a Compton polarimeter sensitive to gamma-rays in the energy range 50-500 keV. It consists of an array of scintillator bars optically coupled to Multi-Anode Photo Multipliers. In POLAR photons undergo Compton scattering in a target made out of 1600 scintillator bars. The azimuthal distribution of the scattered photons inside the target provides information on the photon polarization.**

**The design, results of tests with a demonstration model and the current status of the project are presented.**

***Keywords*: Gamma-ray burst; polarization, POLAR**

## I. Introduction

Gamma-ray bursts (GRBs) are flashes of gamma-rays that appear randomly in the sky and last from milliseconds to tens, or rarely, thousands of seconds. They are produced at cosmological distances, and are the most luminous electromagnetic events in the Universe. Longer wavelength (X-ray, ultraviolet, optical, infrared, and radio) emissions accompanying the gamma-rays and following them are called the *afterglow*.

Long GRBs, typically lasting longer than 2 seconds, are believed to be radiation released from supernovae (hypernovae), collapses of massive, rapidly rotating stars. Short bursts, in turn, are considered to be the result of the merging of two compact objects such as neutron stars and/or white dwarfs.

Since the discovery and the first publications about GRBs in the '60s-'70s, scientific activity in this area has progressed, both in theoretical and experimental domains. Space missions capable of measuring GRBs, e.g. BATSE/CGRO (1991), BebboSAX (1997), HETE-2 (2001), Swift (2004) and FERMI/Glast (2008) keep stimulating these activities.

### A. Theory of GRB polarization

Extensive research in the area of GRB has yielded numerous advances in theoretical models of this phenomenon. In general, these theories reproduce correctly all measured properties of the GRBs: duration, extragalactic origin, typical gamma spectrum, existence of the afterglows, etc.

It should be emphasized that the main GRB models predict different levels of polarization (brief summary in Table I). Thus, a polarization measurement with an accuracy of 20-30% for significant number of bursts could favor one of the competing theories.

TABLE I
THEORETICAL PREDICTION OF POLARIZATION OF PROMPT GAMMA-RAY EMISSION FROM GRBS IN MAIN MODELS

| model | predicted polarization level [%] | reference |
|---|---|---|
| fireball | 10 | [1] |
| electromagnetic | 50 | [2] |
| cannonball | 0-100 | [3] |

### B. Measurement of GRB polarization

Due to the lack of experiments specifically dedicated to polarization measurements, the few existing results are based on difficult analyses of the accumulated data.

The first result published by Coburn and Boggs [4] showing a significant polarization in the GRB 021206 was criticized by Rutledge and Fox [5] and Wigger *et al.* [6]. Recent years have seen few additional results, based on BATSE [7] and INTEGRAL data [8], [9], although these are inconsistent and still controversial.

The situation in the theoretical field, and the current status of the experimental measurement of gamma-ray polarization inspired us to design, build and launch an instrument dedicated to measurement of polarization of gamma-rays from GRB – POLAR.

## II. Space GRB polarimeter

A typical prompt GRB photon spectrum can be described by a smooth broken powerlaw function, known as the Band model [10]. Ten years of the BATSE experiment provided high quality spectra of 350 bursts [11]. According to these data, the maximum of the observed prompt gamma-ray emission from any GRB is located between 10 keV and 1 MeV. The Compton effect is the most suitable choice for measuring electromagnetic radiation in this energy range. Equation 1 presents the simplified, Klein-Nishina differential cross section for Compton scattering of polarized photons on non-polarized electrons:

$$\mathrm{d}\sigma(\theta,\varphi) \sim \mathrm{q}^2\left(\mathrm{q} + \mathrm{q}^{-1} - 2\sin^2\theta\cos^2\varphi\right)\mathrm{d}\Omega \quad (1)$$

where: $q = E_\gamma/E_{\gamma'}$, $E_\gamma$ - energy of the incoming photon, $E_{\gamma'}$ - energy of the scattered photon, $\theta$ - scattering angle and $\varphi$ - angle between the polarization vector and the projection of scattered photon direction on a surface perpendicular to the incoming photon. The factor $\cos^2\varphi$ expresses the relation between the cross section and the polarization direction. The modulation of the azimuthal distribution of the scattered photons carries information about the polarization of the incident photons. From the experimental point of view, Compton

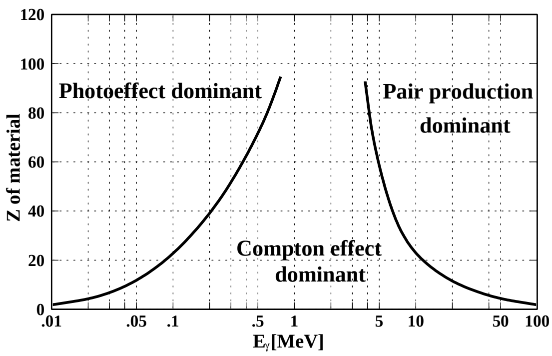


Fig. 1. Areas where the photoeffect, Compton effect and pair production gamma-ray interaction processes are dominant on an $E_\gamma$ .vs. atomic-number (Z) chart.

scattering requires, at least, two independent gamma-ray detectors. In the *first* one, the incoming photon undergoes Compton scattering on an electron and the kinetic energy of the recoil electron is deposited in this detector. In the *second* detector, the scattered photon interacts again, depositing all or some of its energy. Signals from both depositions are to be collected in coincidence.

Within the gamma-ray energy range of interest two main types, scintillation or semiconductor detectors, can be applied. Both types have been used successfully in space as gamma spectrometers or counters. The scintillators seem to be more suitable for polarization experiments because of their fast response, required in the time coincidence technique (several dozen of nanoseconds).

## III. Design of the POLAR instrument

POLAR is described elsewhere [12] and summarized in this section.

A gamma-ray polarimeter requires material optimized for the Compton scattering effect in order to guarantee high polarimetric efficiency. As shown in Fig. 1, the Compton effect dominates in the interesting energy range for low-Z materials. After detailed studies of existing scintillation materials, BC400 was chosen. This light, plastic, scintillator is a chemical compound of Hydrogen (low-Z) and Carbon. It is one of the fastest scintillators (2.4 ns characteristic decay time) with relatively long bulk light attenuation (2.5 m). BC400 is known to be stable to radiation.

As the photodetector, the Hamamatsu H8500 multi-anode photomultiplier (MAPMT) was selected (Fig. 2).

Fig. 2. Hamamatsu H8500 multianode photomultipliers. 8 $\times$ 8 independent pixels, 6 mm $\times$ 6 mm each. 12 dynodes. Quantum efficiency $\approx$25% (for model B). $HV_{\mathrm{max}}$ = 1100V. Gain $10^6$. Photo and data taken from Hamamatsu publicity material.

The goal of the project was to a build small, light, compact, uniform and effective polarimeter.

After an extensive Monte-Carlo simulation (described in the next section) and experimental tests with the H8500 and BC400 scintillator the final arrangement of POLAR was established.

The basic unit of POLAR, called a *module* (Fig. 3 left), consists of one Hamamtsu MAPMT with 64 plastic bars 6 mm×6 mm×200 mm. Each bar is optically coupled to the corresponding pixel of the MAPMT. To ensure optimal light guiding properties of the set-up, the bars are finely polished and wrapped in 3M Viquiti™ reflecting foil. Each module contains a dedicated electronics unit using the analog VA64 IDEAS ASIC. This ASIC is controlled by a programmable Actel FPGA digital chip. POLAR includes 25 independent modules in a 5×5 geometry, see Fig. 4. It constitutes an uniform matrix of 40×40 plastic bars, yielding an

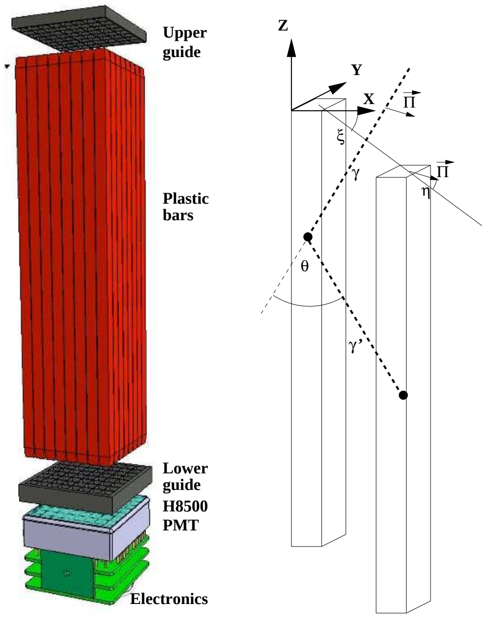


Fig. 3. Single module of the POLAR instrument (left). Two bars and geometry of the event (right): $\gamma$ is an incident photon that Compton scatters in the first bar, $\gamma'$ is a scattered photon that deposits its energy in the second bar, $\vec{\Pi}$ is the polarization vector of the $\gamma$, $\theta$ is scattering angle.The distribution of angles $\xi$ gives information about the polarization of the photons flux.

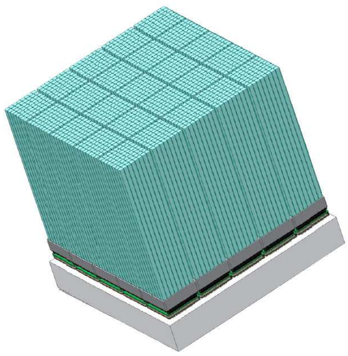

Fig. 4. All POLAR. 25 modules, 8×8 bars each

overall volume of about 30×30×30 cm$^3$ and a total mass of the instrument below about 30 kg. Due to the presence of high energy electrons in low Earth orbit (the expected orbit for the POLAR mission) the entire system is shielded by a 3 mm thick carbon fiber box. This shielding significantly reduces the influence of the electrons without disturbing the gamma-ray flux.

The system is controlled by a dedicated central computer that communicates with each module. There is also a power supply module and a High Voltage (HV) module. The central computer communicates with the ground station via satellite services.

During normal operation the system searches for coincidence signals from two or more plastic bars, both on the level of a single module and the entire system of 25 modules. The on-board computer pre-analyses such events and stores the data in the *background* memory. The on-board software is optimized for automatic detection of bursts (burst mode) and, in case of a burst, stores the events in a dedicated *burst* memory.

### A. *Monte-Carlo simulations*

The geometry and materials of the entire POLAR instrument were reproduced in the GEANT4 CERN Simulation Tool [13]. The results of the Monte-Carlo simulations were the primary source of the optimization of the geometry and the structure of the instrument, e.g. the size of plastic bars and the thickness of the carbon fiber holder. A detailed Mass Model (MM) of

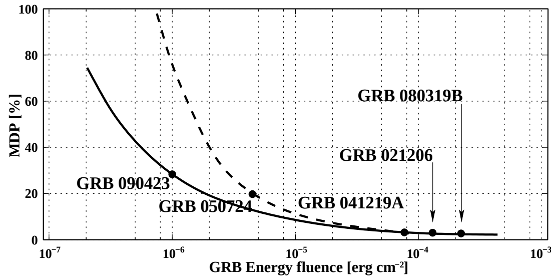


Fig. 5. Monte-Carlo calculated minimum detectable polarization (MDP at $3\sigma$) of POLAR as a function of GRB energy fluence. The solid curve represents the MDP for long bursts, dashed for short ones. Five known bursts have been added to compare with realistic cases.

POLAR yielded the values of the main parameters of the polarimeter: effective area $A_{\rm effm} = 300 - 400$ cm$^2$ (depending on the energy and the incident angle of the burst with respect to the POLAR Z-axis), and the 100% modulation factor $\mu_{100}$ = 0.37. Fig. 5 shows the minimum detectable polarization as a function of the fluence of the GRB.

The Monte-Carlo MM will play a primary role during the POLAR mission. The MM is the only tool that allows the polarization to be extracted from real GRBs. The process of extraction requires the simulation of the response matrices of the instrument. The position of the burst with respect to POLAR, and the energy spectrum of the analyzed burst are required for this simulation. The most recent results of the simulations show that POLAR will be able to provide the burst position without the help of other instruments (see also ID 0881 in this volume and [14]). Due to the bad spectroscopic properties of POLAR, the GRB energy spectrum should be provided by other experiments but the sensitivity of the polarization to the spectrum is weak.

## IV. CURRENT STATUS OF POLAR AND LABORATORY TESTS

The POLAR Demonstration Model (see Fig. 6) consists of two MAPMTs with the corresponding system of 2×(8×8) scintillator bars. The readout of the MAPMTs is performed by a custom made electronics board, connected with a PC via RS232. The main components of the board are two ASICs from IDEAS and a Xilinx Virtex4 FPGA for acquisition and data transfer to PC.

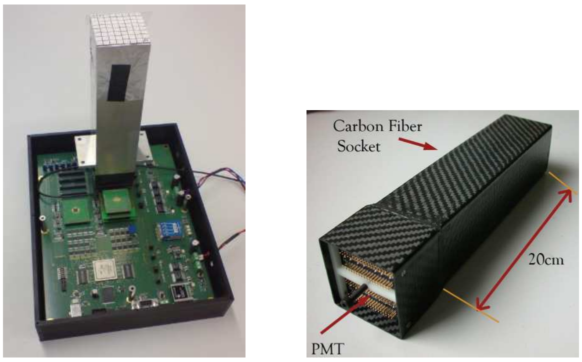


Fig. 6. Demonstration model: 1 module with 64 scintillator bars placed on the top of one MAPMT (left). Prototype of one of the modules of the EQM. Each pack of 64 scintillators, optically coupled with the MAPMT, will be enclosed in a carbon fiber structure. The front-end electronics is at the rear of the MAPMT (right)

A complete single POLAR module has been under test at DPNC since the beginning of 2009. The experimental set-up presented in Fig. 7 is used. This set-up allows

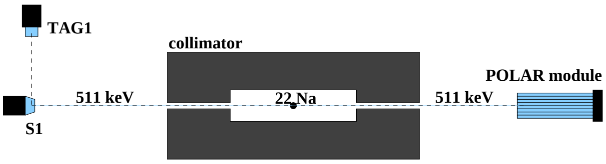


Fig. 7. Set-up of the preliminary experiments with a single POLAR module with a polarized beam of gamma-ray photons. The two correlated 511 keV photons are from the $\beta^+$ decay of a $^{22}$Na radioactive source. **S1** is a plastic scintillator (the Compton scatterer), while **TAG1** is a NaI scintillator (calorimeter). The angle of polarization can be chosen by changing the position of the **TAG1** detector.

the ability of a single POLAR module to measure the degree and angle of polarization of the 511 keV photons produced by the source to be to appraised. A significant level of cross-talk between pixels of the MAPMT has been observed during the tests.

This parasitic effect is partially due to the electric crosstalk in the MAPMT, but also to the light spread at the bottom of the plastic bars, that can reach neighboring MAPMT channels. A modified data analysis, based on searching of “clusters” of active bars instead of single active bars, was used to take this effect into account.

Different angles of the polarization vector have been tested, as well as the impact of including an aluminum block before the POLAR module to absorb part of the incoming photons. The latter test has been performed to study the effect of the external enclosure, planned to contain POLAR and shield it from cosmic charged particles, on the polarization measurement. The campaign of measurements is still ongoing.

The results of all measurements reproduce the expected periodicity and polarization angle in the modulation curves. Fig. 8 shows the result of one of the first measurements performed with a single POLAR module. The modulation curve indicates an angle of polarization of $89^\circ \pm 5^\circ$, correctly reproducing the expected $90^\circ$.

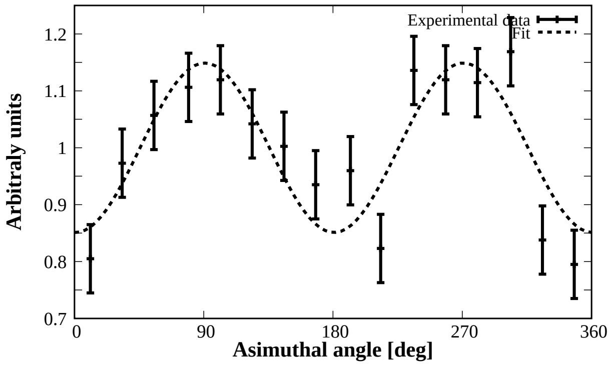


Fig. 8. One of modulation curves obtained in the experiment. In this measurement CAMAC hardware was used for readout.

Further tests for other energies in the range of interest are planned to take place at the European Synchrotron Radiation Facility (ESRF) at Grenoble (France) in the second half of 2009.

## V. Summary

POLAR is a compact array of 1600 plastic scintillator bars. This design gives POLAR the unique capabilities required for the study of GRB polarization, such as a large field of view (∼1/3 of the Sky) and a large effective area (400 cm$^2$). It will be able to determine the degree and angle of polarization of a strong GRB with a fluence $F_{tot} = 10^5$ erg cm$^{-2}$ with a minimum detectable polarization of less than 10% ($3\sigma$). According to the BATSE catalog, POLAR will observe around 12 such GRBs per a year.

The mechanical and electronics design of the full-size engineering-qualification model will be finished in 2010. The flight model will be ready for launch in 2012. The Chinese Space Lab is the candidate for the placement of the POLAR flight model.

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