POLAR: Design of a novel X-ray polarimeter based on plastic scintillators and multi-anode photomultipliers

Daniel Haas*†‖ and Estela Suarez-Garcia†‖

on behalf of the POLAR collaboration

* Email: Daniel.Haas@cern.ch

†Integral Science Data Centre, Université de Genève, 16, chemin d'Ecogia, 1290 Versoix, Switzerland

‖ DPNC, Université de Genève, 24, quai Ernest Ansermet, 1211 Genève 4, Switzerland

***Abstract*— POLAR [1] is a spaceborne hard X-ray polarimeter whose design has been optimized to measure the level of linear polarization of gamma-ray bursts (GRB) in the energy range 50-500 keV. In POLAR, the GRB photons undergo Compton scattering in a target made out of 1600 plastic scintillator bars (6x6x200 mm^3 each). The azimuthal distribution of the scattered photons inside the target provides the information on the GRB polarization. The target is divided into 5x5 units, each one consisting of 8x8 scintillator bars optically coupled with a 64 channel multi-anode photomultiplier (MAPM, Hamamatsu H8500). POLAR, thanks to its large modulation factor ($\mu_{100} = 40\%$), its large effective area ($A_{\rm eff}$ = 400 cm^2), and its large field of view (around 1/3 of the sky) will be able to determine the degree and angle of polarization of a strong GRB of energy 10^{-5} erg cm^{-2} s^{-1} with a minimum detectable polarization of less than 10% (3σ). To be able to measure polarization of photons with energy as low as 50 keV, an energy threshold for each single channel of maximum 5 keV is required. This introduces strong constraints in the photon collection efficiency. To improve it, detailed studies of the scintillator bar surfaces and the available wrapping materials have been performed using both Monte Carlo simulations (GEANT4) and laboratory measurements. At present, a POLAR demonstration model (2 of the 25 units of the final design) is being tested in the laboratory. The engineering-qualification model will be ready in 2010. Investigations conducted by the POLAR instrument will provide very valuable information on how the X and γ-rays are emitted in GRBs. This way, an important contribution to the explanation of the particle acceleration will be achieved. We will present the design and status of POLAR with the newest results acquired from Monte Carlo simulations and from the demonstration model laboratory measurements.**

I. INTRODUCTION

Gamma Ray Bursts (GRB) are one of the remaining mysteries of modern astronomy. These short bursts of non thermal radiation are the most energetic events in the universe ($E_{\rm tot} \approx 10^{51}$ erg). Accidently discovered in the seventies by spy satellites looking for secret nuclear tests, the GRBs are still hard to observe these days. GRBs last only a few seconds and appear at random position in the sky. Four main quantities can be extracted form the observed photons: the detection time and direction, the energy and the polarization. Currently, existing instruments are nearly blind to the polarization information. A polarization measurement could greatly help to distinguish between theoretical models for the creation of GRBs. Three main models are considered today: the fireball, the cannonball, and electromagnetic models. All of them relate the emission of the GRB to the formation of a black hole, but differ in the physical processes involved in the γ-ray generation.

The fireball model [2] relies on internal shocks within the outgoing flow to accelerate particles and produce high energy photons for the prompt emission. The resulting photon polarization is typically low (≈10%) reflecting the hydrodynamic nature of the model. In the electromagnetic model [3] the energy to power the GRB comes from rotational kinetic energy of the central source. It is converted to magnetic energy, transported to large distances by a strongly magnetized wind and used to accelerate particles in the emission region. Photons emitted from this process are expected to present polarization as high as 50%. In the cannonball model [4] a fraction of photons undergo inverse Compton scattering on relativistic electrons from the ejected plasma. Their predicted polarization depends on the opening angle and Lorentz factor of the jet. Therefore GRBs can present according to this model all levels between 0 and 100% polarization.

The spectrum of GRBs is frequently described by the so-called Band function [5] , which is similar to a broken power-law. The parameters of the Band function are the νF_ν peak energy ($E_{\rm peak}$ ≈few hundred keV), and the slopes of the function before (α) and after the break (β). Regarding the time evolution, GRBs present very varied types of lightcurves, where one can often differentiate three parts: the pre-burst, the prompt emission, and the afterglow. The main part of the GRBs at X and γ-rays corresponds to the prompt emission and lasts a few seconds. The level of linear polarization in the prompt emission of GRBs remains one of the crucial and not-yet-determined parameters of GRBs. Its value depends strongly on the emission mechanism, the geometry of the source, and the surrounding magnetic field structure. Its determination would therefore provide very valuable information on how the X and γ-rays are emitted in GRBs.

The cross-section of a hard X-ray photon to interact with a free electron is given by the Compton scattering cross section as described by the Klein-Nishina equation:

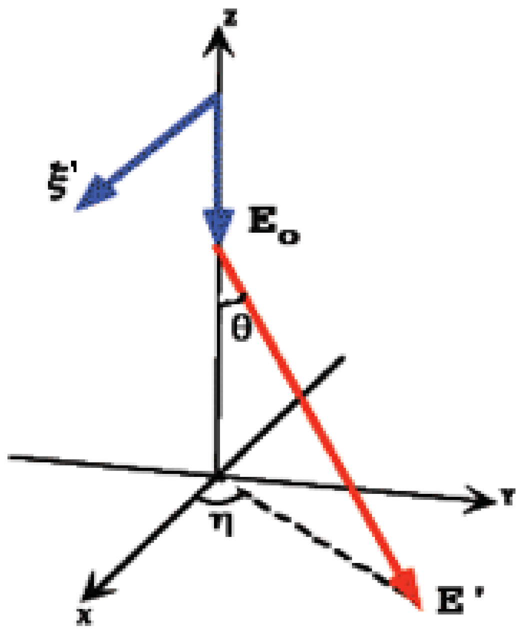

Fig. 1. Schematic of a Compton scattering process: The incoming photon (blue line; kinetic energy E_0; polarization direction ξ') experience Compton scattering when interacting with a free electron. The photon comes out (red line; kinetic energy E') of that process deviating from its original trajectory by an angle θ (Compton scattering angle).

$$d\sigma = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)\left(\frac{E_0}{E'}+\frac{E'}{E_0}-2\sin^2\theta\cos^2\eta\right)d\Omega \qquad (1)$$

where r_0 is the classical electron radius, E_0 and E' are the energies of the photon before and after the scattering respectively, and $d\Omega$ is the solid angle. θ is the angle between photon infall and outfall direction, and η is the angle between the infall polarization and the outfall direction. For a given angle θ the above cross section is highest for $\eta = 90^o$, i.e. photons tend to scatter to the direction that is perpendicular to their initial polarization vector. Making use of that relation one can measure the level of linear polarization of photons in the hard X-ray regime by measuring the azimuthal distribution of scattered photons. A sketch of this detection concept is shown in Figure 1.

The azimuthal distribution of polarized X-ray photons is also called modulation curve and presents the form of a double-sinusoidal curve with a period of π [6] (see Fig. 2). The position of the minimum of the modulation curve corresponds to the angle of polarization of the incoming photons. The amplitude is the so-called modulation factor μ and serves to calculate the degree of linear polarization of the incoming photons:

$$\Pi = \frac{\mu}{\mu_{100}} = \frac{1}{\mu_{100}} \quad \frac{C_{max}-C_{min}}{C_{max}+C_{min}} \qquad (2)$$

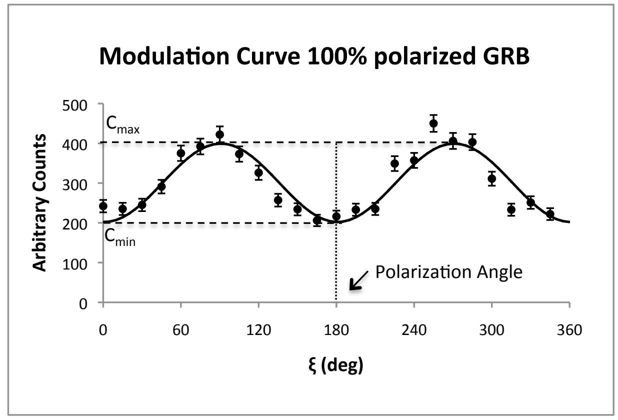

Fig. 2. Modulation curve of polarized photons. The simulated modulation curve of a 100% polarized GRB coming from the zenith is given as example. The modulation curve allows the extraction of polarization angle and level (see Equation 2).

where Π is the polarization degree, C_{min} and C_{max} are the minimum and the maximum of the curve, as marked in Fig. 2, and μ_{100} is the response of the instrument to a fully polarized photon flux. This last value is a characteristic of the instrument and can be determined experimentally or via simulations.

Although several instruments are currently studying different aspects of GRBs, none of the ones which are operating at present is able to perform high energy polarimetry with enough accuracy to constrain the theoretical models.

II. THE POLAR DETECTOR

To design the POLAR detector, the following requirements must be taken into account:

- The compton effect is dominant in the region from 50 keV to about 1 MeV. The instrument should be most sensitive in this region.
- Low Z plastic scintillators enhance the probability for the compton effect.
- The dimensions of the scintillators should correspond to the mean free path lengths of the travelling photons
- To meet space requirements, the instrument should be simple and compact
- Good pointing resolution and energy resolution is not needed and can be obtained from simultaneous observation of other dedicated instruments, but the capability to provide a crude estimation in case of unique observation would be a plus
- Because of the random localization of GRBs in the sky, the instrument needs to provide a large effective area, a large field-of-view (FOV) and a high modulation factor μ_{100}.

All these requirements have led to the conceptual design of POLAR (see Figure 3). It consists of a 40x40 uniform array of light, fast and low Z plastic scintillator bars. The scintillators have a size of 6x6x200 mm^3, matching the mean free path length of photons. They are grouped in packs of

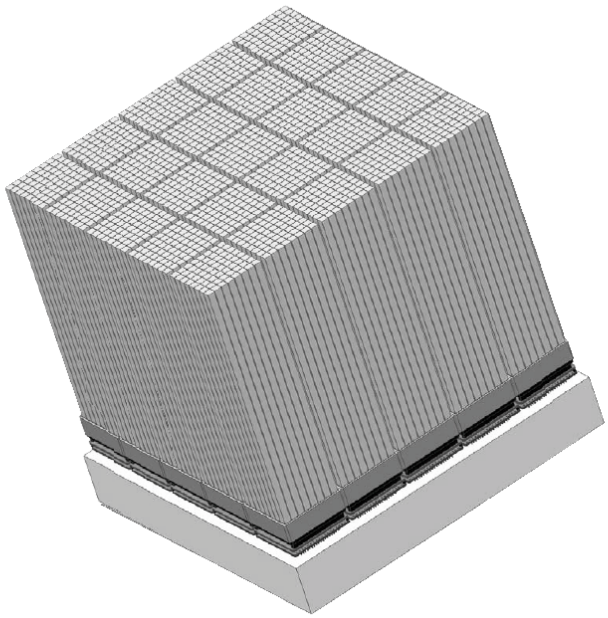

Fig. 3. Conceptual design of the POLAR detector: A uniform array of 40x40 plastic scintillator bars on top of 25 multi-anode photomultipliers.

8x8 and optically coupled to the matching Hamamatsu multi-anode photomultiplier MAPM 8500 (64 channels) that collects the light of each bar individually and transforms it into an electrical signal. The whole target will consist of 25 MAPM, which are read out by ASICs and FPGAs. This detector design achieves an effective area A_{eff} of around 400 cm^2, a modulation factor $\mu_{100} \approx 35\%$ and a field-of-view of about one third of the sky. The detector will be protected by passive shielding (1 mm aluminium equivalent) to protect against low energy cosmic rays. Its total weight, dimensions and power consumption are on the order of 30 kg, 30x30x30 cm^3 and 30 Watt.

The trigger strategy and event selection has to accept events with a minimum deposited energy of about 5 keV in at least 2 scintillator bars (corresponding to an incoming photon energy of about 50 keV). Neighboring channels are excluded and an upper limit on the total deposited energy is applied to reject cosmic ray events.

With the mentioned values for A_{eff}, μ_{100} and FOV, POLAR will be able to determine the degree and level of polarization of a strong GRB (with an energy of around 10^{-5} erg cm^{-2}s^{-1}) with a minimum detectable polarization of about 10% at a 3σ level. According to the BATSE catalog [7], ten to twelve of such GRBs will be observed by POLAR within one year of flight operation. With less precision, a statistical important sample of lower flux GRBs will be collected as input for systematic studies.

Fig. 4. The POLAR Demonstrator Model, equipped with one prototype target of 64 scintillator bars.

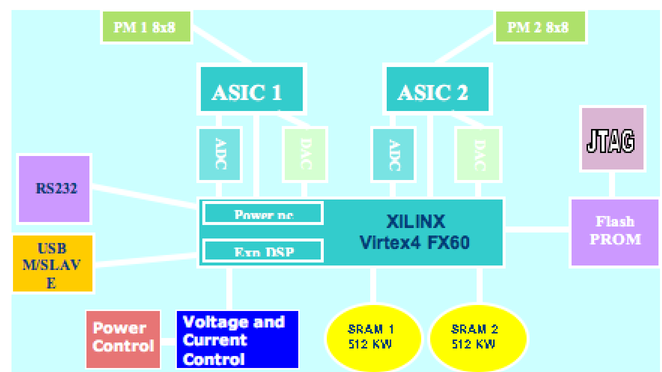

Fig. 5. Block diagram of the DM electronics board.

III. TESTBENCH RESULTS

A. The POLAR Demonstrator Model

The POLAR Demonstrator Model (DM) is shown in Figure 4. It consists of a custom made electronics readout board and slots for up to two Hamamatsu MAPM, including the scintillator targets. The electronics board contains:

- ASICs from IDEAS on piggy-back modules, designed for MAPM and fast scintillator readout
- A Xilinx Virtex4 FPGA for sequencing and data transfer to a readout PC
- RS232 and USB to link to a PC
- Onboard memory for data storage and flash memory for the booting and programming of the FPGA

In addition, the DM electronics provides monitoring circuits for voltages and power consumption via dedicated ADCs. A block diagram of the electronics board is shown in Figure 5.

The DM is used for detailed measurements of the detector response and will be used in test beam campaigns at synchrotron sources like the SLS at PSI, Villigen in Switzerland and the ESRF in Grenoble, France, end of 2008 and during 2009. These results will serve as an important input for

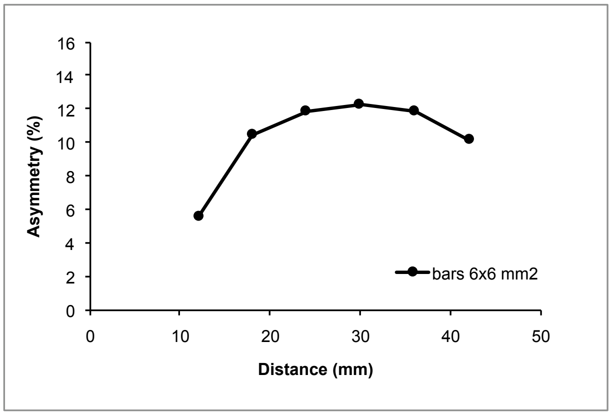

Fig. 6. Polarization measurements with an L-shaped setup of scintillator bars. The asymmetry is shown as a function of the distance from the incoming photon position.

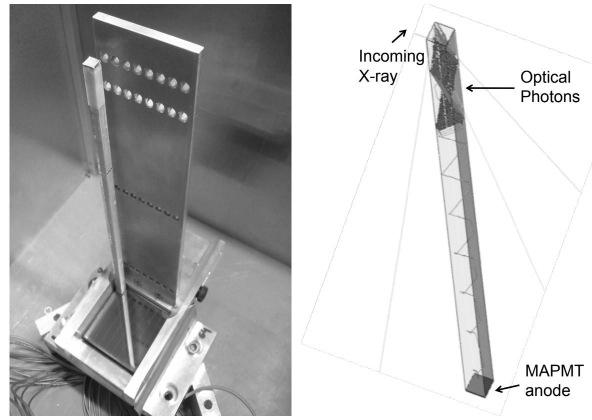

Fig. 7. Left: Laboratory setup for light collection studies. A single scintillator bar is placed on top of the MAPM with an X-ray source holder behind it. Right: Simulation setup. A 5 keV X-ray injected at 19 cm from the MAPM is shown as an example. The produced optical photons reflect in the walls of the scintillator until they are absorbed or they reach the bottom of the bar.

the fine-tuning of the upcoming POLAR engineering and qualification model (see Section IV).

B. Asymmetry measurements

The capability of measuring an asymmetry in the azimuthal distribution of polarized photons with plastic scintillator was tested in the laboratory. For this purpose 8 POLAR scintillator bars where wrapped in aluminum foil and placed aligned on one of the rows of anodes from the MAPM. The most external of those bars was centered in the origin of coordinates of the setup, where it was illuminated from above with partially polarized X-rays from a Cs_{137} radioactive source with a maximum polarization of about 60%, and a mean value of around 40%. These X-ray photons interacted first in this bar, where they were either completely absorbed or experienced Compton scattering. The direction of the photon polarization was aligned to the X-axis of the setup. One expects therefore that most of photons scatter towards the Y-axis, and only a few will do it towards the X-axis.

We measured the asymmetry between the number of photons scattered towards the X- and Y-axis by first aligning our row of scintillator bars on the X-axis and then rotating by 90^o, keeping the first bar always in the origin of coordinates. We observed an excess of counts in the Y direction of about 12% (see Figure 6). This value is in good agreement with the 40% mean polarization of the source, taking into account a μ_{100} of about 0.3 for this setup.

C. Light yield studies

For a successful measurement of incoming photons of 50 keV, a detection threshold of about 5 keV for a single channel is needed. The POLAR detector must be very efficient in uniformly collecting the light output from its target in order to keep such a low threshold. To understand the problem in detail and maximize the light collection, studies of the scintillator bar surfaces and the available wrapping materials have been performed using both Monte Carlo simulations and laboratory measurements.

The light collection of a scintillation element has been studied using the optical photon tools provided by GEANT4 (G4OpticalPhoton). A single scintillator bar (see Figure 7) was implemented applying to it different wrapping materials: air (no-wrapping), refractive paint, Teflon, Teflon with a thin air gap between it and the scintillator, and aluminium with the same air gap. In all cases both the optical properties of the materials and of the contact surfaces were accurately described. Monochromatic photon fluxes were shot perpendicularly to the long sides of the bar, at 1 cm, 10 cm, and 19 cm from the MAPM respectively. The light collection was defined as the ratio between the number of optical photons that were registered at the photomultiplier position and the number of optical photons that had been initially produced by the interacting X-ray photon. The best results were achieved when the scintillator bar was wrapped with aluminum leaving an air gap between the foil and the scintillator surface. The air gap warranties total reflexion for all angles below 68^o due to its lower refractive index, and the aluminium contributes by reflecting back into the scintillator some of the optical photons that were refracted. Using aluminum wrapping, for 50 keV X-rays interacting at 19 cm from the MAPM, 37% of the optical photons produced were detected. When the X-ray was interacting at 1 cm from the MAPM, the amount of collected light was 40% of the initially produced. This speaks of a maximum of 7% variation in the light collection, depending on the position along the bar where the X-ray photons interact.

Several series of laboratory measurements have been performed using different wrapping materials (aluminum foil, teflon, Vikuiti highly reflective tape (3M company), and without wrapping) to cross-check the Monte Carlo predictions. For this purpose a single scintillator bar was optically coupled with one of the anodes from the MAPM (see Figure 7)

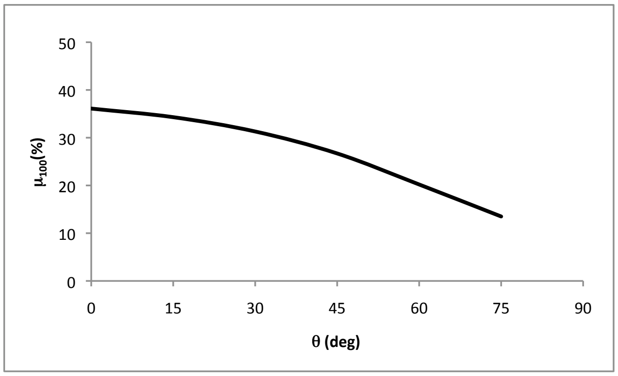

Fig. 8. Dependency of μ_{100} as a function of the incoming photon angle θ in the case of a strong GRB.

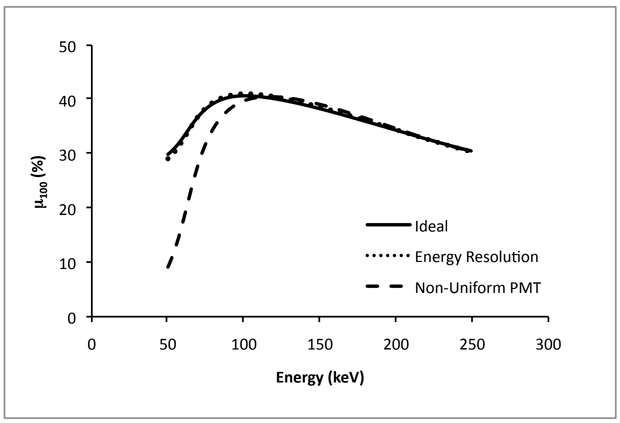

Fig. 9. Dependency of μ_{100} on the energy of the incoming photons. The effect of the poor energy resolution of plastic scintillators and of the non-uniformity of the MAPMT is taken into account in the dotted and dashed lines respectively.

and sequentially irradiated with X-rays of different energies produced by radioactive sources. The output signal of the selected anode was studied in function of the energy of the radioactive source, its position along the length of the bar, and the wrapping material used in the scintillator bar. The strength of the signal changed only about 10-15% between the furthest (19 cm) or at closest (1 cm) position from the MAPM, being only slightly worse than the Monte Carlo simulations previously discussed. The best result was obtained when using the Vikuiti tape as wrapping material because of its high reflective index (bigger than 0.98 with respect to 0.80 for aluminum).

D. Monte Carlo predictions

A detailed mass model has been made using GEANT4 [8] to predict the polarimetric capabilities of POLAR and determine the geometry and materials that provide the best instrument performance. In the actual mass model the 1600 scintillator bars that constitute POLAR target have been implemented, each one of them wrapped in a foil of aluminium with a thickness of 50 μm. The size, material (organic scintillator), and the spatial distribution of the bars were precisely taken into account. To simulate the response of the polarimeter to different kind of particles a realistic particle gun has been defined. The incoming direction, the spectrum, and the type of particles can be generated following the user instructions. All important physical processes that particles can undergo in their travel through POLAR and its surrounding materials have been taken into account, including low energy polarized Compton scattering, low energy gamma conversion, and low energy photoelectric effect, among others. The 100% modulation factor (μ_{100}) can be extracted from the modulation curves obtained from simulations. This factor is a purely instrumental quantity and its value varies in function of the energy and incoming angle of the photon flux (see Figure 8). The maximum μ_{100} is reached for a flux of around 200 keV perpendicularly illuminating the top of POLAR detector. In such a case μ_{100} reached values slightly below 0.4.

For a strong GRB with an energy flux of $E = 10^{-5}\mathrm{erg\,cm^{-2}s^{-1}}$ and a typical Band-spectrum (E_{peak} = 200 keV, α= -1, β= -2.5) the modulation factor for a fully polarized signal was found to be μ_{100} = 0.37 $\pm$ 0.02. Any non-uniformity of the instrument would diminish this value. Some of the possible sources of non-uniformity that could affect POLAR have been studied with simulations. An example of this kind of study is the comparison made between the modulation factor obtained with an ideal POLAR detector, and the same data after taking into account the poor energy resolution of plastic scintillator and the non- uniformity of the MAPM channels, as described in the Hamamatsu data-sheet. It is clearly seen (Figure 9) that while the energy smearing does not diminish the POLAR performance, it is crucial to precisely calibrate each of the instrument channels to correct for sensitivity differences.

IV. TOWARDS AN ENGINEERING AND QUALIFICATION MODEL

An engineering and qualification model (EQM) of the POLAR detector is currently under design. The POLAR EQM is based on a modular design: Each Hamamatsu MAPM 8500 forms a unit with the target scintillator bars and the front-end electronics. The whole is housed in a carbon fiber structure, and a first prototype has been built (see Figure 10).

The EQM will be used for a full test campaign to evaluate the physics performance of a full size detector, but also to qualify the design for space applications. The Hamamatsu MAPM 8500, a key component of the experiment, has already passed preliminary space qualification tests: It has been tested by LAPP Annecy in a thermo-vacuum (temperature range from -25^o to 55^o) as well as on a vibration table (up to around 13 G in random vibration mode). Currently, the front-end electronics is being designed and will soon be produced and tested.

The modular approach allows for individual qualification and calibration of each module, and also for an easy exchange of modules in case of failure. A fully assembled EQM will be ready by end of 2009.

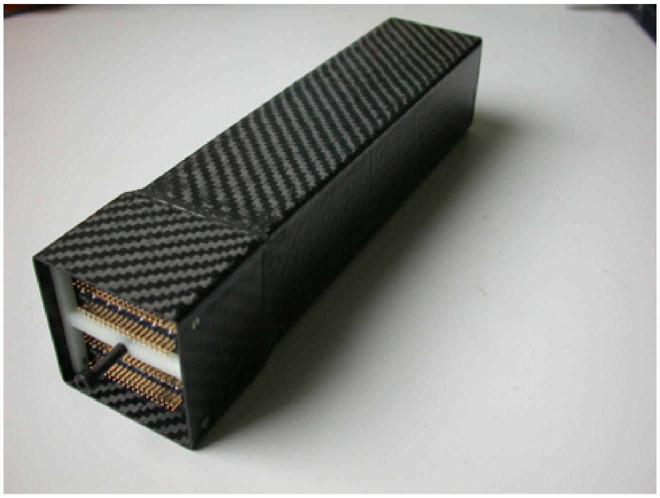

Fig. 10. Prototype of a single POLAR EQM module.

V. CONCLUSIONS AND OUTLOOK

The level of linear polarization in the prompt emission of GRBs is one of the ultimate observables required to fully understand the GRB nature. POLAR is a polarimeter designed to perform such measurements with enough accuracy to make a clear distinction between different theoretical models for the underlying creation mechanism of these bursts.

Asymmetry measurements and light yield studies have been performed as a proof-of-principle. A full size detector and its theoretical performance have been evaluated in extensive Monte Carlo studies, using GEANT4. The POLAR demonstrator model will be tested soon at synchrotrons to further understand systematic effects and estimate the performance of the full POLAR detector. In parallel, an engineering and qualification model of a full-size POLAR detector is under design. Compact, low power and performant front-end electronics are currently under development and mechanical design studies for the POLAR detector are ongoing.

REFERENCES

[1] N. Produit *et al.*, *Nucl. Instrum. Meth.* **A550** (2005) 615.
[2] T. Piran, *Rev. Mod. Phys.* **76**, 1143(2004)
[3] M. Lyutikov, V. I. Pariev and R. D. Brandford, *Astrophys. J.* **597**, 998(2003)
[4] A. Dar and A. de Rujula, Phys. Rep. **405**, 203(2004)
[5] D. Band, *et al.*, *Astrophys. J.* **413**, 281(1993)
[6] M. L. McConnell, *et al.*, *Solar Phys.* **210**, 125(2002)
[7] Y. Kaneko, Spectral studies of gamma-ray burst prompt emission PhD Thesis, Univ. Alabama (2005)
[8] Geant4 webpage: http://geant4.web.cern.ch/geant4/