



## Qualification Tests of the Space-Based POLAR X-Ray Polarimeter

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DOI: 10.7529/ICRC2011/V06/1351

**Abstract:** POLAR (see abstract ID:1128) is a novel compact space-borne Compton polarimeter conceived for a precise measurement of hard X-ray polarization and optimized for the detection of the prompt emission of Gamma-Ray Bursts (GRB) in the energy range 50–500 keV. This paper describes the performances of one modular unit of the Engineering and Qualification Model (EQM) of POLAR measured during the qualification test campaign. In December 2009 we performed a systematic calibration of one modular unit of POLAR with a 100% polarized high-energy (200–511 keV) synchrotron radiation source at European Synchrotron Radiation Facility (ESRF). The detector was displaced several times on the beam line in order to achieve a uniform illumination, which mimics the flux from a GRB placed on the zenith of the experiment. Several rotations of the detector around the beam axis allowed us to test the response of POLAR to several polarization angles. The analysis of ESRF data shows that the input polarization angle is reconstructed within  $2^\circ$  and that the modulation factors  $\mu_{100}$  have values between 30% and 50% depending on the beam energy. Monte Carlo simulations performed with GEANT4 confirm the experimental results. One modular unit of POLAR has also been tested with low-energy synchrotron radiation (22 keV) at the Swiss Light Source (SLS) in PSI to systematically scan the energy threshold of each channel. The tests at SLS show that the ASIC read-out electronics is able to trigger independently on each channel with a threshold of few keV. The combined measurements from ESRF and SLS indicate that POLAR performances are as expected and that POLAR will be able to reach a minimum detectable polarization degree ( $1-\sigma$  level) of about 3% for several GRB measurements per year. The present paper describes also the qualification tests performed during the first 6 months of 2011: vibration, irradiation, thermal and thermo-vacuum tests. A full-scale model of POLAR, consisting of 25 modular units, is currently under construction based on the positive outcome of the qualification tests, in view of a flight on the Chinese spacelab TG-2 expected in 2014.

**Keywords:** Scintillator detector; X-ray polarization; Synchrotron radiation; Astrophysics; Gamma Ray Bursts (GRB); GEANT4 Monte Carlo simulations; Space qualification tests.

## 1 Introduction

Gamma-ray bursts (GRB) are one of the most interesting topics in astrophysics. They are the most luminous bursts in the universe since the Big Bang. Each GRB is related to the creation of a black hole. There are three most accepted GRB emission theory models that have different predictions on the linear polarization level of the prompt emitted photons depending on the physical processes: the fireball model [1], the electromagnetic model [2] and the cannon-

ball model [3]. Therefore, the polarization measurement is a good method to confirm the GRB model and the corresponding emission mechanism of its central engine. POLAR [4, 5] is a space-based mission which is designed as a detector for GRB polarization measurements in the energy range 50 keV to 500 keV. The estimated minimum detectable polarization degree ( $1-\sigma$  level) of POLAR is about 3% for several GRB measurements per year [6]. Simulation results indicate that POLAR also has the GRB local-

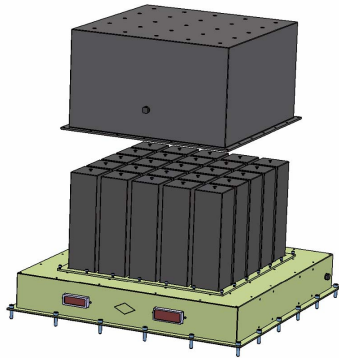


Figure 1: Scheme of POLAR detector.

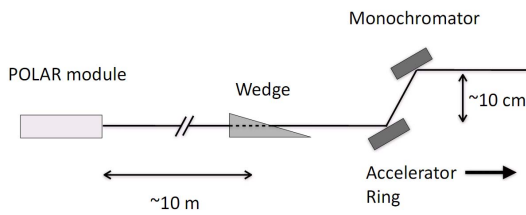


Figure 2: Experimental setup for the beam tests in ESRF.

ization ability [7] which is important for the polarization measurements.

## 2 The POLAR Experiment

POLAR consists of 25 independent scintillator modular units (figure 1), where each modular unit is composed of 64 plastic scintillator (PS) bars ( $8 \times 8$  array), a flat panel multi-anode photomultiplier (MAPMT; H8500D, Hamamatsu) read out by a set of multi-channel ASIC electronics.

Based on the Compton scattering principle, POLAR can track the incident and scattered X-ray photons in the detector plane by collecting the generated fluorescence in PS bars. The incident photons tend to be scattered at a right angle with respect to the initial polarization vector.

## 3 Performance Tests

### 3.1 Tests with High-Energy Synchrotron Radiation

A systematic calibration tests of a modular unit of POLAR engineering model (EM) has been performed at the high-energy diffraction and scattering beam line ID15A at the European Synchrotron Radiation Facility (ESRF). This beam line provides 100% polarized X-rays in the energy range from 30 keV to  $\sim 500$  keV [8]. The experimental setup is shown in figure 2. Before the tests, the new ASIC readout electronics was still under development, therefore

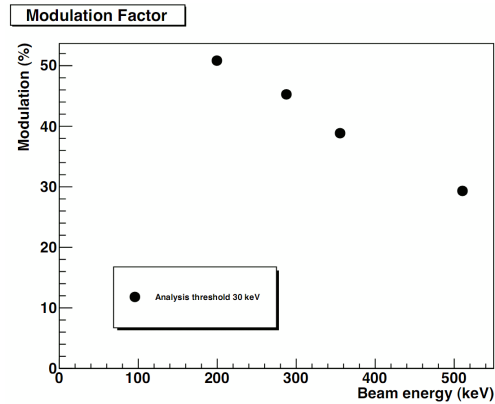


Figure 3: Modulation factor dependence on the beam energy, assuming a minimum deposited energy (imposed during the data analysis) per bar of 30 keV. The error bars are smaller than the markers.

a set of discrete electronics (based on CAMAC and NIM modules) was used in the EM tests. During the beam tests, the detector was installed on an Eulerian cradle, mounted on top of a translating table, allowing the detector to be translated and rotated around the beam axis. Rotations enabled to test the detector with different polarization angles. The beam had a square dimension of  $0.5 \times 0.5 \text{ mm}^2$  and a maximum flux of  $\sim 10^{13} \text{ photons s}^{-1}$ . Therefore, each PS bar (with a cross-section of  $5.9 \times 5.9 \text{ mm}^2$ ) of the modular unit could be scanned with the beam. An aluminum wedge was placed between the detector and the beam in order to reduce the beam intensity to acceptable levels for our data acquisition system. Four high energy (200, 288, 356 and 511 keV) beam were used with different polarization angles. Finally,  $\sim 40$  million events were collected for analysis.

The analysis of the collected data shows that POLAR performances for X-ray polarization measurements are excellent [9]. Both the modulation factor and the polarization angle can be reconstructed from fitting the modulation curve [9]. The unpolarized beam of photons which are constructed by adding offline two data sets of events with orthogonal polarization are also taken into account in the analysis. The polarization angle is reconstructed with an accuracy better than  $2^\circ$ . The modulation factor is decreasing with increasing beam energy (figure 3) in agreement with Monte Carlo simulations [10].

### 3.2 Tests with Low-Energy Synchrotron Radiation

A systematic calibration tests for a modular unit prototype of POLAR qualification model (QM) was performed in May 2011 with a low-energy synchrotron radiation beam line at the Swiss Light Source (SLS) [11, 12] in order to study the lower energy region which is close to the trigger threshold for the single hit (5 keV). This beam line

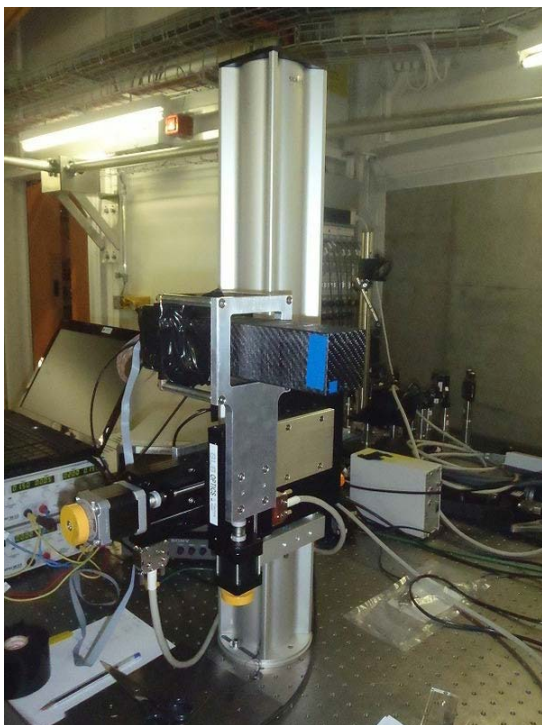


Figure 4: Experimental setup for the low-energy beam tests in SLS.

provides the X-rays in the energy range between 5.5 keV and 22.5 keV. Several fixed energies of beam were used for tests. During the tests, the new ASIC readout electronics were used in the prototype of the QM instead of the former discrete electronics. The experimental setup is similar to the ESRF beam tests. The detector was mounted on motors during the tests to allow for the detector to move horizontally and vertically. Two slits and a filter wheel (with different materials and thickness) were used to reduce the beam's intensity. As different harmonics of the beam can be enhanced or suppressed by different materials, the filter wheel is also used for selecting the beam's spectra [11, 12]. A photo of the experimental setup is shown in figure 4.

A preliminary analysis shows that the system performances are stable for photon fluxes up to about  $10^6$  photons  $s^{-1}$ , and the noise of the electronics is around 3 keV. We demonstrated a usable threshold of several keV on each channel. Data analysis is ongoing and a complete analysis of this data set will be published soon.

## 4 Qualification Tests

According to TG-2 thermal test requirements, POLAR will have to be able to survive temperatures in the range from  $-60^\circ\text{C}$  to  $+50^\circ\text{C}$  in qualification level and from  $-55^\circ\text{C}$  to  $+45^\circ\text{C}$  in acceptance level. Since heaters are inserted in the design which will avoid that the temperature goes below  $-30^\circ\text{C}$  during flight operation, the detector is tested

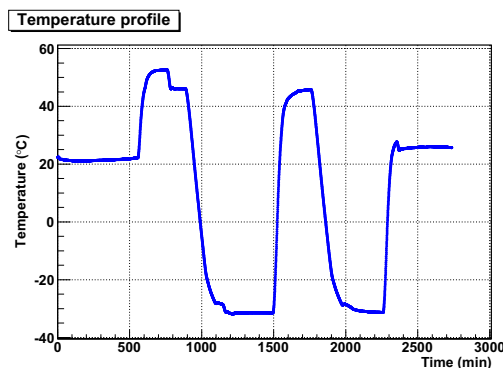


Figure 5: Measured temperature profile of the aluminum holder outside the module.

between  $-30^\circ\text{C}$  and  $+45^\circ\text{C}$  (operational) and  $+50^\circ\text{C}$  (non-operational).

According to the TG-2 vibration test specifications, the maximum acceleration of sinusoidal vibration tests for POLAR in the frequency range of 75 to 100 is 4.8 g at acceptance level and 7.2 g at qualification level in three axes. The specification details won't be present in this paper.

### 4.1 Thermal Tests

A thermal test has been done on a front-end electronics (FEE) unit at room pressure in a climatic chamber in Geneva University with temperature limits  $-40^\circ\text{C}$  and  $+50^\circ\text{C}$ . The test lasted about 25 hours with 4.5 cycles between  $-20^\circ\text{C}$  and  $+50^\circ\text{C}$  and progressive arrival at  $-40^\circ\text{C}$  in steps of  $5^\circ\text{C}$ . The FEE unit was operational at the first  $+50^\circ\text{C}$  and  $-20^\circ\text{C}$  and from  $-25^\circ\text{C}$  to  $-40^\circ\text{C}$ . Finally this FEE unit survived the test nicely. A dependance of the pedestal values as function of temperature is present  $\sim 4$  ADC channel per degree and it can be corrected by software.

### 4.2 Thermo-vacuum Tests

A thermo-vacuum test using one modular prototype of the QM (featuring, scintillating bars, mechanics, PM, front end electronics) was performed at SERMS laboratories [13] in Terni, Italy in June 2011. The module was powered including photomultiplier high voltage. We performed two full temperature cycles in vacuum with temperature limits  $-30^\circ\text{C}$  and  $+50^\circ\text{C}$ , one cycle with hot start and cold start, the other cycle with power on and operational all the time. Fourteen thermal sensors glued on different parts of the module enabled us to measure thermal resistances along the principal thermal path, i.e. to compare the existing simulation-based thermal model to experimental data. A measured temperature profile of the aluminum holder outside the module is shown in figure 5. The preliminary analysis of the data obtained during continuous data acquisition with cosmic rays shows that the detector survived the

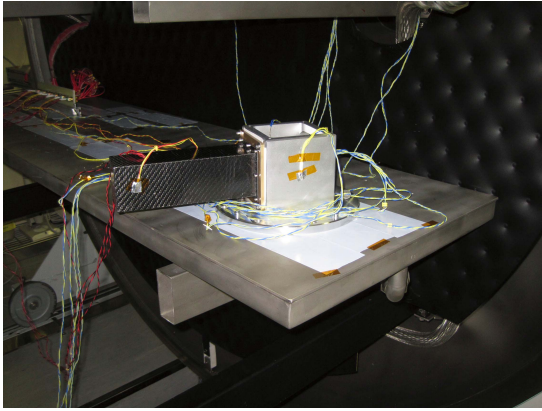


Figure 6: Experimental setup for the thermo-vacuum tests in SERMS. The thermal sensors placed on the outside of the module are also visible.

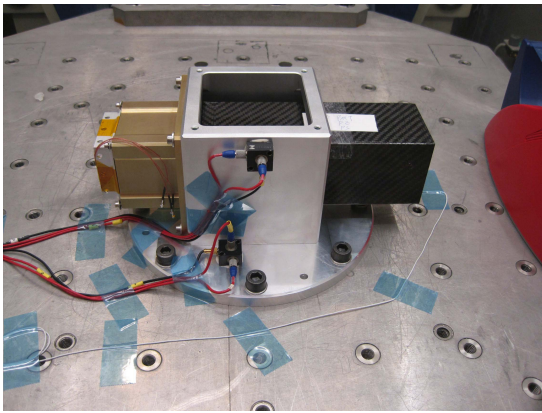


Figure 7: Experimental setup for the vibration tests in the University of Bern.

tests without damage. A photo of the setup used during the thermo-vacuum tests is shown in figure 6.

### 4.3 Vibration Tests

A systematic vibration test using one prototype module of the QM has been done in the Physics Institute of the University of Bern according to the TG-2 vibration test specifications. This module survived the sinusoidal and random vibrations at qualification level. The pedestals of this module increased several hundreds of ADC channel after the vibration test. This is probably due to the increase of the dark current in the electronics. A detailed investigation is ongoing. A photo of the POLAR module during the vibration tests is shown in figure 7.

## 5 Conclusions and Outlook

The tests with high-energy synchrotron radiation at ESRF confirm the excellent polarimetric capabilities of POLAR

predicted by Monte Carlo simulations. Measurements with low-energy X-rays show that POLAR will be able to trigger events with energy depositions of few keV, as required to reach the scientific goals. The preliminary analysis results of the thermal, thermo-vacuum and vibration tests indicate that the design of POLAR will be able to pass the Chinese space station qualification procedures and can be used successfully in space. In the near future, an irradiation test of the readout electronics will be performed in the Geneva university hospital (HUG) with the equivalent irradiation dose according to the lifetime and orbit parameters of the mission. A full-scale model of POLAR is currently under construction and will be tested in the future, in view of the flight of TG-2 expected in 2014.

*The authors acknowledge the European Synchrotron Radiation Facility (Grenoble, France) and the Swiss Light Source (PSI, Villigen, Switzerland) for provision of synchrotron radiation facilities.*

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