Recent Development Status of PoGOLite

K. Kurita[1], Y. Kanai[1], M. Ueno[1], J. Kataoka[1], N. Kawai[1], Y. Umeki[2], H. Yoshida[2], T. Tanaka[2], H. Takahashi[2], T. Mizuno[2], Y. Fukazawa[2], H. Tajima[3], T. Kamae[3], G. Madejski[3], G. Varner[4], M. Kiss[5], P. Carlson[5], W. Klamra[5], M. Pearce[5], F. Ryde[5], S. Larsson[5], H.-G. Florén[6], G. Olofsson[6], G. Bogaert[7], T. Takahashi[8], S. Gunji[9], for the PoGOLite Collaboration

[1]Tokyo Institute of Technology, Meguro, Tokyo, Japan
[2]Hiroshima University, Higashi-Hiroshima, Hiroshima, Japan
[3]Stanford Linear Accelerator Center, Menlo Park, CA, USA
[4]University of Hawaii, Honolulu, HI, USA
[5]Royal Institute of Technology (KTH), Stockholm, Sweden
[6]Stockholm University, Stockholm, Sweden
[7]École Polytechnique, Palaiseau, France
[8]ISAS/JAXA, Sagamihara, Kanagawa, Japan
[9]Yamagata University, Kojirakawa, Yamagata, Japan
E-mail(K. Kurita): kurita.k.aa@m.titech.ac.jp

Abstract

The light-weight Polarized Gamma-Ray Observer (PoGOLite) experiment is designed to measure the linear polarization of celestial soft gamma-rays in the 25 keV − 80 keV energy range. Polarized gamma-rays are expected from a wide variety of sources including rotation-powered pulsars, accreting black holes and neutron stars, and jet-dominated active galaxies. Polarization has never been measured at soft gamma-ray energies where non-thermal processes are likely to produce high degrees of polarization. The polarization is derived from the azimuthal distribution of Compton scattering angles in the sensitive volume of the instrument. The scattering angle will be measured by detecting coincident Compton scattering and photo-absorption sites in an array of 217 phoswich detectors. The PoGOLite experiment is being developed by groups in USA, Sweden, France and Japan.

We present the status of recent PoGOLite developments, including results from a polarized X-ray beam test performed at the KEK Photon Factory in Feburuary 2008.

Key words: Polarimetry, Soft Gamma-Rays, Balloon Experiment

1. Introduction

Polarization measurements in the X-ray and gamma-ray energy range provide crucial information about astrophysical objects such as isolated pulsars, jet-dominated active galaxies, accreting black holes and neutron starts. Strong X-ray and gamma-ray polarization can arise from synchrotron emission in an ordered magnetic field, photon propagation through extremely strong magnetic fields (magnetic field B $\geq 10^{12}$ Gauss) and anisotropic Compton scattering (Lei, F., A. Dean, J. & Hills, G. L. 1997). In all cases, the orientation of the polarization plane depends on the direction of the magnetic fields or the matter distribution, hence it probes the source geometry and emission mechanism.

Despite the potential importance of polarization measurements, the Crab Nebula has been the only source outside of the Solar system from which polarization has been detected significantly: the OSO-8 satellite viewed the Crab at 2.6 and 5.2 keV and measured the polarization using Bragg diffraction (Weisskopf, M. C. et al. 1978). Other sources including the Crab pulsar are below the sensitivity of past measurements (Silver, E. H. et al. 1978) and no systematic study of X-ray and gamma-ray polarization has been performed. Today many objects in high-energy astrophysics still await polarization study (Kataoka, J. et al. 2005).

The light-weight Polarized Gamma-Ray Observer (PoGOLite) is a new balloon-borne instrument capable of detecting 10% polarization from a 200 mCrab source in the 25∼80 keV energy range in a single 6-hour flight for the first time. In order to detect the polarization, PoGOLite measures the azimuthal angle asymmetry of Compton scattering and the subsequent photoabsorption in an array of detectors. This array consists of 217 well-type phoswich detector cells (PDCs) and 54 side anticoincidence shield (SAS) detectors made of bismuth germanete

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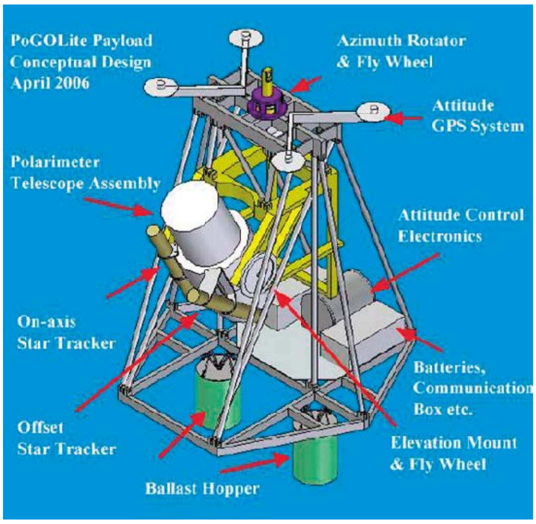

Fig. 1. PoGOLite payload. The dimension will be 2.5×2.5 m^2 in footprint and 3.5 m in height.

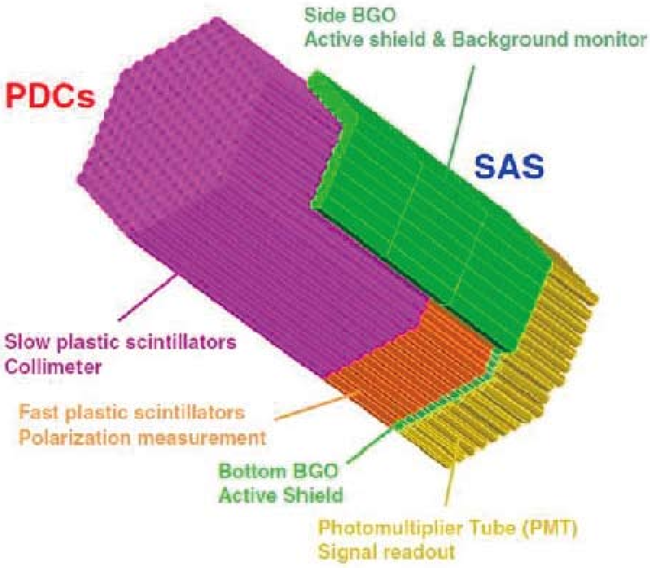

Fig. 2. PoGOLite detector design.

oxide (BGO) scintilators (Kamae, T. et al. 2008). The adoption of a well-type phoswich detector provides a narrow field-of-view (1.25 msr), a large effective area (∼228 cm^2 at 40 keV), a high modulation factor (more than 25 %) and the low background (∼ 100 mCrab) required to conduct high-sensitivity polarization measurements.

PoGOLite is scheduled for launch in 2010 (engineering flight) and will observe polarization from astrophysical objects above 25 keV for the first time.

2. PoGOLite Payload and Detector Configuration

2.1. Payload

The PoGOLite payload, shown schematically in Fig. 1, consists of a polarimeter telescope assembly, a data acquisition system, and a precision pointing gondola. The telescope assembly is covered by a wall of polyethylene (except for the field-of-view), enclosed in an aluminum structure and mounted on an offset pivot to allow full-sky viewing. The pointing accuracy will be better than ∼10% of the field-of-view (or 0.2°) which maximizes the effective area during observation. The assembly can monitor the angular distribution of cosmic-rays and rotate around its viewing axis: these features will allow us to minimize possible bias in observed polarization.

The PoGOLite payload and attitude control system have been designed various flight possibilities in mind: they include long-duration flights in the mid and high latitude regions of the northern and southern hemispheres, and, target-of-opportunity flights to catch long-lasting flares and outbursts.

2.2. Detector Configuration

The PoGOLite detector consists of 217 well-type phoswich detector cells (PDCs) to measure energy spec-

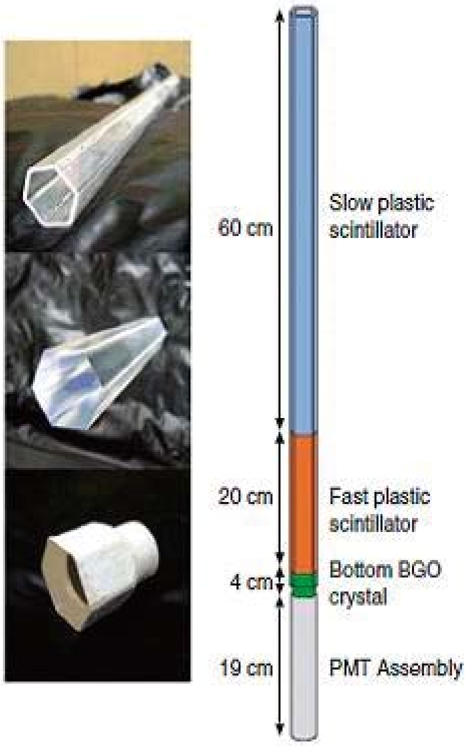

Fig. 3. Phoswich Detector Cell: (right) drawing; and (left) photos of a slow, fast, and bottom BGO scintillators before being glued together.

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trum and polarization from azimuth angle asymmetry and 54 side anticoincidence shield (SAS) to reduce the background (Fig. 2). The arrangement of the PDCs is detailed in Fig. 3.

Each PDC is composed of hollow tube of slow plastic schintilatpr at the top (length 60 cm, decay time $\sim$ 285 ns), a solid rod of fast plastic scintilator (length 20 cm, decay time $\sim$ 2 ns), and a bottom BGO crystal (length 4 cm, decay time $\sim$ 300 ns), all viewed by one photomultiplier tube (PMT).

The slow scintillator tube acts as an active collimator, limiting the feld of view to about 1.25 msr (2.0° $\times$ 2.0°). Photons or charged particles entering the instrument from the rear are detected in the bottom BGO crystals. The fast scintillator is the detector component where Compton scatterings and photoelectric absorptions take place. The three components are viewed by a single PMT, and by using pulse shape discrimination based on the scintillation decay times of the materials, signals from the different components can be distinguished (Kamae, T. et al. 2008). With the active collimator and BGO shields, background will be considerably reduced (e.g. $\sim$ 10 mCrab at 40 keV, $\sim$ 100 mCrab at 80 keV).

3. Photomultiplier Tubes

PoGOLite is designed to minimize the background by an improved phoswich configuration, which enables a detection of 10 % polarization in a 200 mCrab source in a 6$\sim$8 hour observation. To achieve such high sensitivity, low energy response of the detector is important because the source count rate is generally dominated by the lowest energy photons. We have developed new PMT assemblies specifically designed for PoGOLite to read-out weak scintillation light of one photoelectron level. The PMT assembly consists of PMT R7899EG (1 inch diameter, high QE type; Hamamatsu), a divider circuit, and a built-in DC/DC converter (improved C4900-51; Hamamatsu). The DC/DC converter operates on +12 V power supply. It amplifies the input control signal (0$\sim$5 V) by a factor of 250, and provides an output of an arbitrary high voltage in the range 0 $\sim$ +1250 V to each PMT. Note that lengthy HV cables can be eliminated completely in the PoGOLite flight system, since only +12 or +5 V (MAX) signal to each PMT assembly is required. Power consumption of each PMT ASSY is $\sim$ 300 mW, and total power amounts to 81 W for 271 units. This is within an acceptable range of the power budget of PoGOLite (Kataoka, J. et al. 2005).

4. Readout Electronics

To handle 271 PMT output signals with high flexibility and high throughput, we have been developing a new Data Acquisition (DAQ) system. This system consists of two types of SpaceWire boards, an flash analog to digital converter (FADC) board and a digital I/O board, controlled and read by a SpaceCube (Fig. 4). SpaceWire is a new global standard of the communication interface for scientific missions under development by ESA, ISAS/JAXA, Osaka University and other institutions and companies (Takahashi, T. et al. 2004). SpaceCube is a microcomputer to control instruments, and to process and transfer the data in the SpaceWire system (Takahashi, T. et al. 2007).

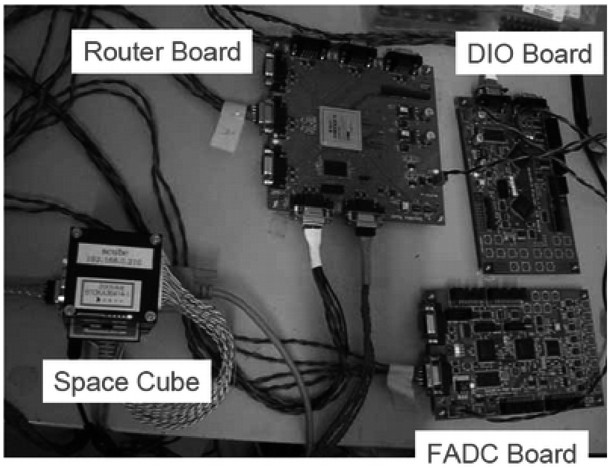

Fig. 4. Prototype SpaceWire boards for the PoGOLite DAQ system.

The PoGOLite FADC board consists of 8 fast Charge Sensitive Amplifier (CSA), 8 channel pipelined FADC, 8 channel digital to analog converter (DAC) to control high voltage supply in PMT assemblies and two Field Programmable Gate Arrays (FPGA) (Xilinx Spartan-3). One of two FPGAs is used for the inter-board interface (SpaceWire), and the other is used for the processing of PMT output signals digitized by the FADC. Therefore, each FADC board can handle up to 8 PMT signals, and 31 and 7 FADC boards will be used for the PDC and the SAS, respectively, in the flight model DAQ system. The network among the boards and the SpaceCube is constructed by using a SpaceWire router.

In our system, all signals from the last dynode of PMTs are fed into an individual fast CSA and then immediately digitized by the FADC. Therefore, most of the signal processing is done by digital circuits in the FPGA, enabling the reduction of the mass, the volume and the power consumption of the DAQ system. We also note that the front-end electronics are common between the PDC and the SAS, and the same FADC board can be used for either system only by changing the onboard FPGA firmware.

The digital I/O board consists of 2 FPGAs and digital I/O interface. This board collects trigger signals from the PDC FADC boards and veto signals from the

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Fig. 5. The 19-unit prototype polarimeter used in the 2008 KEK beam test. The prototype was rotated azimuthally in 30 deg steps.

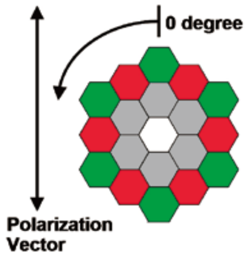

Fig. 6. Arrangement of the 19-PDC prototypes. We defined gray is group1, red is group2 and green is group3.

SAS FADC boards, and figures out if the event is consistent with the valid events or the background. It then send a global data recording trigger to each FADC board (Tanaka, T. et al 2007).

5. Event Selection

Candidates for Compton-scattered events will be selected in the off-line analysis using waveforms in three steps.
Step 1: Select the PDC where photo-absorption took place by requiring the waveform to be compatible with a clean hit in the fast scintillator with energy deposition greater than 15 keV.
Step 2: Waveforms of all neighboring PDCs (up to two layers or 18 PDCs) will be searched for a Compton scattering signal. This threshold was about 0.3 photo-electrons in the 2007 and 2008 KEK beam tests. We conservatively assumed the threshold for detecting Compton scattering to be 1.0 photo-electron in all computer simulations presented in this proposal.
Step 3: Compton-scattering events are selected through the two energy depositions at the photoabsorption site and the Compton-scattering site.

We determine the azimuthal angle of scattering for each event, correct it for the pointing axis and rotation of the Polarimeter Telescope Assembly, and derive the modulation curve. Fitting the modulation curve with computer simulated modulation curves determines the polarization (Kamae, T. et al. 2008).

6. KEK Beam Test 2008

We performed a beam test for a prototype polarimeter in February 2008. The prototype PoGOLite detector used in the test is constructed with 19 PDC units (Fig. 5), all of them were read-out by a flight-design DAQ consisting of three FADC boards and a digital I/O board. Each FADC board is equipped with 8 individual CSA with a time constant of 1 μs and digitizes CSA output to 12 bit accuracy and 36 MHz sampling rate. FPGAs onboard

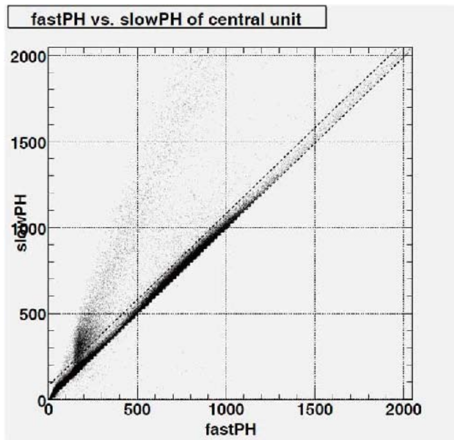

Fig. 7. Two dimensional plot of pulse heights integrated with a short time interval (~110 ns) and a long one (~ 420 ns), obtained under the irradiation of 50 keV beam on the central unit. Two dotted lines indicate the region to select clean fast scintillator signal.

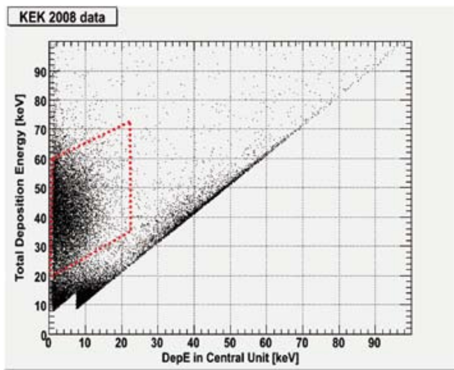

Fig. 8. Relation of the deposit energy in the central unit (Compton site) and the total energy deposition to 50 keV beam. Event selection region is given in red dotted lines. An edge at around 8 keV corresponds to the trigger threshold.

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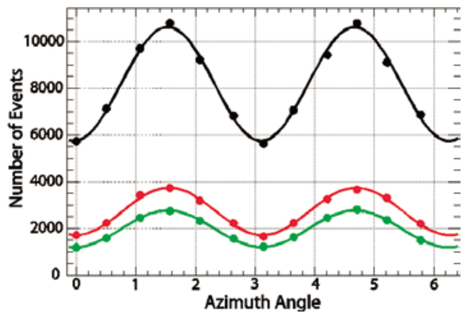

Fig. 9. The measured modulations at a ∼89.7% polarized 50keV beam in the 2008 KEK test for the 3 PDC sets group1 (black), group2 (red) and group3 (green) shown in Fig. 6. The beam entered at the center PDC of Fig. 6.

check for each transient signal and issue trigger signals for events compatible with an energy deposition in the fast scintillator above ∼8 keV. Digital I/O boards collects trigger signals from three FADC boards and sends a global trigger signal. An onboard computer, the SpaceCube, controls these two types boards and records waveform data of 19 PDC units for offline analysis.

The experiment was carried out at station A of beam line 14 (BL14A) at KEK Photon Factory in Tsukuba, Japan. The beamline delivers a vertically plane-polarized X-rays via two Si(533) monochromator crystals. The beam polarization was ∼ 89.7%. We irradiated 50 keV beam to the central PDC unit and thereby the unit acted as an active scatterer with other 18 units absorbing the scattered photons.

To select a clean fast scintillator signal, waveform data are processed in the following way: the charges from PMTs are integrated over the fast (∼ 110 ns) and slow (∼ 420 ns) intervals and are compared. As illustrated in Fig. 7, clean fast scintillator signals fall in a narrow diagonal region and slow/BGO scintillator signals from the upper branch. By selecting events between two dashed lines in the figure, clean fast signals is obtained from each PDC unit.

We studied the distribution of the sum of any two energy depositions versus the energy deposition at the central unit (Fig. 8). Events enclosed by the dashed lines are valid Compton events, first Compton scattered in the central unit and then photoabsorbed in one of the other units.

Distributions of valid Compton events along the azimuth angle are shown in Fig. 9 separately for the 3 PDC groups, group1, group2 and group3 (see Fig. 6). The modulation depended on the distance between the Compton scattering site and photoabsorption site as predicted by our Geant4-based simulation program. We detected average modulation factor (MF) 31.3±0.4 %, which agrees in 5 % compared with data and simulation.

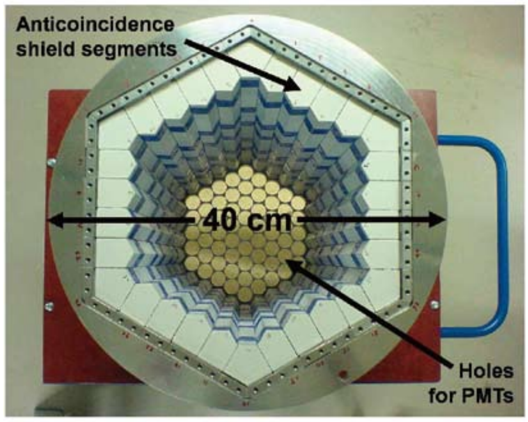

Fig. 10. Top view of the detector array mechanics of the PoGOLite Pathfinder currently under construction in Stockholm

7. PoGOLite Pathfinder

A 61-unit proof-of-principle instrument, the PoGOLite "Pathfnder", is currently under construction in Stockholm (Fig. 10). It is scheduled for its frst flight from the Esrange ballooning facility in Northern Sweden in August 2010. The instrument will be used to measure polarization from the Crab nebula and Cygnus X-1, as well as to assess in-flight background in preparation for the flight of the full-size instrument.

The spin axis of the Crab system has been predicted to be at about 124°-126° based on observations with the Chandra X-Ray Observatory (Ng, C.-Y. et al. 2004). X-ray emission from the Crab is believed to be synchrotron emission from high-energy electrons trapped in toroidal magnetic structures around the system (Aschenbach, B. & Brinkmann, W. 1975), and if this model is correct, the polarization angle of the X-ray emission is expected to be parallel with the spin axis of the system (Kamae, T. et al. 2008). However, using an instrument on-board the OSO-8 satellite, the polarization angle at 2.6 keV and 5.2 keV was measured (Weisskopf, M. C. et al. 1978), and was found to be rotated relative to the spin axis by about 30°. If a 19% polarization degree, as measured on-board OSO-8, is assumed in the PoGOLite energy range, the Pathfinder instrument will be able to measure the polarization degree of the Crab nebula with a 7σ significance and determine the polarization angle with a precision of about 5° in a single six-hour flight. Such a measurement will not only reveal whether the polarization degree remains constant with energy, but also determine if the polarization angle aligns with the spin axis at higher energies, thus testing the paradigm that the X-ray emission from the system is synchrotron emission from electrons trapped in magnetic torii around the pulsar (Kamae, T. et al. 2008).

For Cygnus X-1 in the hard state, the PoGOLite Pathfinder will be able to measure as low as 10% polar-

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ization. This enables the predicted energy dependence of the polarization to be tested against measurements (Axelsson, M. et al. 2007).

8. Summary

PoGOLite is a balloon-borne soft gamma-ray polarimeter designed to enhance the signal-to-noise ratio and secure a large effective area for polarisation measurement ($\sim$228 cm^2 at 40 keV) by limiting the field of view of individual pixels to 1.25 msr (FWHM) based on well-type phoswich detector technology. Thick neutron and gamma-ray shields have been added to reduce background to a level equivalent to $\sim$100 mCrab between 25$\sim$50 keV. PoGOLite can detect a 10% polarisation from a 200 mCrab object in a 6 hour balloon flight and will open a new observational window in high energy astrophysics. In February 2008, we performed a synchrotron beam test at KEK Photon Factory, and we detected average modulation factor (MF) 31.3$\pm$0.4% polarization with PDC 19 units and the MF agree in 5% compared with data and simulation. An engineering flight is scheduled for launch in 2010 and will observe polarization from astrophysical objects above 25 keV.

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