Low Energy Response of a Prototype Detector Array for the PoGO Astronomical Hard X-ray Polarimeter

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ABSTRACT

The Polarized Gamma-ray Observer (PoGO) is a new balloon-borne instrument designed to measure polarization from astrophysical objects in the 30−200 keV range. It is under development for the first flight anticipated in 2008. PoGO is designed to minimize the background by an improved phoswich configuration, which enables a detection of 10 % polarization in a 100 mCrab source in a 6−8 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 PoGO to read-out weak scintillation light of one photoelectron (1 p.e.) level. A beam test of a prototype detector array was conducted at the KEK Photon Factory, Tsukuba in Japan. The experimental data confirm that PoGO can detect polarization of 80−85 % polarized beam down to 30 keV with a modulation factor 0.25 ± 0.05.

Keywords: Polarimetry, soft Gamma-rays, balloon experiment

1. INTRODUCTION

In modern astrophysics, the analysis of compact X-ray and gamma-ray sources has been confined to three-parameter space, which is defined by the spectral characteristics, time variability and the projection image of the source. These approaches, however, are often *degenerate*, in the sense that quite different models can often equally well explain all observational properties. Another observational approach, which may potentially discriminate amongst various emission models, involves the measurement of X-ray and gamma-ray polarization. This can provide unique information for a wide variety of astronomical sources, such as pulsars, jet-dominated active galaxies, and accreting neutron stars and black holes with a wide range of masses.[1] Astronomical X-ray polarimetry has a history nearly as long as X-ray astronomy itself, but is still an unexploited field. In the X-ray observations of extra-Solar systems, polarization has been measured only once, of the Crab(nebula+pulsar) at 2.6 and 5.2 keV with OSO-8 satellite.[2,3]

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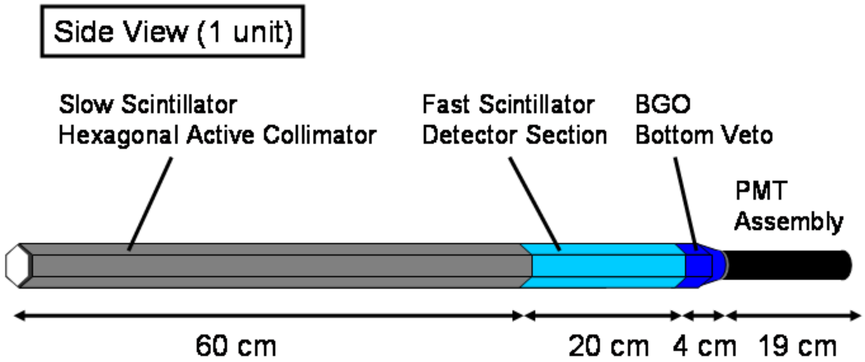

Figure 1. One well-type phoswich detector cell consisting of 60 cm anti-coincidence hexagonal well made of slow plastic scintillator, a 20 cm long detection part made of fast scintillator, and 4cm long BGO crystal. All scintillators are optically coupled and read out by 1 inch PMT assembly (see §2).

Table 1. Bright candidate sources for the hard X-ray polarization

Source Name	Category	flux at 40 keV
Crab	pulsar + nebular	1.0 Crab
Vela X-1	pulsar	0.6 Crab
Her X-1	pulsar	0.12 Crab
Cyg X-1	black hole	0.6 Crab
GX 339-4	black hole	0.3 Crab
1E1740.7-2942	black hole	0.23 Crab
GS 2023+338	black hole	2.5 Crab
GS 2000+25	black hole	0.3 Crab
GRS 1915+105 (flare)	μ-QSO	0.24 Crab
GRO J1655-40 (flare)	μ-QSO	1.0 Crab
GS 2023+ 338	X-ray nova	2.5 Crab
Mrk 501 (flare)	AGN	0.23 Crab
Cen A	AGN	0.06 Crab
3C 273	AGN	0.035 Crab
NGC 4151	AGN	0.04 Crab
NGC 4945	AGN	0.02 Crab

Astronomical measurements of polarization have never been performed at photon energies greater than 10 keV, except for a chance detection of strong (80±20 %) polarization from a bright gamma-ray burst GRB 021206 by RHESSI satellite.[4] The result had an impact on various fields of astrophysics, but other authors claimed *non*-detection of polarization using the same data.[5] The discrepancy might be due to uncertainty in background subtraction, as well as different selection criteria of the scattered events. Clearly, the next step towards advancements in X-ray polarimetry requires much better sensitivity with a high signal to noise ratio. We believe that well-known astronomical targets are preferable over serendipitous sources such as GRBs since their accurate positions are established prior to the detection of X-ray/gamma-ray emission. Therefore, bright sources in our Galaxy - as well as extra-galactic sources undergoing prominent flares - provide ideal "first round" targets for measurement of X-ray / gamma-ray polarization. Table 1 summarizes the bright candidate sources recommended for the future X-ray polarimetry. Note that more than 15 Galactic/extra-galactic sources could be observed above 10 mCrab (0.01 Crab) sensitivity at 40 keV.

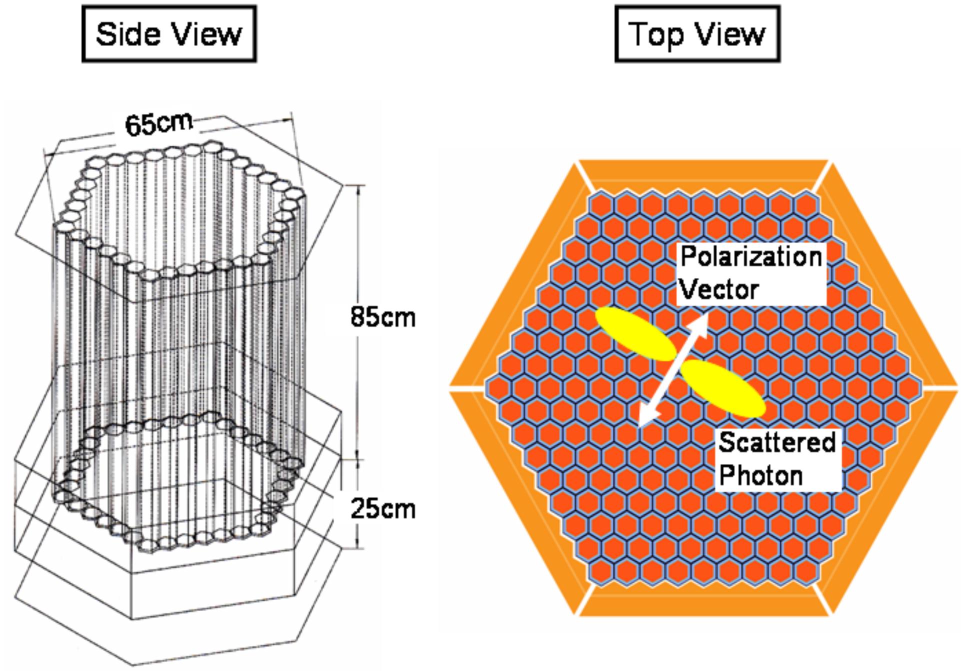

Figure 2. Arrangement of phoswich detector cells in the PoGO assembly from the side view (*left*) and the top view (*right*). The flight model will have 217 cells in total of which 48 cells are in the periphery.

The Polarized Gamma-ray Observer (PoGO) is a new balloon-borne instrument designed to measure polarization from astrophysical objects in the 30−200 keV range. It is under development for the first flight planned for 2008. The PoGO instruments utilizes a method for polarization measurements which was adopted from the Well-type Phoswich Counter, which in turn was successfully developed and demonstrated through a series of balloon experiments[7,8] and also implemented as the Hard X-ray Detector (HXD) onboard the Astro-E[9–11] and Astro-E2 satellite missions.[12,13] Phoswich configuration has proven to be highly effective to reduce the background events, which dominate over the weak signals from the astrophysical sources in the hard X-ray energy band. This is partly via restricting the field-of-view to the small (~ 5 deg^2) region of the sky where the celestial source is located.

The conceptual design of the PoGO instrument is shown in Figure 1 (one unit) and Figure 2 (217 units). A hexagonal array of fast plastic scintillators (decay time $\tau \sim 2$ nsec) works as a Compton polarimeter for hard X-rays by measuring the azimuthal scattering angle asymmetry. This fast scintillator part is surrounded by bottom and side veto-detectors made of BGO scintillators ($\tau \sim 300$ nsec), and the aperture is defined by active collimators made from thin tubes of slow plastic scintillators ($\tau \sim 300$ nsec). Signals from the fast plastic scintillator and those from the slow plastic or BGO scintillators can be separated using a pulse shape discrimination technique by examining signal time profile in two different time windows (e.g., 50 nsec and 1 μs). The current design of PoGO consists of 217 phoswich units yielding a geometrical area of $\sim$930 cm^2 and an effective area of $\sim$230 cm^2 at 40 keV (Figure 2). Detailed Monte-Carlo simulations show that PoGO will achieve the sensitivity to measure ≤ 10 % polarization from a 100 mCrab sources in a 6 hour balloon observations.[6]

2. DEVELOPMENT OF PHOTOMULTIPLIER TUBE ASSEMBLIES FOR POGO

In order to achieve the best performance of PoGO sensors in the balloon environment, various parameters must be carefully examined and optimized during the design phase, as given in detail in Chen et al. (2003). Here we focus on the requirements on the photomultiplier tube (PMT) and the voltage supplies, as those are among the essential parts in the PoGO flight system.

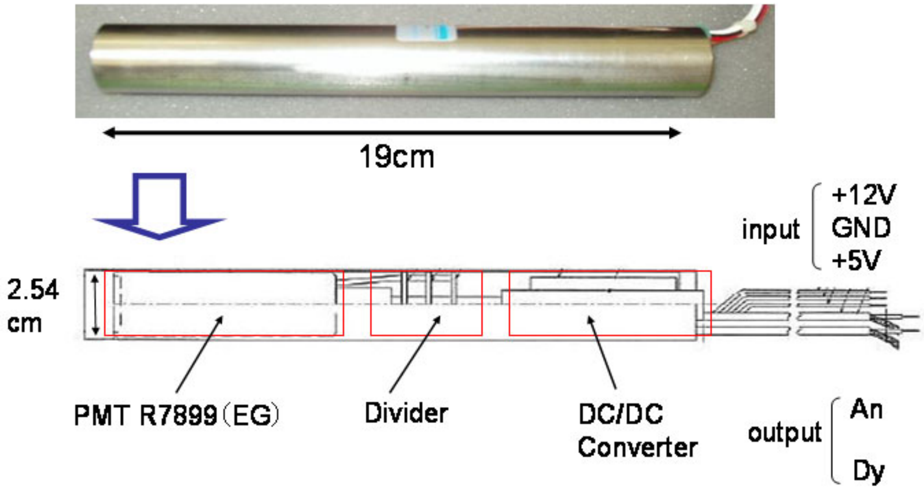

Figure 3. Dimension of PMT ASSY and its internal structure developed for the flight PoGO sensors.

Let us consider the lowest energy range of PoGO observation, where the constraints are most severe. At 30 keV, for scattering angles between $60-120°$, only 1-3 keV of energy goes to the Compton electron. This results in emission of 10 to 30 photons in the fast plastic scintillator to be collected and detected by the PMT. Since the effective quantum efficiency (QE) of PMTs is typically about 20 %, this gives 2 to 6 photoelectrons for perfect light collection, but $1-3$ photoelectrons in a realistic case. Therefore PMT assembly for PoGO flight sensor requires high QE and low-noise characteristic, while the system must be implemented in a very narrow package of 1 inch diameter. In addition, general requirements for the balloon experiments are;

- All the resources (such as available power and weight) are limited, while in general, the power consumption of PMTs is relatively high.
- PMTs must be operated under the low pressure, facing with a risk of electrical discharge.
- Charged particle flux can be severe, which may result in a significant detector dead time.

In a laboratory system and even in most balloon experiments, a group of PMTs can be connected with the same HV module through a lengthy HV cable. In such a configuration, however, a crack in the cable may sometimes cause a fatal damage by electrical discharge under the low pressure environment. Once a certain PMT unit breaks down, this can lead to a chain reaction of other PMTs connected to the same HV module. It is thus necessary to carefully solder, pot, and check the HV cable just before the launch. This would be very time-consuming, especially when the detector consists of large number of channels as is the case for the flight PoGO system. Furthermore, such a configuration is inflexible to any changes and/or modifications, once the potting has been completed. Of course such situation is undesirable, but might be unavoidable especially when a faulty connection is found.

To overcome such difficulties, we have designed a novel PMT assembly (hereafter PMT ASSY) to read-out each PoGO phoswich unit. Each PMT ASSY is 19 cm in length and 228 g in weight (Figure 3). This assembly consists of a PMT R7899EG (1 inch diameter, high QE type; Hamamatsu), a divider circuit, and a build-in DC/DC converter (improved DC4900-51; Hamamatsu). The DC/DC converter operates on +12 V power supply. It amplifies the input control signal ($0-5$ 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 PoGO flight system, since only +12 or +5V (MAX) signal to each PMT assembly is required. Power consumption of each PMT ASSY is $\sim$ 300 mW, and total power amounts to 65 W for 217 units. This is within an acceptable range of the power budget of PoGO.

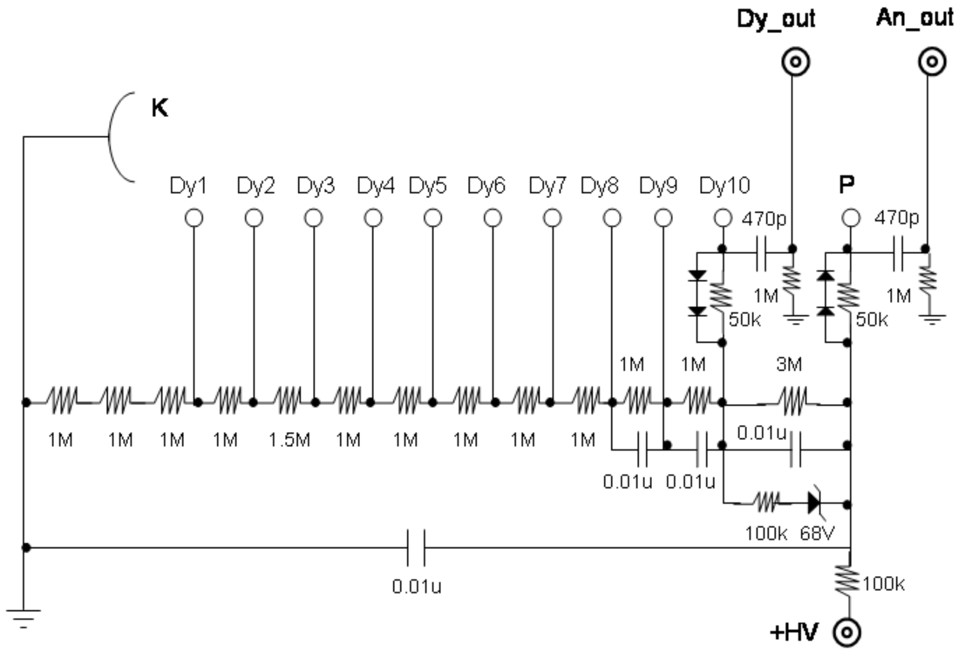

Figure 4. The circuit diagram of the improved PMT divider.

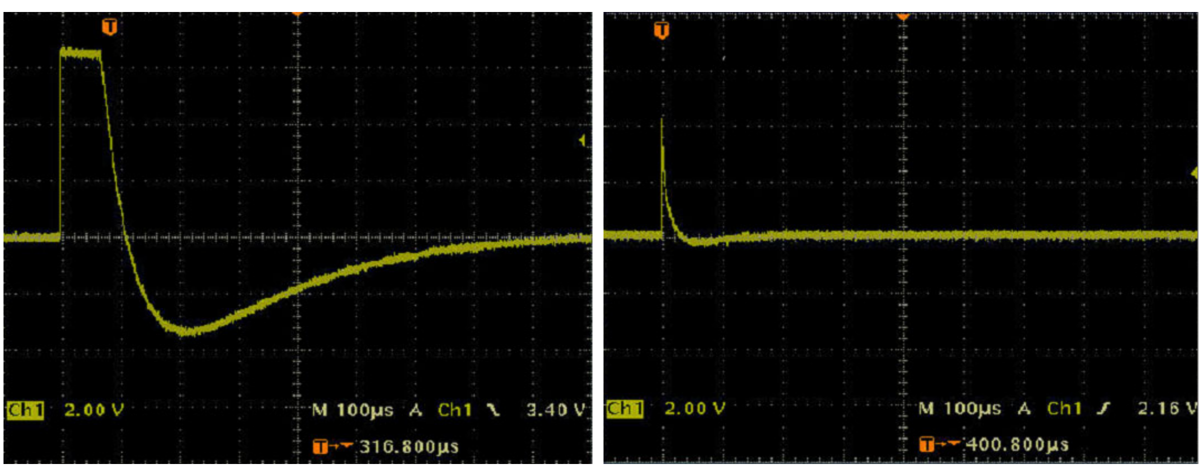

Figure 5. *left*: The preamplifier output for a few tens MeV deposit pulse using the original bleeder. *right*: The preamplifier output for a few tens MeV deposit pulse using the improved bleeder circuit (Figure 4). Note that recovery time was shortened by a factor of 20 as compared to the original circuit.

In orbit, charged particle background is also a serious problem since both the rate and the energy deposition are very high. Expected rate would be ≥ 100 cts s^{-1} unit^{-1}, which is two orders of magnitude larger than signals from astronomical sources. Energy deposited by each charged particle typically amounts to few tens – 100 MeV for each PoGO phoswich sensor. Such a large signal would make a long tail in the output of charge sensitive pre-amplifier as reported in literature.[15] In order to minimize the recovery time of the charged particle signal from the phoswich counters, we adopted a well-studied design of a voltage divider used in the Astro-E Hard X-ray Detector[15] (Figure 4). Figure 5 shows a waveform of the pre-amplifier output for the deposited signal corresponding to few tens of MeV, measured with an original, ready-made bleeder (*left*) and our newly designed divider circuit (*right*). Note that it took more than 800 μs to recover the initial level in the left panel. Since the expected count rate of charged particles is expected to be as much as 100 Hz, this would result in > 10 % deadtime. Meanwhile the recovery time is significantly shortened to ~ 50 μs using the improved divider circuit.

3. POLARIZED BEAM TEST AT KEK-PF

3.1. Goal of This Experiment

To demonstrate the ability of PoGO to measure polarization, we performed a beam test experiment with a PoGO prototype at the Advanced Photon Source Facility (APS) of the Argonne National Laboratory during November 10−18, 2003. This experiment was very successful, as polarization was measured at 60, 73 and 83 keV and the result was reproduced at the 10% level as compared to the results obtained from the computer simulation package Geant4.[16] In that experiment, however, we used 7 fast plastic scintillators and bulky PMTs (3.4 cm photocathode diameter: R580 Hamamatsu) coupled to the same *negative* high voltage power unit. This configuration inevitably produced unnecessary 2.2 cm space between each of the hexagonal scintillators, which is quite different from the flight sensor configuration.[16] Furthermore, we should note that the measurement at lower energy band is probably more important, because the source count rate is generally dominated by the lowest energy photons reflecting a steep power-law spectral shape ($\sim E^{-2}$) of astronomical sources.

At the low energy end, coincidence measurement of Compton scattering becomes increasingly more difficult due to the limited photon statistics in the first scattering scintillators, as we have commented in § 2. In order to detect a 30 keV photon with both the scattering and absorption scintillators, we need to make a coincidence from 1 p.e trigger signal. This is a difficult requirement, since the HV is always operated with the *positive* polarity in balloon experiments, in order to avoid discharge between the glass tube and the photo-cathode. In general, ripple noise is more critical in positive polarity, because signal outputs (Dynode, or Dy-out, and Anode, or An-out, in Figure 4) are inevitably aligned close to the high voltage line.

We therefore planned a follow-up beam test at the KEK Photon Factory (KEK-PF) at Tsukuba in Japan, using more realistic prototype of PoGO sensor. The goal of this experiment is two fold: (1) to measure polarization with a realistic prototype geometry, and (2) to test the low energy response of prototype sensor in 30−70 keV range.

3.2. Instrumental Setup

We have conducted a test-beam experiment with a 7 unit PoGO prototype sensors at KEK-PF during December 3−5, 2004. Because the main objective of the beam test was to measure the low energy response of Compton polarimetry, the prototype was arranged as an array of 7 hexagonal ELJEN EJ-204 scintillators, each 2.68 cm wide and 20 cm long, optically coupled to the PMT ASSY through the acrylic light guide (Figure 6). Note that the geometry of light guide mimics that of the BGO scintillator, and that transmission efficiency is almost equal between the BGO and the acrylic bottom (70−80 %). Similar to the flight PoGO configuration, seven hexagonal detector units are tightly bundled together in a closely packaged hexagonal array.

The center scintillator acted as a Compton scattering target and outer six scintillators detected the scattered photons. The array was mounted on a rotation stage, as shown in Figure 7, to allow measurement of modulation factor by rotating about the center scintillator aligned to the incident photon beam. Here the modulation factor is defined, in terms of the counting rate ($R(\phi)$) at azimuthal scattering angle ϕ, as:
$(R(\phi)_{\max} - R(\phi)_{\min})/(R(\phi)_{\max} + R(\phi)_{\min})$.

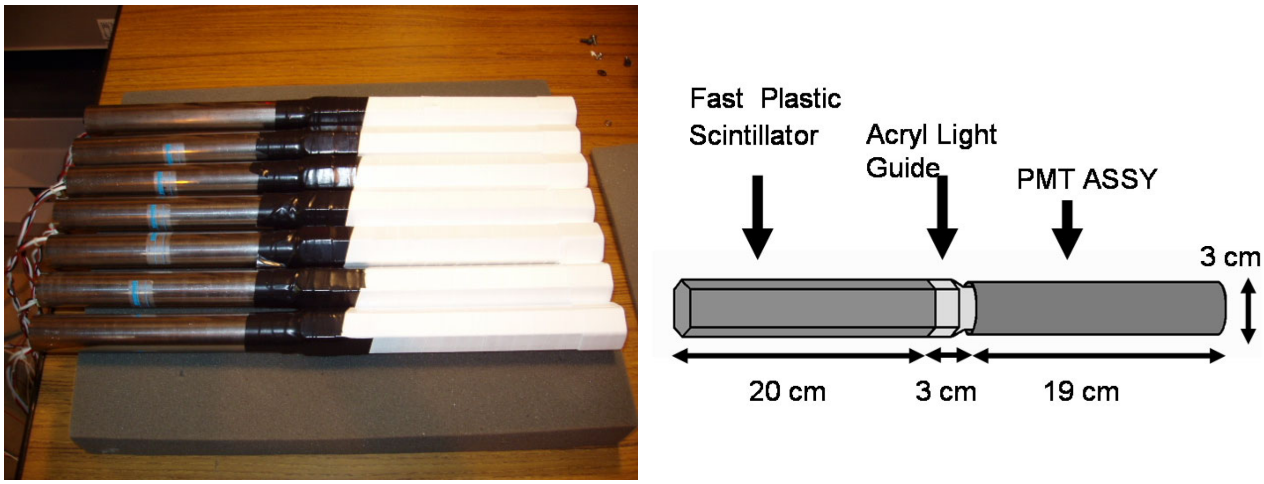

Figure 6. *left*: A photograph of seven PoGO prototype sensor fabricated for the KEK-PF beam test. *right*: Schematic picture of one unit PoGO prototype sensor.

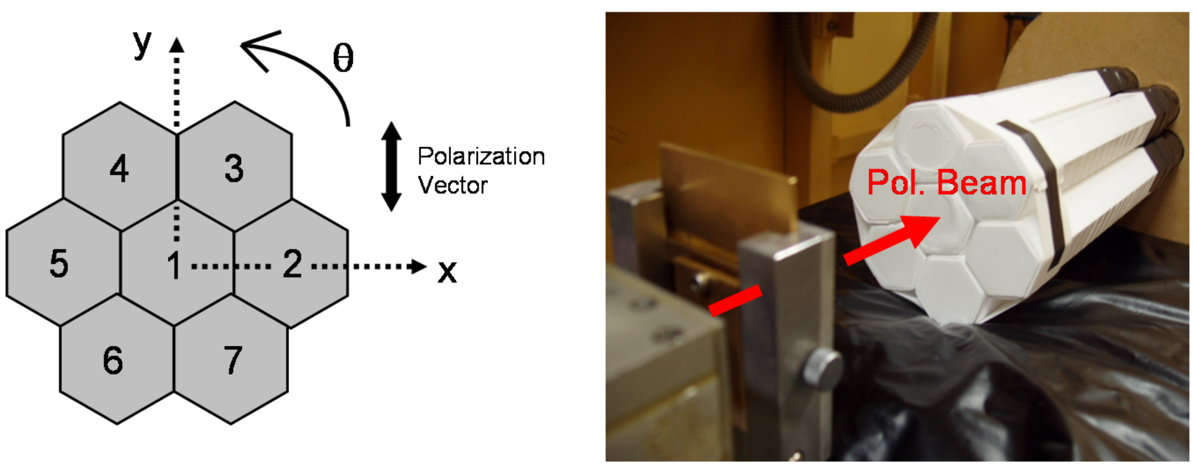

Figure 7. *left*: The layout and numbering scheme of scintillators viewed from the beam origin. Detector rotation angle is defined to be 0° when scintillators ch-1, ch-2, and ch-5 are along the horizontal (x-axis), and increased with anti-clockwise direction. *right*: A photograph of the PoGO prototype mounted on the rotation stage attached to the experimental table.

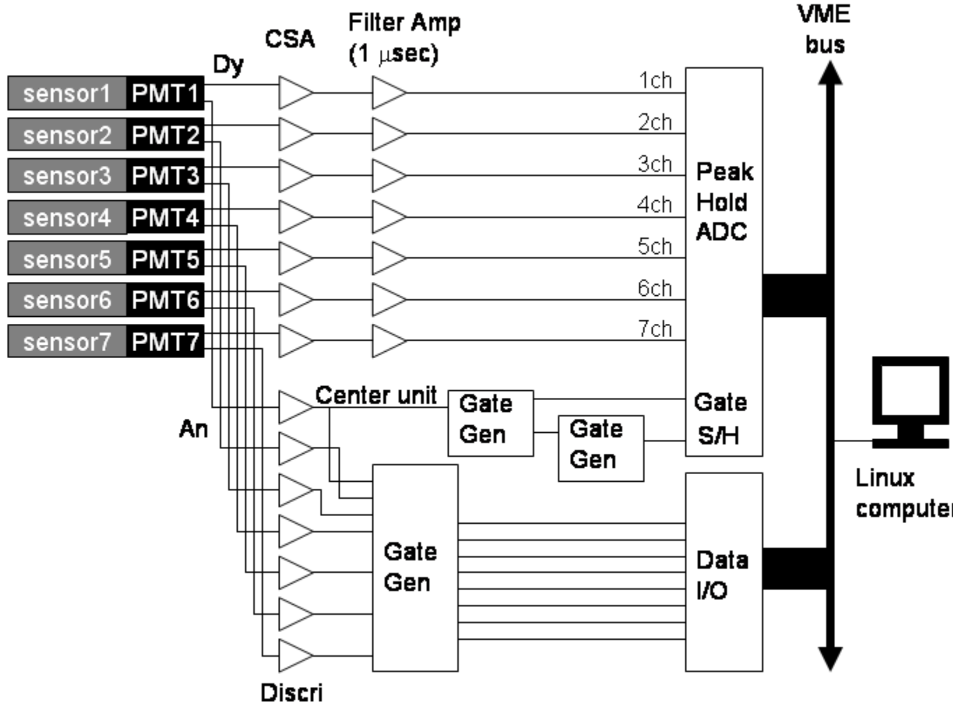

Figure 8. The data acquisition system of the KEK-PF experiment. Outputs from anodes are used to trigger the system, whereas those from dynodes are used for spectroscopy.

To measure the detector response to various orientations of the polarization vector, the instrument was rotated in 15° steps covering the azimuthal angle range from 0 to 360°.

The signals from each PMT dynodes were fed into charge-sensitive preamplifires (Clear Pulse 557) and amplified by shaping amplifiers with 1μs shaping time (Clear Pulse 4066). The outputs of these amplifiers were fed into the peak hold ADC (Clear Pulse 1113A) and used for spectroscopy (Figure 8). Meanwhile the output from each PMT anodes was used for trigger generation and for recording of the hit-pattern information in the Data I/O board (Clear Pulse 2610). In this experiment, we did not take advantage of the *hardware* coincidence between the central scintillator and in any one of surrounding scintillators. Only the signal hit at the center unit ($E \geq 1$ keV) is required to start the ADC, but we can easily select various event hit patterns after data are recorded on a computer.

The experiment was installed in the BL-14A station at KEK. The prototype detector was exposed to a plane-polarized photon beam at 30 keV, 50 keV and 70 keV delivered through a double-scattering monochrometer Si(553) upstream. Typical flux of the polarized beam was 10^{6-7} photons s^{-1}, but was further reduced with Pb or W attenuators, resulting in a trigger rate of a few kHz at the center scintillator. The beam size was adjusted to 1×1 mm^2 square by thick collimator. The degree of polarization was not accurately measured in our experiments due to the limited beam time, but it had been measured to be in the range of 80−85 % in 30−70 keV. Background was negligibly small, and affects only 0.1−0.2 % of trigger rate of the detector.

3.3. Measurement at 30, 50, 70 keV

A raw data sample at 30 keV taken with *software* coincidence between ch-1 and ch-2, measured at 0° rotation is shown in Figure 9 (*left*). This figure is a scatter-plot of energy detected in the central scintillator and the sum of the two energy deposits in ch-1 and ch-2. We can see a clear separation between events in which Compton scattered photons are photo-absorbed in the peripheral scintillator (total energy deposit is about 30 keV), and

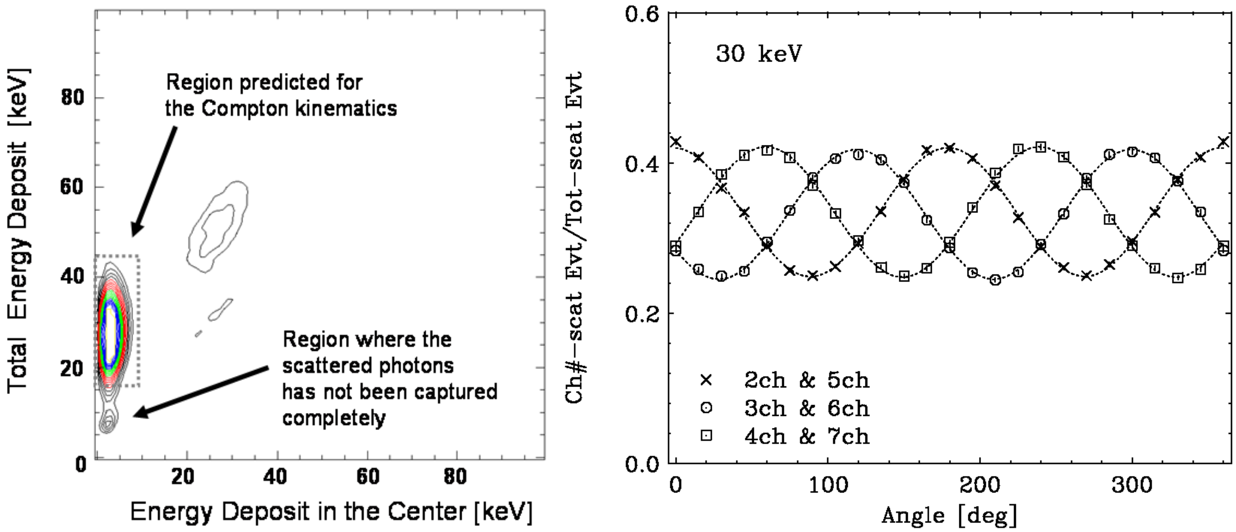

Figure 9. *left*: Relation of deposit energy in the central scintillator (ch-1) and the sum of the two energy deposits in ch-1 and ch-2, for 30 keV incident beam. Full details are given in the text. *right*: The dependence of the two-hit events as a function of instrument rotation angle. Event rates are normalized by the total two-hit events including all outside scintillators.

those in which the scattered photons escaped (total energy deposit below 10 keV). In order to select valid Compton-scattered events, we applied following criteria to calculate the modulation factor:

- The central scintillator and only one of the outside scintillators detected a hit, where detection threshold was set at 1 keV for all the sensor units. This is almost equal to the single photo-electron noise.
- The energy detected in the central scintillator (E_1) is below 10 keV.
- The sum of the energy deposited ($E_{\rm sum}$) is in the range of 30±19 keV, considering the broadening by energy resolution of the detector.

The selection criteria are also shown in Figure 9 (*left*). Polarization then could be measured from the dependence of the hit rates in each of the peripheral scintillators. The results for 30 keV incident beam are given in Figure 9 (*right*). The crosses show the dependence of two-hit events (sum of "ch-1 and ch-2", and "ch-1 and ch-5") as a function of instrument rotation angle. Note that event rate is normalized by the total two-hit events including all outside scintillators, just to cancel out the time dependence of the beam injection rate. Similarly, other combinations of two-hit events are shown in circles (ch-3 and ch-6) and squares (ch-4 and ch-7), respectively. Note that the sum of cross, circle, and square becomes always equal to unity by definition.

A clear modulation is apparent, where the count rate reaches maximum at θ=0° and falls down to the minimum at θ=90° for ch-2 and ch-5 (crosses). This is actually expected since both scintillators are perpendicular to the polarization vector at θ=0° while they are parallel at θ=90° (see Figure 7 *left*). We fitted the resultant modulation to a sinusoidal curve and obtained a modulation factor of (26±1)/P [%] for 30 keV experiment, where P is the polarization degree of incident photon beam (0.80−0.85 for this experiment).

Similarly, we select only the Compton events within the ranges, $E_1 < 15$ keV and $E_{\rm sum} = 50\pm24$ keV, to derive the modulation curve for 50 keV beam data (Figure 10 *left*). For the 70 keV beam, we select the scattering events in the ranges of 4 keV $< E_1 <$ 30 keV and $E_{\rm sum} = 70\pm25$ keV (Figure 11 *left*). Modulation factors thus calculated are (24±1)/P % and (29±1)/P %, respectively for 50 keV and 70 keV beam (Figure 10 *right* and Figure 11 *right*). This is consistent with that expected from Geant4 simulations using the same geometry, which predicts the modulation factor of ∼25−30 %.

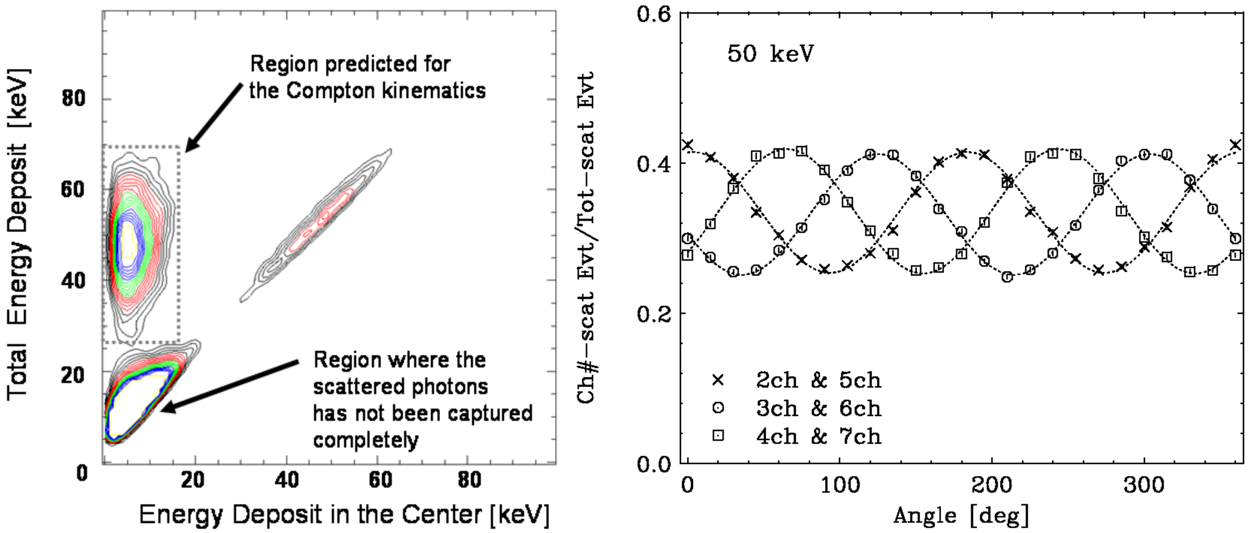

Figure 10. *left*: Relation of the deposited energy in the central scintillator (ch-1) and the sum of the two energy deposits in ch-1 and ch-2, for 50 keV incident beam. Full details are given in the text. *right*: The dependence of two-hit events as a function of instrument rotation angle. Event rates are normalized by the total two-hit events including all outside scintillators.

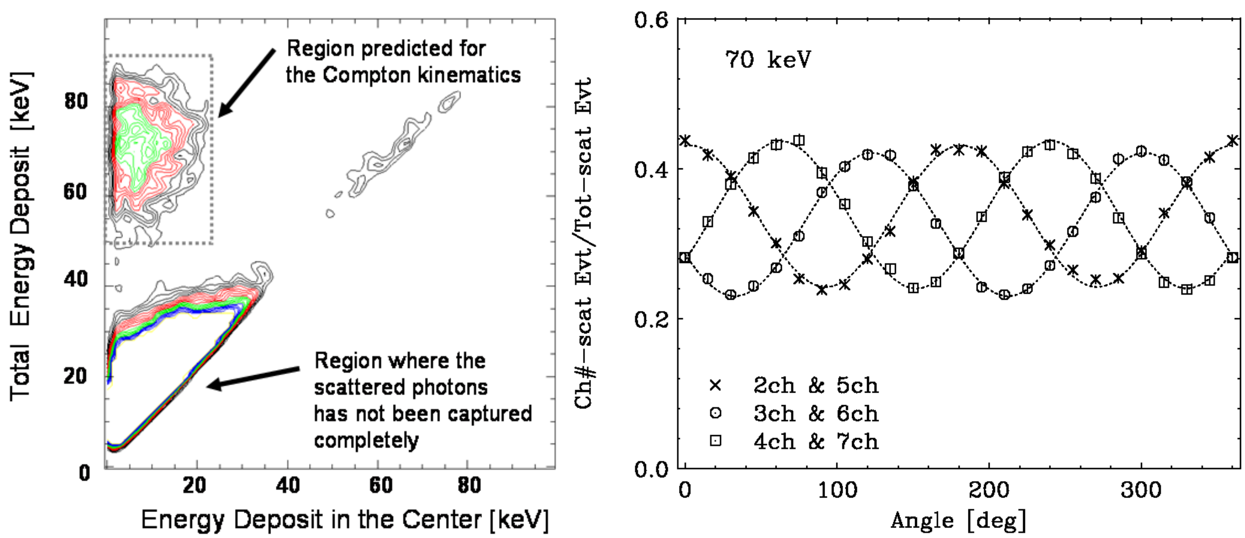

Figure 11. *left*: Relation of deposit energy in the central scintillator (ch-1) and the sum of the two energy deposits in ch-1 and ch-2, for 70 keV incident beam. Full details are given in the text. *right*: The dependence of two-hit events as a function of instrument rotation angle. Event rates are normalized by the total two-hit events including all outside scintillators.

By comparing the scattered plot for 30, 50, and 70 keV, one can see that more and more events are accumulated in the bottom left corner of the plot with the increasing energy of incident photons. This is the region where the scattered photons have not been captured completely in the outside scintillators, and escape from the prototype sensors. The number of such events is significantly reduced by increasing the number of units surrounding each scintillator, such as the flight configuration of 217 units. We are preparing follow-up beam tests using 19 PoGO phoswich units in 2005 and 2006 for further quantitative studies.

4. CONCLUSIONS

We have summarized the design and current status of the Polarized Gamma-ray Observer (PoGO) project. By using a novel photomultiplier assembly (PMT ASSY) specifically designed to PoGO, we have conducted a polarization beam test experiment on a prototype sensors at KEK-PF Tsukuba in Japan. The prototype consists of seven hexagonal fast plastic scintillators optically coupled to each PMT ASSY through the acrylic light guide. The modulation signal was successfully recorded at 30 keV, 50 keV, and 70 keV, with the modulation factor of 0.25±0.05 for incident 80−85 % polarized beam. This modulation factor is in good agreement with that expected from the Geant4 simulation, and proves that the PoGO can clearly detect polarization signal even at the lowest end of observational energy range 30−200 keV. We are planning follow-up beam tests in the end of 2005 at APS (USA: above 60 keV) and KEK-PF (JAPAN: below 60 keV), using 19 units of PoGO flight sensors. Further tests and optimization is still underway, preparing for the first launch planned for 2008.

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