# POLARIZATION MEASUREMENTS WITH THE MEGA TELESCOPE

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## ABSTRACT

The tracking Medium Energy Gamma-ray Astronomy telescope MEGA, which detects gamma-rays via Compton scattering and pair creation, has been calibrated at the High Intensity Gamma Source of the Free Electron Laser facility at Duke University. Exposures to monoenergetic (range 710 keV to 50 MeV, dE/E < 2%), 100% linearly polarized pencil beams allow the derivation of the imaging and spectral properties, sensitivity and field of view of this prototype instrument. Since the gamma-ray test beam is generated by Compton back-scattering inside a free electron laser, the degree and angle of polarization are completely determined. We describe the measured response of MEGA to these polarized photons in the range below about 5 MeV, where Compton scattering is the dominant detection process.

Key words: Compton telescope; polarization; gamma-ray astronomy.

## 1. INTRODUCTION

The tracking Medium Energy Gamma-ray Astronomy telescope MEGA has been developed at the Max-Planck-Institute for extraterrestrial Physics (Garching, Germany). It is designed to detect gamma-rays in the energy range from 400 keV up to at least 50 MeV via Compton scattering and pair creation (Kanbach et al., 2003). The basic design and the measurement principle of the telescope are shown in Fig. 1.

MEGA consists of a tracker, in which the primary Compton scatter or pair creation event takes place, and a calorimeter, which absorbs and measures the secondary particles. A prototype for MEGA has been built (see Fig. 2), which has 12-times less volume than the satellite version under study.

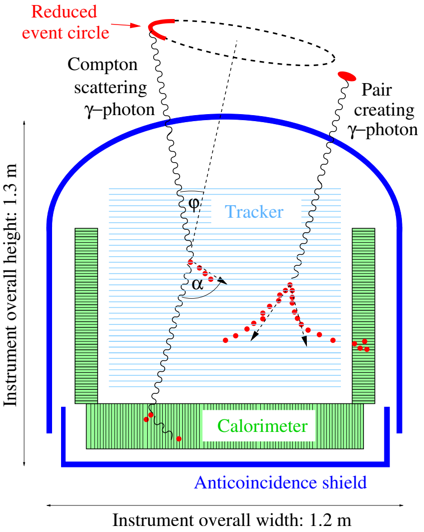

*Figure 1. Baseline design and measurement principle of the full MEGA telescope. The recoil electrons from Compton scattering as well as the pair creation products are tracked in a stack of Silicon strip detectors and the secondary particles are stopped in the CsI calorimeter.*

The prototype's tracker consists of eleven layers of double-sided Si-strip detectors (3 x 3 wafers of 6 cm x 6 cm, 500 $\mu$m thick, with a pitch of 470 $\mu$m). Roughly one third of the lower hemisphere is covered by a calorimeter made of CsI crystals (5 mm x 5 mm cross section) with lengths of 2 cm (upper side), 4 cm (lower side) and 8 cm (bottom).

In April/May 2003 the prototype was calibrated at the High Intensity Gamma Source HIGS (Litvinenko et al., 1995) at Duke University (Durham, North Carolina). The calibration used monoenergetic (dE/E < 2%) and 100% linearly polarized pencil beams at different energies (0.7 MeV, 2 MeV, 5 MeV, 8 MeV, 10 MeV, 12 MeV, 17 MeV, 25 MeV, 37 MeV and 49 MeV) and different incident angles (0°, 30°, 60°, 80°, 120°, 180°). The polarization of the beam was fixed to horizontal alignment. Therefore, this beam is well suited to determine the polarization response of the MEGA prototype.

For a detailed description of the prototype and its calibration see Andritschke et al. (2004).

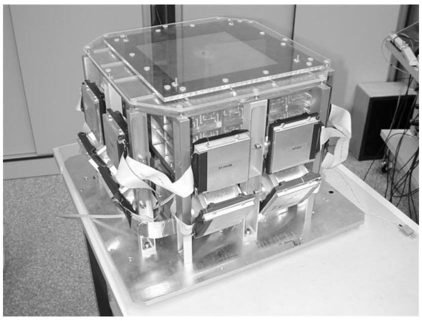

*Figure 2. MEGA prototype: The tracker (central box) is surrounded by 20 calorimeters*

## 2. COMPTON POLARIMETRY OVERVIEW

Most processes in high energy astrophysics, such as synchrotron radiation, bremsstrahlung, Compton scattering, etc., generate polarized gamma-rays. But all past and present gamma-ray telescopes have only limited capabilities to detect polarization. The next generation of Compton telescopes, like MEGA, can detect gamma-rays under large scatter angles and down to a few hundred keV. They are ideally suited to detect polarization in the Compton regime. Thus, these telescopes can be of great value to understand the emission mechanisms of different astrophysical sources of gamma-rays.

Compton scattering preserves the polarization information of linearly polarized photons up to a certain degree. Depending on scatter angle and total energy the distribution of the scattered photons follows the differential cross section for unbound Compton scattering:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E_g}{E_i}\right)^2\left(\frac{E_g}{E_i} + \frac{E_i}{E_g} - 2\sin^2\varphi\cos^2\chi\right) \quad (1)$$

Here $r_e$ is the classical electron radius, $E_i$ is the energy of the initial and $E_g$ the energy of the scattered gamma-ray. $\varphi$ is the Compton scatter angle and $\chi$ is the azimuthal scatter angle.

Three important, qualitative facts describe this polarization dependence:

- The scattered photons tend to scatter at right angles to the original polarization vector, where the factor $-2\sin^2\varphi\cos^2\chi$ is smallest.
- At higher energies and therefor lower average Compton scatter angles, the modulation of the azimuthal distribution is reduced.
- For small and very large Compton scatter angles $\varphi$ the detectable polarization signature is weak ($\sin^2\varphi$ is close to zero).

The polarization signature of the incident photons is visible in the distribution of the azimuthal scatter angle $\chi$, which is shaped like a cosine: $P(\chi) = P_0 + A\cos(2(\chi - \chi_0 + \pi/2))$. Here $\chi_0$ is the direction of the original polarization vector.

A quality factor $\mu$ (also called modulation) for the polarization response of a detector is the ratio between the amplitude $A$ and the offset $P_0$ of the azimuthal scatter angle distribution. For a 100% linearly polarized beam of gamma-rays, it is given by the following equation:

$$\mu = \frac{A}{P_0} \quad (2)$$

The modulation as a function of incidence energy $E_i$ and scatter angle $\varphi$ is shown in Fig. 3. The maximum of the modulation shifts from $\varphi = 90°$ for low energies to $\varphi = 54°$ at 5 MeV.

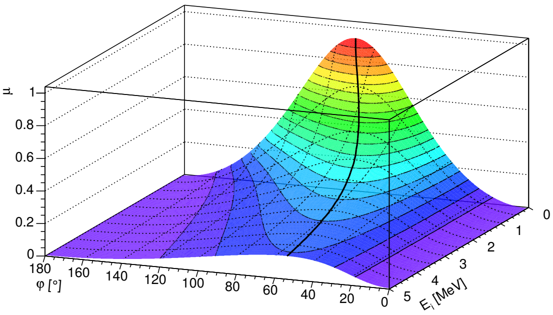

*Figure 3. Modulation as a function of incidence energy $E_i$ and Compton scatter angle $\varphi$ as derived from the Klein-Nishina cross section. The thick black line indicates the maximum of modulation for a fixed initial gamma-ray energy. The thin lines indicate levels of the same modulation, the dotted lines are the grid. Each real polarimeter aims at getting as close as possible to this ideal values.*

For a deeper insight in the basic principles of Compton polarimetry refer to Lei et al. (1997).

## 3. DATA CORRECTION

To retrieve the polarization signal out of the azimuthal scatter angle distribution, one has firstly to identify the event (see Zoglauer et al. (2004) for event reconstruction) and secondly to correct for detector efficiency, detector geometry and background.

In the ideal case one would make one measurement with 100% polarization and one without polarization, which can then be used to correct for efficiency and geometry. Nevertheless, due to the production process of the gamma-rays (100% polarized IR or UV photons are Compton back-scattered), it was not possible to turn off the polarization. Other simple correction techniques, like rotating the detector or the polarization vector to smear out those systematics, were not possible either.

In addition, lab measurements alone were not well suited to correct the data either: (1) Strongly varying detector efficiencies between the measurements in the lab and in HIGS, (2) problems correcting far-field (HIGS) with near-field lab measurements and (3) substituting radioactive sources for the 'no-polarization' measurement with close but not identical energies (e.g. 662 keV of $^{137}Cs$ vs. 710 keV) circumvent a good data correction.

As a consequence, a different approach had to be chosen: Firstly, the most disturbing problem is caused by time varying detector efficiencies in the calorimeters. These originate mainly from the time varying trigger and read-out thresholds between the different detectors (average: 150-250 keV). To overcome this problem, only those events were selected which have at least a deposit of 300 keV in one single crystal. But as a negative side effect, this selection leads to a restriction to smaller scatter angles and thus the detected polarization signature decreases. After this selection all remaining differences are expected to be time invariant, like defective pixels or the coupling between crystals and PIN-diodes. So the remaining efficiency correction can be done with previous lab measurements.

Secondly, the greatest influence on the azimuthal shape is due to the geometry. At low energies the holes between individual calorimeter modules are visible in the azimuthal scatter angle distribution. At higher energies the four edges of the bottom calorimeter are visible. Since no suitable measurement was available, the geometry was taken from simulations.

The background does not need a correction since it can be easily suppressed by data cuts: Firstly, selecting only events from the known path of the very focused beam eliminates practically all of the room background (especially the 1.461 MeV line of $^{40}$K). Secondly, incompletely absorbed events and chance coincidences are eliminated (1) by the event reconstruction, (2) by selecting only events originating from the known source position and (3) by using only events with the correct energy.

Thus the final correction applied to the data was:

$$P_{corr}(\chi) = \frac{P_{meas}(\chi)}{P_{geo}(\chi) P_{eff}(\chi, \varphi, detector)} \tag{3}$$

## 4. POLARIZATION RESPONSE

As seen from Fig. 3, the polarization response of a Compton telescope has two main dependencies which have to be reproduced by the MEGA measurements: As a function of energy the modulation has to increase with lower energies and as a function of Compton scatter angles it has to reach its maximum at medium scatter angles (below 90°, depending on energy).

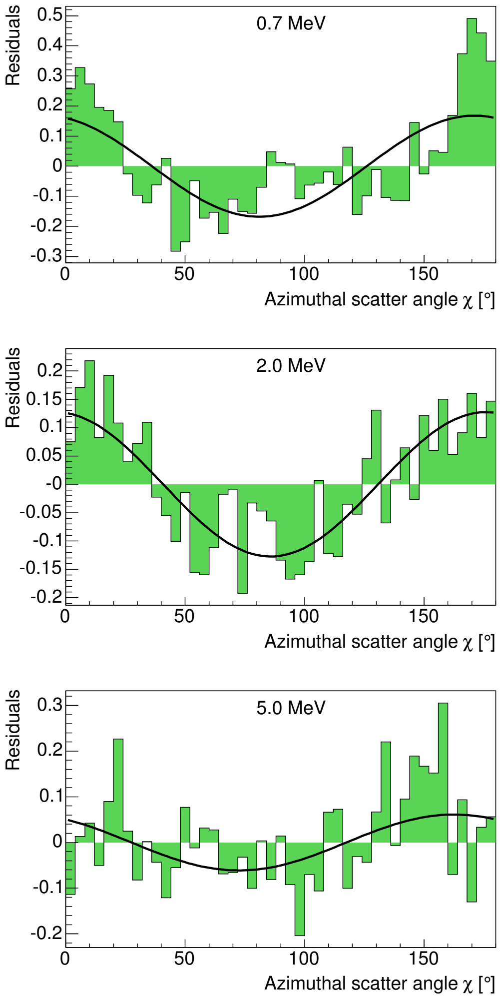

*Figure 4. Polarization response as a function of energy: The black line indicates the best fit with a cosine. The origin of the scatter angle x-axis corresponds to the vertical direction as MEGA is mounted at HIGS.*

The measured energy dependence can be seen in Fig. 4. If no Compton scatter angle selections were applied, the modulation decreases from 0.17 ± 0.04 at 0.71 MeV to 0.12±0.03 at 2 MeV down to 0.06±0.03 at 5 MeV. At 8 MeV no significant modulation was seen. All measurements have been compared to Geant4 simulations (version 6.0). The simulations take into account a detailed detector description, realistic measurement errors, chance coincidences, read-out limitations, etc. Within the errors all measurements are in good agreement with the simulations.

In particular at 710 keV the retrieved modulation signal is dominated by the event selections and the limitations of the detector: Firstly, at large scatter angles, where most of the polarization information is preserved, but only a little energy is deposited, not correctable non-linearities in the energy measurement of the calorimeter lead to an underestimation of the measured energy of weak signals. Secondly, the average deposited energy per D2 crystal is normally between 250 and 300 keV, which is very close to the time-varying trigger thresholds. And thirdly, only ∼90% of the detector voxels were working. As a result, most of these events are not measured or they lack energy and cannot be imaged into the point source and are therefore not selected for the polarization calculation. Accordingly, the statistics as well as the polarization signal are diminished.

On the other side, since the source signal dominates the background and since only one source is present, it is also possible for these measurements to do a polarization calculation without the necessity of imaging the event into the source location and without restricting the energy. With this method the polarization is determined only geometrically by the two interaction positions. Only an upper energy cut has to be applied to suppress room background from the concrete walls ($^{40}$K).

This results in a modulation of 0.30±0.08 at 710 keV, which is almost a factor 2 higher than the analysis with the initial event selections, but suffers from a much higher measurement uncertainty. For higher energies, there is almost no difference between these two event selections.

The polarization vector of the HIGS beam was horizontally aligned in the room and therefore the maxima of the measured modulation are expected perpendicular to this direction. Thus the minima, which correspond to the polarization angle, have to be found at 90° in Fig. 4. The measured values, 82°±24° at 0.7 MeV, 86°±11° at 2 MeV and 74°±18° at 5 MeV, all differ slightly from the expected value. While the values at 2 MeV are in good agreement, the largest difference at 5 MeV can be explained by the weak polarization signal and the poor statistics. At 0.71 MeV the deviation is mainly due to varying detector efficiencies. Nevertheless, all values are within the measurement errors.

The modulation as a function of the Compton scatter angle can be found in Fig. 5 for the 2 MeV measurement. As expected, the modulation reaches its maximum around 66° and the measurement is in good agreement with the simulations.

## 5. CONCLUSIONS

The MEGA prototype shows that the MEGA satellite will be a perfect polarimeter in the Compton regime. Especially the well-shaped geometry of MEGA allows it to detect Compton events under large scatter angles, which carry most of the polarization information. Furthermore, an envisioned MEGA satellite telescope will be able to measure photons down to ∼400 keV, where most of the polarization information of the original photons is preserved. While MEGA will not be able to distinguish those low energy photons from background in normal operation mode, for special sources like bursts or flares, the polarization properties can be easily determined, because they are short and strong events, where the origin is easily recoverable and thus the background does not play a dominating role.

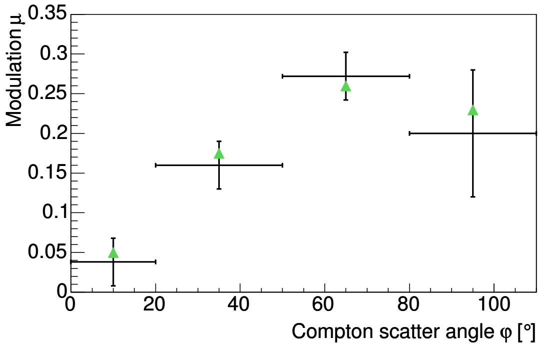

*Figure 5. Dependence of modulation on the Compton scatter angle for 2 MeV photons. The triangles represent the values from Geant4 simulations, which are in good agreement with the measurements. The maximum is reached as expected around 66°. At 95°, the poor statistics leads to a larger measurement error.*

The properties of MEGA (which of course are also present in most other envisioned Advanced Compton Telescopes) will add a new dimension to gamma-ray astronomy – polarization.

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## REFERENCES

Andritschke R. et al., 2004, *Calibration of the MEGA prototype*, these proceedings

Kanbach G. et al., 2003, *Concept study for the next generation medium-energy gamma-ray astronomy mission – MEGA*, Proc. SPIE 4851, 1209-1220

Lei F. et al., 1997, *Compton scatter polarimetry in gamma-ray astronomy*, Space Sci. Rev., 82, 309-388

Litvinenko V. et al., 1995, *High power Inverse Compton $\gamma$-ray Source at the Duke storage ring*, SPIE 2521, 55-77

Zoglauer A. et al., 2004, *Data analysis for the MEGA prototype*, NewAR 48, 231-235