Imaging Properties of the MEGA Prototype

Andreas Zoglauer, Robert Andritschke, Peter Bloser, Gottfried Kanbach

***Abstract*— The tracking Medium Energy Gamma-ray Astronomy telescope MEGA, which can detect gamma-rays via Compton scattering and pair creation, has been calibrated with lab sources (511 keV up to 1836 keV) from January to March 2003 and during April/May 2003 at the High Intensity Gamma Source (HIγS) at Duke University (Durham, North Carolina). The latter calibration was performed with monoenergetic (dE/E $<$ 2%) and 100% polarized pencil beams in the energy range from 710 keV up to 48.9 MeV for different incident angles (0°, 30°, 60°, 80°, 120°, 180°). This paper describes preliminary results of the imaging properties of the telescope, including angular resolution, point source location accuracy, field of view, and polarization detection. Laboratory measurements of extended sources as well as of multiple sources in the near-field of the telescope are also presented.**

***Index Terms*— gamma-ray astronomy, telescopes, imaging**

I. INTRODUCTION

THE tracking Medium Energy Gamma-ray Astronomy telescope MEGA has been developed at the Max-Planck-Institute for extraterrestrial Physics (Garching, Germany) as a successor of the telescopes COMPTEL [1] and EGRET [2] (lower energies only). Thus, the MEGA telescope 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. 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 is 12-times smaller than the satellite version under study. Its tracker consists of eleven layers of double-sided Si-strip detectors (3 x 3 wafers of 6 cm x 6 cm, 500 μm thick, with a pitch of 470 μm). The lower hemisphere is surrounded by a calorimeter made of CsI crystals (5 mm x 5 mm cross section) with lengths of 2 cm, 4 cm (side) and 8 cm (bottom). A more detailed description can be found in [3].

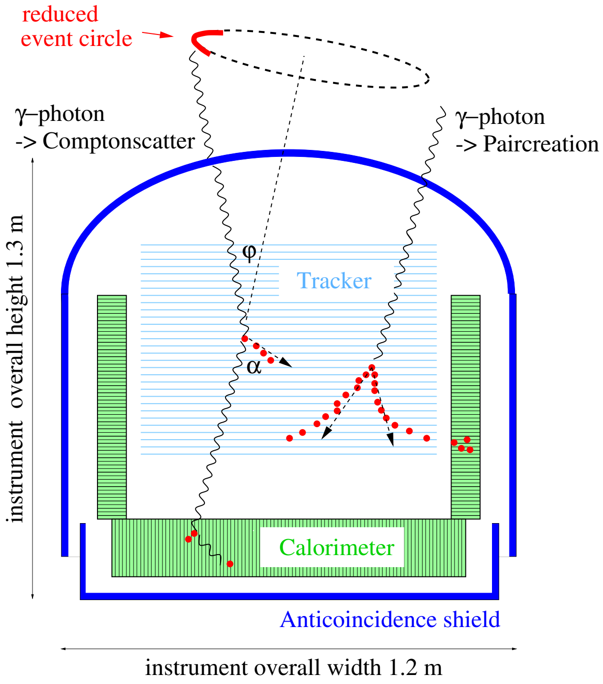

Fig. 1. Baseline design and measurement principle of the full MEGA telescope. The recoil electron of Compton scattering as well as the pair creation products are tracked in a stack of Silicon strip detectors and the secondary particles are stopped in the CsI calorimeter.

From January to March 2003 the prototype was calibrated with laboratory sources (^{22}Na, ^{137}Cs, ^{88}Y) in the near-field, and in April/Mai 2003 it was calibrated at the High Intensity Gamma Source HIγS [4] at Duke University (Durham, North Carolina) in the far-field. The latter calibration used monoenergetic (dE/E $<$ 2%) and 100% 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°). Based on these data, preliminary imaging properties of the telescope have been determined.

The image reconstruction itself is done with an unbinned maximum-likelihood method called list-mode maximum-

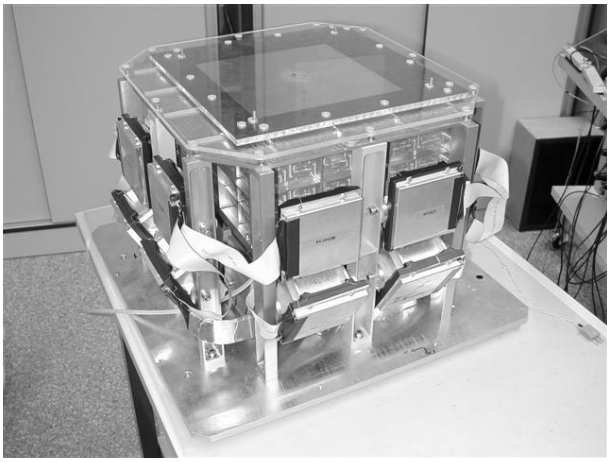

Fig. 2. MEGA prototype: the tracker (central box) is surrounded by 20 calorimeters

A. Zoglauer, R. Andritschke and G. Kanbach are at the Max-Planck-Institut für extraterrestrische Physik, Garching, Germany and P. Bloser is at the NASA/GSFC, Greenbelt, MD, USA.

likelihood expectation maximization, which originally was developed for medical imaging of a SPECT camera [5] and later it was adapted for its use in astrophysics [6]. This method allows the incorporation of different event types (tracked and untracked Compton events as well as pair events) into one image while preserving all measured information.

II. THE COMPTON REGIME

A. *Response*

Ideally, a tracking Compton telescope should measure all parameters to directly calculate the origin of the incoming photon: direction and energy of the scattered photon as well as direction and energy of the recoil electron. Below 2 MeV the energy of the electron is in most cases not sufficient to generate a track in MEGA. For these events the origin of the photon can only be restricted to the classical cone section, which is represented by circles in the far-field and ellipses/hyperbolas in the near-field. Both lead to a large ambiguity of the origin of these photons. The width of this cone section is mainly determined by the energy measurement. On the other hand, even with the knowledge of the electron direction, the origin cannot be restricted to a single point: Molière (small-angle) scattering in the Silicon results in a large uncertainty in the direction of the electron track. The good knowledge of the cone section, determined by the measured energies, in combination with the electron track, restrict the possible origins of the photon to short arcs of the cone section, as seen in Fig. 3.

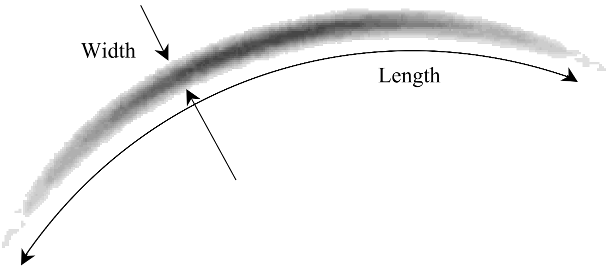

Fig. 3. The possible origins of tracked gamma-rays are restricted to an arc: The cone angle φ is determined by the Compton equation, the width is determined by the energy measurement and the length by the Molière scattering of the recoil electron.

B. *Angular resolution*

One method of measuring the width of the response and therefore the angular resolution is the Angular Resolution Measure (ARM). It is defined as the difference between the real and the measured Compton scatter angle. An example is given in Fig. 4. This distribution contains tracked as well as untracked events at 2.0 ± 0.2 MeV and has a FWHM of 7.4°. If only untracked events are considered, then the shape gets narrower (6.2°), whereas tracked events lead to a much broader ARM (13.4°). This behavior is expected, since tracked events suffer especially strongly from the limited energy resolution in the calorimeters: On the one hand tracks are only generated if sufficient energy is transfered to the electron. This results in lower energy deposits in the calorimeter and therefore a higher relative energy measurement error for the scattered gamma-ray. On the other hand, the measurement error, which plays the most important role for determining the error in the Compton scatter angle φ for large scatter angles, is the energy measurement error of the scattered gamma-ray. With the current and still preliminary energy resolution, which ranges for example in the 8 cm bottom calorimeters from $\frac{\Delta E}{E} = 0.15$ to 0.22 at 662 keV, the angular resolution for tracked events is far away from the physical limit, which is given by Doppler-broadening. At 2 MeV Doppler-broadening would lead to an average width of ~0.2° in Silicon [8]. Therefore having a calorimeter with an excellent energy resolution is crucial for the performance of a tracking Compton telescope.

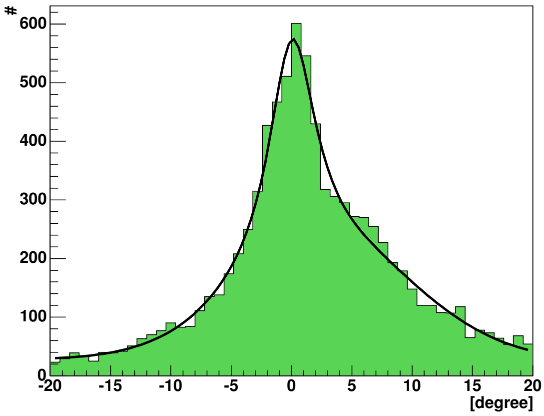

Fig. 4. ARM distribution at 2 MeV with a FWHM of ~7.4°. It contains tracked and untracked events in the energy range from 1.8 to 2.2 MeV.

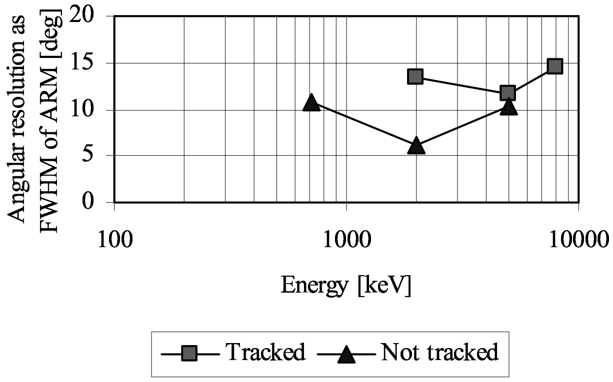

Fig. 5. Angular resolution of Compton events as a function of energy.

The angular resolution as a function of the energy (Fig. 5) at lower energies is mainly determined by the measurement error of the energy. Going from lower to higher energies, the performance first improves and then deteriorates again, since incomplete absorptions start to dominate: The scattered photons leak and the electrons are no longer stopped in the tracker. Nevertheless, incomplete absorption will be much less pronounced in the larger satellite geometry with its more compact calorimeter.

C. Direction of electron tracks

The most important characteristics of a tracking Compton telescope is the electron track. Fig. 6 shows a distribution of the difference between the real and measured electron direction as a projection on the event circle. The measurement was performed with ^{88}Y, where only tracked events in a 10% interval around the 1.8 MeV line were selected. The HWHM of the distribution is with ~42° close to the physical limit, which is determined by Molière scattering. More than 85% of all tracks can be reconstructed correctly.

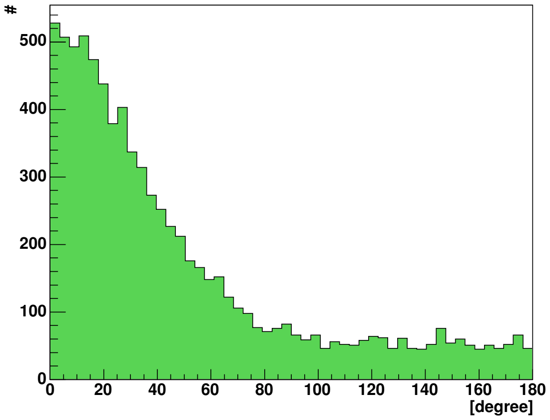

Fig. 6. Distribution of the difference between the real and measured electron direction in a projection on the event circle.

D. Polarization

Most processes in high-energy astrophysics can generate polarized gamma radiation (e.g. synchrotron radiation, bremsstrahlung, Compton scattering, etc.). Therefore, polarization measurements are of great value to understand the emission mechanisms of gamma-rays. Since the Compton cross section is polarization-dependent and this dependence is most prominent for large Compton scatter angles, MEGA with its geometry (see Fig. 1) is well-suited to detect polarization.

Fig. 7 shows such a polarization signal. The measurement was performed with 100% polarized gamma-rays at an energy of 710 keV at HIγS. Due to the production process of the gamma-rays, it was impossible to “turn off” the polarization, in order to retrieve the detector response to unpolarized gamma-rays, which is needed for a geometry correction. Thus, a data set from the preceeding lab measurements was taken, with a ^{137}Cs source (662 keV), which was located one meter above the detector. Geant4 [7] simulations show, that the geometry correction between a parallel beam of 710 keV photons and a divergent beam of 662 keV photons at a distance of one meter differs only by 2.0% for the applied event selections.

The calibration beam had a rather low flux at 710 keV and the average trigger rate was only 20 counts per second. This results in low statistics, but has the advantage that it leads to almost the same signal (S) to background (B) rate in the energy range below 1 MeV, as we had in the geometry measurement with ^{137}Cs, namely $S/B \approx 5$.

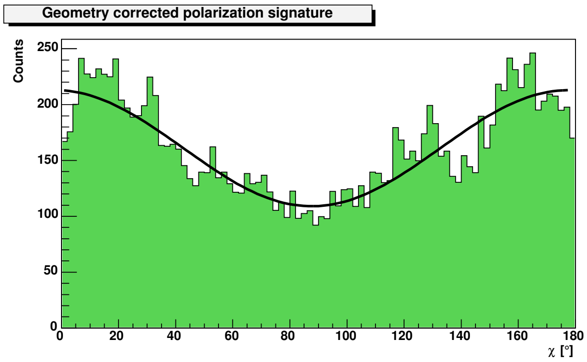

Fig. 7. Geometry corrected event distribution of the azimuthal scatter angle χ: The modulation of the form $\mu(\chi) = a\cos(2(\chi + \chi_0)) + b$ indicates the polarization of the incoming gamma-rays.

To avoid any problems with low statistics, the only event selection was an upper energy cut at 1.2 times the expected energy – smaller measured energies are mainly incomplete absorptions, which do not harm the polarization signal, since only the positions of the first and second Compton interaction are necessary to derive the azimuthal scatter angle distribution.

The modulation factor μ, which gives the degree of polarization, is defined as

$$\mu = \frac{N_{max} - N_{min}}{N_{max} + N_{min}} \quad (1)$$

where N_{max} and N_{min} are the number of counts at the maximum and the minimum of the azimuthal distribution. From the 100% polarized beam of the Duke measurement this modulation factor was determined as $\mu_{100} = 0.31 \pm 0.03$ (Fig. 7). The large error is induced by the low statistics and not yet corrected time-varying detector responses. An additional correction for the slightly incorrect geometry measurement would lead to a modulation of $\mu_{100}^{corr} = 0.30 \pm 0.03$. Geant4 simulations result in a modulation of $\mu_{100}^{sim} = 0.304$, which is in very good agreement with the measurements.

Considering the beam setup and the fact that Compton scattering happens preferentially perpendicular to the polarization vector, the expected maximum of the polarization distribution is at 0°, whereas the measured is $\chi_0 = (-4.6 \pm 2.1)°$.

Additional measurements at 2 MeV, which have even less statistics, show a modulation of $\mu_{100}^{corr} = 0.13 \pm 0.04$, which is also in agreement with the simulations.

E. Multiple sources

In a realistic astrophysical environment a telescope has to detect multiple sources at the same time. Therefore, a measurement with five sources of different energies, different intensities and at different positions in the field of view of MEGA has been performed. The positions relative to the detector as well as the reconstructed near-field images are shown in Fig. 8. All five

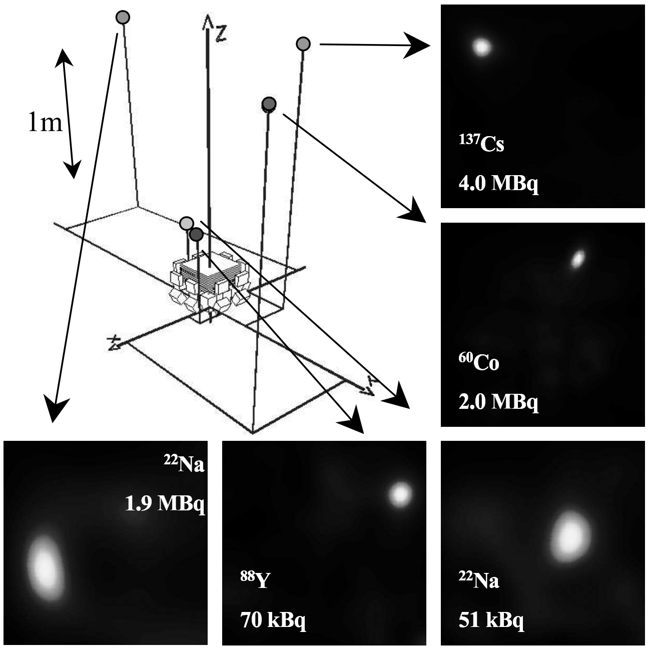

Fig. 8. Multiple sources in the near-field of MEGA. All images are reconstructed with a ±10% energy cut around the true energy. Since only vertical and horizontal planes have been used in this near-field reconstruction, some sources appear non-circular.

sources have been reconstructed at the correct positions. This measurement proves that MEGA is well-suited for measuring multiple sources.

F. Extended sources

For MEGA it is necessary to resolve extended sources like supernova remnants or OB-associations. This ability can be demonstrated by a measurement, where two ^{88}Y sources have been mounted on a rotating propeller located 27 cm above the center of the tracker. The reconstructed image can be found in Fig. 9. The propeller performed a circle with radius 7 cm, which corresponds to a diameter of ~29° at infinity. The image contains ~138000 Compton events in the energy range from 0.8 to 1.0 MeV. The minor irregularities on the circle result from the assumption that all detectors have the same efficiency.

III. THE PAIR REGIME

In Silicon the transition from Compton scattering to pair creation takes place around ~8 MeV.

A. Angular resolution

The angular resolution of pair events is dominated by the unknown recoil of the nucleus and Molière scattering in the Silicon layer of the first hit. The influence of both effects reduces with increasing photon energy. The angular resolution, given as the half-angle of a cone, which contains 68% of all events, can be found in Fig. 10. At 49 MeV it is roughly a factor two better than in the EGRET telescopes and it will also exceed the expected performance of GLAST and AGILE, since all those telescopes contain converter foils, which increase the angular dispersion due to Molière scattering.

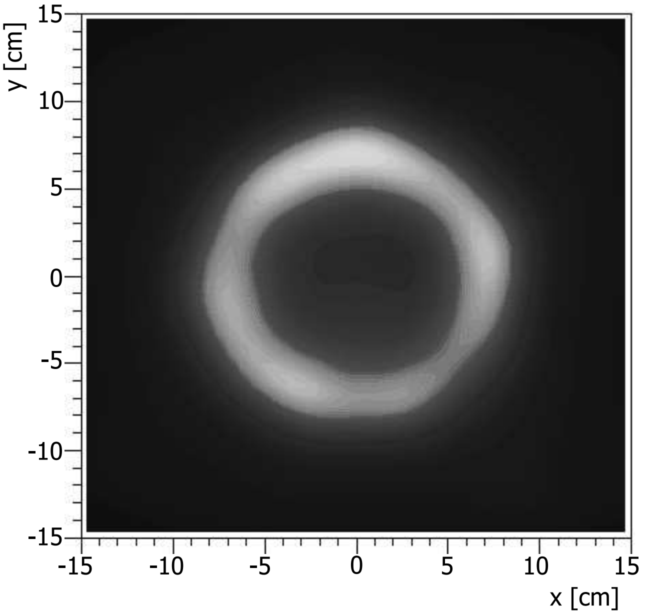

Fig. 9. Extended source generated by ^{88}Y rotating on a propeller 27 cm above the center of the tracker.

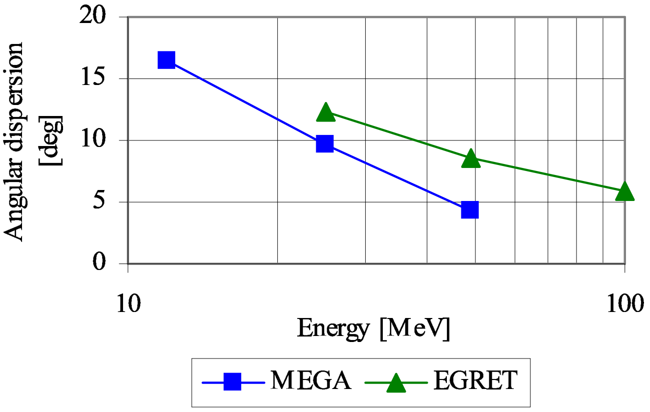

Fig. 10. Comparison of the angular resolution of MEGA and EGRET: At 49 MeV MEGA is a factor of two better than EGRET.

B. Field of view

Fig. 11 contains reconstructed images at incidence angles from 0° to 80° at 49 MeV. This demonstrates the large field of view of the camera. At 80° the longer path of the electrons in the layer of the first hit broadens the response. In addition, simulations show, that electrons, which move almost horizontally through the layer, have a larger probability to be stopped or to exit the layer in a more vertical angle than the incident angle. In the reconstructed images this leads to a reconstruction of the sources too close to the instrument axis as seen in Fig. 11 at 80° ("fish-eye" effect). Fig. 12 gives the

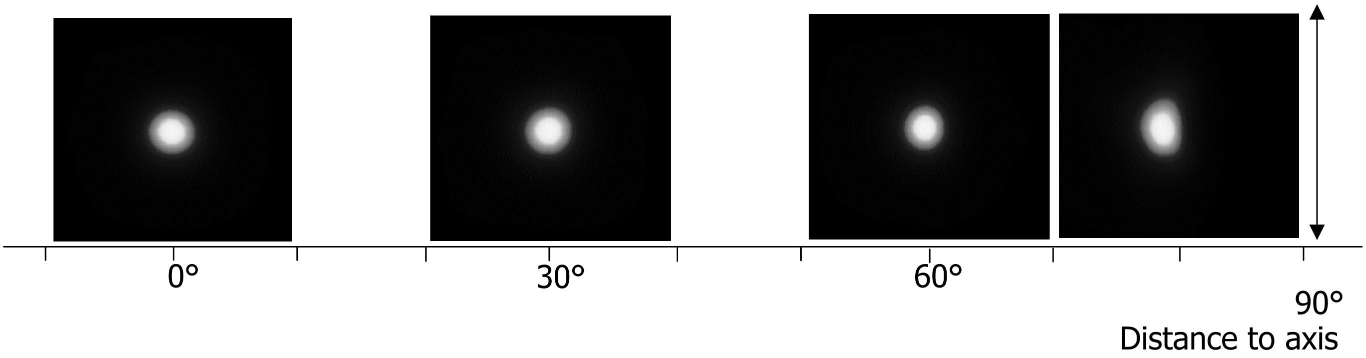

Fig. 11. Reconstructed beam images at 49 MeV: Up to 60° all point sources are reconstructed at the correct position. Only for very inclined incidences a deviation is visible.

numbers for this location accuracy, which is for low incidence angles near the alignment accuracy ($\sim 0.05°$) and is then tilted slightly towards the axis.

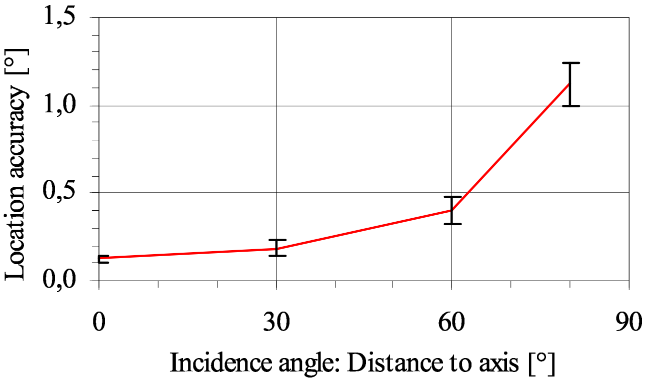

Fig. 12. Location accuracy for pair events. About 25000 events are used at each position.

IV. CONCLUSION

With this preliminary data analysis, it has been proven that the MEGA technique of detecting gamma-rays works for a large energy range (from 500 keV up to 49 MeV and more) and in a extremely wide field of view (up to 80°). It has been proven that MEGA can detect polarization up to at least 2 MeV, and that in the pair regime the telescope has an excellent angular resolution. The only exception is the angular resolution in the Compton regime, which is dominated by the poor energy resolution in the calorimeters. Nevertheless, an improved version of the calorimeter is under development, which is based on drift-diodes. That will result in a better energy resolution (at least a factor of two to three) and lower thresholds (at least a factor of three). Simulations show that with the usage of drift-diodes in combination with the larger satellite geometry, which has a more compact calorimeter, the desired angular resolution for tracked events of $\sim 2°$ at 2 MeV is achievable.

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