Evaluation of Timepix3 for applications as Compton scatter polarimeter in the hard X-ray and soft gamma-ray band

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1. The detector – Timepix3

- Timepix3 is a hybrid pixel detector, 256×256 pixels, pixel pitch 55 µm
- It records **simultaneously** time of arrival (ToA) and time over threshold (ToT)
- Timepix3 allows for **3D track reconstruction** of MIP particles using the time projection chamber principle [1]

2. X-ray polarimetry – Motivation

- X-ray polarimetry opens **a new window** in study of the most extreme environments in Universe, such as neutron stars, accretion discs or gamma ray bursts
- X-ray polarimetry could probe anisotropies in astrophysical sources, such as ordered magnetic fields, anisotropic matter distribution, black hole spin effects [2] or could detect effects of vacuum birefringence in high magnetic fields [3]

3. Compton X-ray polarimetry – How?

- Detection of ensuing **Compton scattering and photoemission** by one photon
- Polarized photons scatter anisotropically with modulation in azimuth

$$f(\varphi) \propto 1 + \mu \cos[2(\varphi - \varphi_0)]$$

where **modulation factor** μ is directly proportional to degree of polarization and φ_0 is at 90° to the polarization plane (experiment results in fig. 3)

4. Simulation

- Simulation of monoenergetic X-ray beams hitting 1 mm thick silicon sensor (fig. 1)
- **Geant4** (energy deposition), **Allpix-2** (charge propagation) and custom **C++ software** (signal processing in Timepix3)

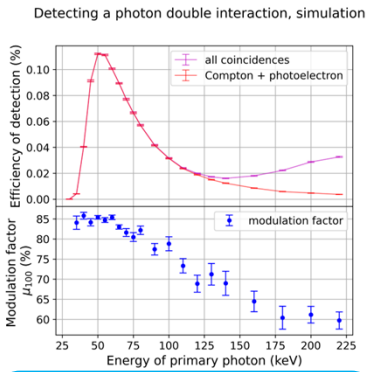

Figure 1 Simulation of monoenergetic X-ray beams. Efficiency of coincidence detection (top) and μ_{100} modulation factor created by 100% linearly polarized X-rays (bottom).

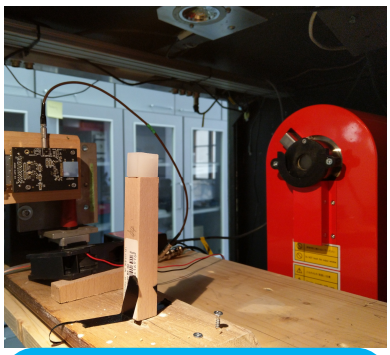

Figure 2 Experiment setup photo. X-ray tube (right, red colour) shone X-rays on a polyethylene target (centre, white cube) where they scattered and were detected by Timepix3 detector (left, behind the plastic target).

5. Experiment

- X-rays from an X-ray tube scatter in a PE target and then they are detected by Timepix3 with 1 mm thick silicon sensor at 90° scattering angle (fig. 2)
- **The scattered radiation is partially polarized** (fig. 3)

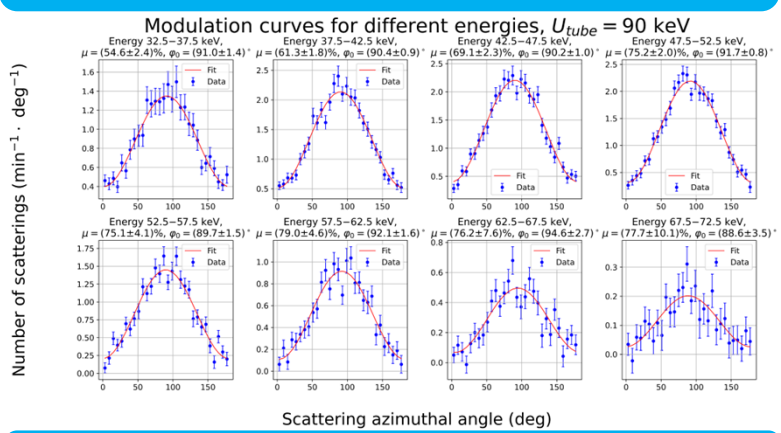

Figure 3 Modulation curves of the scattered radiation in energy range 32.5-72.5 keV. Modulation factor μ goes up to almost 80 %.

6. Predicted sensitivity to Crab nebula polarization

- Assuming Timepix3 with 1 mm thick silicon sensor in a focal plane of NuSTAR X-ray mirror [4] (reflective up to 79 keV)
- Assuming **zero background rate** ($R_{\mathrm{bcg}} = 0$)
- **Minimum detectable polarization** (MDP) in measurement of duration T (fig. 4)

$$\mathrm{MDP}_{99\,\%} = \frac{4.29}{\mu_{100} R_{\mathrm{src}}} \sqrt{\frac{R_{\mathrm{src}} + R_{\mathrm{bcg}}}{T}}$$

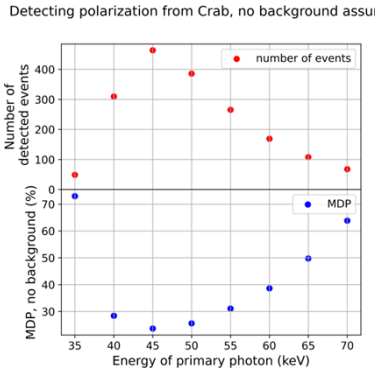

Figure 4 Predicted sensitivity to Crab nebula polarization assuming no background in the detector. Top plot shows the number of Compton scattering + photoemission events detected in various energy bins (bin width ±2.5 keV) after 300 ks measurement whereas the bottom plot shows MDP.

7. Compton camera

- Imaging of X-ray and γ-ray sources
- Applications in astronomy, medicine and environment monitoring [5]
- From 3D positions and energies of Compton scattering and photoemission, we can construct **surface of a cone** where the photon **must have come from**
- Intersection of multiple cones can tell the **position of the source** (fig. 5)

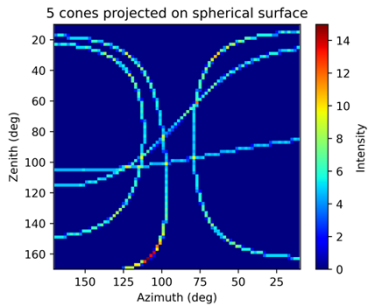

Figure 5 Multiple cones projected on a spherical surface in front of the detector.

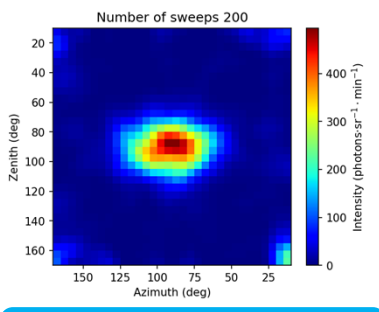

Figure 6 Compton image after 200 OE-RR sweeps, 14184 photons.

8. OE-RR method of Compton camera imaging

- Origins ensemble with resolution recovery (OE-RR) [6] **takes into account uncertainties** of the cone parameters (fig. 6)
- It is a Monte Carlo Markov chain method that tries to update photon positions one by one and either accepts or rejects the move based on likelihood function

9. Conclusions

- Timepix3 as a Compton polarimeter offers **high modulation factor** – up to ~80 % in experiment with highly polarized X-rays (fig. 3) and predicted up ~85 % for 100% polarized X-rays in simulation (fig. 1)
- Silicon Timepix3 in focal plane of NuSTAR X-ray mirror could do **energy-sensitive polarimetry** in range ~32.5-72.5 keV; MDP 24 % in 42.5-47.5 keV range, 300 ks measurement of Crab nebula assuming no background (fig. 4)
- The same dataset from the experiment was used for **Compton camera imaging** (fig. 6) with standard deviation of the image "blob" 13-18°

References

[1] Bergmann, B. et al. *3D track reconstruction capability of a silicon hybrid active pixel detector*, The Eur. Phys. Jour. C (2017)
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[3] Soffitta, P. *The Imaging X-ray Polarimetry Explorer (IXPE) and New Directions for the Future*, Instruments (2024)
[4] Harrison, F. A. et al. *The Nuclear Spectroscopic Telescope Array (NuSTAR) high-energy X-ray mission*, The Astrophys. Jour. (2023)
[5] Parajuli, R. K. et al. *Development and Applications of Compton Camera – A Review*, Sensors (2022)
[6] Andreyev, A et al. *Resolution recovery for Compton camera using origin ensemble algorithm*, Med. Phys (2016)