Design and Tests of the Hard X-ray Polarimeter X-Calibur

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Abstract

X-ray polarimetry promises to give qualitatively new information about high-energy sources, such as binary black hole (BH) systems, Microquasars, active galactic nuclei (AGN), GRBs, etc. We designed, built and tested a hard X-ray polarimeter ***'X-Calibur'*** to be used in the focal plane of the InFOCuS grazing incidence hard X-ray telescope. X-Calibur combines a low-Z Compton scatterer with a CZT detector assembly to measure the polarization of 10-80 keV X-rays making use of the fact that polarized photons Compton scatter preferentially perpendicular to the electric field orientation. X-Calibur achieves a high detection efficiency of order unity.

Scientific motivation

Scientific potential of spectro-polarimetric hard X-ray observations:

- Constrain BH masses & spins and the inclination of binary BH systems (Fig.1, left).
- Constrain orientation of inner accretion disk and corona geometry (Fig.1, right).
- Study particle acceleration processes in pulsars, pulsar wind nebulae, and magnetars.
- Reveal magnetic structure of relativistic jets from AGN & GRBs.
- Test Lorentz invariance with unprecedented accuracy (probing helicity dependence of speed of light).

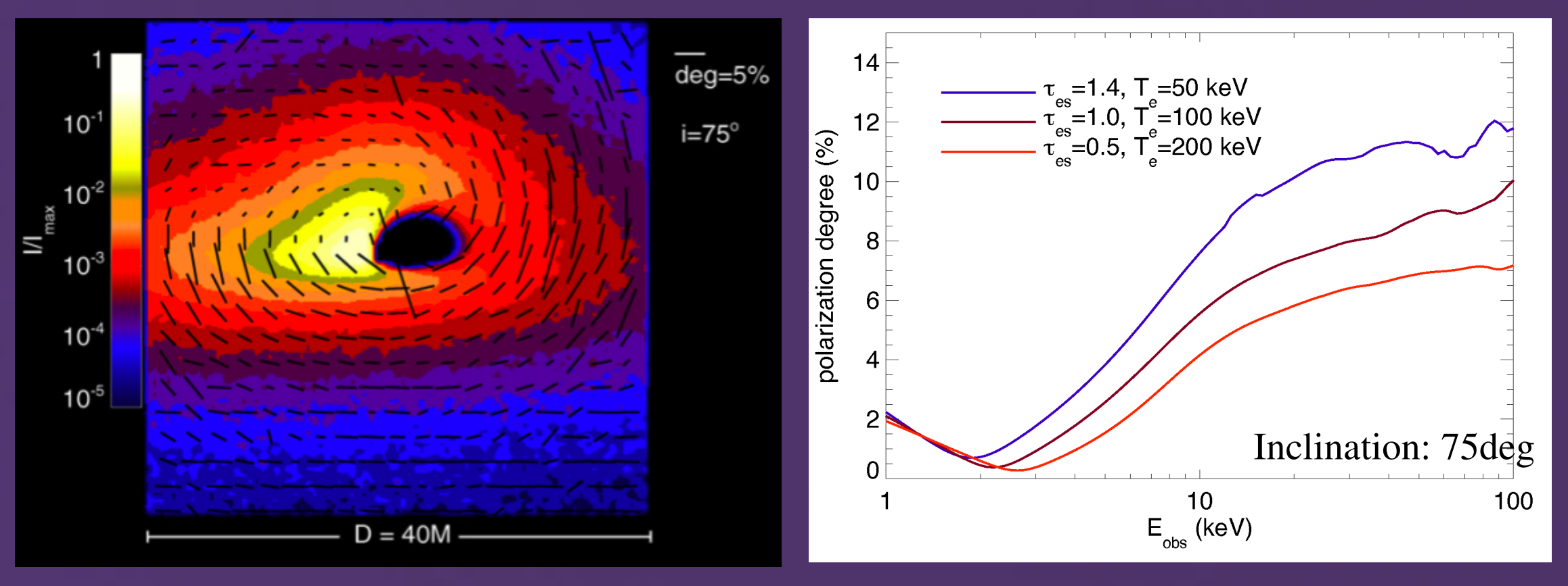


Fig. 1: *Left: Simulated image of a mass accreting BH (from [3]). The color scale shows the emitted intensity and the bars show the orientation of the electric field vector of the emitted radiation. Right: Energy-dependent polarization degree for a 10 solar mass BH sandwich corona (varying optical depth τ_{es} and electron temperature T_e [3]).*

Addressing these science goals requires spectro-polarimetric observations over a broad energy range.

Technical Design

The conceptual design of the X-Calibur polarimeter is illustrated in Figure 2: A low-Z scintillator is used as Compton-scatterer. The scattered X-rays are photo-absorbed in the surrounding high-Z CZT crystal rings. Linearly polarized X-rays will preferably scatter perpendicular to their E field vector – resulting in a signature in the azimuthal event distribution.

The detector assembly (scintillator rod, CZT detectors, and ASIC readout electronics) is shown in Figure 3. The scintillator is read out by a PMT allowing to select scintillator/CZT events (Compton candidates). An azimuthal rotation mechanism of the assembly reduces systematic effects.

The X-Calibur polarimeter will be situated in the focal plane of the InFOCuS X-ray telescope (Fig. 4). A Wolter mirror focuses the X-rays onto the polarimeter aligned with the optical axis. The advantages of the design:

(1) High detection efficiency
(2) Low background
(3) Minimization and control of systematics

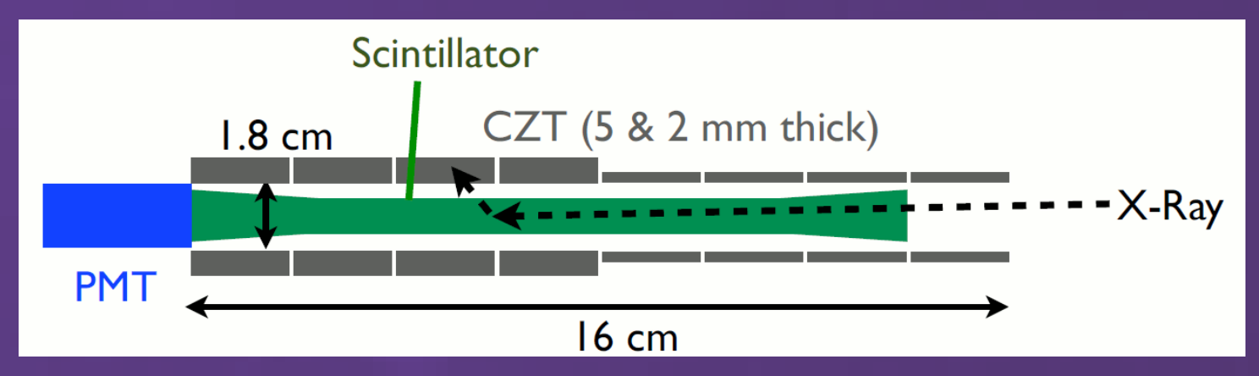


Fig. 2: *Incoming X-rays are Compton-scattered (scintillator rod) and subsequently photo-absorbed in a CZT detector.*

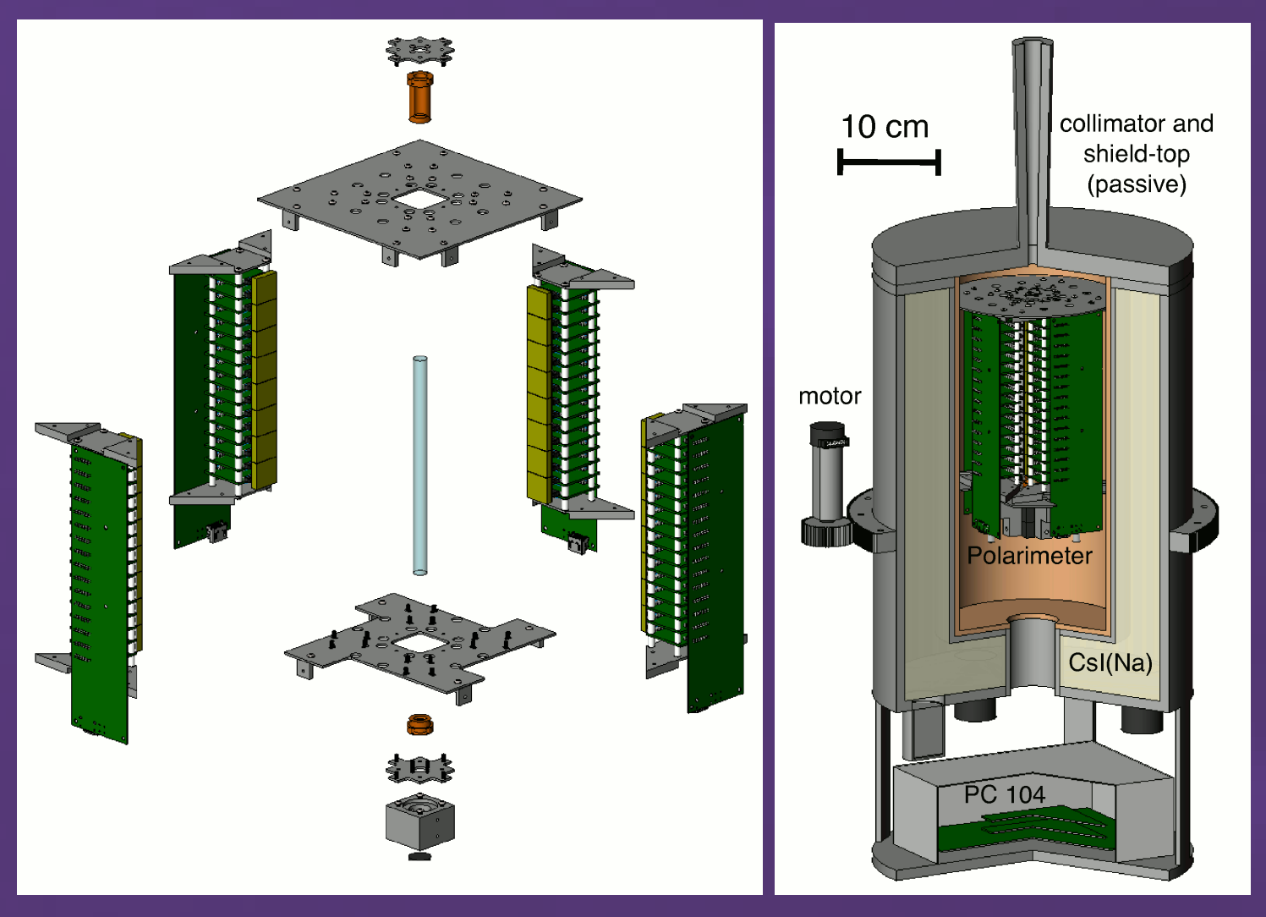


Fig. 3: *Left: View of the polarimeter (exploded): 4 sides of detector columns surround the central scintillator rod (optical axis). Right: Polarimeter with shielding and azimuthal rotation bearing.*

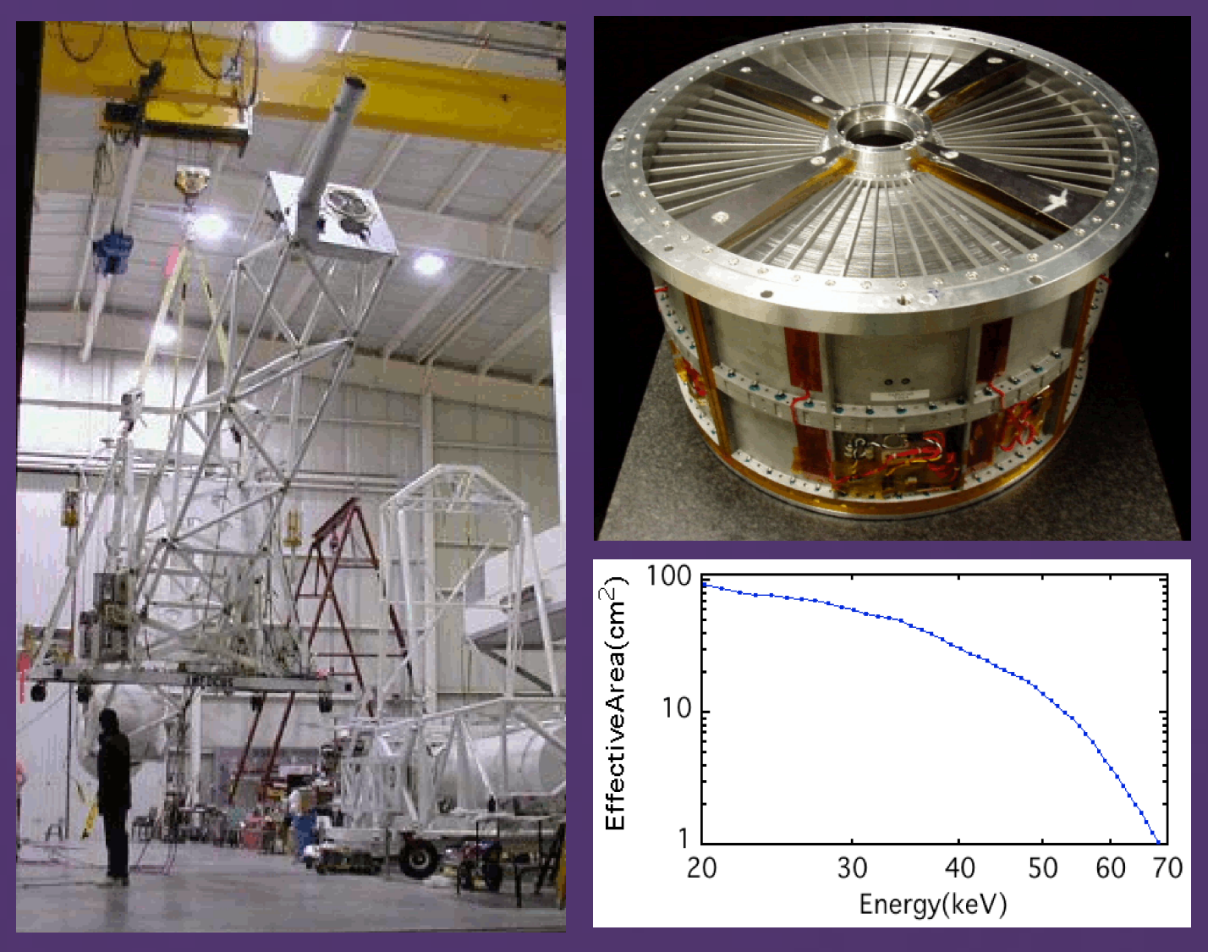


Fig. 4: *Left: InFOCuS balloon gondola. Top right: Wolter-type X-ray aluminum mirror (f=8m). Bottom right: effective area of the X-ray mirror.*

Simulations

Simulations were performed using the Geant4 package with the Livermore physics list. We assume a balloon flight in the focal plane of the InFOCuS mirror assembly [1]. We accounted for atmospheric absorption at a residual atmospheric depth of 2.9 g/cm².

A Crab-like source was simulated for a 5.6 hr balloon flight. We assumed a power-law energy spectrum, and a continuous change of polarization degree & angle between the values measured at 5.2 keV with OSO-8 [5] and >100 keV with Integral [6]. The expected X-Calibur measurements are shown in Figure 5.

We also compared the performance of X-Calibur to the performance of competing designs (Fig. 6). X-Calibur is substantially more sensitive in the <100 keV regime. More details on the comparison can be found in [4].

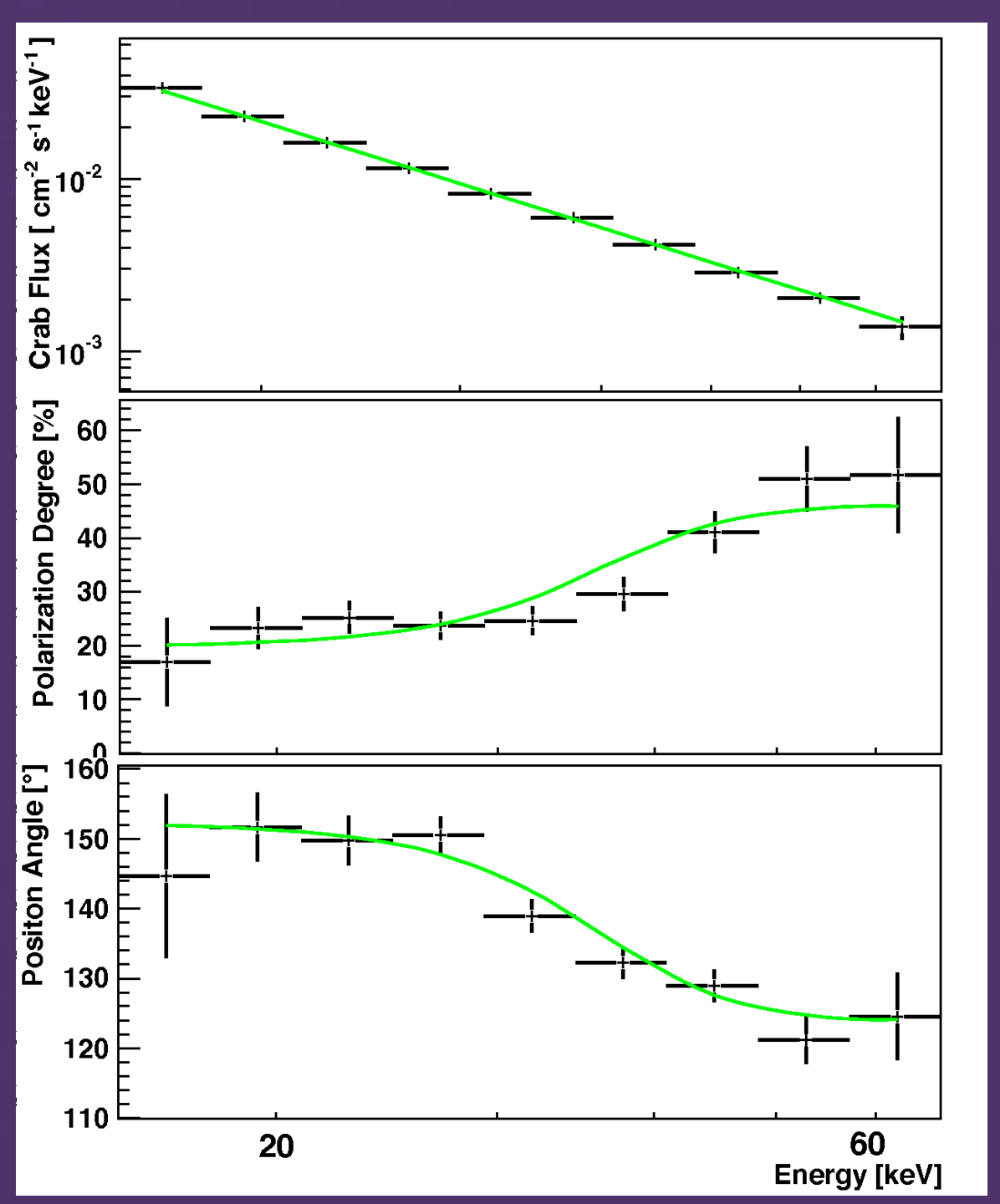


Fig. 5: *Simulated Crab observation (5.6h): reconstructed spectrum (top), polarization degree (middle), and polarization angle (bottom) for assumed model (green).*

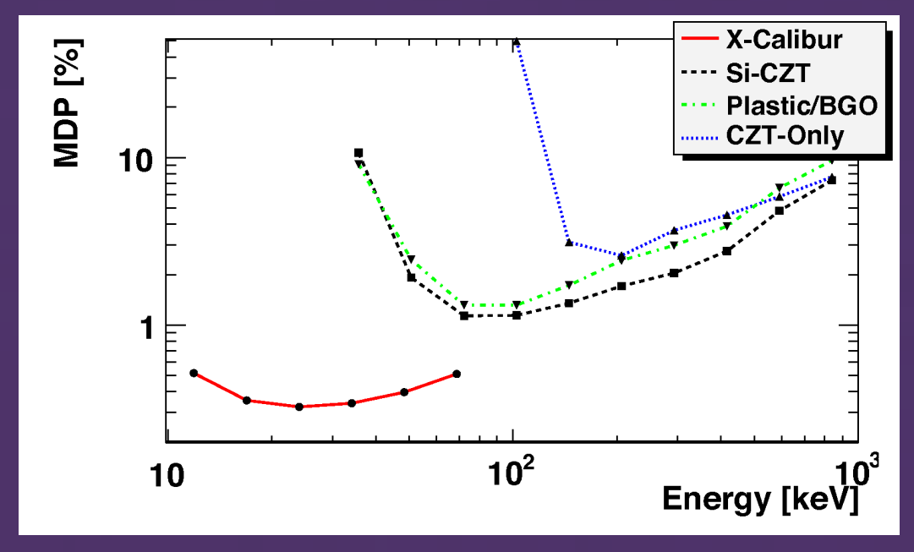
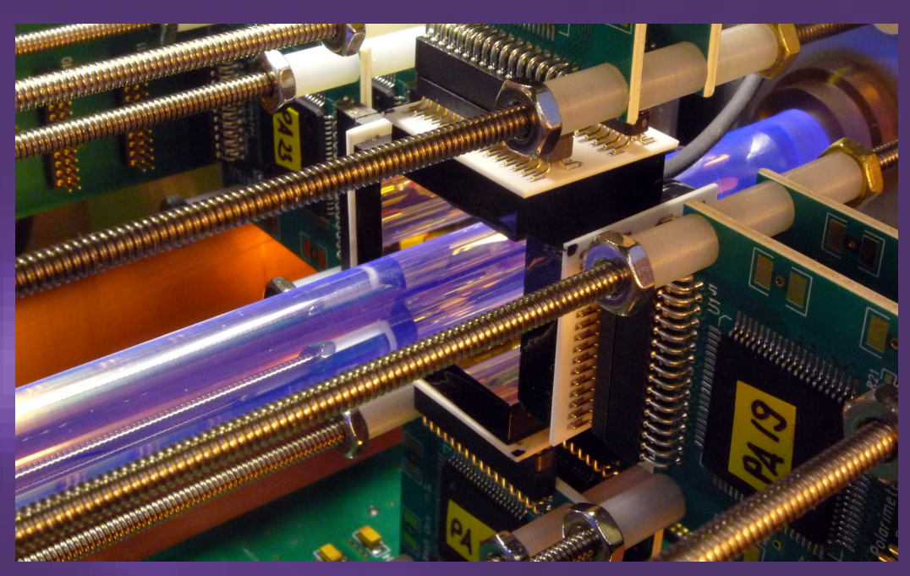


Fig. 6: *MDP sensitivity (100ksec, Crab) for 4 SMEX-scale Compton polarimeters (A_{eff}: 500cm² [X-Calibur], and 1600cm² [others])*

Lab measurements



Using funding of the *McDonnel Center for the Space Sciences*, we are assembling and testing a flight-ready version of the X-Calibur polarimeter.

Figure 7 shows a single CZT detector unit (8x8 pixel matrix) and the readout electronics. Four detector units form a 'ring' surrounding the scintillator slab (photos on the left). The scintillator is read out by a Hamamatsu R7600U-200 PMT. Each CZT detector is read out by two digitizer boards (32 channel ASIC [7] and 12-bit ADC). 16 digitizer boards (8 CZT detectors) are managed by one harvester board (each) transmitting the data to a PC-104 computer (6.25 Mbits/s). X-Calibur will comprise 2048 data channels.

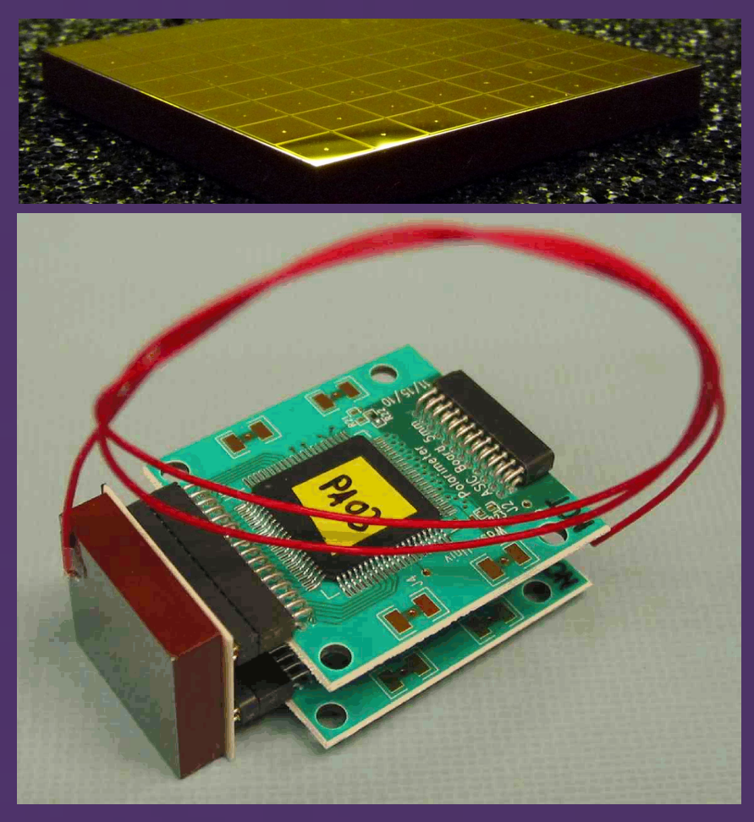


Fig. 7: *Top: 2x2x0.2cm³ CZT detector (64 pixels on the anode side). Bottom: 2x2x0.5cm³ CZT detector bonded to a ceramic chip carrier, plugged into 2 ASIC read-out boards. The HV supply is glued to the detector cathode (red wire)*

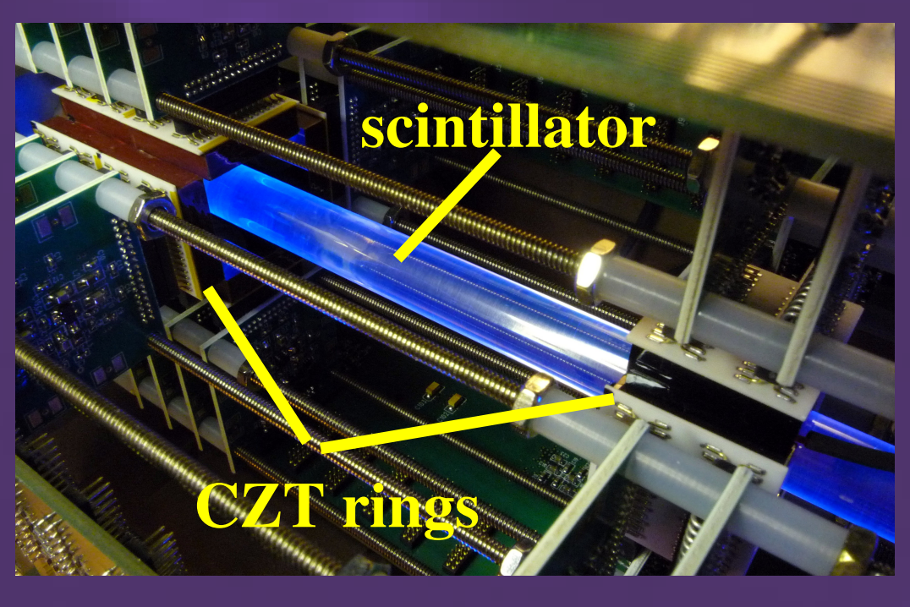


Fig. 8: *X-Calibur after the installation of 3 CZT detector rings (2 left, 1 right) surrounding the scintillator (blueish glow)*

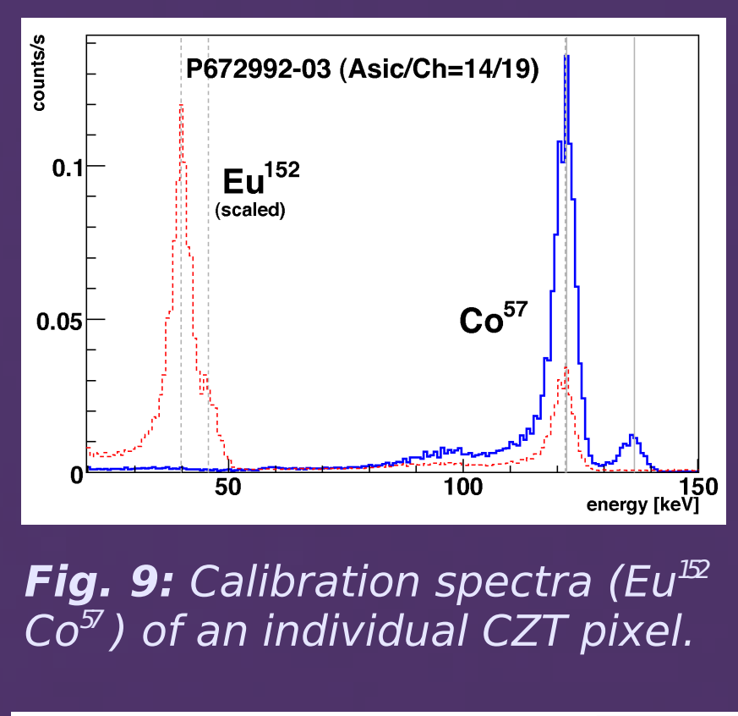


Fig. 9: *Calibration spectra (Eu^{152} & Co^{57}) of an individual CZT pixel.*

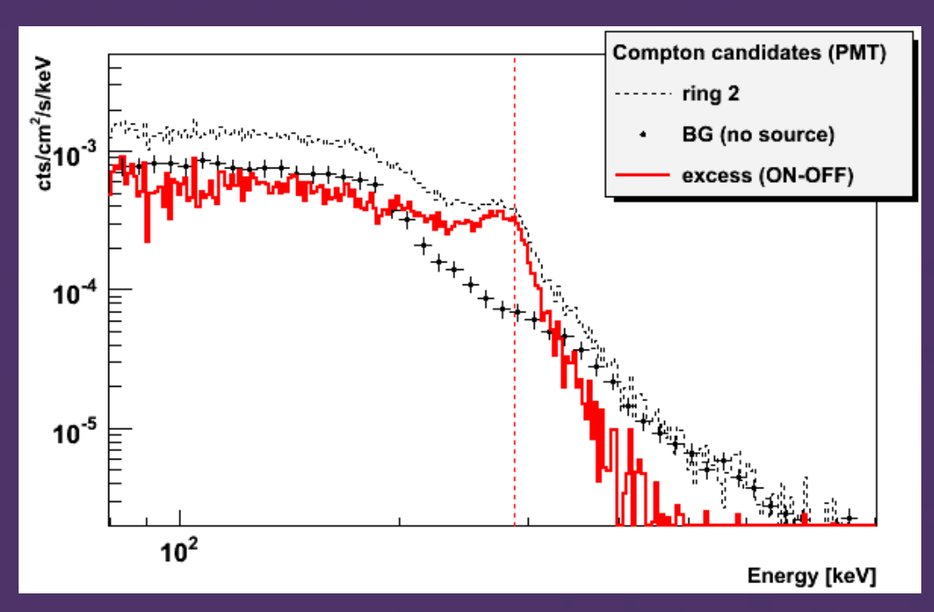


Fig. 10: *Energy spectrum of 288 keV X-rays (partially polarized) after being scattered in the scintillator (different scattering angles). The BG measurement is done without a source (cosmic rays). The vertical line (288 keV) indicates the energy of the incoming X-ray beam.*

First results

First measurements with 3 detector rings (12 detectors):

- **CZT calibration:** Eu^{152} (lines at 40&122 keV, Fig.9).
- Event rates are normalized by the azimuthal angle ΔΦ covered by the corresponding pixel.
- **Unpolarized beam:** azimuthal detection acceptance
- **Polarized beam:** scatter strong Cs^{137} source (662 keV) off a lead brig. Only allow X-rays with scattering angle of 90° to enter the polarimeter (288 keV, polarized to ~55%, modulation factor of μ=0.4). Expected amplitude in normalized Φ distribution: 0.55x0.4=0.22
- **Coincidence:** Only CZT events with a simultaneous (30 us) scintillator trigger are used (Compton candidates).

The energy spectrum of the scattered/polarized beam as measured in the 2nd X-Calibur ring is shown in Figure 10.

Figure 11 shows the azimuthal distribution of the polarized and unpolarized beam. The data of the polarized beam are corrected for the acceptance of the polarimeter (derived from the unpolarized X-ray beam). A 180° modulation can be seen in case of the polarized beam, well described by a sine function (fit) with a relative amplitude of 0.22.

Data are in excellent agreement with expectations.

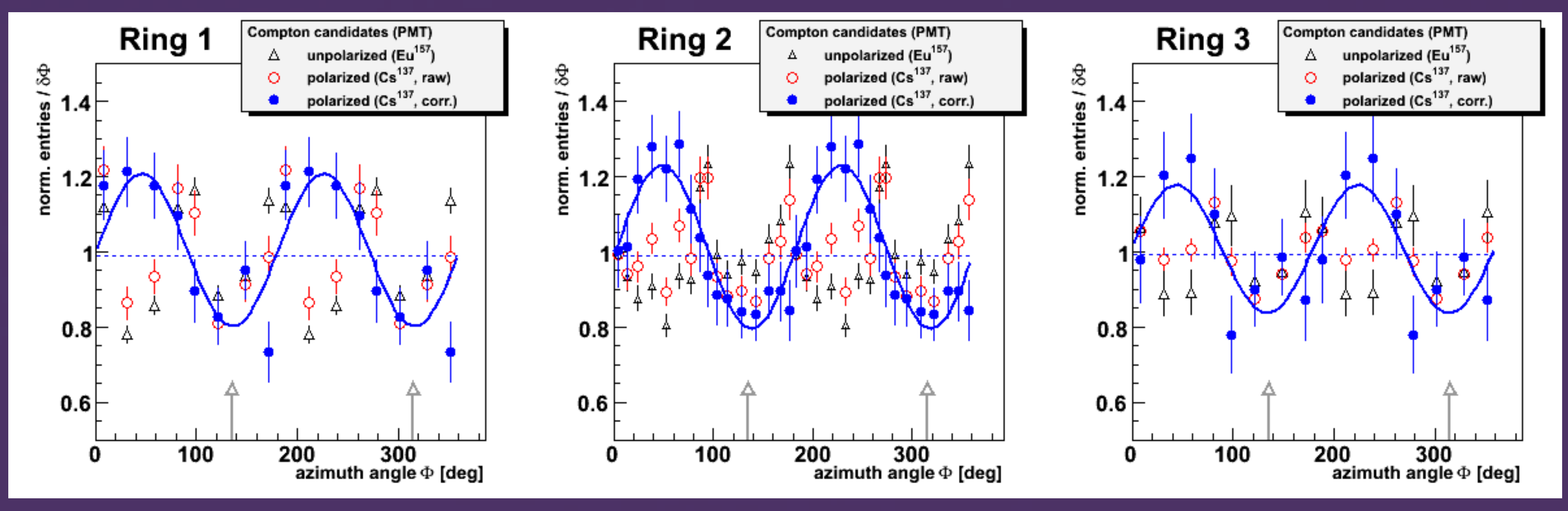


Fig. 11: *Azimuthal event distribution (3 CZT rings). Counts divided by the covered azimuthal angle ΔΦ of the corresponding pixels). Shown are raw events of the polarized beam (red), an unpolarized beam (black), and the acceptance corrected polarized events (blue). A sine function was fit to the data. The vertical arrows indicate the plane of the electric field vector of the polarized beam for which a minimum in scattered photons is expected.*

Conclusion and Outlook

We designed a hard X-ray polarimeter X-Calibur and studied its performance and sensitivity when flown in the focal plane of the InFOCuS X-ray telescope. X-Calibur combines a detection efficiency of close to 100% with a high modulation factor of μ~0.5, as well as a good control on systematic effects. X-Calibur was successfully tested in the lab with a polarized 288 keV beam. Future plans:

- Further lab measurements (different orientations, 2mm vs 5mm CZT detector thicknesses, shielding, rotation mechanism, etc.).
- We applied for a 1-day X-Calibur/InFOCuS balloon flight (fall 2012). Our tentative observation program includes: Crab, Her X-1, Cyg X-1, GRS 1915, EXO 0331 & Mrk 421.
- Two more long-duration balloon flights (northern and southern hemisphere) are planned in the near future, possibly with increased effective mirror area.

References

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