Polarisation performances of CdTe pixel detector for Laue hard X-ray focusing telescopes

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Why Hard-X ray polarimetry?

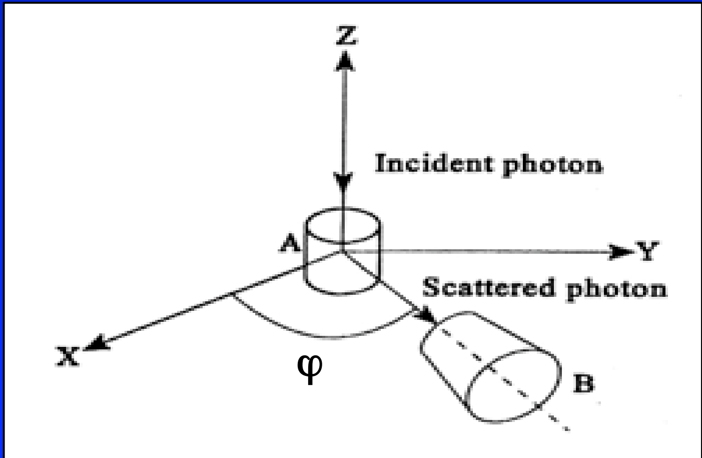
Conventional analysis (imaging, spectroscopy and timing) of the high energy radiation from cosmic ray sources often provides two or more different models that successfully explain the observations; **The combined measurement of polarization angle and degree of linear polarization can provide vital extra information to discriminate among the models.**

- **Solar Flares** Solar flare emission is contaminated by thermal emission at lower energies and by lines above 1 MeV, the best energy range for polarimetry investigation from solar

Interesting sources for focusing instruments

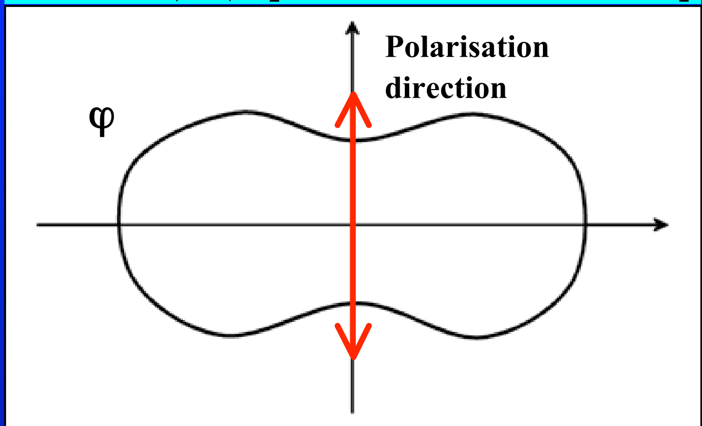
- ***Pulsars***: hard X-ray polarimetry to understand the extent to which gamma-ray photons are related to those at longer wavelengths (e.g. a ***polarisation level >20% is expected from the CRAB pulsar***).
- ***Soft Gamma-ray Repeaters: one by-product of magnetic photon splitting (50-500 keV) is that the reprocessed photons would exhibit a polarization level of ~25%***.
- Other possible sources
- **Massive Black Hole:** the geometry of the the accretion disk; ***For optical thin disks polarization levels as high as 30-60% are possible while in the optically thick regime lower levels (~5-10%) are predicted.***

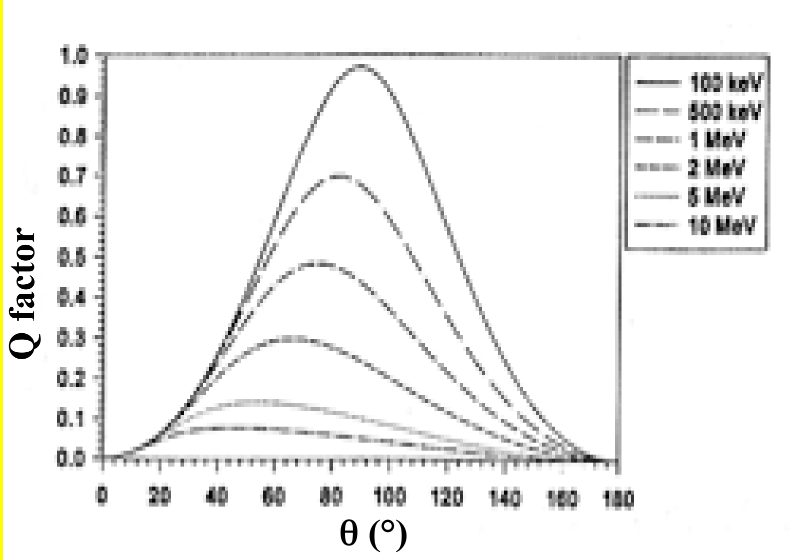
The basic of Compton Scattering polarimetry



Klein-Nishina cross-section for linearly polarized photons:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right]$$



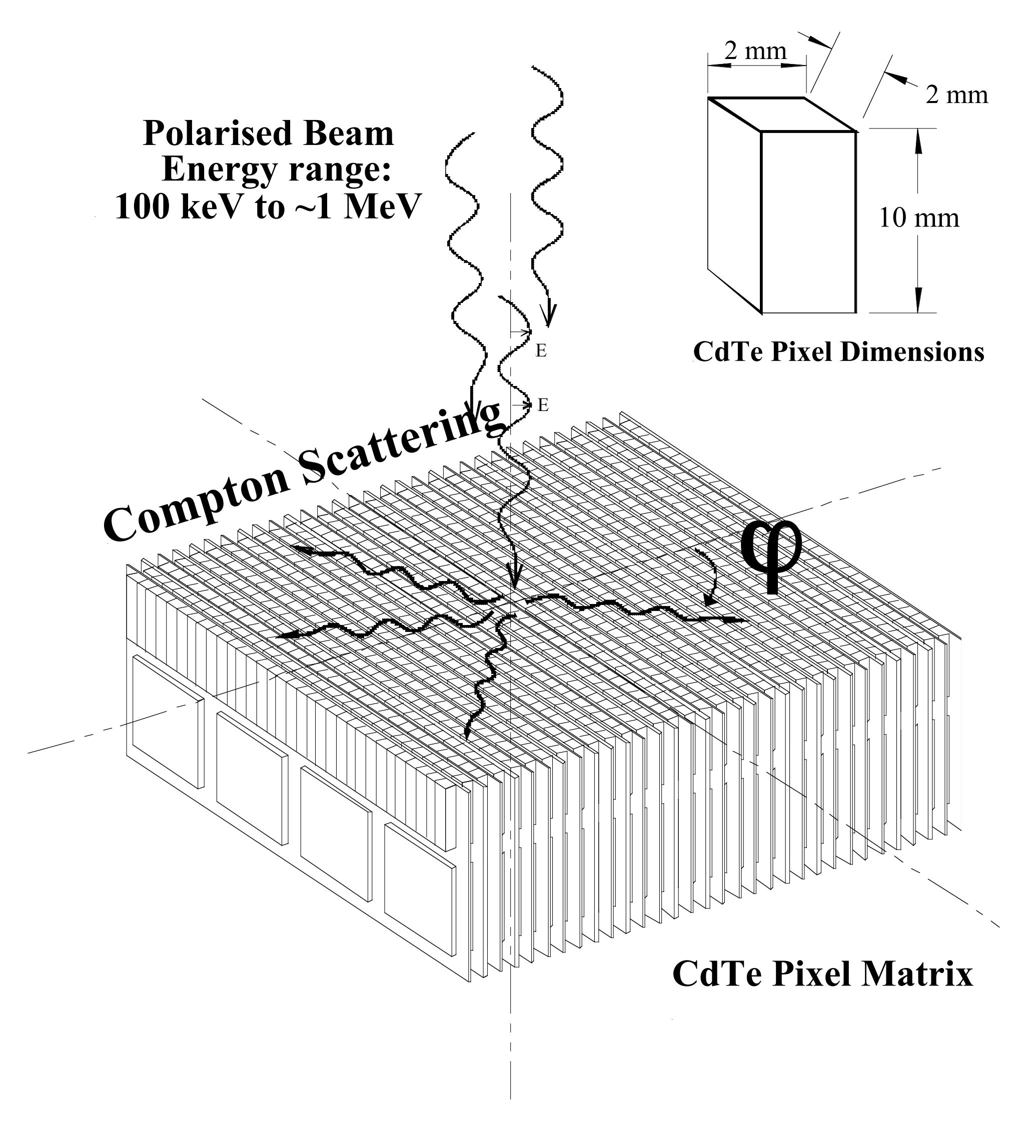


Modulation Factor (Q)

$$Q = \frac{d\sigma(\varphi = 90) - d\sigma(\varphi = 0)}{d\sigma(\varphi = 90) + d\sigma(\varphi = 0)}$$

$$Q = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

$$Q = \frac{\sin^2\theta}{\frac{E'}{E} + \frac{E}{E'} - \sin^2\theta}$$

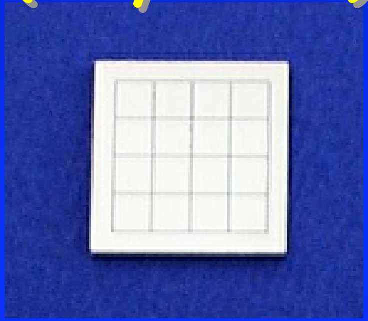


Advantages of

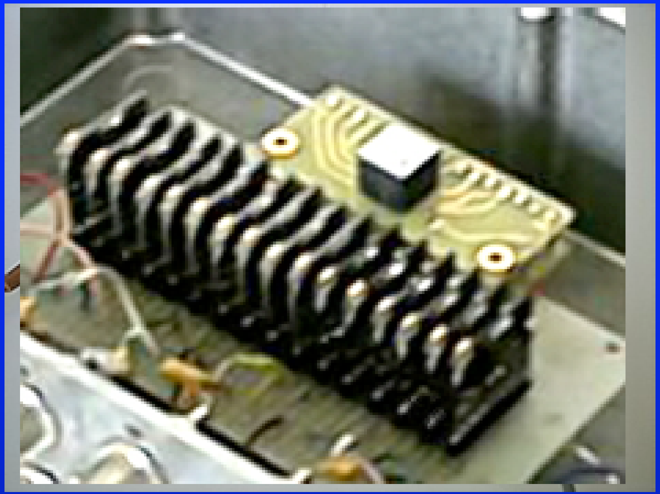
a pixel detectors:

- Each element of the dectection plane is both a scatterer and a detector. Therefore all the sensitive area is used as polarimeter
- The geometry of the detector select only events with a scattering angle close to 90º. For these scattering angles we have the best modulation factor.

The POLCA pixellated CdTe detectors
Experiment at the beam line ID15 of the ESRF (July 2002)



Thickness (mm)	Pixel (mm^2)	Bias (V/mm)	Resistivity (Ω.cm)	D.C. (nA)
3.4 – 5 – 7.5	**2.5 × 2.5**	**~100**	**1–5 $x10^9$**	**20 - 40**



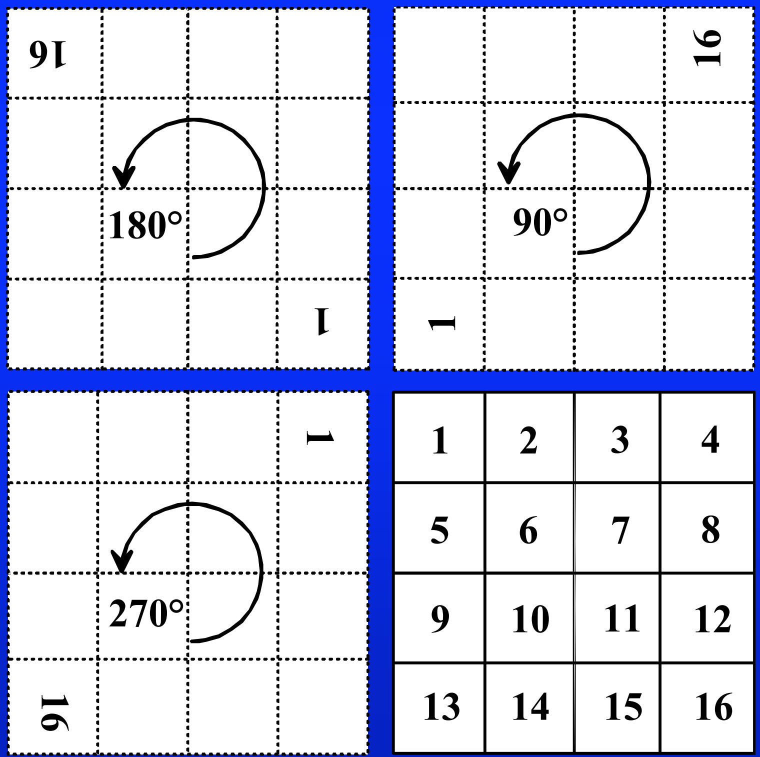
Custom Multi-parametric system with16 shaping amplificator, coincidence logic, auto-calibration system, ADC (12 bit) and parallel data output:

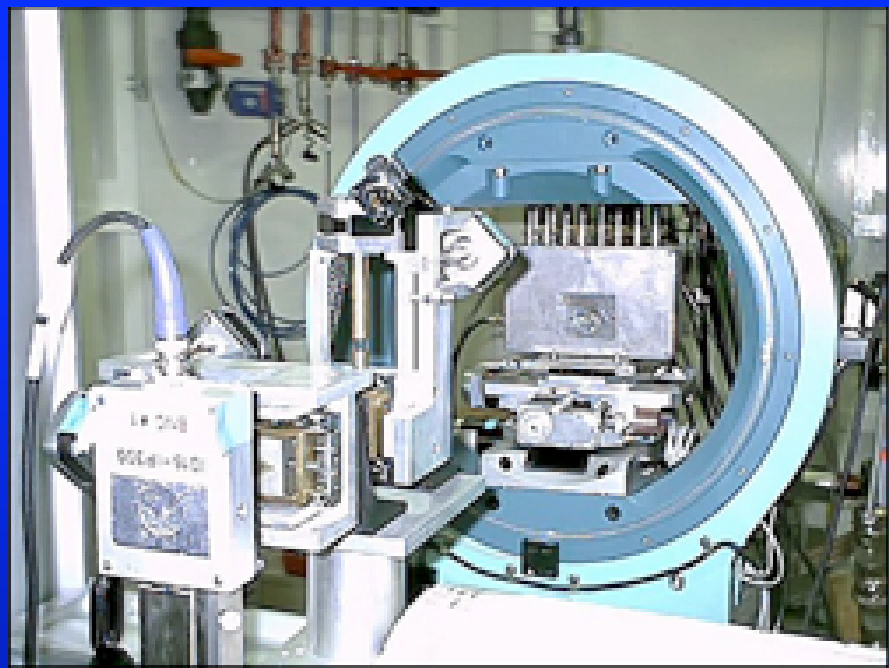
- ❑ Coincidence time: 5 μs
- ❑ Trigger threshold: 25-30 keV
- ❑ Dynamic range: 50 (20-1000 keV)

POLCA: Experiment at the beam line ID15 of the ESRF (July 2002)

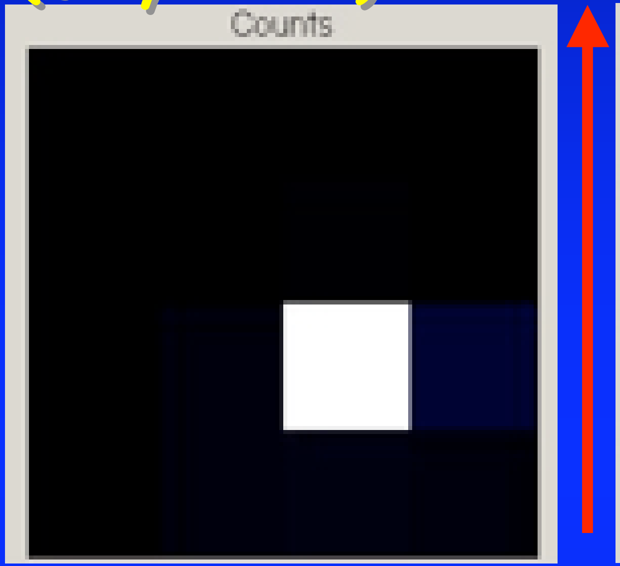
- Corner pixel irradiaton
- Rotation of the 4x4 matrix
- 90° double events distribution symmetry

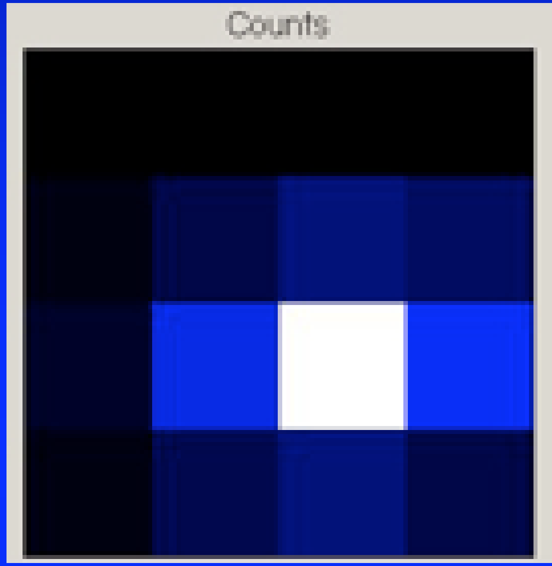
Allows extrapolation to a 7x7 matrix





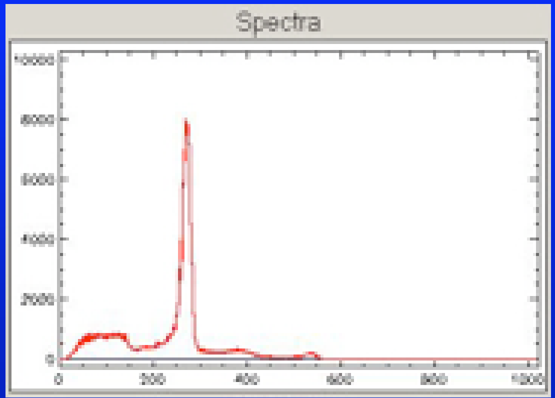
POLCA: Experiment at the beam line ID15 of the ESRF (July 2002)

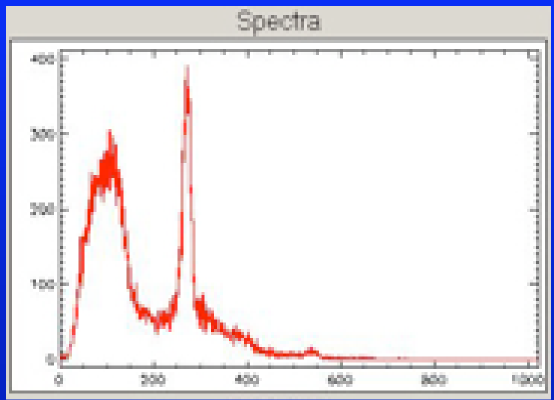




Single events

Double events





The single events are used to correct the double counts maps for pixel response non uniformity in order to reduce sistematics effects on the evaluation of the Q factor:

$$N_{x/y} = M_{x/y} \times N_t/N_{sxy}$$

M = detected double events

N_t = Total events

N_s = Single events

The red arrow give the polarisation plane direction

POLCA vs MonteCarlo

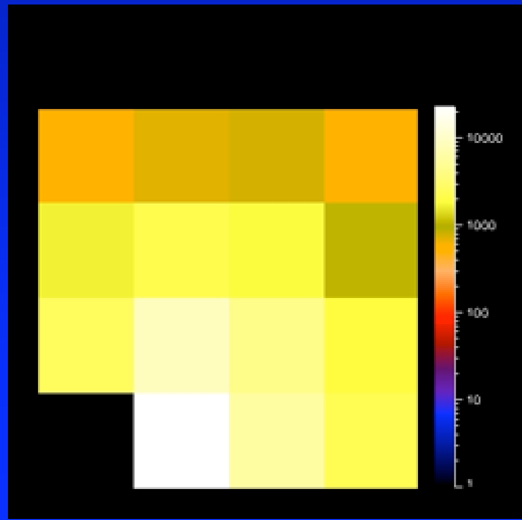
POLCA experiment

Matrix number (thickness)	*Polarimetric Q factor*		
	100 keV	*300 keV*	*400 keV*
1167/11 (3.4 mm)	0.15 ± 0.051	0.46 ± 0.036	0.36 ± 0.091
1283/26 (5.0 mm)	–	0.40 ± 0.12	0.33 ± 0.13
1186/49 (7.5 mm)	–	0.39 ± 0.060	0.31 ± 0.065

POLCA

7.5 mm

300 keV



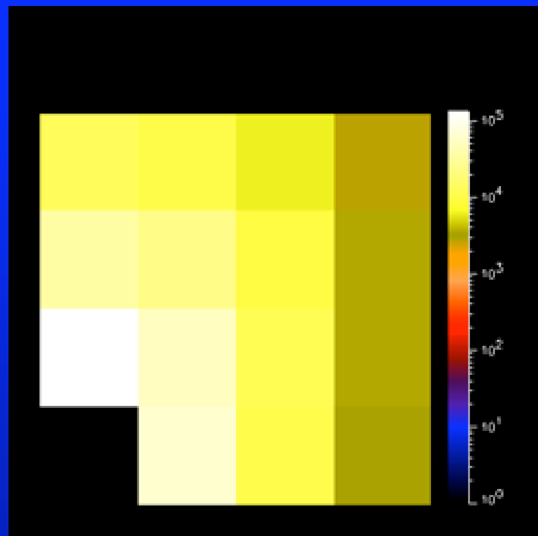
Monte Carlo

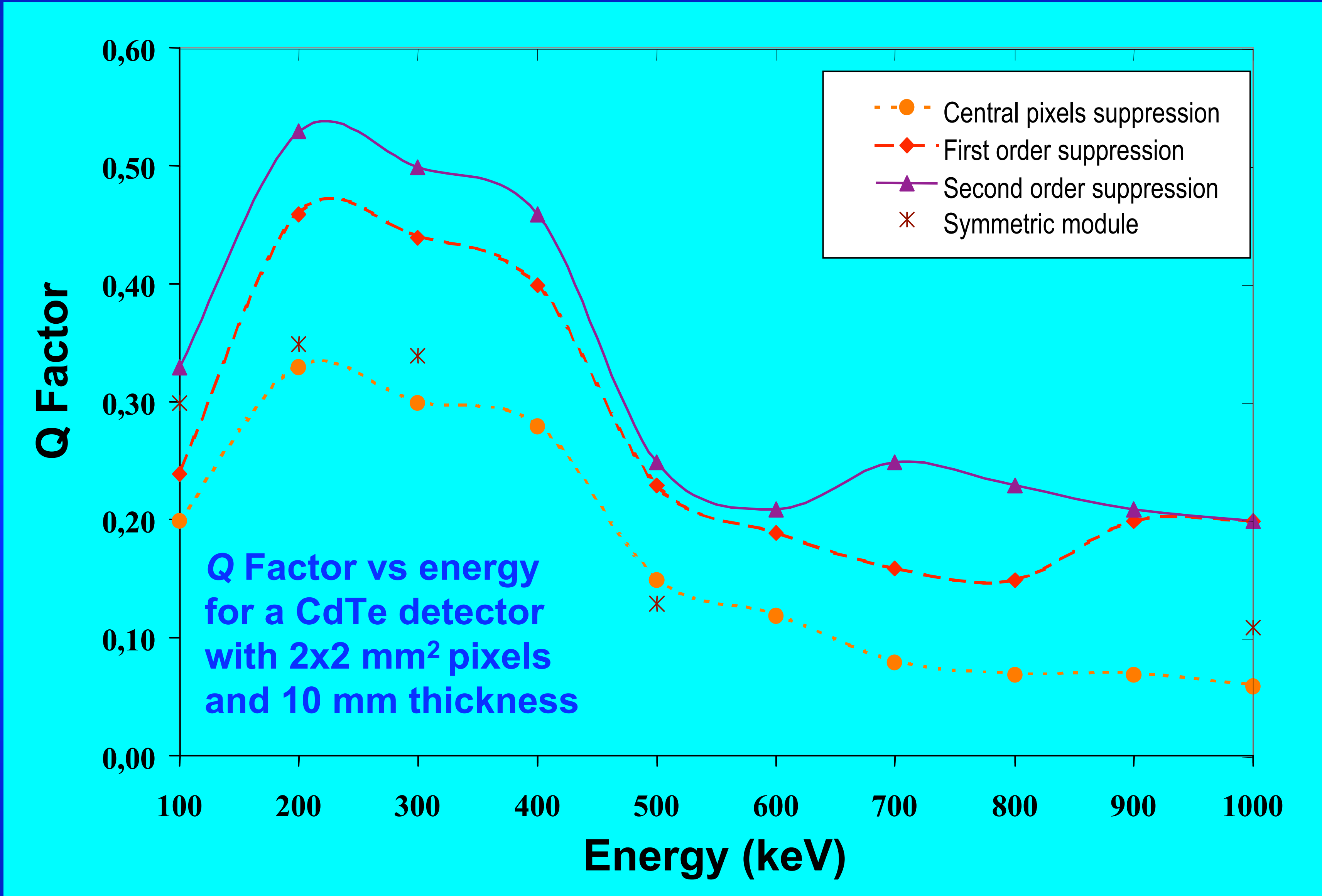
Matrix number (thickness)	*Polarimetric Q factor*		
	100 keV	*300 keV*	*400 keV*
1167/11 (3.4 mm)	0.49 ± 0.005	0.47 ± 0.003	0.43 ± 0.003
1283/26 (5.0 mm)	–	0.43 ± 0.002	0.39 ± 0.003
1186/49 (7.5 mm)	–	0.40 ± 0.002	0.35 ± 0.002

MC

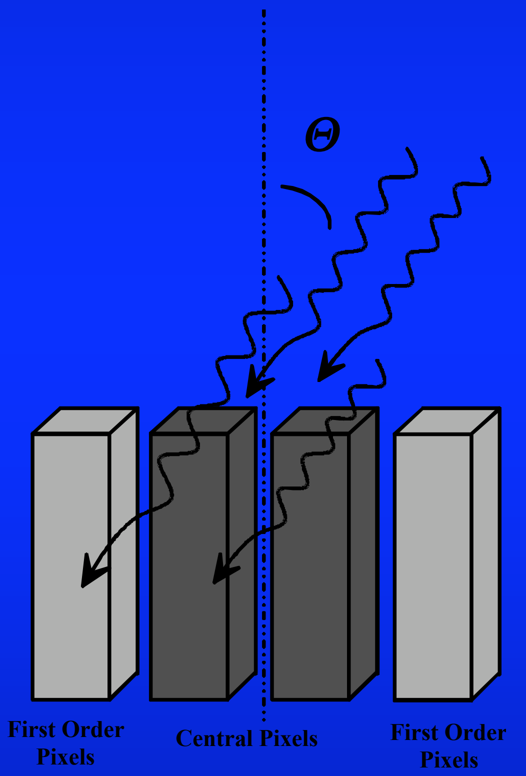
7.5 mm

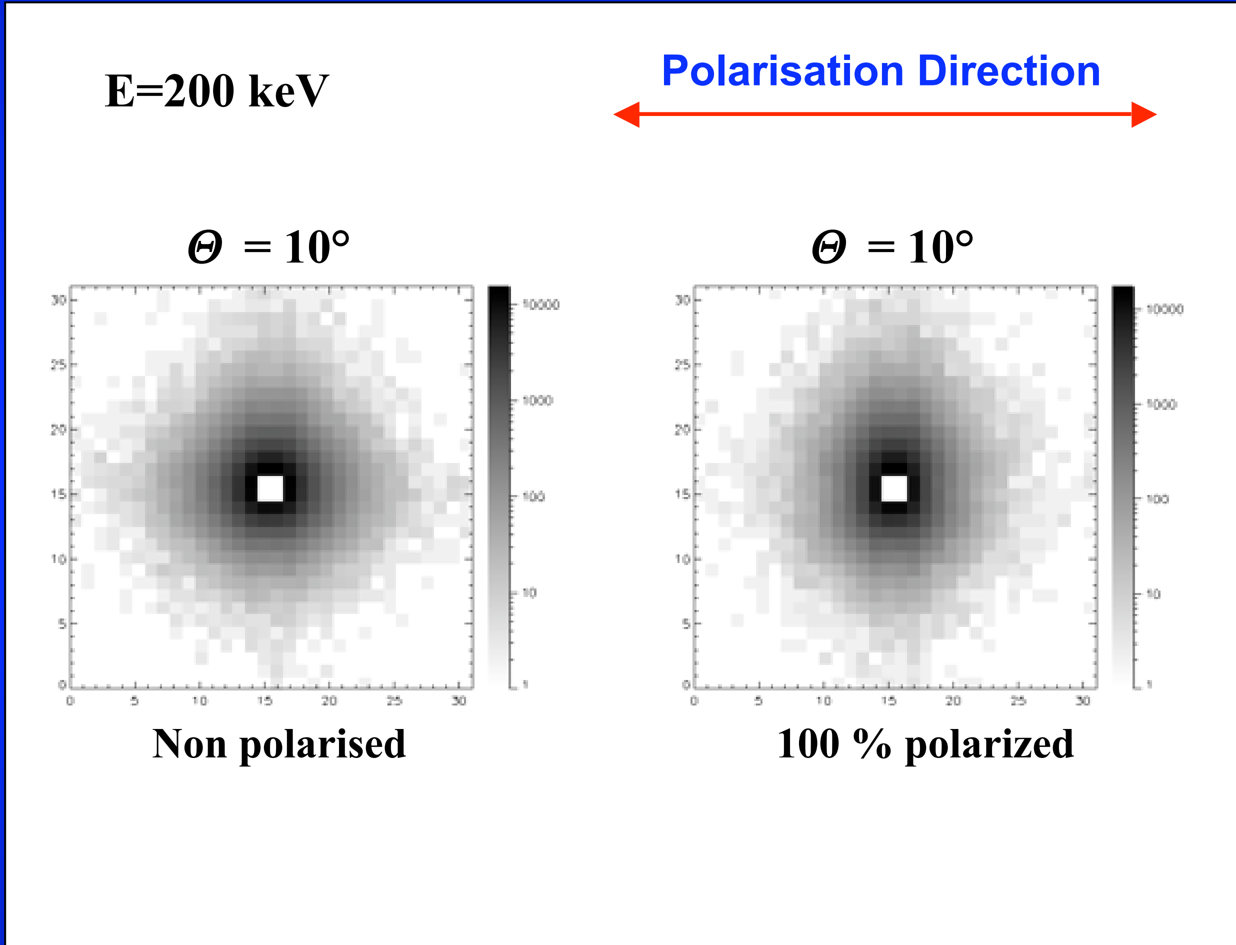
300 keV

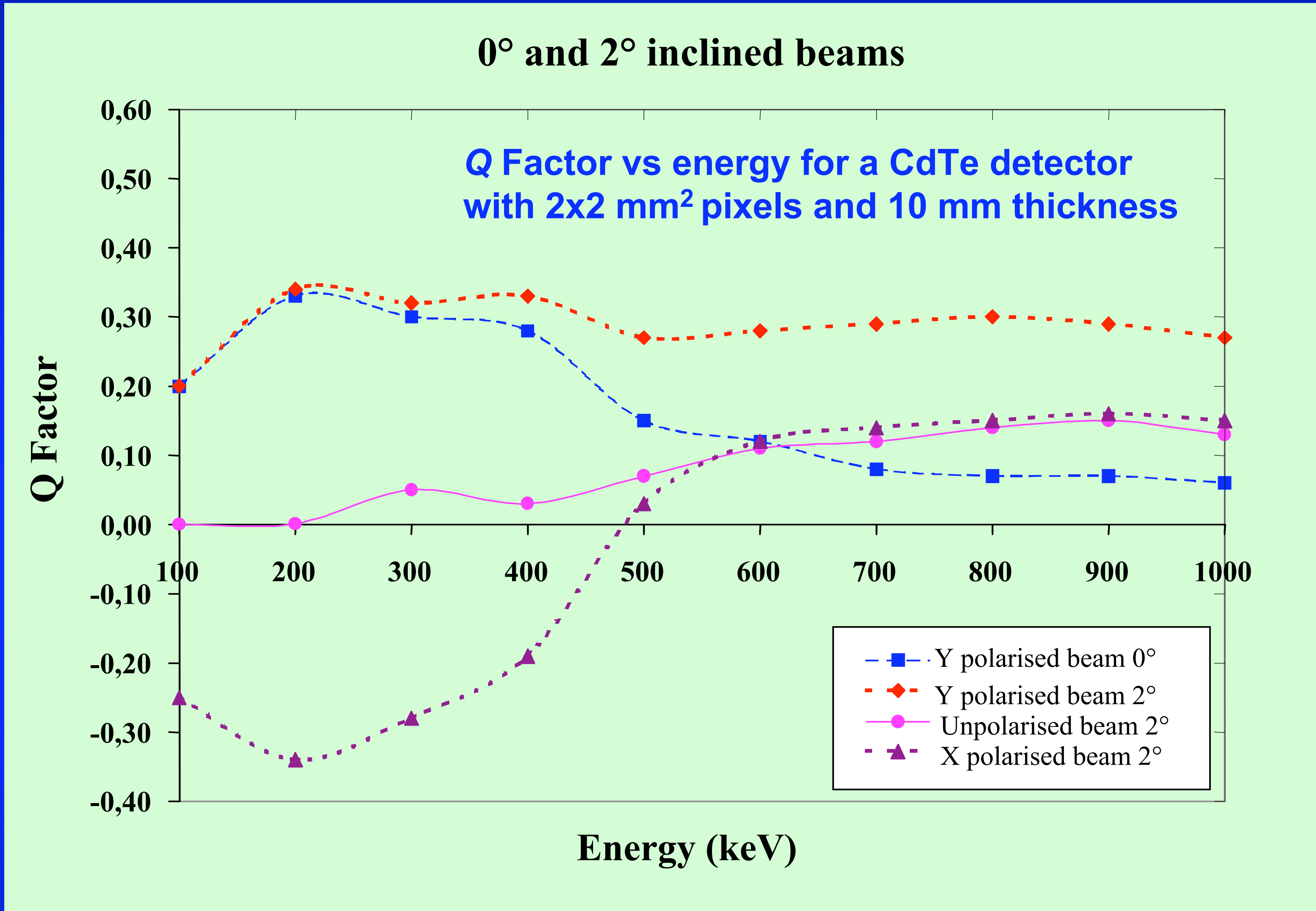



0,60
0,50
0,40
0,30
0,20
0,10
0,00
Q Factor
100
200
300
400
500
600
700
800
900
1000
Energy (keV)
Central pixels suppression
First order suppression
Second order suppression
Symmetric module
Q Factor vs energy
for a CdTe detector
with 2x2 mm2 pixels
and 10 mm thickness

The effect of photon incidence angle (i.e. focussing photons) on the scatter distribution





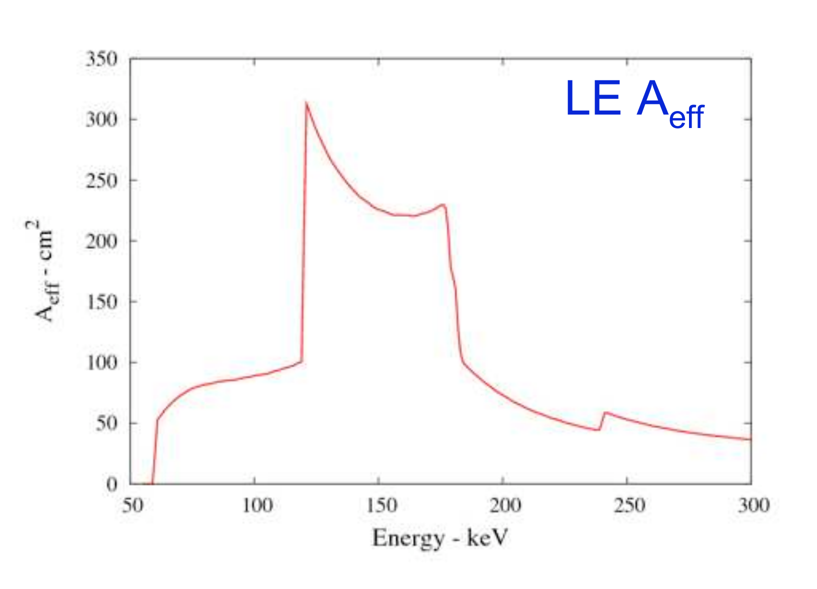


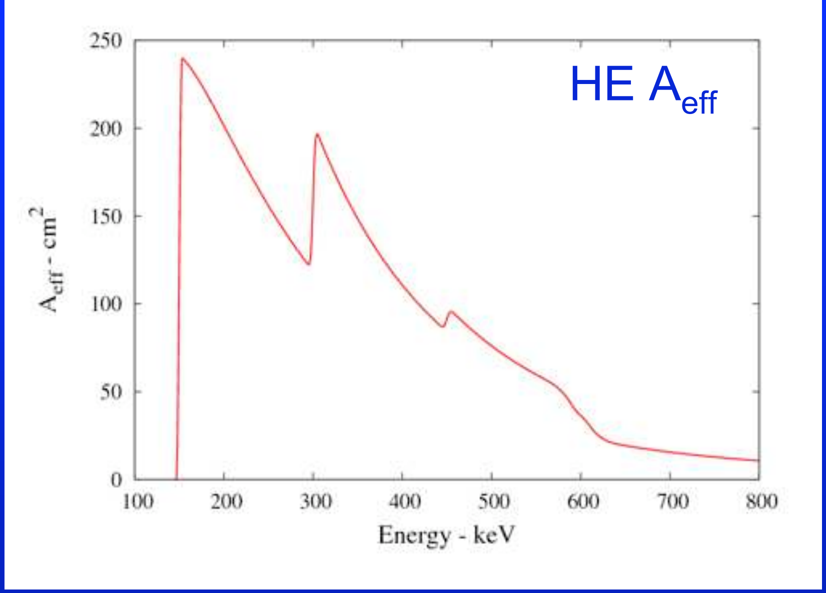
In the proposed configuration the inclination of photon coming out from the laue lens is <2º

CZT pixel detector with Laue wide band lens

Monte Carlo Parameters:

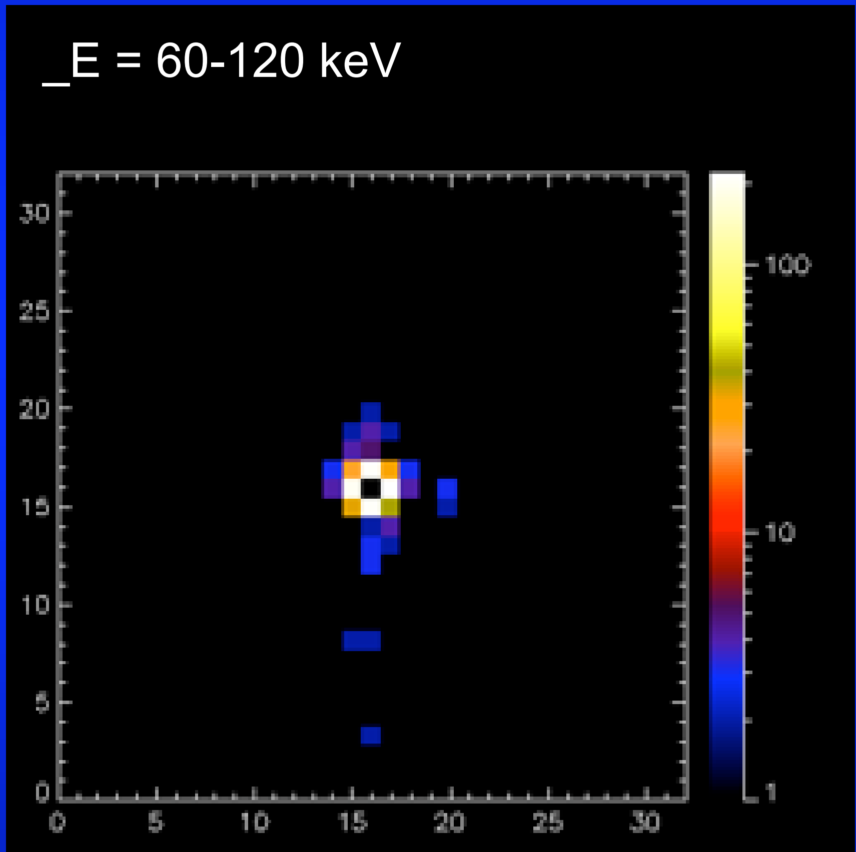
- **PSF:** 2 cm Ø (FWZR) independent from Energy (first order approximation)
- **Energy band**: 2 band for LE lens (60-120 keV, 120-200 keV) and 3 energy band for the HE lens (150-250 keV, 250-400 keV, 400-600 keV)
- **Spectra:** Crab like spectra (E^{-2}, $ph/cm^2/s/keV$)
- **Background**: LEO, High inclination (ISS), conservative hypothesis
- **Detector:** CZT (planar square pixel array)

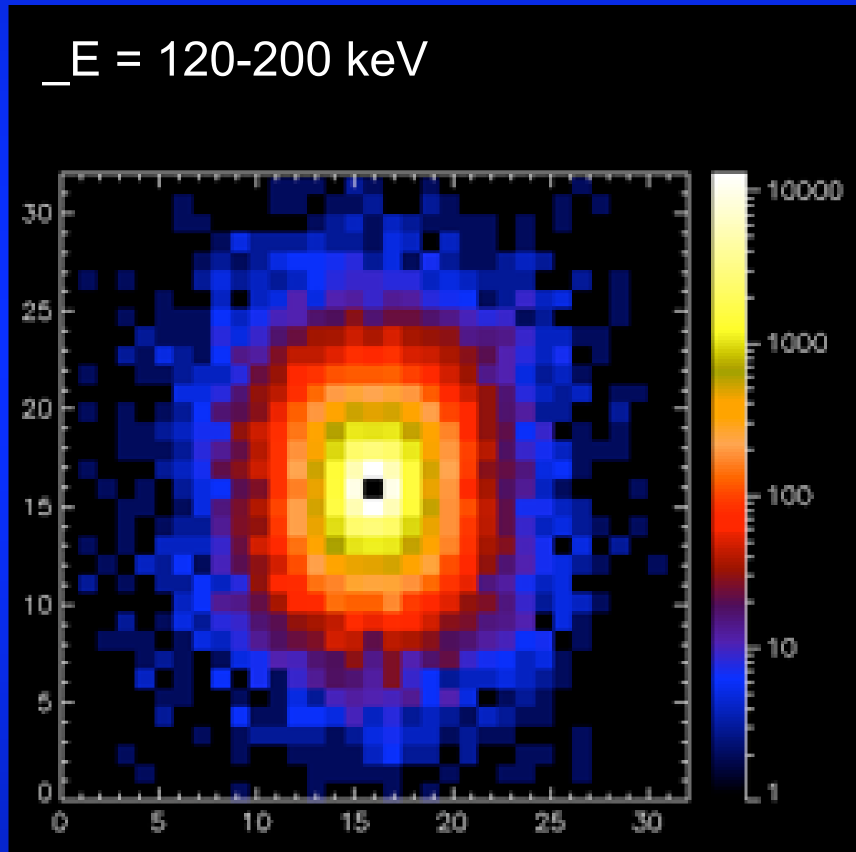




LE lens scattered events maps

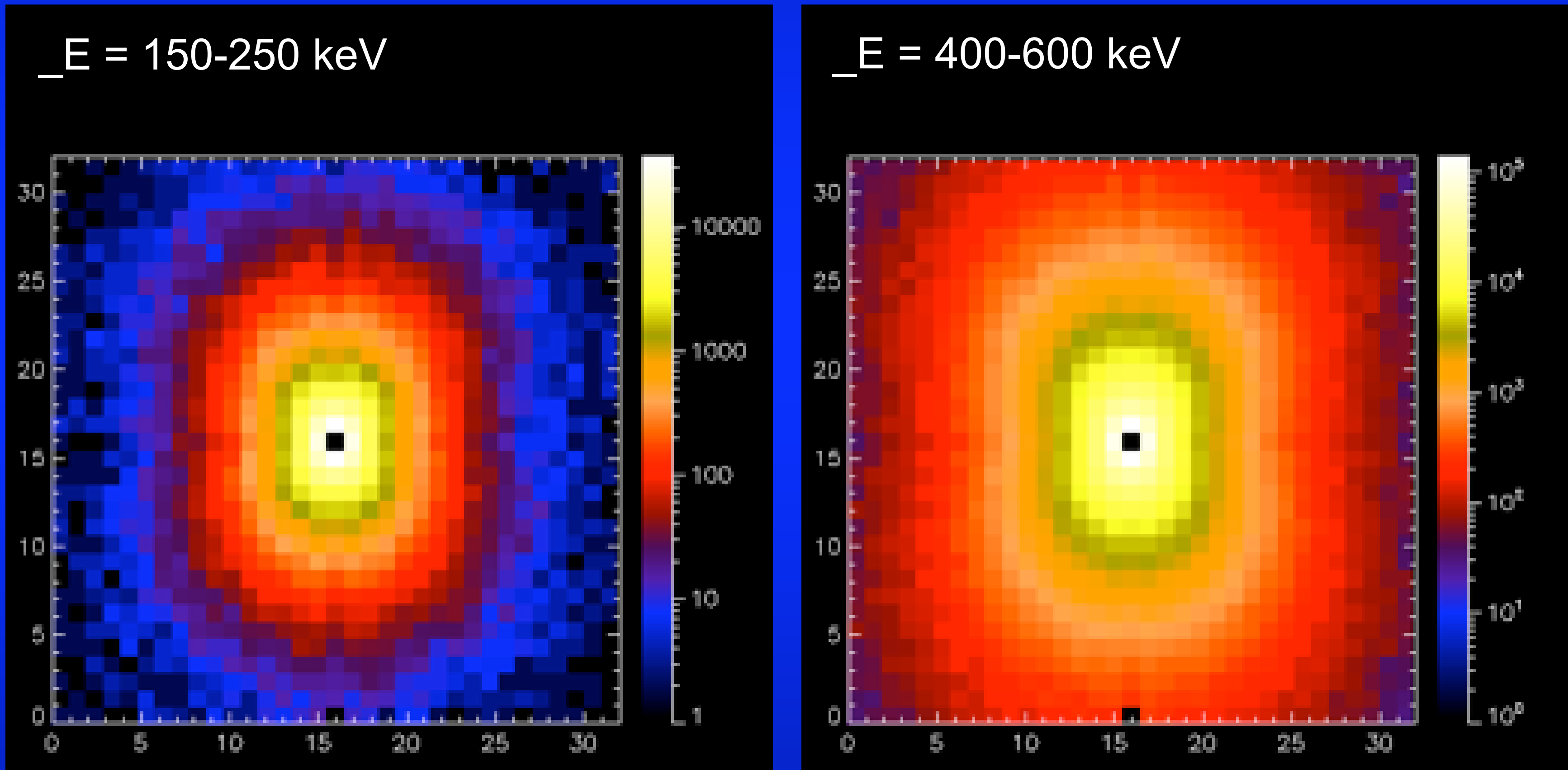
Detector parameters: pixel = 1x1 mm^2, thickness = 10 mm





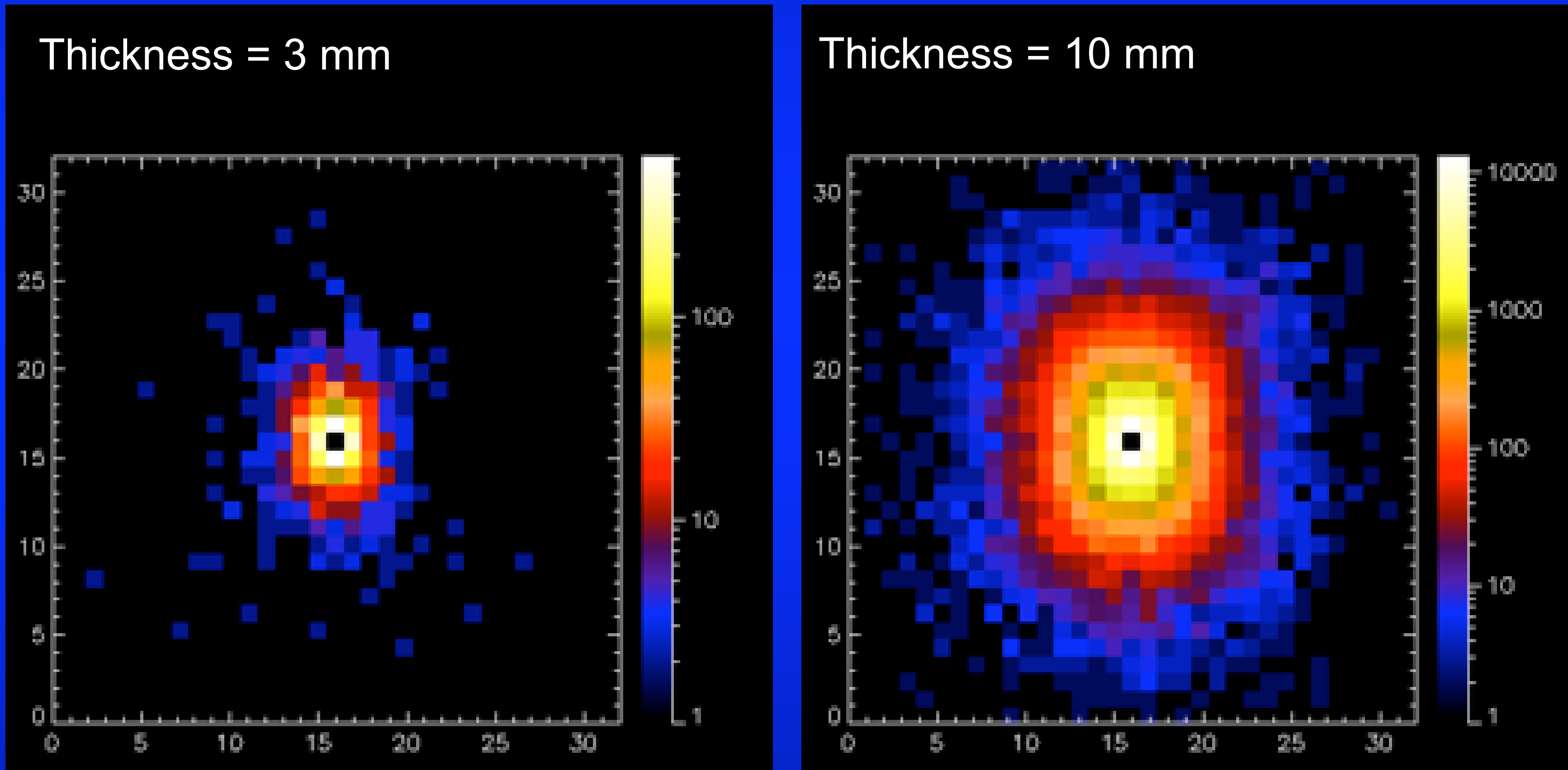
HE lens scattered events maps

Detector parameters: pixel = 1x1 mm^2, thickness = 10 mm



LE lens scattered events maps

Detector pixel = 1x1 mm^2; _E = 120-200 keV



Polarimetric Perfomance

Minimum Detectable Polarisation

$$MDP(100\%) = \frac{n_\sigma}{A.\varepsilon.S_F.Q_{100}}\sqrt{\frac{A.\varepsilon.S_F + B}{T}}$$

Polarimetric Sensitivity

$$F_{min} = \frac{n_\sigma}{\varepsilon \cdot Q_{100}}\sqrt{\frac{B}{AT\Delta E}} \quad ph/(s \cdot cm^2 \cdot keV)$$

A = geometric sensitive area (cm^2)

_ = double events efficiency

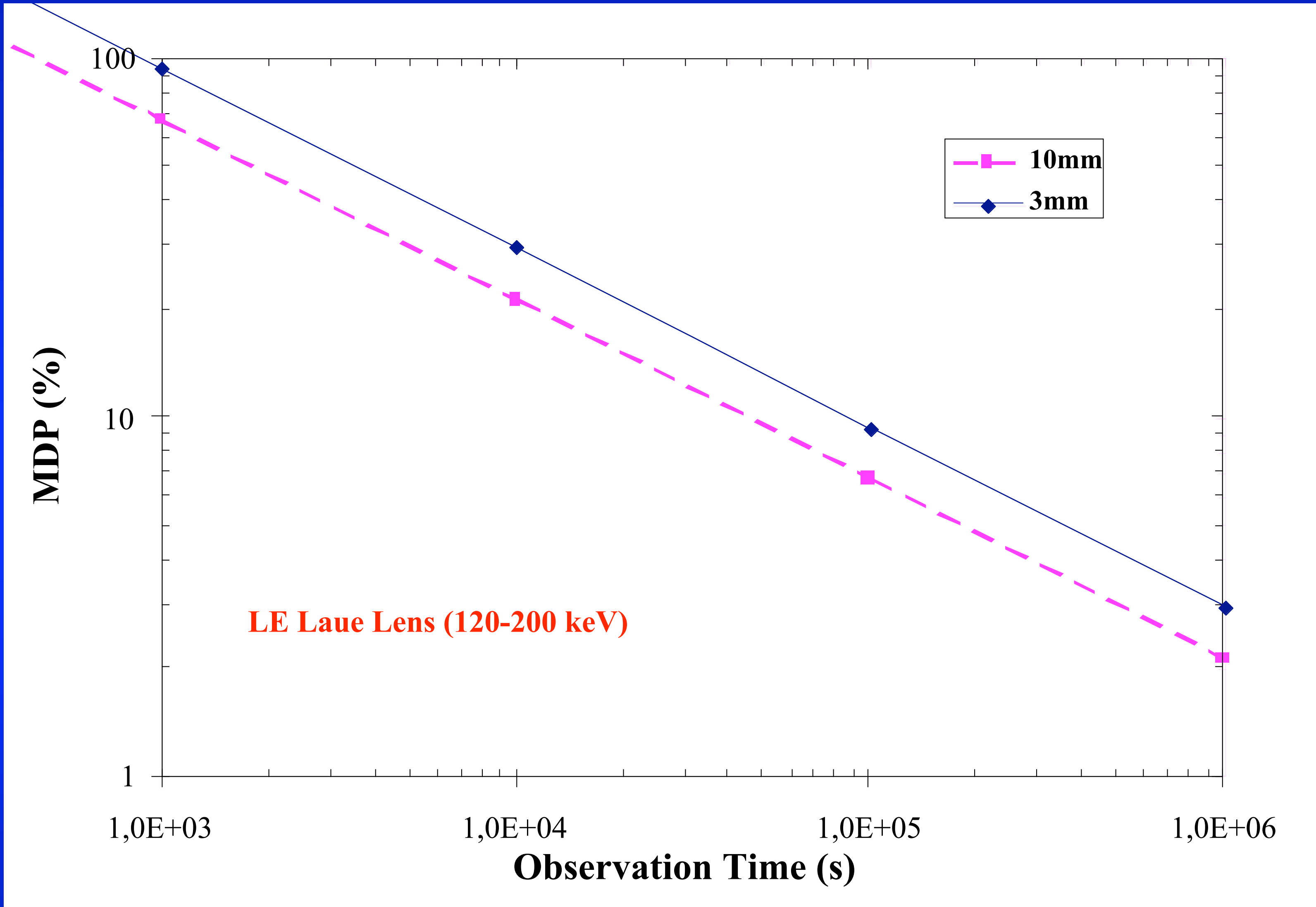
S_F = source flux ($ph/s/cm^2$)

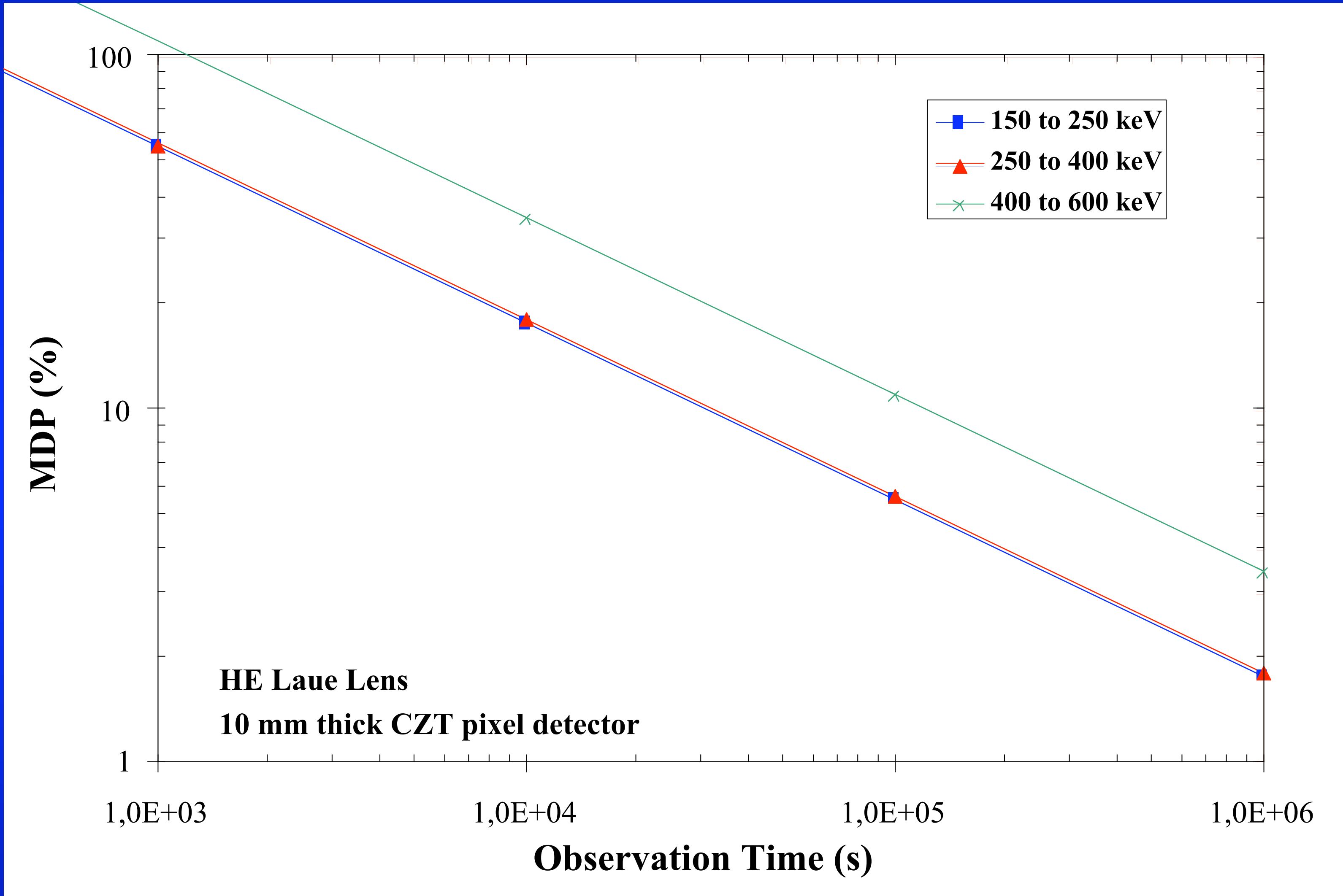
B = background (c/s)

Q_{100}= modulation factor for 100% polarised photons

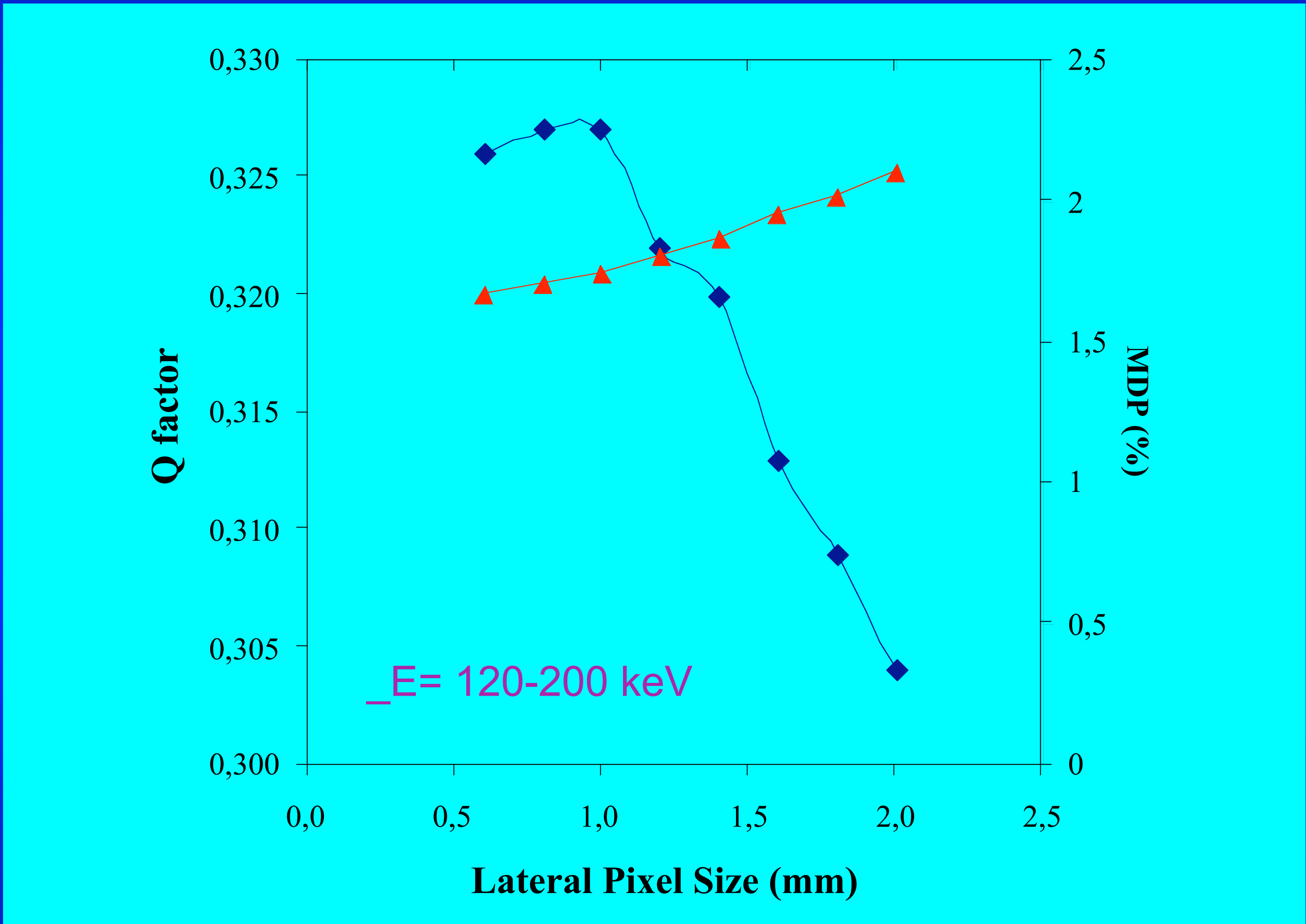
T = observation time (s)

_E = energy band width (keV)

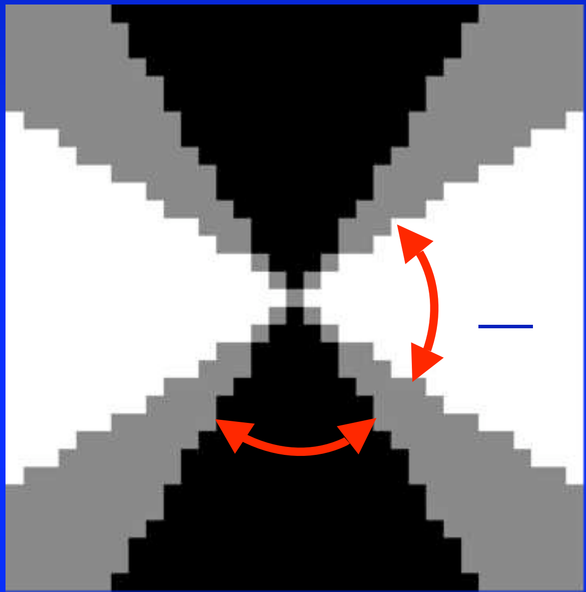

100
10
1
MDP (%)
10mm
3mm
LE Laue Lens (120-200 keV)
1,0E+03
1,0E+04
1,0E+05
1,0E+06
Observation Time (s)

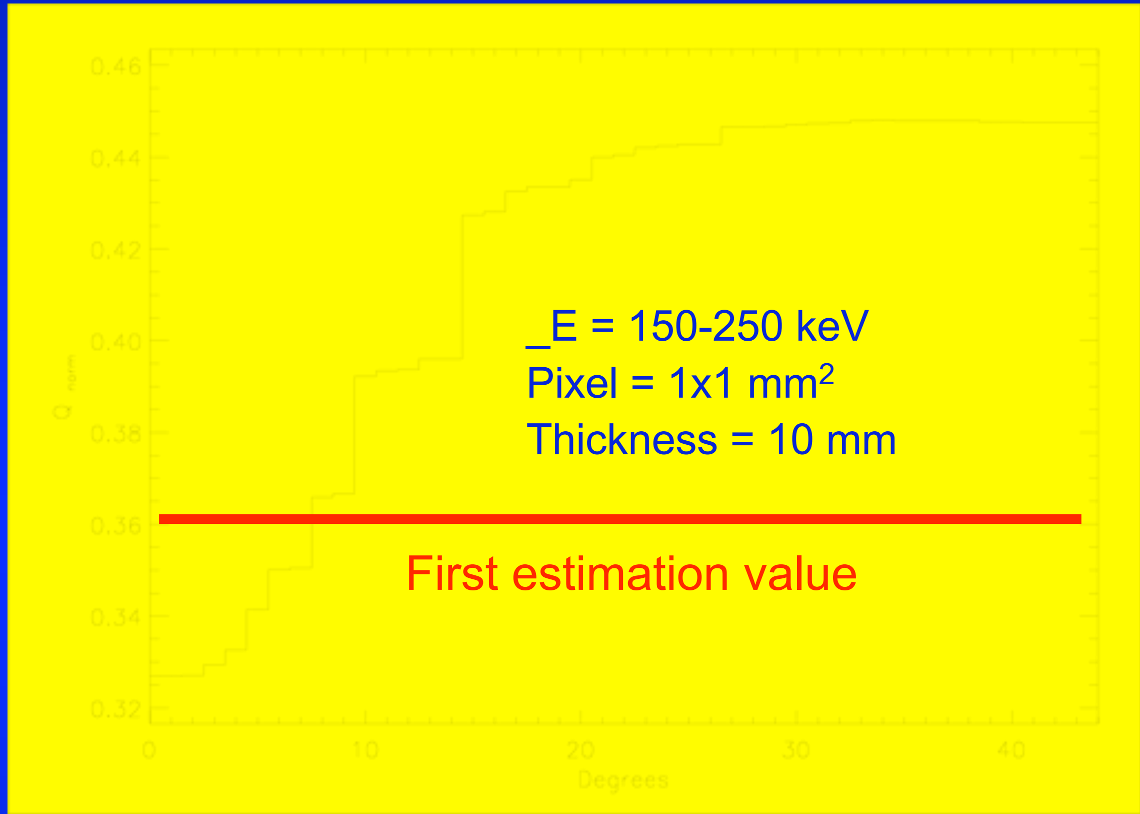

100
10
1
MDP (%)
1,0E+03
1,0E+04
1,0E+05
1,0E+06
Observation Time (s)
150 to 250 keV
250 to 400 keV
400 to 600 keV
HE Laue Lens
10 mm thick CZT pixel detector

Modulation Factor vs Pixel Size



Q factor optimisation I





The structure is due to the large scale pixellisation and to the criteria for acceptance (inside a) of any pixel inside the integration over the __ wide detector sector.

The second plot is the effective Q factor that take into account the fraction of double events that are used in the calculation.

Q factor optimisation II

Background reduction methods:

- Accept only events that have one hit inside the PSF of the pointed source.
- Reject event in which the two energy deposits are not compatible with the Compton kinematics.
- Reconstruction of the photons incidence cone using Compton kinematics in order to accept (or reject) only photons for which the incidence cone is compatible with the instrument aperture (lens).

The efficiency of these methods is very sensitive to the performance and the characteristics of the focal plane detector: energy resolution, spatial resolution (pixel size in XY), thickness (Z axis).

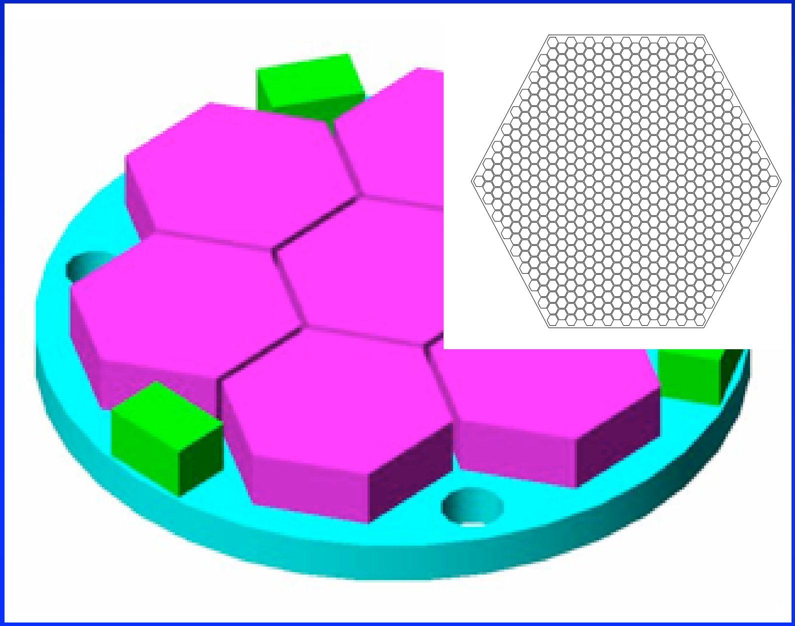
The Doppler broadening should be taken into account for the photon incidence cone direction and aperture uncertainties evaluation (between 1° and 10° in CZT detectors with the considered geometry depending on energy.

Expected Polarimetric performance

Source Polarisation Level	Sensitivity for a polarized source (10^6 s, 3_) Ph/cm^2/s/keV
	_E = 60-600 keV
50%	5×10^{-8} (~0.5 mCrab)
10%	2.5×10^{-7} (~2 mCrab)
2%	1.3×10^{-6} (~10 mCrab)

MDP for a 100 mCrab source (3_)	
Time	_E = 60-600 keV
10^4 s	10%
10^5 s	3%
10^6 s	1%

The study is in progress........



POLCA II Experiment

40x40 mm^2 CZT detector
2.5x2.5 mm^2 pixel,
16x16 pixels
5 mm thick
ASIC readout electronics

- Polarimetric response on the range 100-700 keV
- Q factor vs the angle between polarisation vector and detector axis

Monte Carlo Development

Implementation of a more symmetric configuration (e.g. Hexagonal)

SNR improvement using background reduction methods based on Compton kinematics

Better modelling of the Laue lens PSF (vs E and off-axis sources)

Conclusion……

The implementation of the Laue lens technique can provide an improvement in sensitivity of about 2 orders of magnitude with respect to current hard X and soft gamma ray telescopes.

A detector that can exploit high polarimetric performance together with good imaging and fine spectroscopy in the focal plane of this kind of telescope can attain unprecedented performance

……..Why not add this challenging feature to the same detector we will use for spectroscopy, imaging and timing ?

Detection efficiency vs energy for a CdTe detector with 2x2 mm^2 pixels and 10 mm thickness