POLarimetry with **C**admium telluride **A**rray (**POLCA**)

Evaluation of Polarimetric capabilities of CdTe Array prototypes for hard X- and gamma ray astronomy

Experiment No MI-592 Report

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Beamline:	ID 15
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1. Introduction

The POLCA (POLarimetry with Cadmium telluride Array) experiment, has been developed in a collaboration between the Laboratoire PHASE (PHysique et Applications des SEmi-conducteurs), CNRS, Strasbourg, France and the IASF –Sezione di Bologna (Istituto di Astrofisica Spaziale e Fisica Cosmica), CNR, Italy. It has been constructed as a prototype of a telescope for making polarimetric measurements of hard X-ray and soft gamma ray (100 keV – 10 MeV) celestial sources, known as the CIPHER (Coded Imager and Polarimeter for High Energy Radiation) telescope [1]. The novel design of this telescope, using a matrix of thick CdTe micro-spectrometers detection plane will allow this type of measurement to be performed for the first time. As part of the design process, a sophisticated Monte Carlo simulation code based on the GEANT4 program was developed, and an extensive polarimetric study was performed [2] in order to evaluate the response and performance of the detection plane when subjected to linearly polarised radiation, as is likely to be produced in astrophysical sources where magnetic fields play an important role [3]. In order to compare these results with experiment, we have constructed prototype detectors of 4×4 pixels, and we have studied their response to linearly polarised radiation in the 100keV – 1 MeV energy range using the high energy beam line at the ERSF (European Synchrotron Radiation Facility) in Grenoble. This set of measurements was complementary to a stratospheric balloon flight of a similar detector which was undertaken in July 2002, and which is being used to analyse the background expected in this detector in typical high energy telescope conditions [4].

2. Experiment description

The POLCA experimental set-up is schematically shown in Figure 1. The following four

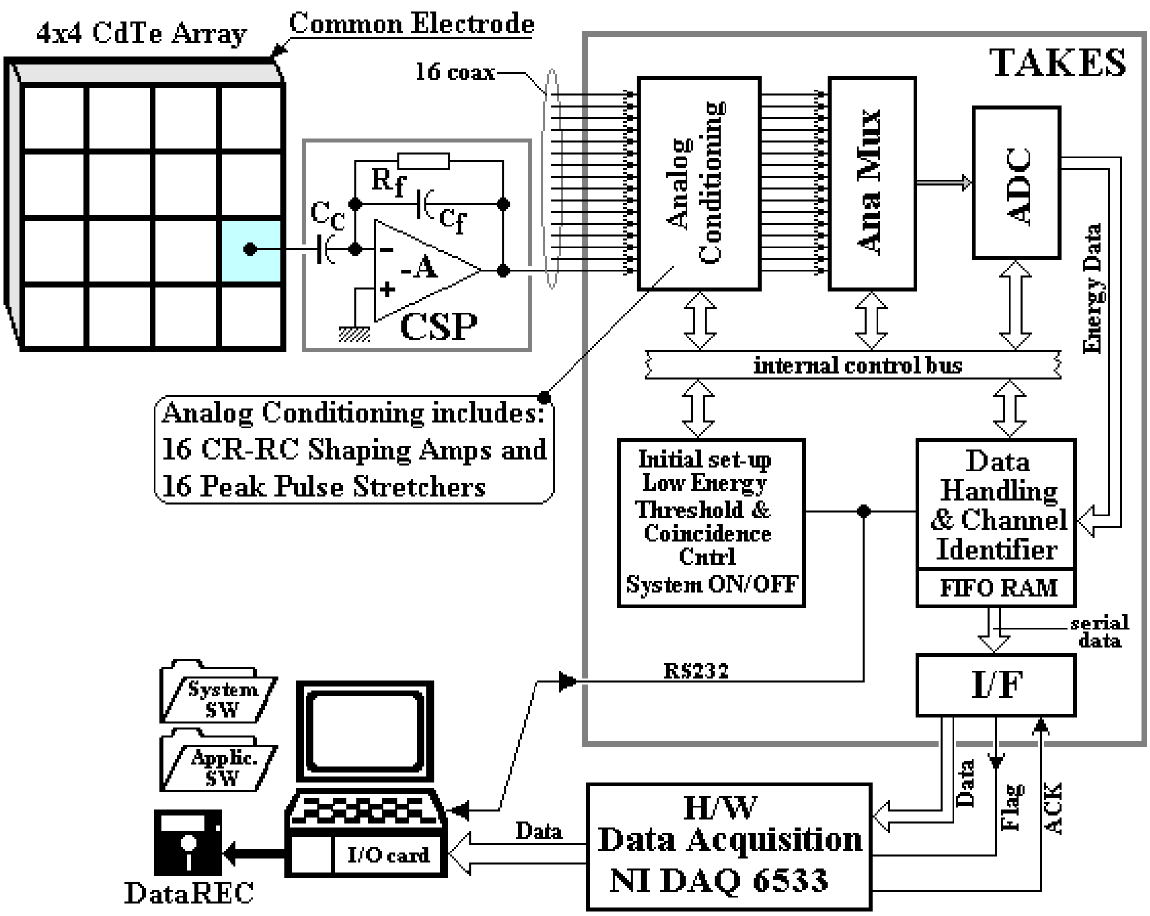

***Figure 1.** The POLCA experiment*

main functional subsystems can be identified:

The CdTe detector and the front-end electronics. Three Eurorad CdTe detector arrays (Table 1), each organized as 4x4 pixels, were used in the experimental set-up and separately exposed to the γ-ray beam. The front-end electronics simply consists of 16 Charge Sensitive Preamplifiers (CSP), each connected to a detector electrode so as to separately analyze the spectroscopic performance of each individual detector channel (Table 2). An overall view of this subsystem is given in Figure 2.

Table 1
Principal characteristics of the Eurorad CdTe etectors

Thickness (mm)	Pixel (mm)	Bias (V/mm)	ρ (Ohm/cm)	D. C. (nA)
3.4, 5, 7.5	2.5	~100	$1 - 5 \times 10^9$	20 - 40

Table 2
Main characteristics of the Eurorad CSP

Sensitivity	2 V/pC
Sensitivity vs photon energy	70 mV/MeV
Rise time	< 200 ns
Equivalent noise	< 3 keV
Bias	+/- 12 V

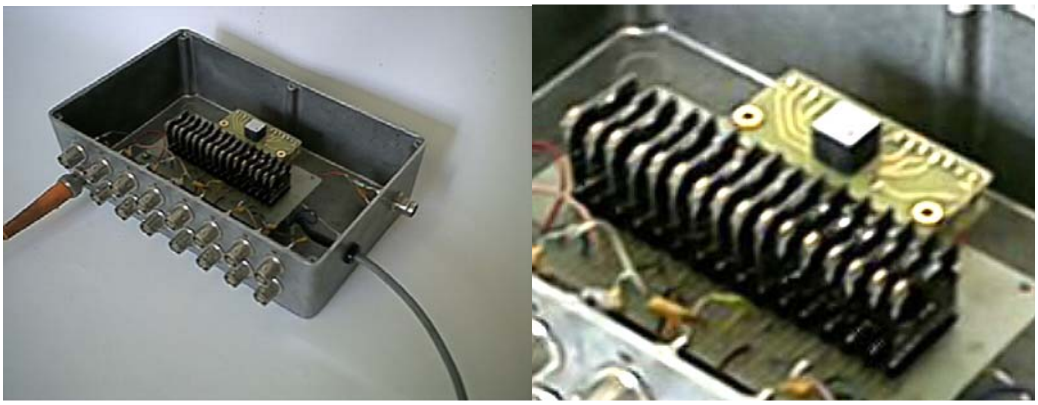

***Figure 2**. The left picture shows the tight-light box containing the pixellated detector (the little dark cube in the centre) and the 16 preamplifiers close to the CdTe crystal (zoomed in the right picture).*

The analog processing electronics (TAKES) [5]. The Takes subsystem is a custom electronics designed and wired to process analog signals from CdTe detector arrays of up to 32 channels. TAKES, which is remotely programmable via RS232 by the experiment control CPU, controls the functions also listed in Figure 1, consisting of the following subsystems:

- an analog processing subsystem that provides the filtering, active shaping and stretching of the 16 detector signals;
- a coincidence or anticoincidence event logic. When operating in coincidence mode, all signals exceeding the low energy threshold are passed to the the Analog-to-Digital Conversion (ADC) if they overlap within a preset time window. The coincidence time window, which is remotely presettable in the range [2÷20]μsec, was set at 2 μsec during the exposure to the γ-ray beam;
- a 16-to-1 Analog Multiplexer whose output is connected to a 12 bit “flash” ADC. The 10 most significant bits are used to code the event energy, while information on the channel address is provided by the Coincidence/Anticoincidence control logic on the internal control bus. Each event consists of a 16-bit data word, 10 bits being used for the Energy code, 4 bits for the channel address, one bit for the overflow, one bit for the end-of-event (multiple events within the set energy window are stored in th sequence in the FIFO memory, the last of which has e end-of-event bit set to “1”, the rest to “0”).

- the data handling subsystem which collects and stores the ADC data in an 8 kB temporary FIFO memory used to randomize the data.
- the output interface which passes the data collected in the FIFO memory to the external world synchronously with the request coming from the data acquisition hardware subsystem interposed between the TAKES and the CPU.

The data acquisition unit. This subsystem is based on a commercial data acquisition card PXI DAQ-6533 provided by National Instruments connected to a PC and controlled by a LABVIEW application that allows the control of the data acquisition and the saving of the data by means of an user-friendly graphical interface shown in Figure 3 [6].

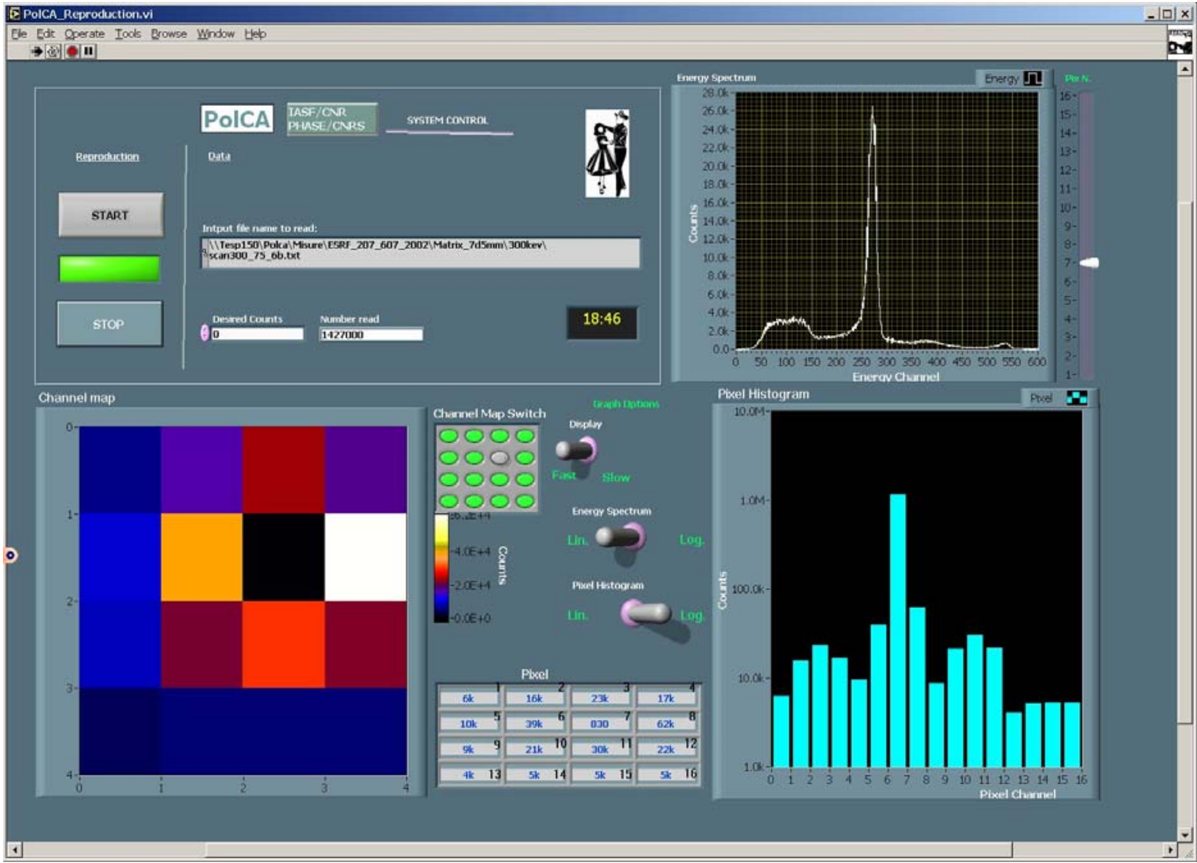

Figure 3. *The LABVIEW graphical interface of the quick-look s/w developed for the POLCA data acquisition units*

3. Beam tests at ESRF

The beamline chosen to perform the POLCA tests was the ID 15 (*High Energy X-Ray Scattering*) (see Table 3) that allows the user to obtain almost 100% linearly polarised photons in the range between 100 keV to about 1 MeV [7].

The detector container was mounted with the thin (50 μm) Al entrance window perpendicular to the beam on a plate with an XY micrometric movement inside a jig allowing rotation around an axis perpendicular to the XY plane [Figure 3].

During the measurements we have utilized monochromatic beams at three different energies: 100, 300, and 400 keV. Between the beam from the monochromator bench and the detector window a tungsten collimator with a variable square aperture was used (Fig. 3): 0.2×0.2 mm^2 at 100 keV; 0.4×0.4 mm^2 at 300 keV. For the 100 and 300 keV measurements we have further reduced the intensity of the incident beam by adding a 1 mm thick Pb layer at the exit of the collimator slice in order to avoid as much as possible electronic pile-up effects.

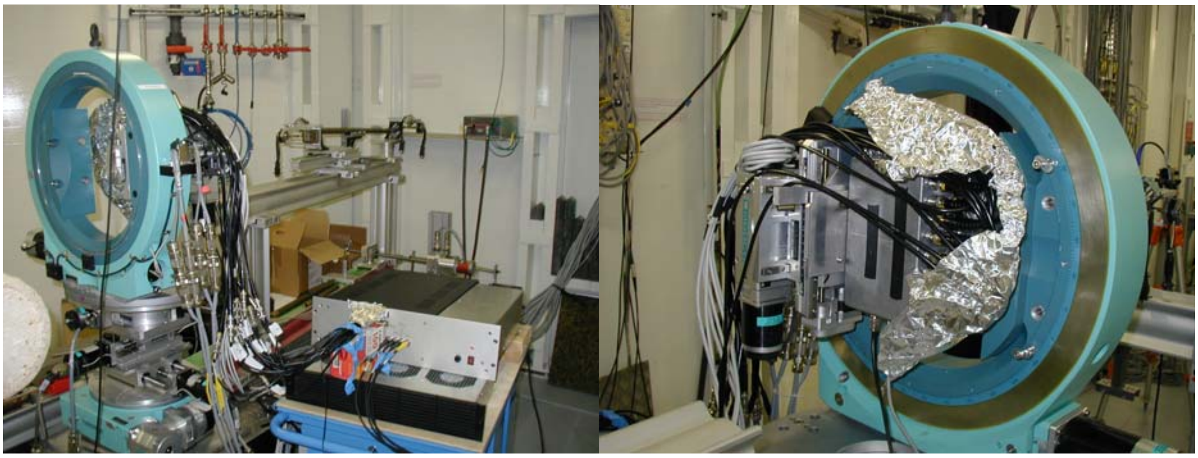

Figure 3. *In the left picture the POLCA setup inside the ID-15 beam line hutch; it is clearly visible the analog processing electronics (TAKES) on the right. The right photo shows a zoom on the detection subsystem.*

We checked the trigger energy threshold and the gain alignment of the front-end electronics using a ^{57}Co radioactive source and the 3.3 mm thick detector. The operational energy threshold was adjusted to be equivalent to 30-50 keV, the exact value depending on the pixel. As a first step we performed some measurements on the background level in the experimental hutch without the beam. These tests showed a very clean environment, with the measured background being only a few counts/s over the entire POLCA operational energy range (~50-1000 keV).

After these preliminary operations we started the proper scans using the following procedure:

1. Centering the CdTe array. Using the quick-look s/w the PSD was moved until the counts distribution in the 4 central pixels become uniform (i.e. difference of ~10/15% in the pixels counts rate);
2. Moving the beam to the centre of pixel 1 (top left corner)
3. Scanning the entire CdTe array moving from pixel centre to adjacent pixel centre (each scan lasting from a minimum of 3 to a maximum of 10 minutes)
4. Rotation of the by 90 degrees around the centre, followed by repetition of steps 1, 2, and 3. The rotation was applied to correct systematic effects due to the positioning error in the beam spot: due to the distance between the detector surface and the collimator slit exit, the estimated spot diameter on the CdTe surface was double the size of the collimator aperture. This step is essential for later normalisation in the search for polarimetric asymmetry.

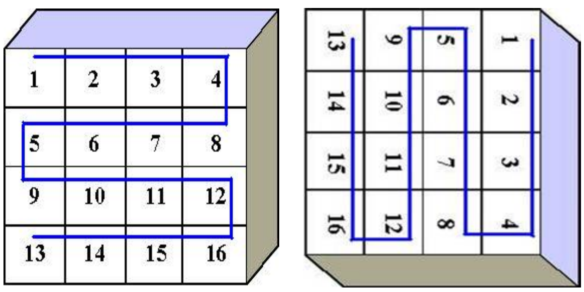

Figure 4. *The scan path applied to each detector before (Step 3) and after the 90 degree rotation*

All the data acquired during the measurements was recorded in ASCII files in which each line represents a 16 bit coded word containing the information of each analyzed hit, from the most to the least significant bits: pixel number (4 bits), end event flag (1 bit), energy overflow flag (1 bit), signal amplitude (10 bits).

4. Pixel response uniformity

The first analysis step was the measurement of the efficiency uniformity with respect to single and double events (i.e. Compton scattered events that trigger either one or two separate pixels inside the coincidence window). This study is particularly important for the evaluation of the polarimetric modulation factor. Figure 5 show a sample of single hit event spectra at different beam energies and for different pixel of the same array, while Figures. 6 summarize the evaluation of the pixel relative efficiency for both single and double hit events in the three CdTe arrays for each beam energy used. The relative efficiency is defined as the ratio

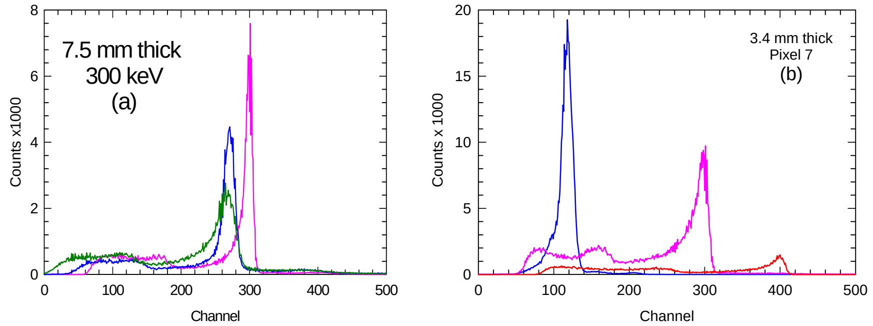

Figure 5. *(a) Single events spectra obtained in three different pixels of the 7.5 mm thick array at 300 keV; (b) The response of 3.4 mm thick array pixel n. 7 at all the used beam energies.*

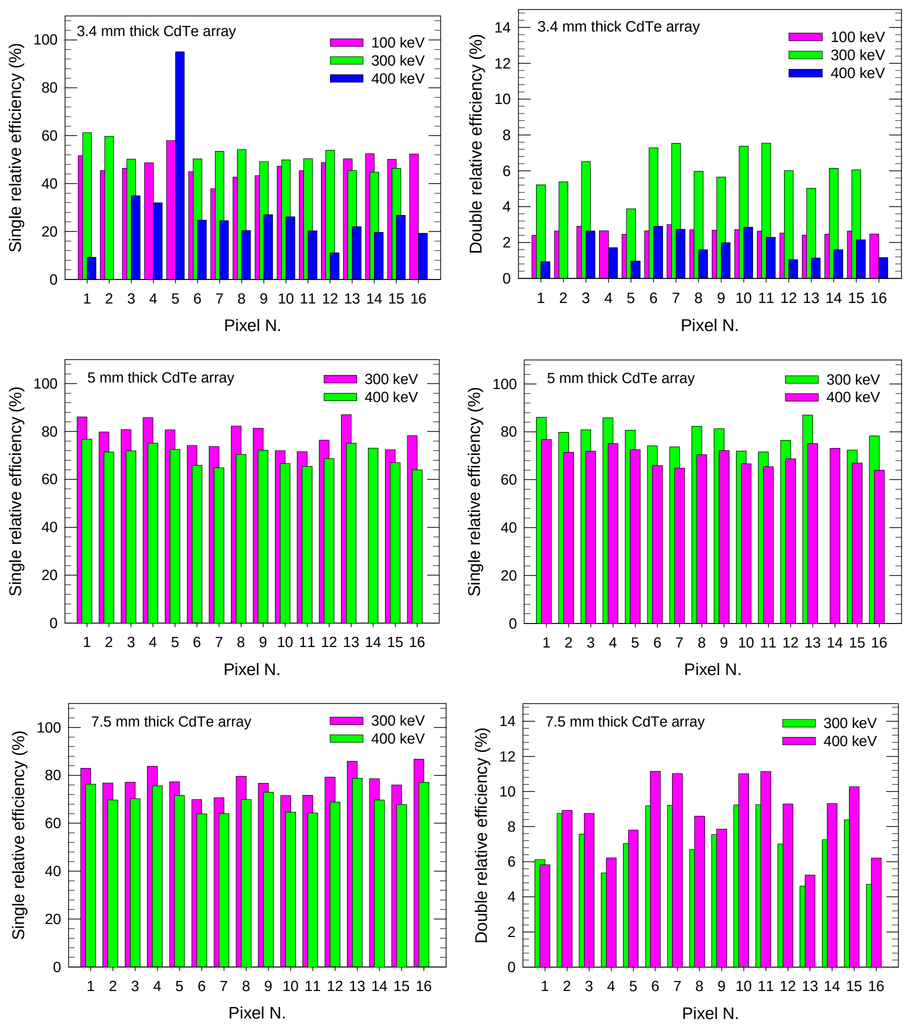

Figure 6. *Relative efficiency of the single hit events (left) and the double hit events (right) of CdTe pixels for the three tested detectors.*

between the number of detected single/double events in the beam incidence pixel and the total detected counts in the array during the same measurement. The dispersion of the single event efficiency values confirms the better homogeneity of the two thicker CdTe detectors with respect to the 3.4mm unit. In the case of the thinner matrix the relative efficiency at 100 keV is on average lower than at 300 keV because of the use of a low energy threshold which is around 40 keV for each pixel. The relative single event efficiencies for each pixel have been used to correct the double events distribution for non-uniformity before evaluating the polarimetric quality factor Q as described in the following sub-section. The quasi periodic structures in the distribution of the double hit events efficiency are mainly due to the geometric position of the pixels: in general the efficiency of the corner pixels (1,4,13,16) is noticeably less than for the core pixels (6,7,10,11) due to the scattered event loss through the two free pixel sides. As expected the side pixels exhibit efficiency values that are in average between these two extreme situations. Furthermore the double efficiency data at 100 keV for the thinner array confirms the effect of the threshold.

5. The Polarimetric Quality factor

The polarimetric performance of an instrument can be evaluated by analysing the distribution of double events through the polarimetric modulation factor, *Q*. This is obtained by integrating the Compton polarimetric differential cross section formula over the solid angles defined by the physical geometry of the detection plane (see Figure 7):

$$Q = \frac{N_x - N_y}{N_x + N_y} \qquad (1)$$

Here we obtain *Q* through the orthogonal *x*- and *y*-axis directions defined over the detector plane, to a polarised beam whose electric vector points in the y direction. N_x and N_y are the number of counts in each of the orthogonal directions.

The single events obtained in each of the directly irradiated pixels allow us to determine the response map of the 4×4 detector pixels. Therefore we are able to later correct the non uniformity of the response of our monolithic CdTe detectors using these distributions. This is done through the irradiation of the detector surface by a photon beam in the same condition of our measurements, obtaining a pixel response non dependent on the polarisation of the incident beam, as is the case of the single events detected in the pixel directly irradiated by the beam. Then we calculate the true double events counts N_{true} for

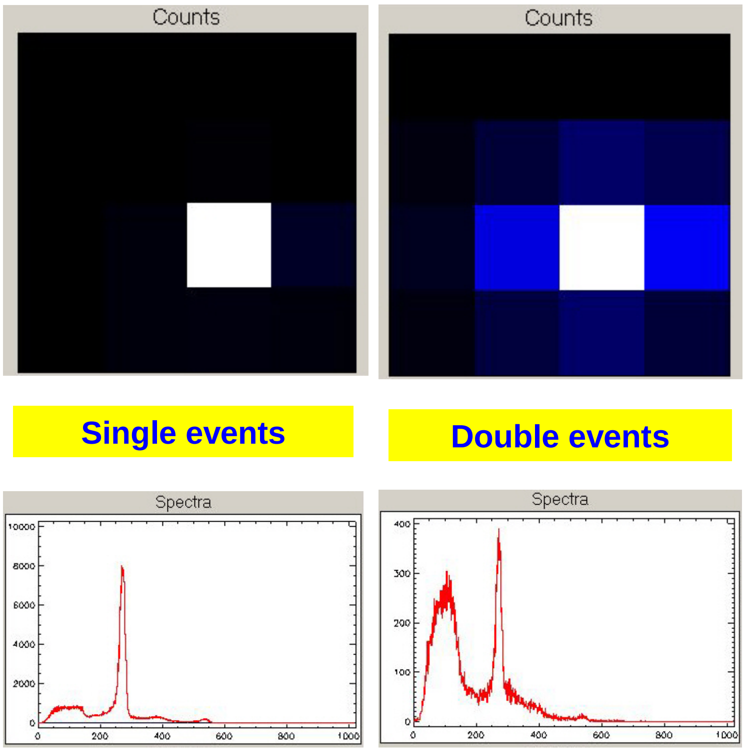

Figure 7. *The spatial distribution of single an double hit (scattered) events in the 7.5 mm thick CdTe array together with respective measured spectra. It is well evident the asymmetry due to the beam polarization in the double events distribution*

each pixel by:

$$N_{true} = \frac{N_{pol}}{N_{non}} N_{\max} \qquad (2)$$

where N_{pol} is the number of double events detected (that depend on the beam polarisation), N_{non} are the single events detected when the pixel is directly irradiated and N_{max} is maximum value among all the matrix pixels N_{non} [2].

The 90° matrix rotation allowed us to verify that our extrapolation method to a 7×7 pixel matrix is justified. By irradiating the matrix corner pixels we are able to obtain double event distributions throughout the crystal volume until third order pixels. Therefore we studied the double event distributions corresponding to corner pixel irradiation (pixels: 1, 4, 13 and 16). In Figure 8 we present double event distributions for two monochromatic 100 % polarised photon beams (300 and 400 keV) produced in the 7.5 mm detector. As can be seen the double event distribution has a higher number of hits in the direction orthogonal to the beam polarisation vector direction, as predicted by (1). From the double event distributions we can calculate the polarimetric modulation factor Q of our prototypes through (1) as if a 7×7 pixellated matrix was used. Table 3 shows the polarimetric modulation Q factors calculated for the three CdTe polarimeter prototypes used in our polarimetric study as a function of the polarised photon beam energy. The polarimetric Q factors were calculated after the correction for the non uniformity of the response of the detector throughout its pixelated volume using equation (2).

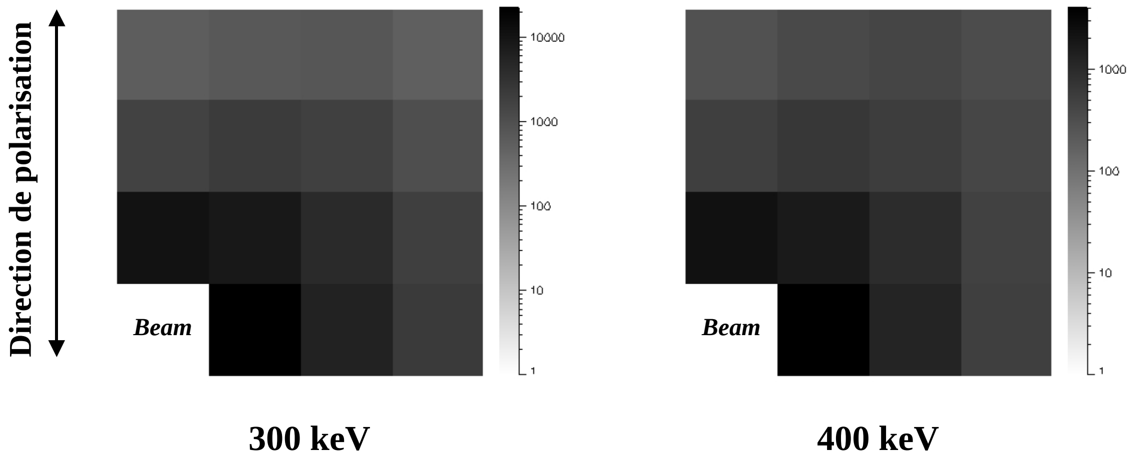

Figure 8. *Double events distributions obtained after irradiating a corner pixel of a 7.5 mm CdTe 4×4 matrix by a 100 % polarised beam. The direction of the polarisation vector of the incoming beam is represented*

Table 3
Polarimetric Q factors calculated (and standard deviation) from double events distributions produced by the 100 % polarised photons of the ID-15 beamline.

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

The POLCA experiment results show that a CdTe planar matrix can be a very efficient polarimeter for X- and γ-ray sources as polarimetric *Q* factors of the order of 0.4 can be obtained together with double event relative efficiencies higher than 20%. It was also shown that the polarimetric performance of a planar CdTe matrix is improved by reducing the pixel thickness, even though the detector efficiency decreases correspondingly.

To achieve further information, in particular on the polarimetric performace of this type of position sensitive detector and its dependence on the angle between the photon polarization plane and the detector axis, we will intend to repeat the beam test with a better energy coverage of the 100-1000 keV range and with a larger CdTe arrays as the polarimetric Q-factor increases with distance between the two pixels involved in a compton scattered event.

Achnowledgement

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