Experimental measurements obtained with the CZT PolCA detector at Leicester University

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TABLE OF CONTENTS

Aims

This document presents the experimental set-up used at Leicester University to realize a hybrid detector prototype composed by a spare CMOS CDD of the EPIC/XMM as soft X-ray detector and a CZT matrix (Imarad) as hard X-ray detector, the results of the calibration phase of the CZT detector carried out at INAF/IASFBologna and the performed tests on the hybrid detector.

1. Documents Applicable

1) P.J. Pool, R. Holtom, D.J. Burt, A.D. Holland.
"Developments in MOS CCDs for X-ray astronomy".
NIMA, 436, (1999) 9 – 15.

2) A.D. Short, R.M. Ambrosi, M.J.L. Turner.
"Spectral re-distribution and surface loss effects in Swift XRT (XMM-Newton EPIC) MOS CCDs".
NIMA, 484, (2002) 211–224.

3) T. Abbey, N. Auricchio, R. Ambrosi, E. Caroli, S. Del Sordo, A. Donati, D. Ross, F. Schiavone, G. Ventura.
"CZT Bo/Pa Set-up for the hybrid experiment at the Leicester University".
Internal Report IASF/BO n. 425/2005.

4) N. Auricchio, E. Caroli, A. Donati, Filomena Schiavone, Leonardo Abbene, Stefano del Sordo, Richard Ambrosi, A. F. Abbey , C. Brown, H. Su.
"Experimental set-up and measurements with a hybrid detector prototype at the Leicester University".
Internal Report INAF/IASF-Bo n. 529/2008.

5) G. Ventura, E. Caroli, N. Auricchio, A. Donati, G. Landini, F. Schiavone, R. M. Curado da Silva.
"*POLCA2 (POLarimetry with CZT Arrays): experimental set-up, calibration procedures and results"*.
Internal Report IASF/BO n. 444/2006.

2. Summary

The scientific objectives of next high throughput mission in X-ray astronomy require new type of focusing telescopes able to extend the observational range at least up to 100 keV to solve crucial question concerning the nature of the high energy emission from cosmic source and the origin of the cosmic X-ray background. A challenging technology to extend the classical grazing incidence range to higher energy is today offered by the development of multilayer optics that are effective as X-ray concentrators between few keV up to 80/100 keV. A useful arrangement for this type of mission concept (e.g. NHXM) can foresee the soft (e.g. 0.1-10 keV) X-ray optics nested and coaxial with the hard-X mirrors. This means that the focal plane of the telescope shall operate on the overall energy range (from 0.1 to 80/100 keV) fulfilling at the best the different requirements of the two optics type in terms of detection efficiency, spatial resolution and spectroscopic performance. A solution for this kind of focal plane detector is given by an hybrid design with a soft X ray detector (e.g. CCD) in front and coaxial to an hard-X ray detector (e.g. Pixel CZT spectrometer).
In this contest our collaboration (Space Research Centre of the Leicester University and INAF/IASF-Bologna/Palermo) had the idea to assemble a hybrid detector prototype using as soft X-ray detector a spare CMOS CDD of the EPIC/XMM instrument developed at Leicester University and a CZT array designed at INAF/IASFBologna as hard X-ray detector.
This report describes the experimental set-up used during a second session of measurements carried out at the Leicester University, that utilizes a spare CMOS CDD of the EPIC/XMM and a pixel detector read by a custom electronics, and presents the results obtained.
The main characteristics of the two detectors are shown in Table 1.

Detector	**Type**	**Operative Range**	**Spatial resolution**	**Energy Resolution**	**Efficiency**
CZT	Pixellated (16x16)	10 keV-1.5 MeV	2.5 mm	~9% @ 122 keV	99.9% at 60 keV
EPIC CCD22	MOS CCD	0.2 -10 keV	40 μm	~ 3% @ 3 keV ~ 2% @ 10 keV	~ 80% @ 3 keV ~ 25% @10 keV

Table 1. The main characteristics of the two detectors used for the Hybrid prototype.

3. Spectroscopic performances of the detectors

3.1 PolCA CZT detector

We have used a detector, illustrated in Figure 1, based on a 5 mm thick CZT crystal with the anode segmented into 16×16 pixels (2.5×2.5 mm^2) from Imarad. In the current configuration only an array of 11×11 pixels (sensitive area of 2×2 cm^2 with an interpixel gap of 0.5 mm) is connected to the readout electronics. The pixel readout is provided by eight eV PRODUCTS 16-channel ASICs with peaking time set at 1.2 μs and gain of 200 mV/fC. The HV bias for the detector (-600 V) is provided by a DC-DC converter (EMCO), while the low tensions for both the ASIC's board and the DC-DC converter are generated by an external custom made power unit [1].

The multiparametric back-end electronics is able to read up to 128 independent channels with filters, coincidence logic and ADC units. This system is connected, through a high speed 32 bit parallel NI-DIO/PXI board, to a PC with quick-look and storage s/w developed in LABVIEW.

The detection system is schematically represented in Figure 2: it comprises the pixel spectrometer with the analogue front end electronics, the data processing electronics and the data acquisition system.

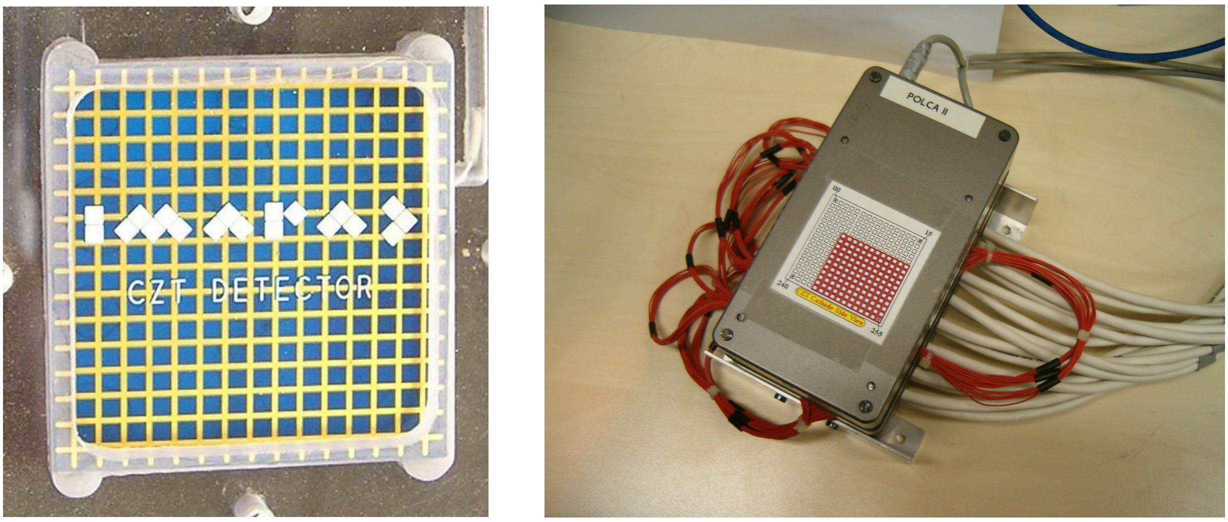

Figure 1. PolCA detector with top cover removed (left) and in its standard housing (right).

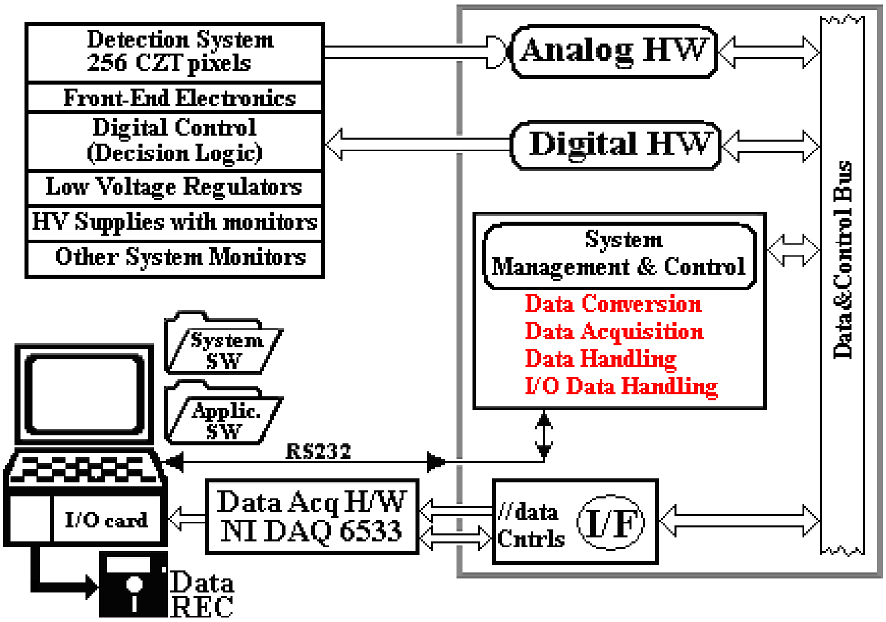

Figure 2. The functional scheme of the detection system: (left top box) the CZT pixel detector with the Analogue front-end electronics; (right box) the multiparametric data processing.

Since the Takes internal amplification factor is set at too high values for the ASIC eV-16 output levels, it is necessary to lower the overall amplification factor by using series resistors on any measurement channel (R = 15 kΩ). Furthermore, the AC coupling of the Takes electronics' input channels ensures for the elimination of the DC offset provided by any ASIC eV output channel.
Data are acquired by the PC through a National Instrument NI DIO 6533 digital interface which is managed by a HW handshake. The PC resident SW is able to manage the experiment and to output both energy and position data, as well as data storage.

Calibration measurements were carried out at INAF IASF/Bo with ^{241}Am and ^{109}Cd uncollimated sources using the same gain and peaking time of the tests performed at Leicester University. We have concentrated the data analysis on a subset of the pixels less noisy, ~ 40. In Figure 3 we report the energy spectra of the pixels acquired with these sources.

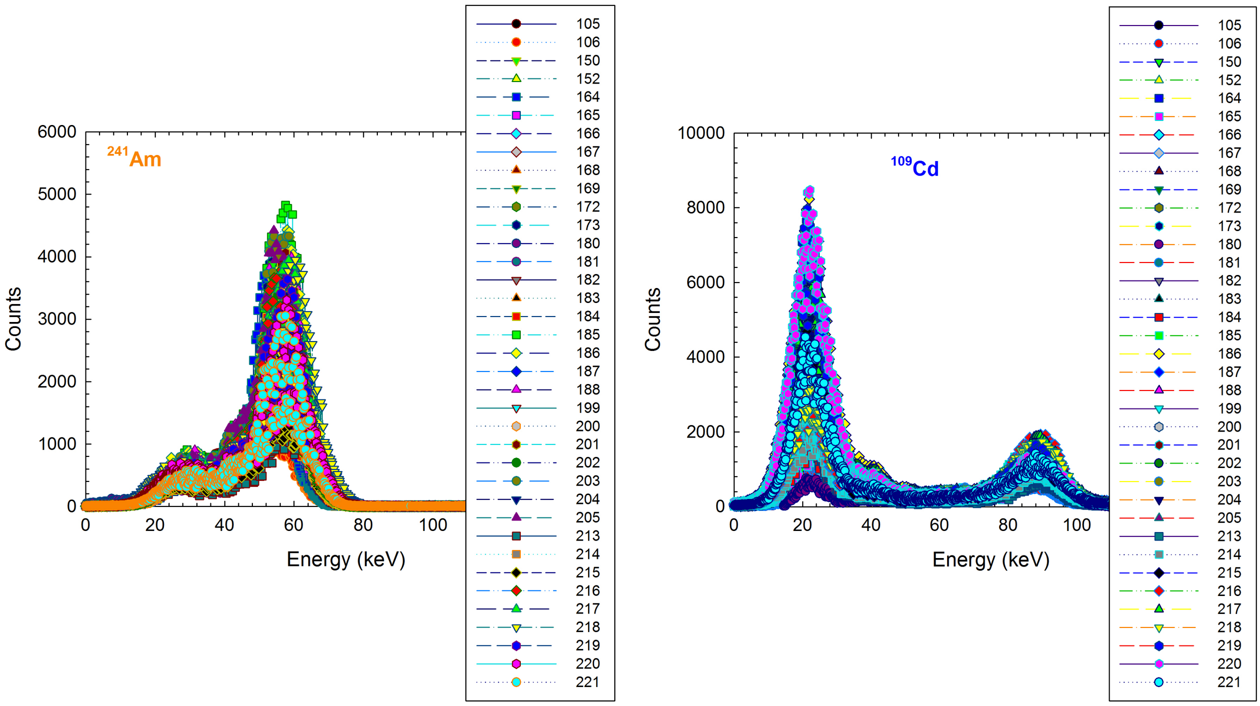

Figure 3. Energy spectra of ^{241}Am (left) and ^{109}Cd (right) acquired by illuminating ~40 pixels.

In Figure 4 the calibration lines of the pixels, obtained by fitting the experimental data at 22.1 and 88 keV, are reported while the behaviour of the photopeak centroid normalized to its maximum value is shown in Figure 5.

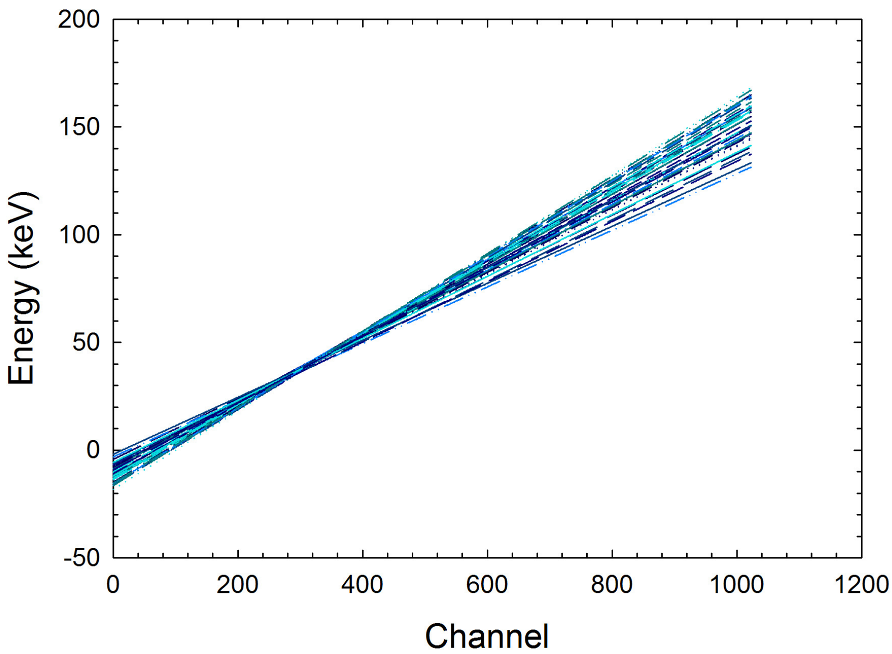

Figure 4. Calibration curves obtained using the centroids at 22.1 and 88 keV. The equalization of the channels was done in another environment at 1% level about six months before, but there was no time to repeat it.

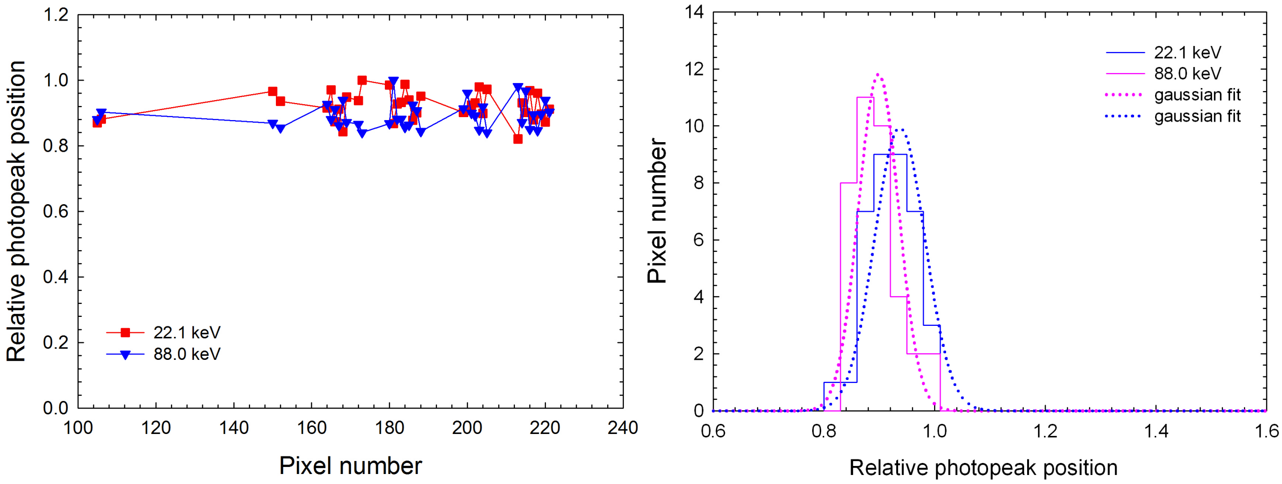

Figure 5. Behaviour of the photopeak centroid of the examined pixels at 22.1 and 88 keV, each value is normalized to the relative maximum (left); histogram of the centroid values (right).

The maximum dispersion is ~15%, while the mean value of the normalized centroids is (0.94±0.05) at 22.1 keV and (0.90±0.04) at 88 keV.

3.2 A spare CMOS CCD of EPIC/XMM

The CCD22 is a three-phase frame transfer device, which utilises high resistivity silicon and an 'open' electrode structure in order to achieve useful quantum efficiency in the energy range 0.2–10 keV. Each CCD is three sides buttable and has an imaging area of 2.5×2.5 cm^2.
The CCD image section is a 600×600 pixel array of 40×40 μm^2 pixels. The storage region is a 600 × 602 pixel^2 array of 39×12 μm^2 pixels. The readout register is split into two sections, each of 300+5 elements, ending in a readout node. The full CCD image may be read out using either node, or may be split and read out using both nodes simultaneously. The CCDs may also be operated in fast timing mode (spectroscopy but no imaging), and window mode (rapid readout of a central imaging area only). These modes allow spectroscopy to be conducted over a wide range of source flux. This capability is important for observing sources as bright as several times the intensity of the Crab. A simplified CCD schematic is given in Figure 6.
The low-energy response of a 'conventional' front illuminated CCD is restricted to energies greater than 700 eV due to X-ray absorption in the electrode structure. This may be improved by thinning one of the electrodes, as demonstrated for the JET-X CCDs developed by the University of Leicester and e2v Technologies for the Russian Spectrum-X-Gamma observatory [2]. For XMM a further improvement was required in order to increase the quantum efficiency below 300 eV. In order to achieve this, one of the three phases is enlarged to occupy a greater fraction of each pixel, and comprises electrode fingers, leaving 'holes' to the gate oxide [3 and 4]. This gives an 'open' fraction of 40%. In the open areas, the surface potential is pinned to the substrate potential by means of a 'pinning implant'. Details of this electrode structure are still the subject of commercial confidentiality, so a greatly simplified schematic is given in Figure 7. High-energy efficiency is maximised by using epitaxial silicon of the highest available resistivity (typically 4000 Ω cm). The depletion depth is about 30 μm thick, the epitaxial layer is 80 μm thick (p-type) and the substrate is 200 μm thick.

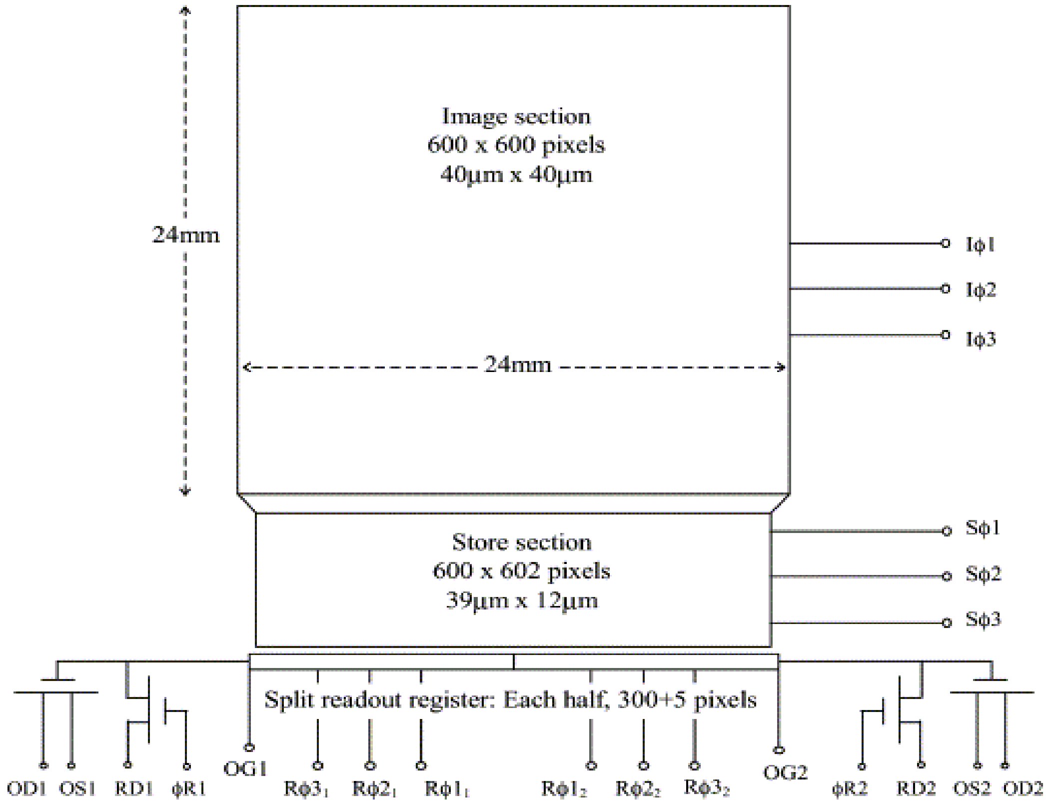

Figure 6. CCD22 simplified schematic.

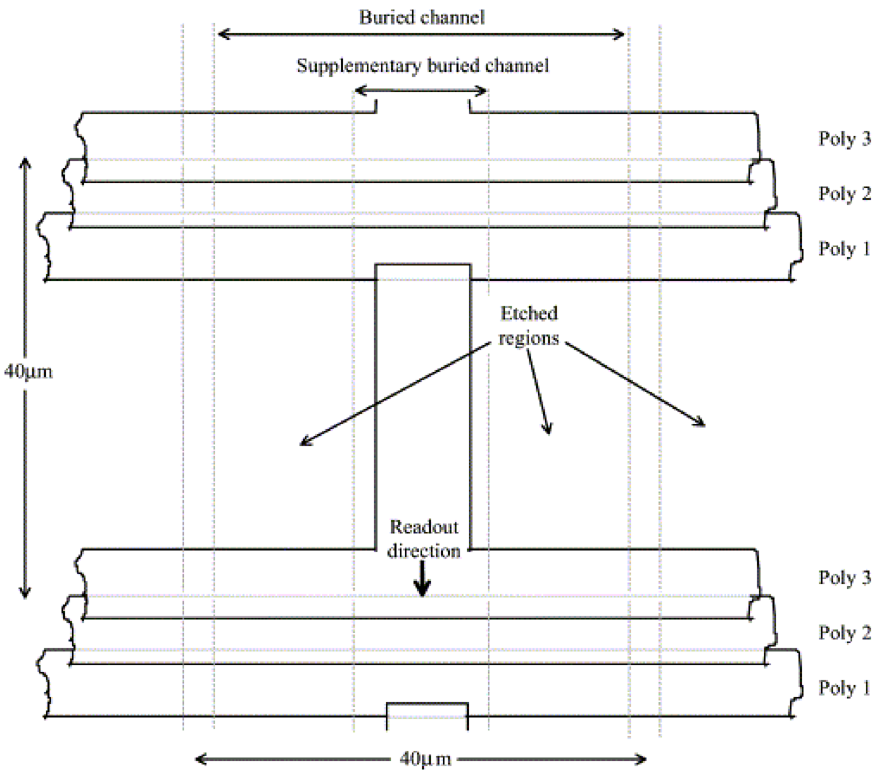

Figure 7. Simplified CCD22 electrode structure.

In the following figure we present the energy spectra acquired with a single pixel and with 4 pixels. We have used an attenuating Al filter placed in front of the ^{109}Cd source thick 288 µm.

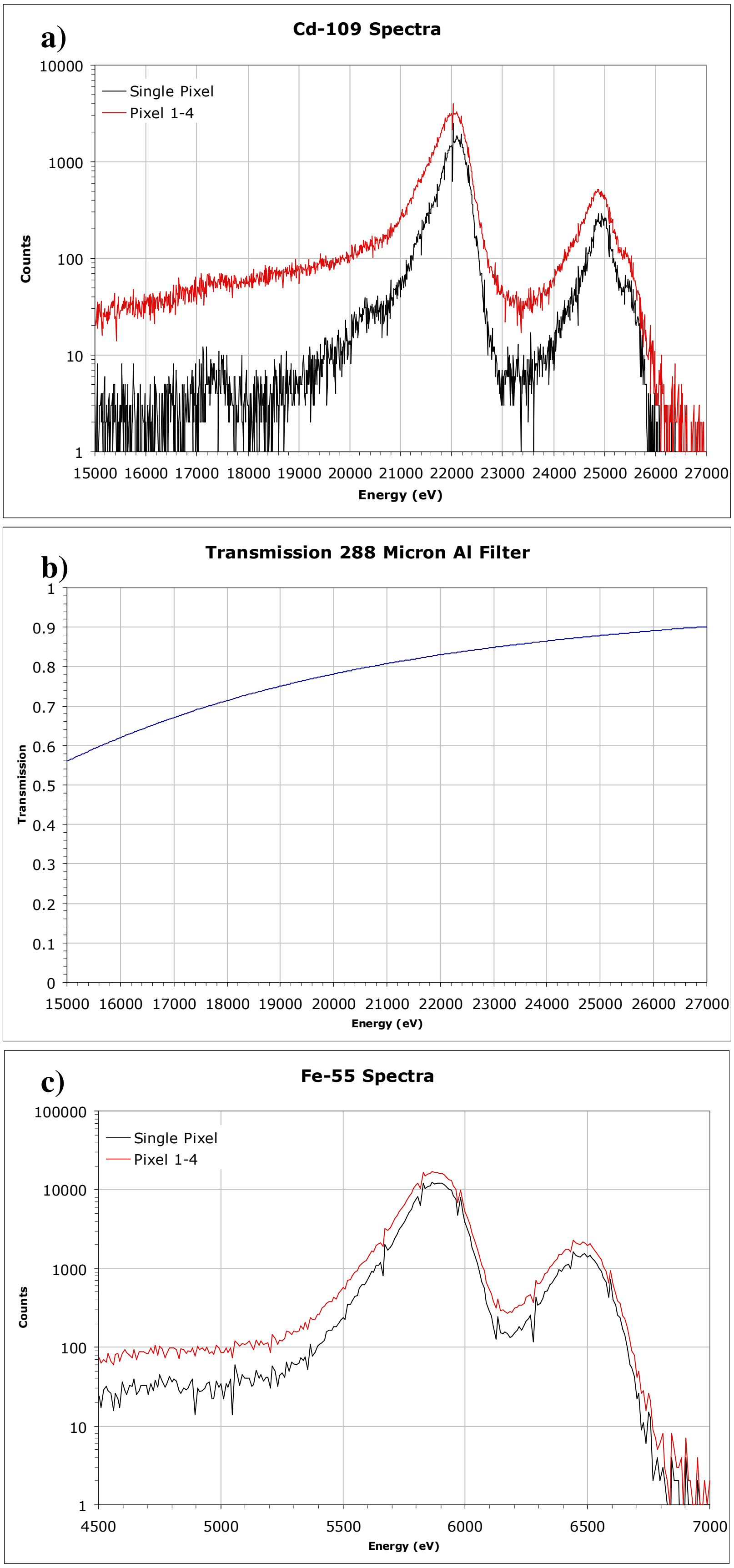

Figure 8. a) Pulse height spectrum recorded with ^{109}Cd source; b) transmission calculated for the 288 micron Al filter; c) spectrum acquired with ^{55}Fe without attenuating filter.

4. Experimental set-up

The IASF Bologna and Palermo groups in Italy together with the University of Leicester, Space Research Centre, have initiated a collaborative instrument development program to build a hybrid position sensitive detector consisting of a Cadmium Zinc Telluride (4x4 pixel array) and a thinned EPIC CCD22. This detector would be sensitive over the 0.2 to 100 keV energy range. The aim of the collaboration is to produce a breadboard model that could be exploited in a future X-ray astronomy mission opportunity.
An experimental program has been defined to integrate the two detectors in a specifically designed facility at the University of Leicester and carry out a series of live X-ray tests over the sensitive range of the detector. The CZT pixel detector is mounted on a Plexiglas support outside of the vacuum chamber (see photo 10, on the left) and irradiated with radioactive sources through a window of 10x10 mm^2 size, composed of a Al layer 25 μm thick and a kapton layer 500 μm thick. The use of such materials allows the transmission of 95% at 22.5 keV and 99% at 88 keV. In Figure 9 the vacuum chamber containing the CCD and in Figure 10 the overall view of the system are shown.

Figure 9. Vacuum chamber containing the CCD.

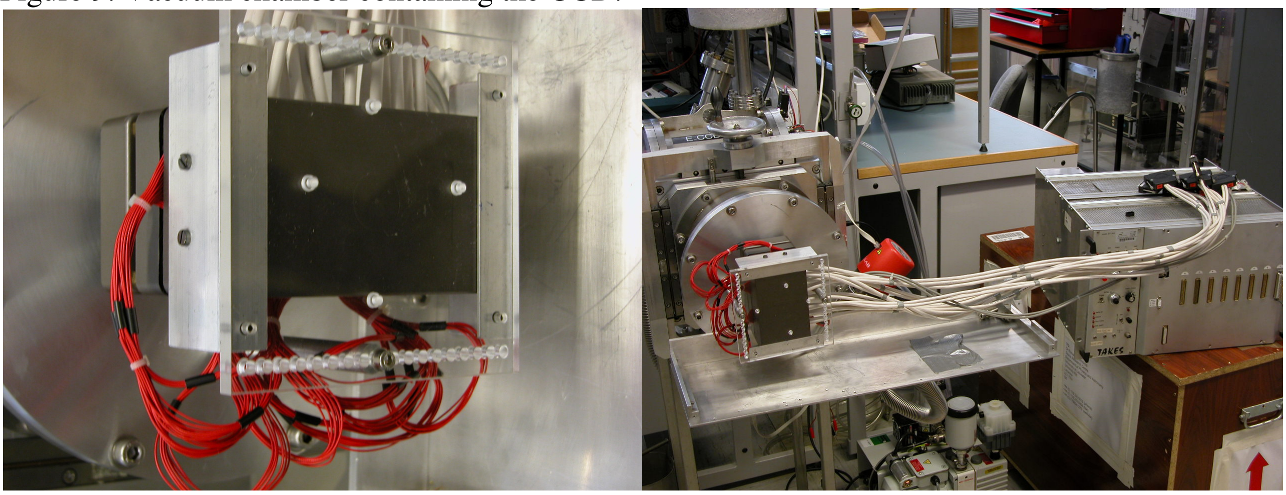

Figure 10. The pixel detector on the left; overall view of the used system on the right.

5. Spectra analysis

Calibration measurements were repeated at Leicester University with ^{241}Am and ^{109}Cd uncollimated sources and the energy spectra are displayed in Figure 11.

The spectra have been analyzed using the PeakFit software package (PeakFit v4.0. Peak separation and Analysis Software: User's Manual, Jandel Scientific Software, 1995) in order to obtain several parameters as the photopeak pulse amplitude and the energy resolution. The main characteristics of the spectra are: a Gaussian photopeak component corresponding to the energy of the incident photons and an asymmetric component caused by trapping effects. The first component has been modelled using a Gaussian distribution and the second was fitted using a typical chromatographic asymmetric function known as a Half-Gaussian Modified Gaussian.

In Figure 12 the photopeak centroids at 59.54 keV, normalized to its maximum value, are reported for the analysed pixels.

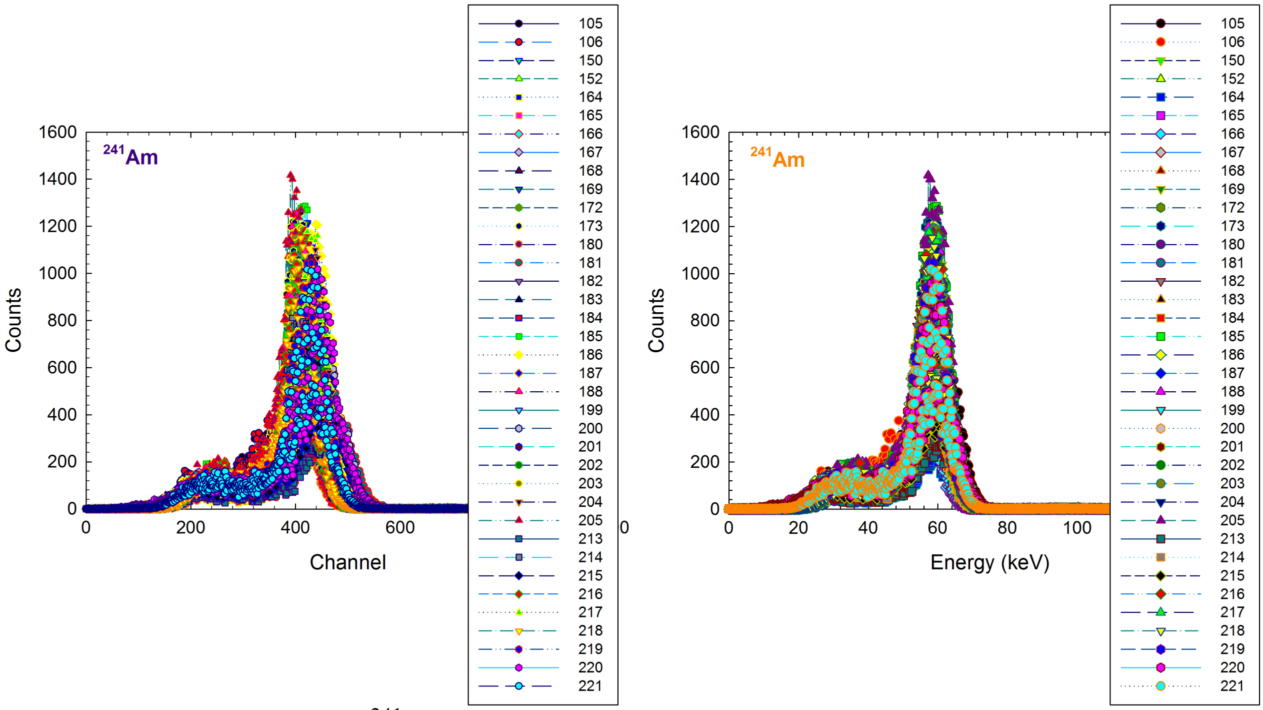

Figure 11. Energy spectra of ^{241}Am before (left) and after calibration (right).

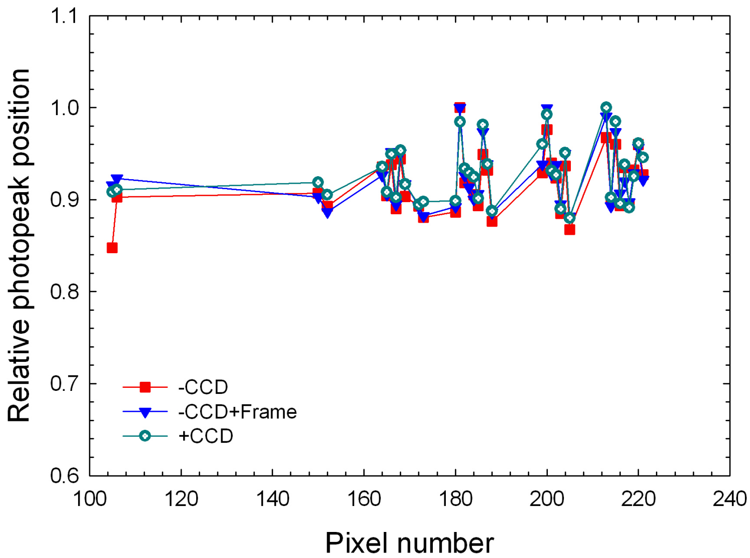

Figure 12. Behaviour of the photopeak centroid at 59.54 keV.

The graph illustrates the behaviour of the normalized centroids in relation to three measurements acquired with ^{241}Am , without CCD in front of the CZT detector, with only the frame of the CCD and with the frame and the CCD switched on in front of the pixel detector. The maximum dispersion of channels is ~12-15% for each measurement. We can see the stability of the device.
The main control panel of the software, developed in LabVIEW to read measurements previously acquired and recorded, is displayed in Figure 13, where we can see 4 major sections dedicated to different functions:

1 quick – look replay section: the input data file path allows to select the file to read, the start button allows to run the data reading and activate all the quick-look functions, the stop button allows to stop the Quick-look. The interface also displays information concerning to the measurements;
2 Pixel Map section: false colour map of integrated pixel counts. The active graphic cursor allows to select a pixel in order to plot the energy spectrum;
3 Energy Spectrum Pixel section: the graphic window shows, in real time, the energy spectrum (counts per channel) of the selected pixel on the Pixel Map. This section allows to perform a statistical analysis on the energy spectrum (centroid, FWHM);
4 Pixel Histogram section: the graphic window shows, in real time, the counts for each active pixel as histogram.

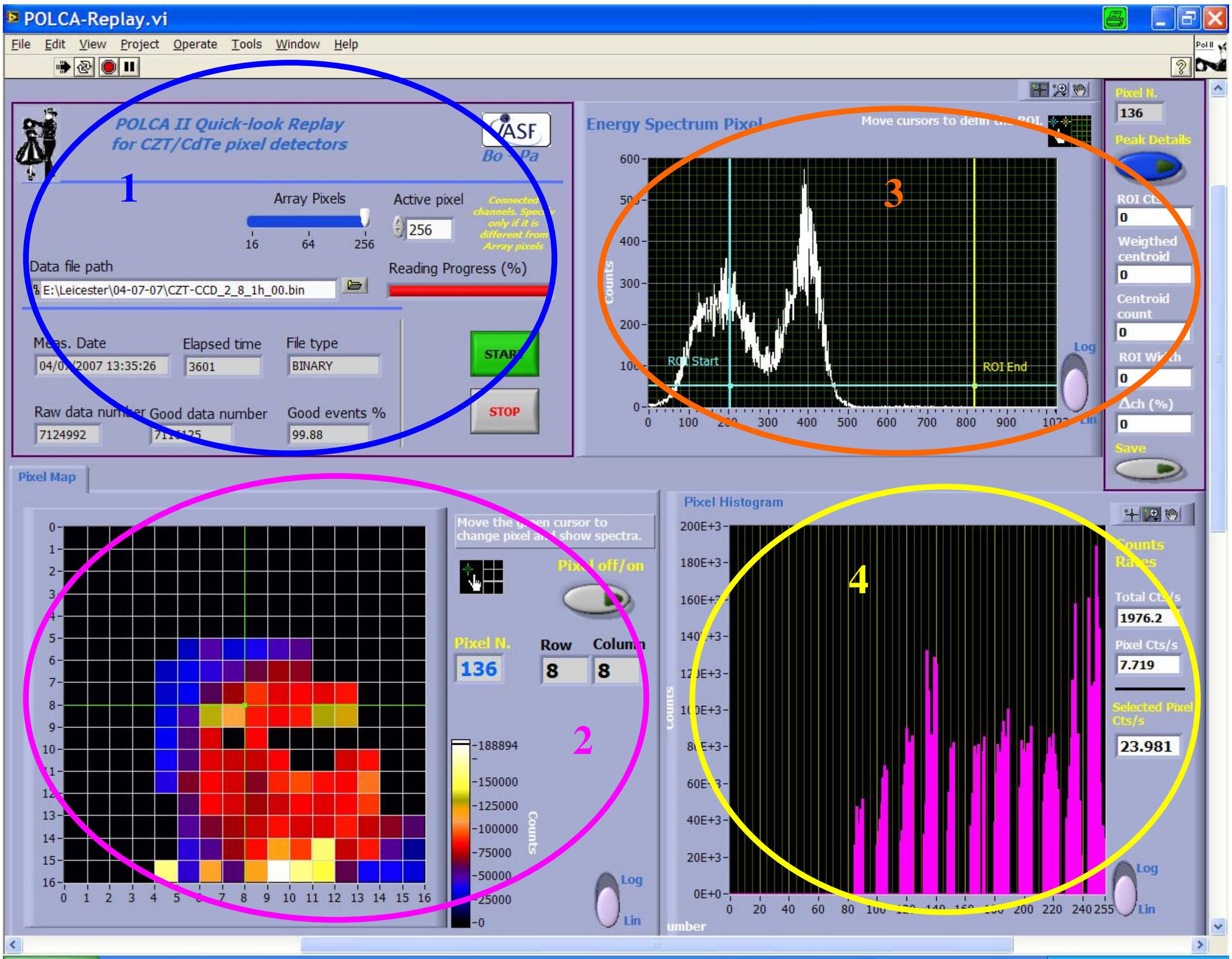

Figure 13. Main control panel of the software realized in LabVIEW to read the stored measurements.

In the pixel map section (2) we can see the region of the detector illuminated from the source, composed from pixels in red and yellow.

6. Performed measurements and results

The aim of the recorded measurements is to verify the coupling of a hybrid detector prototype using as soft X-ray detector the spare CMOS CDD of the EPIC/XMM and the CZT pixel detector as hard X-ray detector.
After calibrating the CZT detector and adjusting the low energy threshold we have performed some measurements as follows:

1) a background spectrum was acquired in order to subtract it from each pixel;
2) a source of ^{241}Am irradiated both detectors in coincidence mode;
3) a source of ^{55}Fe was placed immediately behind the source of ^{109}Cd; in this way the two sources irradiated both the CCD and the pixel array. The low energy photons of ^{55}Fe (~ 6 keV) interacted within the CCD but their energy was below the value of the CZT threshold, on the contrary the ^{109}Cd lines at 22.1 keV and 25 keV was measured both by the CZT and by the CCD.

We have carried out two tests:

a. the first without CCD in front of the CZT array,
b. the second with CCD in front of the CZT detector.

In following figures the measurements described above are reported.

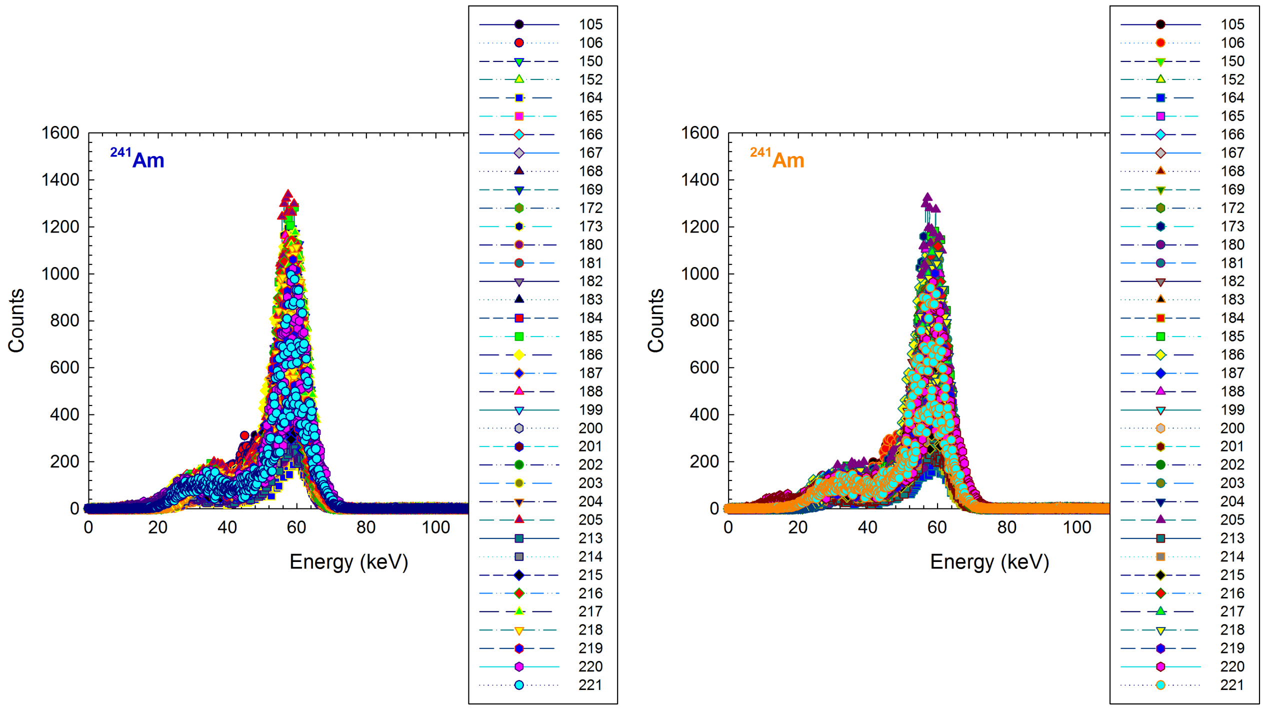

Figure 14. Measurement recorded without CCD in front of the CZT pixel detector (left); with CCD turned on in front of the CZT array (right) by irradiating with the ^{241}Am source .

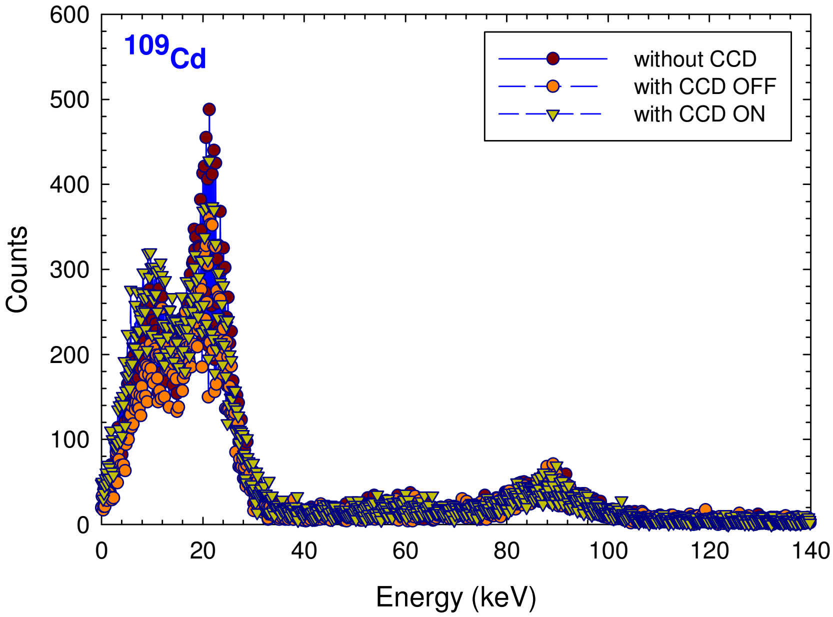

Figure 15. Measurement acquired without CCD in front of the CZT pixel detector; with CCD turned off in front of the CZT array and with CCD switched on using the sources of ^{55}Fe and ^{109}Cd. We have reported the sum of the analysed spectra.

For each measurement the energy spectra of the analysed pixels are summed in order to obtain the overall response of the detector and calculate the CCD transparency. The obtained results are:

- at 59.54 keV the CCD transparency is ~(97.0±0.1)%;
- at 22.5 keV the CCD transparency is ~(94.96±0.70)%;
- at 88 keV the CCD transparency is ~(98.5±1.0)%;

7. Comparison between expected and measured transparency of a spare CMOS CCD of EPIC/XMM

In Figure 16 the expected transparency of a CCD22 (calculated considering the materials placed in front of the source) is reported as a function of the energy.

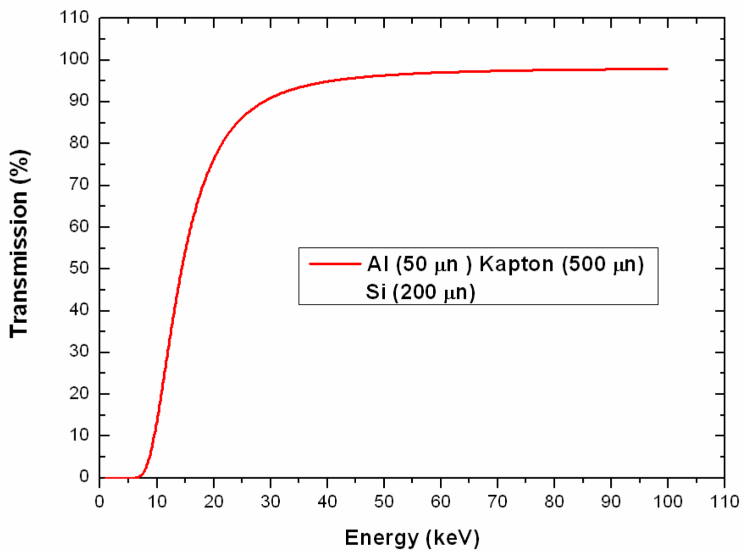

Figure 16. Expected transparency.

It is worth noticing that the values of transmission measured in the previous section are in good agreement with the theory.

8. Conclusion

The next satellite missions in the X-ray range (0.5-80 keV) will involve the use of nested and coaxial optics optimised for low and high energies (for example, grazing incidence mirrors that utilize thin glass shells coated with depth graded multi-layers to extend the bandpass and field of view compared to those achievable with standard metal surfaces). Detectors in the hybrid configuration described in this report are appealing as focal plane detector.

References

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3. H. Tsunemi, K. Yoshita, A.D.T. Short, P. Bennie and M.J.L. Turner, Nucl. Instr. and Meth. A 437 (1999), pp. 359–366.

4. J. Hiraga, H. Tsunemi, A.D. Short, A.F. Abbey, P.J. Bennie and M.J.L. Turner, “Measurement of the sub-pixel structure of the EPIC MOS CCD on-board the XMM Newton satellite”, Nucl. Instr. and Meth. A 465 (2001), p. 384.

Appendix 1 Measurement Logbook

In the following pages the list of the measurements taken during the Campaign (July 2007) is reported.
The data log is shown day by day as a table. The measurements are classified for type: e.g. background (bkg) and with monochromatic sources. Filename, detector set-up, source type and notes are reported for each measurement. Below the table there is the list of the corresponding measurements taken directly from the quick look data log.

File name	**Detector**	**Sources**	**Note**
cd109-cal_00.bin	CZT	^{109}Cd	calibration measurements
am241-cal_00.bin	CZT	^{241}Am	
Fondo-cal_00.bin	CZT		bkg
CZT+CCD_2_8_1h_00.bin	CZT/ EPIC CCD22	^{241}Am	collimated source
CZT-CCD_2_8_1h_00.bin	CZT/	^{241}Am	only CZT
CZT-CCDFrame_1h_00.bin	CZT	^{241}Am	only CZT
CZT-CCD+Frame_bkg_1h_00.bin			bkg
Cd-Fe-CCD_1h2_00.bin	CZT	^{109}Cd - ^{55}Fe	collimated source
Cd-Fe+CCD_1h2_02.bin	CZT/ EPIC CCD22	^{109}Cd - ^{55}Fe	CCD off
Cd-Fe+CCD_1h4_00.bin	CZT/ EPIC CCD22	^{109}Cd - ^{55}Fe	CCD on
Cd-Fe-CCD+Frame2_1h_00.bin	CZT	^{109}Cd - ^{55}Fe	only CZT

E:\Milena\Polca2\Misure\cd109-cal_00.bin El-Multiparametrico
Number Read.:54085632 -- Date and Time: 14/06/2007 17:03:58 -- Elapsed Time (s): 3600
peaktime 1.2 microsec
gain 200
threshold 3.1 cd centrato

E:\Milena\Polca2\Misure\am241-cal_00.bin El-Multiparametrico
Number Read.:92916736 -- Date and Time: 14/06/2007 18:07:37 -- Elapsed Time (s): 3600
peaktime 1.2 microsec
gain 200
threshold 3.1 am centrato

E:\Milena\Polca2\Misure\Fondo-cal_00.bin El-Multiparametrico
Number Read.:61423616 -- Date and Time: 14/06/2007 19:13:31 -- Elapsed Time (s): 3600
peaktime 1.2 microsec
gain 200
threshold 3.1 senza sorgente

C:\CCD-CZT\Misure\CZT+CCD_2_8_1h_00.bin El-Multiparametrico
Number Read.:7834624 -- Date and Time: 04/07/2007 12:27:46 -- Elapsed Time (s): 3601
senza scheda 3 e 6
Con CCD
vthr=2.8
1 hole verso il basso (da 8 a 7 a partire dall'alto)
Americio

C:\CCD-CZT\Misure\CZT-CCD_2_8_1h_00.bin El-Multiparametrico
Number Read.:7124992 -- Date and Time: 04/07/2007 13:35:26 -- Elapsed Time (s): 3601
senza scheda 3 e 6
Senza CCD
vthr=2.8
1 hole verso il basso (da 8 a 7 a partire dall'alto)
time=3600 s
Source= Am

C:\CCD-CZT\Misure\CZT-CCDFrame_1h_00.bin El-Multiparametrico
Number Read.:7984128 -- Date and Time: 04/07/2007 16:19:30 -- Elapsed Time (s): 3600
senza scheda 3 e 6
Senza CCD+Frame di supporto
vthr=2.8
1 hole verso il basso (da 8 a 7 a partire dall'alto)
time=3600 s
Source= Am

C:\CCD-CZT\Misure\CZT-CCD+Frame_bkg_1h_00.bin El-Multiparametrico
Number Read.:2399300 -- Date and Time: 04/07/2007 17:26:50 -- Elapsed Time (s): 3602
senza scheda 3 e 6
Senza CCD +Frame di supporto

vthr=2.8
1 hole verso il basso (da 8 a 7 a partire dall'alto)
time=3600 s
Background
No vuoto

C:\CCD-CZT\Misure\Cd-Fe-CCD_1h2_00.bin El-Multiparametrico
Number Read.:5237186 -- Date and Time: 05/07/2007 10:17:32 -- Elapsed Time (s): 3601
Source Cd and Fe
without CCD
without CCD Frame
Time 1 h

C:\CCD-CZT\Misure\Cd-Fe+CCD_1h2_02.bin El-Multiparametrico
Number Read.:8147891 -- Date and Time: 05/07/2007 11:56:16 -- Elapsed Time (s): 3601
Source Cd (strong) and Fe
Time 1 h

C:\CCD-CZT\Misure\Cd-Fe+CCD_1h4_00.bin El-Multiparametrico
Number Read.:5084077 -- Date and Time: 05/07/2007 14:05:50 -- Elapsed Time (s): 3601
Source Cd (strong) and Fe
Time 1 h
vuoto
CCDon, raffreddato

C:\CCD-CZT\Misure\Cd-Fe-CCD+Frame2_1h_00.bin El-Multiparametrico
Number Read.:3620427 -- Date and Time: 05/07/2007 16:33:03 -- Elapsed Time (s): 3602
Source Cd (strong) and Fe
Time 1 h
vuoto
CCDoff, Frame
scheda 6+att