HEXITEC 2 × 2 tiled hard X-ray spectroscopic imaging detector system

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ABSTRACT: HEXITEC is a spectroscopic imaging X-ray detector technology developed at the STFC Rutherford Appleton Laboratory for X-ray and γ-ray spectroscopic imaging applications. Each module has 80 × 80 pixels on a 250μm pixel pitch, and has been implemented successfully in a number of applications. This paper presents the HEXITEC 2 × 2 detector system, a tiled array of 4 HEXITEC modules read out simultaneously, which provides an active area of 16 cm². Systems have been produced using 1 mm thick Cadmium Telluride (CdTe) and 2 mm thick Cadmium Zinc Telluride (CdZnTe) sensor material. In this paper the system and data processing methods are presented, and the performance of the systems are evaluated.

The detectors were energy calibrated using an 241 Am sealed source. Three types of charge sharing correction were applied to the data-charge sharing addition (CSA), charge sharing discrimination (CSD), and energy curve correction (ECC) which compensates for energy lost in the inter-pixel region. ECC recovers an additional 34 % of counts in the 59.5 keV peak in CdTe compared to the use of CSD; an important improvement for photon-starved applications. Due to the high frame rate of the camera system (6.3 kHz) an additional End of Frame (EOF) correction was also applied to 6.0 % of events to correct for signals that were readout whilst the signal was still forming. After correction, both detector materials were found to have excellent spectroscopic performance with a mean energy resolution (FWHM) of 1.17 keV and 1.16 keV for CdZnTe and CdTe respectively. These results successfully demonstrate the ability to construct tiled arrays of HEXITEC modules to provide larger imaging areas.

KEYWORDS: Electronic detector readout concepts (solid-state); Gamma detectors (scintillators, CZT, HPGe, HgI etc); Solid state detectors; X-ray detectors

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1 Introduction

HEXITEC is a spectroscopic imaging X-ray detector technology developed at the STFC Rutherford Appleton Laboratory [1] for high energy X-ray and γ-ray applications [2]. The use of single detector modules have been demonstrated for a number of applications, including materials science [3], solar physics [4], medical imaging [5, 6], and security applications [7, 8].

There is a demand from many of these applications for detectors with the same high quality spectroscopic performance and high frame rate, but with larger active areas than the 4 cm² achieved with a single HEXITEC module. It is not currently possible to manufacture large area single crystals of high-quality CdTe and CdZnTe material for use in a large monolithic detector. This has motivated the development of a tiled array of single HEXITEC modules read out simultaneously and processed as a single image in order to achieve a larger active area. An overview of the 2×2 tiled HEXITEC DAQ system is presented here, along with the performance of these systems when using 1 mm thick CdTe and 2 mm thick CdZnTe sensors.

2 HEXITEC detector system

The HEXITEC ASIC measures the energy and position of every X-ray that interacts in the sensor material in order to measure the X-ray spectrum. A high-Z compound semiconductor sensor is
bonded to the ASIC to form a detector module. Each module is 80 × 80 pixels on a 250 μm square pitch. The detector system presented here consists of 4 modules in a 2 × 2 array, connected to a single camera unit; all 160 × 160 pixels are read out simultaneously. The 4 modules give a total active area of 16 cm² containing 25,600 fully spectroscopic pixels. A photograph of the detector system and the 2 × 2 detector module is shown in figure 1. The combination of a 150 μm physical gap and a guard ring around the pixel array results in an ~ 2 pixel wide dead area between detector modules. The two detector materials presented here are 1 mm thick Acrorad Schottky Cadmium Telluride (CdTe) [2] and 2 mm thick Redlen high-flux Cadmium Zinc Telluride (CdZnTe) [9], both high-Z compound semiconductor sensors operated at room temperature. The CdZnTe detector has a 225 μm pad and 25 μm inter-pixel gap, and the CdTe detector has a 200 μm pad and 50 μm inter-pixel gap; this results in different charge-sharing behaviour which will be discussed in section 4 of the paper.

![Figure 1](image)

**Figure 1.** (a) The 2 × 2 HEXITEC camera system. (b) The 2 × 2 CdTe detector array. One edge of each of the 4 modules has wire bonds that connect the ASIC to the readout PCB. These bond regions have been orientated to minimise the gap between detectors to 150 μm.

Each sensor is flip-chip bonded to a read-out ASIC using a silver-loaded-epoxy and gold stud technique [10]. The photons interacting in the sensor material generate a cloud of charge with an electron-hole pair generated for every 4.4 eV (CdTe) or 4.6 eV (CdZnTe) [11] deposited. A negative bias voltage is applied to the large planar electrode which causes the electrons to drift towards the pixelated anode inducing a charge in the pixels of the ASIC. These induced charge signals are converted to a voltage by a charge sensitive amplifier in each pixel of the ASIC. The magnitude of this voltage is directly proportional to the charge, hence it measures the original energy deposited by the X-ray photon.

Following the pre-amplifier there is a shaper and peak track and hold circuit on every channel on the ASIC. The pre-amplifier output is shaped and filtered in order to remove noise, with a rise time (τrise) of 2 μs. The charge amplifier has a slew-rate limited feedback which results in the shaper recovery taking ~ 8 μs to return to baseline (τfall). The peak track and hold circuit records the maximum magnitude of the voltage signal and stores it until it is read out by a rolling shutter readout system, which reads the pixel array row by row in four parallel blocks of 20 pixels per column. This enables the camera system to be run at high frame rates of up to 6.3 kHz; higher frame rates are limited by the bandwidth of the USB3.0 connection.
The peak-hold output is read out by the front-end VSR (very small readout) board, designed and manufactured by aSpect Systems [12]. A photograph of the board is shown in figure 2 and a block diagram of the VSR boards in the camera housing is figure 3. Each VSR board is attached to two HEXITEC modules which operate synchronously. The board digitises the analogue peak-hold output into a 14-bit value, hence the output unit is ADU (analogue-to-digital unit). The VSR board performs dark corrections by subtracting the average value from 8,000 frames of data on a per pixel basis before sending the frames to the PC. The VSR board also provides clocks and power to the detector modules. As well as the frames of data the VSR board sends environmental monitoring data to the PC.

**Figure 2.** The VSR board which interfaces with two HEXITEC modules, designed and manufactured by aSpect Systems Gmbh Germany [12]

**Figure 3.** A block diagram of a HEXITEC $2 \times 2$ camera system. There are 2 VSR boards, each connecting to 2 HEXITEC modules to achieve a $2 \times 2$ tiled array.
A flow diagram of the system is shown in figure 4. The camera control box collates data from 2 VSR boards to form frames of $160 \times 160$ pixels. The frames, and environmental information from the HEXITEC camera, are sent to the computer via USB3.0. The bias voltage applied to the detector is set by the user on the computer — it is capable of supplying voltages down to $-1000$ V. For Cd(Zn)Te sensor material, generally a field strength of $-500$ V/mm is adequate for producing high resolution spectroscopy (i.e. $-1000$ V for the CdZnTe and $-500$ V for the CdTe tested here). The camera control box can also be triggered to start data collection and outputs triggers to indicate data has been collected.

![Flow diagram of the HEXITEC system](image)

**Figure 4.** A flow diagram of the HEXITEC system

The PC runs the SpeXIDAQ framework [13] which was developed by Ghent University and adapted for use with the HEXITEC DAQ. The software controls the DAQ system and also provides live tracking of the temperature and humidity of the HEXITEC modules. As well as data acquisition, this software can apply charge sharing and dark level corrections that track the detector leakage as a function of time. The GUI shows the global spectrum and images for a given energy window which is updated in real time. Data is saved as energy spectra per pixel as a default but the raw frames can also be saved.

## 3 Method

### 3.1 Sealed source characterisation

Both the CdTe and CdZnTe detectors were tested using $^{57}$Co and $^{241}$Am sealed sources. The activity of the two sources is 180 MBq for the $^{241}$Am and 1.3 MBq for the $^{57}$Co. For the $^{57}$Co source, one hour of data was collected at a frame rate of 6.3 kHz. For the $^{241}$Am source, owing to its higher activity, 30 minutes of data was collected at the same frame rate. At this frame rate the camera system produces data at a rate of 18.5 GB/minute. In both cases the camera was at a distance of 15 cm from the sealed source in order to ensure a flat field across the entire detector area. The sequence of data processing used to generate the spectrum per pixel is shown in figure 5.

As the ASIC voltage, leakage current and noise of each Cd(Zn)Te detector can vary, a module specific dark correction was applied to each frame and noisy pixels masked. A noisy pixel was defined as any pixel where the mean occupancy of a frame is more that 1% (i.e. more than 1% of frames contain an event above threshold in that pixel), which is well above the global occupancy of
Figure 5. The process used to analyse the data from the $2 \times 2$ HEXITEC detector system.

0.47%. The global occupancy should always be kept below 10% when using HEXITEC detectors in order to identify charge sharing events. The low energy threshold was calculated on a per-pixel basis. After dark correction any pixels not containing an event formed a normal distribution centred on zero signal. This normal distribution was fitted on a per-pixel basis and the threshold was defined as $\mu + 8\sigma$. Figure 6 shows the global spectrum after corrections recorded by CdZnTe and CdTe systems when irradiated with each of the sources.

3.2 End of frame events

The HEXITEC ASIC operates with a leakage current compensation circuit that returns the preamplifier and subsequent shaper to baseline following an event without the need to reset [1]. When a pixel is readout, the peak hold output is sampled and then reset ($\tau_{\text{read}} = 0.24\,\mu s$) at which point it immediately starts tracking the shaper signal level. An End-of-Frame (EoF) event occurs when the readout of a pixel coincides with the output of the shaper either still rising ($\tau_{\text{rise}} = 2\,\mu s$) or returning to baseline ($\tau_{\text{fall}} = 8\,\mu s$). This leads to one of three scenarios:

a The pixel is readout whilst the output of the shaper is still rising. The signal measured in frame $N - 1$ is significantly smaller than the maximum value. In frame $N$, the signal has continued to rise and the output of the peak hold gives the correct value. In this instance the value in frame $N$ is kept and the value in frame $N - 1$ is rejected.

b The pixel is readout as the output of the shaper is reaching it’s peak. The signal recorded in frame $N - 1$ is slightly less than the maximum value. Following readout, the peak-hold is reset and immediately tracks the output of the shaper but by this time the output has fallen slightly meaning frame $N$ also records a slightly lower than expected value. Neither of the frames contains the full signal and so both are rejected.

c The pixel is readout while the shaper is returning to the baseline. The maximum signal is readout in frame $N - 1$ but the signal in frame $N$ is significantly smaller than the maximum value. The value in frame $N - 1$ is kept and the value in frame $N$ is rejected.
Figure 6. The global spectra recorded by (a) the CdZnTe and (b) the CdTe HEXITEC systems under irradiation with an $^{241}$Am (black) and $^{57}$Co (red) sealed source. The main peaks from these sealed sources are 13.94, 17.75, 59.5 keV ($^{241}$Am), 122 and 136 keV ($^{57}$Co). A charge sharing discrimination has been used to remove the contribution of shared events.

Table 1. Actions for the three possible end of frame scenarios based on the ratio of the signals in frame $N-1$ and frame $N$.

| Ratio     | frame[x, y, $N-1$] | frame[x, y, $N$] |
|-----------|---------------------|------------------|
| a $< 0.95$ | Reject              | Accept           |
| b $0.95-1.05$ | Reject          | Reject           |
| c $> 1.05$ | Accept              | Reject           |
EoF events were identified by finding pixels that contained events in the same pixel in two subsequent frames \( N - 1 \) and \( N \); the strategy for dealing with these events is given in table 1. Two genuine events are unlikely to be mistaken for EoF events due to the low global occupancy (0.47\%) and the fact that noisy pixels have been removed from the analysis. EoF events accounted for 6.0\% of all events in both CdTe and CdZnTe and showed no spatial variation across either detectors. Figure 7 shows a schematic of the different type of EoF events described as well as the spectrum of the rejected EoF events of each type. Of those EoF events detected, in 48\% of cases the correct value was identified and included in the spectrum while in 52\% of cases both values were rejected. The total percentage of EoF events can be estimated as:

\[
\text{EoF Events [%]} = 100 \times \frac{\tau_{\text{rise}} + \tau_{\text{fall}}}{\tau_{\text{frame}}}
\]  

(3.1)

It should be noted that this assumes the rise and decay of the shaper is linear when in reality it is more complex. For a frame rate of 6.3 kHz, \( \tau_{\text{frame}} = 158.7 \mu s \), and with \( \tau_{\text{rise}} = 2 \mu s \) and \( \tau_{\text{fall}} = 8 \mu s \), 6.3\% of events can be expected to be EoF. The percentage found in the data is consistent with this estimate. As the proportion of events showing EoF effects is inversely proportional to the frame time (\( \tau_{\text{frame}} \)), EoF events will become more prominent at higher frame rates.

3.3 Charge sharing

Charge sharing occurs in Cd(Zn)Te detectors when an individual interaction occurs in the volume between two pixels. The charge created by the interaction is then split between neighbouring pixels resulting in a low energy background in spectra as well as double counting of individual events. In order to achieve high resolution spectroscopic performance, these charge sharing events need to be corrected. Three approaches to these corrections have been implemented for the HEXITEC 2 \times 2 data. The first is charge sharing discrimination (CSD) which rejects events that are identified in neighbouring pixels in any given frame. This correction provides the best possible spectroscopic performance but has a negative impact on the detection efficiency as charge sharing events account for \( \sim 50\% \) of all events. The second correction implemented is charge sharing addition (CSA), in this instance the individual components of a charge sharing event are summed together and assigned to the pixel with the largest share of the total. The CSD and CSA techniques are well-established and are regularly used for the correction of HEXITEC data [14]. Recently, a third technique has been implemented by a number of groups [15–17] which combines CSA with an additional energy correction curve (ECC).

Each pixel of the sensors is separated from the others by an inter-pixel gap, a region of bare material on the sensor between the individual pixel electrodes. This gap in the electrode leads to local variations in the electric field creating regions in which drifting charge can become trapped leading to a reduction in the detected energy [18, 19]. In HEXITEC data, these effects normally manifest in a reduction in the energy of an event after simple CSA correction compared to the expected energy, \( E_0 \). The amount of energy lost for any given event depends on both the lateral position and the depth of the interaction in the sensor. The nature of these events can be characterised by studying the ratio \( (R) \) of the energy deposited in each pixel, \( E_1 \) and \( E_2 \):

\[
R = \frac{E_1 - E_2}{E_0}
\]  

(3.2)
If $R$ is close to 0 the energy is evenly distributed between the two pixels suggesting that the interaction occurred in the centre of the inter-pixel region where, as the charge carriers approach the pixel, the electric field will be most non-uniform; this results in a large proportion of energy being lost. For events occurring closer to one or other pixel, $R$ tends towards 1 and the amount of energy lost decreases. An exception to this is in those events in which a Cd or Te X-ray fluorescence photon is generated during the original interaction. These XRF photons have a relatively large range ($\sim 100 \mu m$) compared to the pixel size ($250 \mu m$), and can escape to the adjacent pixel without
interacting in the inter-pixel volume. The resulting charge sharing event appears similar to those previously described but shows no charge loss when the components are summed together; this is due to the fact that none of the charge carriers drifted in the inter-pixel volume. These sharing events occur at specific ratios, due to the fixed energy of the Cd and Te XRF photons, and have been identified in figure 8 as the green coloured events. These events can be isolated by examining the pixel values and comparing them to the Cd and Te XRF energies; here a tolerance of ±5% has been applied. When identified, these events can be discarded or corrected using a simple CSA correction without the need for any charge loss correction.

Figure 8. The distribution of energies in two-pixel charge sharing events in the CdTe detector under irradiation with a 59.5 keV $^{241}\text{Am}$ source. Standard charge sharing events are shown in blue while events containing either a Cd or Te XRF photon are shown in green. The red curve is a quadratic fit of total measured energy to charge sharing ratio for the standard charge sharing events.

The ECC technique has been developed to correct for the energy loss experienced in two pixel events in the CdTe HEXITEC system. The energy loss (ECC) has a quadratic dependence on the charge sharing ratio, $R$:

$$\text{ECC}(R) = E_0 - (aR^2 + bR + c)$$  \hspace{1cm} (3.3)

where the coefficients a,b and c are found using a least squares regression to the equation:

$$E_1 + E_2 = aR^2 + bR + c$$  \hspace{1cm} (3.4)

The quadratic fit is shown in red in figure 8 and the corresponding ECC is shown in figure 9.

For all three methods of charge sharing corrections, the Python package ‘sci-kit image’ [20] was used to find connected components in the image (i.e. two or more pixels connected by a charge sharing event). As the global occupancy is low it is very likely that any neighbouring pixels with values above threshold in a given frame are two separate events. Figure 10(a) shows a small section
of a frame before charge sharing corrections. There are 7 events, 6 of which show charge sharing. In the sci-kit image algorithm every pixel above threshold is identified, and connected components (pixels above threshold which share an edge or a corner) are identified as a cluster. For each cluster, the values of all the pixels are summed and assigned to the pixel with the highest value. This can be seen in figure 10(b). The same 7 events are visible but every event is 1 pixel in size. For CSD the same algorithm is used to identify events, but rather than sum the values in clusters they are all set to zero and excluded from the spectra. In this particular section of a frame this would result in only 1 of the 7 events being accepted and included in spectra.

4 Results

4.1 Threshold per pixel

The threshold per pixel defines the lowest intensity signal a pixel can detect and is defined as the mean of the low energy noise plus 8 standard deviations ($\mu + 8\sigma$). The mean threshold for CdZnTe and CdTe are broadly similar, being 2.98 keV and 3.40 keV respectively. Higher leakage current at the edge of each crystal leads to a higher thresholds along the boundary of each detector and defects in the detector material also create pixels with higher thresholds, which can be seen in figure 11.

4.2 End of frame corrections

End of frame (EOF) corrections are applied following the calculation of the per pixel threshold. Of all events, 6.0% were found to be EOF events in both the CdZnTe and CdTe detectors and the effect is spatially uniform. These events were categorised as explained earlier – if the energy of the events were within 10% of one another they were both removed, otherwise the smaller of the two values

$$R = \frac{(E_1 - E_2)}{E_0}$$

**Figure 9.** The calculated dependence of the energy loss experienced for two pixel charge sharing events in the HEXITEC CdTe detector for the 59.5 keV emission of $^{241}\text{Am}$ source.
Figure 10. An example of the application of the CSA correction algorithm in a $30 \times 30$ pixel section of a single frame of data recorded with the CdTe HEXITEC system when irradiated with an $^{241}$Am source. (a) The values per pixel after EOF corrections, thresholds and energy calibration have been applied. 7 events can be seen ranging from 1 to 4 pixels in size. (b) The same frame after the application of a CSA correction. The values in each cluster have been added together and assigned to the pixel with the largest value in that cluster. The same 7 events can be seen but they are all 1 pixel in size after correction.

Figure 11. The low energy threshold calculated for each pixel of (a) the CdZnTe and (b) the CdTe detector. The threshold was defined as 8 standard deviations from the mean after dark subtraction.

was removed and the larger value kept. Overall, of those events flagged as being EOF, 48% of events were kept and 52% were removed. The spectra formed by each set of events for both the CdTe and CdZnTe detectors is shown in figure 12. The rejected events consist of an undesirable low energy noise continuum while the events that are accepted contain the same spectral peaks as seen in the CSD spectrum. These spectra demonstrate that the application of this correction technique does not degrade the spectral performance of the detector; this is particularly positive because the EOF method is independent of any information on the source used.
Figure 12. The spectra of EOF events as measured with (a) the CdZnTe detector and (b) the CdTe detector when irradiated with an $^{241}$Am source. Three spectra are shown in each plot, the CSD spectrum (black), the spectrum of the accepted EOF events (green) and the rejected EOF events (red).

4.3 Calibration

A linear fit is used to calibrate the detectors using the different energy emissions of the $^{241}$Am source. Peaks at 13.94, 17.75, and 59.54 keV were used to convert from ADU (analogue-to-digital units) into keV for each pixel. Figure 13 (a) and (b) show the spatial distribution of the calibration coefficients calculated for each detector. The mean gradient of the CdZnTe and CdTe were found to be 29.4 eV ADU$^{-1}$ and 28.7 eV ADU$^{-1}$ respectively; the difference between the two is consistent with the difference in the electron-hole pair creation values of the two materials. Some structure is
also visible in the maps of gradient per pixel which is due to the arrangement of the DAQ system. Each ASIC is read out in four $20 \times 80$ pixel blocks, each of which is connected to an ADC in the DAQ via a separate amplifier; this manifests as four horizontal sections of slightly different gradient in each detector module. The mean intercept is 0.80 keV and 1.40 keV for the CdZnTe and CdTe respectively. The intercept is higher at the boundaries of the detectors and where defects are present in the detector material, as shown in figure 13 (c) and (d).

![CdZnTe](image1.png) ![CdTe](image2.png)

**Figure 13.** Maps of the per pixel calibration coefficients for the CdZnTe and CdTe detectors. Maps are shown for (a) the CdZnTe gradient, (b) the CdTe gradient, (c) the CdZnTe intercept and (d) the CdTe intercept.

### 4.4 Charge sharing corrections

An evaluation of the charge sharing events in both the CdZnTe and CdTe detectors demonstrate that the vast majority of events occur in either 1 or 2 pixels, as shown in table 2. The proportion of events occurring in either 1 or 2 pixels was 85.3\% and 85.2\% for CdZnTe and CdTe respectively. The percentage of events demonstrating charge sharing of any multiplicity was 58.9\% and 53.7\% for the CdZnTe and CdTe respectively.
Table 2. Percentage of events by each cluster size for the 59.5 keV events.

| Cluster Size | CdZnTe [%] | CdTe [%] |
|--------------|------------|----------|
| 1            | 41.14      | 46.29    |
| 2            | 44.12      | 38.90    |
| 3            | 9.59       | 7.49     |
| 4            | 4.94       | 7.03     |
| 5            | 0.18       | 0.25     |
| 6            | 0.03       | 0.04     |
| 7            | <0.01      | <0.01    |
| 8            | <0.01      | <0.01    |
| 9            | <0.01      | <0.01    |

In figure 14 global spectra, the sum of all non-edge pixels, are shown for three different techniques. The raw spectrum shows a large low energy continuum which is a result of charge sharing in the detector. The rejection of shared events by the charge sharing discrimination (CSD) algorithm produces the best spectral performance removing the low energy continuum and improving the width of the peaks, however, the use of this results in a reduction in the counting efficiency of the detector as ~ 50% of events are removed. The use of charge sharing addition (CSA) recovers the detector counting efficiency as observed by the increase in the peak height but also leads to an increase in the width of the peak compared to the CSD. The advantage of the HEXITEC system is that all of the raw frames are recorded and the precise correction algorithm applied to the data is a choice made by the user in post-processing.

In the case of the CdTe detector the use of a simple CSA correction results in the introduction of a broad low energy tail to the main 59.5 keV peak, this can be seen in figure 15. The formation of this tail is a result of the energy loss experienced in charge sharing events due to trapping of charge in the inter-pixel region. As described earlier, this can be compensated through the use of the energy curve correction (ECC) technique. For the CdTe detector the ECC algorithm adds up to a maximum of 5.52 keV to charge sharing events involving two pixels for a photon energy of 59.5 keV, see figure 9(a).

Before applying the correction, each cluster is inspected to see whether one of the components is due to the generation of a Cd or Te XRF photon. Of the two pixel sharing events measured in the CdTe detector, 47% were found to contain a fluorescence event while the remaining 53% were due purely to geometric charge sharing. In the case of the identified XRF events, no ECC correction is applied and a standard CSA correction is used; the spectrum of these corrected events can also be seen in see figure 9(a). While a significant number are contained within a peak at the expected energy, a similar number are still found at lower energies. These events are due to the simple 10% tolerance used in the identification of the XRF events, some geometric charge sharing events will also have mistakenly been included. As with other corrections, the user can choose whether to include or discriminate these events in post-processing.

For those events identified as geometric charge sharing the ECC technique is applied, see figure 15(a). The spectrum of the corrected events no longer shows the pronounced low energy tail and appears much more Gaussian than the standard CSA correction or the XRF-CSA correction.
Figure 14. The global spectra recorded by (a) the CdZnTe and (b) CdTe detector for different correction techniques. Spectra are shown for the raw data (Black), for CSD, single pixel events (green) and with the inclusion of two pixel events corrected using CSA (red).

Figure 15(b) compares the final spectra produced using the three correction techniques, CSD, standard CSA and CSA+ECC. While the CSD technique provides the highest energy resolution, the combination of CSA+ECC is successful at recovering the counting efficiency of the detector increasing the counts in the 59.5 keV peak by 34% compared with CSD; this is achieved without a significant impact on the spectroscopic performance. It should be noted that the correction coefficients used in Equation 3.4 have an energy dependence as at higher energies photons have a greater probability of interacting at larger depths in the inter-pixel volume where the greatest
Figure 15. The application of different charge sharing correction techniques for 2-pixel events for the 59.5 keV $^{241}$Am peak. a) A comparison of the shared events using a simple CSA correction for all events (black), using CSA only for those events containing a Cd/Te XRF photon (red) and using the ECC technique for non-XRF sharing events. b) A comparison of the final spectrum obtained using the CSD technique (black), a simple CSA correction (red) and the ECC technique (green).
variation in the electric field is expected. To apply the correction across a wider range of energies would require calibration of these coefficients as a function of photon energy.

In the case of the CdZnTe detectors, the smaller inter-pixel gap of (25 μm) and greater detector thickness (2 mm) means that negligible charge loss is experienced compared to the CdTe sensor which has a larger inter-pixel gap (50 μm) and lower thickness (1 mm).

4.5 Energy resolution (FWHM)

As stated earlier, the CSD technique results in the highest resolution spectroscopic performance out of all the corrections. Figure 16 shows the number of counts in the 59.5 keV peak and the corresponding FWHM value per pixel for the CSD corrected spectra. For CdZnTe a mean FWHM of 1.17 keV is measured while for CdTe the value is 1.16 keV. In CdZnTe 99.74 % of pixels have FWHM of less than 2 keV, and in CdTe this figure is 99.75 % of pixels. Full details of the FWHM performance for each of the charge sharing corrections can be found in table 3. These values compare well to those previously seen for the Redlen CdZnTe [9] and Acrorad CdTe [2] using the single module HEXITEC DAQ system.

Table 3. FWHM and the number of counts detected using each of the charge sharing corrections in CdZnTe and CdTe. The mean value of the FWHM including the standard deviation across all pixels. Peak Counts is defined as the mean number of events in the $^{241}$Am 59.54 keV spectral peak within the limits 58–61 keV.

|         | CdZnTe |                  | CdTe  |
|---------|--------|------------------|-------|
| FWHM [keV] | Peak Counts | FWHM [keV] | Peak Counts |
| Raw     | 1.13 ± 0.16 | 3015         | 1.13 ± 0.13 | 3480         |
| CSD     | 1.17 ± 0.17 | 2924         | 1.16 ± 0.14 | 3386         |
| CSA     | 2.01 ± 0.26 | 5070         | 1.31 ± 0.30 | 4254         |
| ECC     | -      | 4535         | 1.27 ± 0.18 |             |

4.6 X-ray imaging example

A simple example of the imaging capabilities of the system can be seen in figure 17. The sample is a 1 mm thick steel grid with 5 mm diameter holes, imaged with a 5 minute exposure with an $^{241}$Am sealed source. Using the spectroscopic information recorded in each pixel it’s possible to produce images for different energy windows. At lower energies (10–25 keV) the 1 mm thick steel is effective at attenuating the emissions from the source while at the higher energy (45–61 keV) the steel is less attenuating; the result is a lower contrast image for the higher energy image. For these images, a 2 pixel gap has been added between individual modules to account for the dead area described earlier. As shown by the alignment of the apertures in the steel, this gap accurately aligns the images recorded in each of the 4 modules.

5 Conclusion

The performance of the $2 \times 2$ HEXITEC camera system has been demonstrated using both CdZnTe and CdTe detector material. Each camera system consists of four modules each with a 80 × 80 pixel array on a square pitch of 250 μm giving a total active area of 16 cm$^2$ and 25,600 pixels each
Figure 16. Maps of the spectroscopic performance of the CdZnTe and CdTe HEXITEC 2 x 2 systems. Maps are shown for the number of counts in the 59.5 keV peak in (a) the CdZnTe and (b) the CdTe systems. The FWHM per pixel is also shown for (c) the CdZnTe and (d) CdTe systems.

capable of high resolution spectroscopy. Data recorded with these systems require a number of different corrections which have been applied in this paper. Due to the high frame rate of the camera system (6.3 kHz), events occurring at the end of a frame can result in the measurement of an erroneous event. These End of Frame (EoF) corrections were found to occur in 6.0% of all events and this was consistent with the properties of the HEXITEC shaping circuit and the frame rate of the system. Having identified these events, 48% were able to be recovered and included in the spectra while the remaining 52% were rejected. Three types of charge sharing correction were also applied to the data-charge sharing addition (CSA), charge sharing discrimination (CSD), and energy curve correction (ECC) which compensates for energy lost to the inter-pixel region. In the case of the CdZnTe detector, no ECC correction was required due to the smaller inter-pixel gap compared to the CdTe sensors. In the case of the CdTe detector, ECC successfully recovers 34% of counts in an $^{241}$Am 59.5 keV peak compared to a simple CSD correction, this gain in counting efficiency is important for photon-starved applications. The energy resolution of the
Figure 17. (a) A photograph of the 1 mm thick steel grid. The apertures have a diameter of 5 mm. (b) An example of single pixel CSD spectra recorded by a pixel at the centre of the aperture (red) and under the steel grid (black). (c) The image recorded with the $2 \times 2$ CdZnTe HEXITEC camera for events with energies between 10–25 keV. (d) The same image but for an energy window of 45–61 keV.

detector system were also measured using the 59.5 keV peak. Both detector materials were found to have excellent spectroscopic performance with mean energy resolution (FWHM) of 1.17 keV in CdZnTe and 1.16 keV in CdTe. The results presented here successfully demonstrate the potential to tile HEXITEC detector modules in to larger arrays which can be read-out simultaneously in order to achieve a larger imaging area. This has been achieved without any significant impact on the detector spectroscopic performance.

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