Photon-counting imaging camera for high-resolution X-ray and γ-ray applications

2011 JINST 6 C01022

(http://iopscience.iop.org/1748-0221/6/01/C01022)

PUBLISHED BY IOP PUBLISHING FOR SISSA
RECEIVED: *September 7, 2010*
REVISED: *October 15, 2010*
ACCEPTED: *October 20, 2010*
PUBLISHED: *January 11, 2011*

12th INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS,
JULY 11th–15th 2010,
ROBINSON COLLEGE, CAMBRIDGE U.K.

Photon-counting imaging camera for high-resolution X-ray and γ-ray applications

D.J. Hall[1] and A. Holland

e2v Centre for Electronic Imaging, Planetary and Space Sciences Research Institute, The Open University, Walton Hall, Milton Keynes, MK7 6AA, U.K.

E-mail: d.j.hall@open.ac.uk

ABSTRACT: Standard X-ray imaging techniques using CCDs require the integration of thousands of X-ray photons into a single image frame. Through the addition of a scintillating layer to the CCD it is possible to greatly increase the X-ray detection efficiency at high energies. Using standard imaging techniques with the inclusion of the scintillating layer does, however, leave serious limitations on the spatial resolution achievable due to the spreading of the light generated in the scintillator.

The Electron-Multiplying CCD (EM-CCD) shares much of the common architecture of the standard CCD but for the inclusion of a supplementary readout register. This additional high-voltage register allows the signal electrons to be 'multiplied' before reaching the readout node of the CCD, increasing the signal before any significant noise is introduced. The increase in the signal-to-noise ratio allows very low signals to be extracted above the noise floor, leading to the common use of EM-CCDs in night-vision and security applications.

Through the coupling of a scintillator to an EM-CCD it is possible to resolve individual X-ray photon interactions in the scintillator above the noise floor. Without this extra gain these low signals would be lost beneath the noise floor. Using various centroiding techniques it is possible to locate the interaction position of the incident X-ray photon in the scintillator to the sub-pixel level, with measurements here at 59.5 keV giving an initial FWHM of the line spread function of 31 μm.

This high-resolution, hard X-ray imager has many potential applications in medical and biological imaging, where energy discrimination at a high resolution is desired. Further applications include synchrotron-based research, an area in which high-resolution imaging is essential.

KEYWORDS: X-ray detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, CCDs, EBCCDs etc)

[1]Corresponding author.

doi:10.1088/1748-0221/6/01/C01022

Contents

1 Introduction

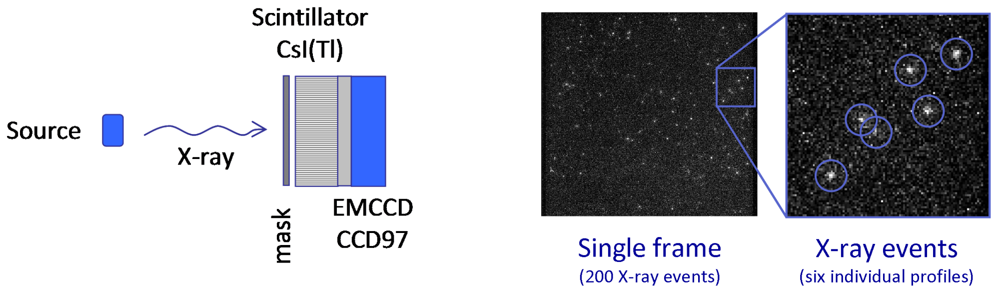
Over the last decade, rapid advancements in CCD technology have led to significant developments in the field of low-light-level Electron-Multiplying CCDs (EM-CCDs). With the addition of a gain register before the output node the signal electrons can be multiplied without increasing the noise. With this low effective readout noise very low signal levels can be detected above the background.

At low X-ray energies, the EM-CCD is an effective detector, but at higher energies (up to 140 keV in this study) the detection efficiency of the EM-CCD is dramatically reduced. One option to increase the detection efficiency of a camera system utilising the EM-CCD is to use a scintillator. The detector used in this study is based on an e2v CCD97 [1]. The CCD97 used here is a back-illuminated device with an image area of 512×512 pixels (16 µm $\times$ 16 µm pixel size).

The alkali halide caesium iodide (thallium doped) is one of the most popular scintillation materials due to its many highly desirable properties. The scintillator converts X-rays into light at visible wavelengths. Approximately 65 photons are produced per keV of incident X-ray with wavelengths of $\sim$ 550 nm, matching the peak in the quantum efficiency of the CCD97 [1]. These photons spread out as they pass through the scintillator giving Gaussian-like profiles with peaks of a few photons, not resolvable above the noise in a standard CCD but visible with an EM-CCD, where the number of photons is proportional to the energy of the incident gamma or X-ray .

The spreading of the visible photons produced in the scintillator acts to 'blur' the image, having a detrimental affect on the spatial resolution if the spreading of the light is included in the final image: an *integrated* image. This 'blurring' of the image can be removed through the use of various techniques, with the technique of *photon-counting* shown here to give large improvements in the spatial resolution achievable with such a camera system [2].

The *photon-counting* method involves the acquisition of many frames, taken in quick succession, as opposed to a single image taken over a longer integration time (the *integrated image* method). The individual interactions of X-rays in the scintillator can then be imaged and resolved independently. Techniques such as sub-pixel centroiding can then be used to increase the spatial resolution [3]. In an integrated image, any information on the energy of the incident X-rays is lost.



(a) Experimental set-up

(b) A single frame in photon-counting mode

Figure 1. (a) The experimental set-up. (b) A single frame containing 200 individual X-ray events, with an enlarged selection of six events, each spread over 25 pixels. Adapted from [3].

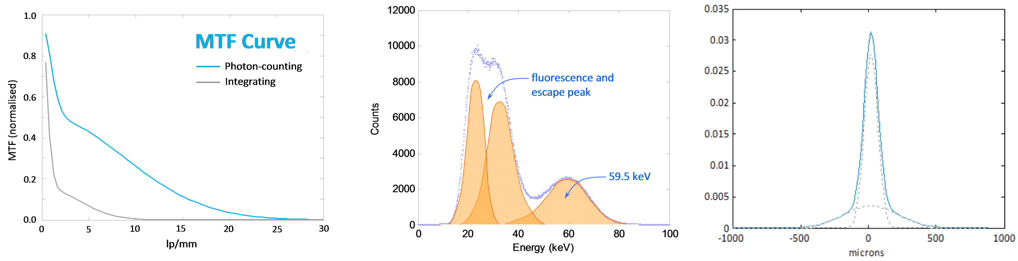
Using a photon-counting technique opens the door for energy discrimination, allowing the images to be used to relate the characteristics of each X-ray interaction to a specific energy [4].

In this paper, the basic camera system is described alongside a demonstration of the improvements achievable through the use of the photon-counting methodology at an energy of 59.5 keV. The photon-counting technique allows the spatial resolution to be dramatically improved. Through the process of energy discrimination, it is also shown how the spatial resolution can be further improved, giving an extra 20% enhancement on the basic methods.

2 Scintillator-coupled EM-CCD: photon-counting at 59.5 keV

The testing detailed here uses the set-up shown in figure 1(a). A solid source is placed several centimeters from the mask. Although this does not supply a parallel beam of X-rays (required for the best-case results), it provides an indication of the image quality and detection process and allows the principles involved to be demonstrated. The influence of the internal X-ray fluorescence in the scintillator is not negligible and will be revisited in section 3.

The low-light-level performance of the CCD97 allows the photons from individual X-ray interactions in the scintillator to be analysed. The frame shown in figure 1(b) was taken at 59.5 keV with a pixel readout rate of 1 MHz (approximately 4 fps). Individual events have been circled in the close-up view, where the apparent distortion of the event profile shapes is attributed to the non-uniformity of the columnar scintillator and the Poisson noise on the low signal levels. The frame rate at which the detector is operated depends upon the incident flux. In order to accommodate a much higher incident flux, a higher frame rate will be required. The device can be operated at up to approximately 15 MHz (60 full frames per second) with updated drive electronics. The increase in amplifier noise from the faster readout rates can be countered with the EM-CCD by increasing the multiplication gain on the signal, thereby keeping the effective readout noise at a sub-electron level. The photon-counting technique requires the acquisition of many of these images (with the number required dependent on the image quality required), each containing several hundred individual X––ray interactions in the scintillator. By centroiding each individual event, a sub-pixel location can be achieved. These sub-pixel locations can then be used to form the image, removing the spread of light inside the scintillator and dramatically improving the spatial resolution.



(a) Modulation Transfer Function (b) Energy spectrum at 59.5 keV (c) Fitted line spread function.

Figure 2. Spatial and spectral resolution measurements. The orange curves below the experimental results (blue) in the energy spectrum are given as indicators only. Adapted from [3]. The fitted line spread function (blue) is composed of two Gaussian components (grey), allowing a fit to the primary and secondary interaction components.

3 Experimental results

3.1 Spatial resolution

Using an oversampled edge to produce a Line Spread Function (LSF) the Modulation Transfer Function (MTF) has been derived. The improvements using the photon-counting method over an integrating method are shown in figure 2(a) for incident 59.5 keV X-rays. The 'step' in the MTF is caused by reabsorbed K-shell fluorescence X-rays generated in the scintillator by the Cs and I.

Using the ^{241}Am source at 59.5 keV the LSF Full Width at Half Maximum (FWHM) spatial resolution was measured for the two imaging modes. The results presented here show an improvement in spatial resolution from 80 μm to 31 μm. It should be noted that the FWHM quoted here is a measurement from the LSF shown in figure 2(c), where it can be seen that the standard single-Gaussian form is not adhered to.

When considering the LSF, it was found that a 'two Gaussian' approach provided the optimal fit to the experimental data. The two Gaussian profiles used represent the spread of the re-absorbed fluorescence events from the initial interaction location (shown by the broader Gaussian profile) and the spread of the ejected electrons from the initial interaction points (shown by the narrow Gaussian profile). The Gaussian profiles are the result of the convolution of the scintillator-CCD system response with the electron and fluorescence X-ray spread respectively. It is this 'two Gaussian' approach that gives the 'knee' in the MTF curves shown in figure 2(a). The substantial drop in MTF at low spatial frequencies, still clear in the photon-counting results, is a result of the re-absorbed fluorescence X-rays detected away from the primary interaction location. It is not possible to reduce this through improvements to the centroiding algorithm.

3.2 Energy discrimination

Through the process of summing the signal producing each 'event', a spectrum has been obtained at 59.5 keV, showing the influence that the reabsorbed K-shell X-ray fluorescence has on the events recorded by the EM-CCD, figure 2(b). Although the current results do not allow spectroscopy as such, the distinction between the full-energy and fluorescence/escape peaks allows a degree of

2011 JINST 6 C01022

'energy discrimination', allowing the analysis of interactions in the scintillator on an event-by-event basis, a process that is not possible in an integrated image.

The spatial resolution can be further improved using *energy discrimination*. In this case, for 59.5 keV incident X-rays reacting in a CsI(Tl) layer, the fluorescence of the scintillator, along with the subsequent escape electron, can be removed from the final images. An energy cut-off can be set, here at approximately 45 keV, with all events below this cut-off removed from the final image, leaving the initial interaction points of the incident X-rays to dominate. Although this process will also remove primary X-ray events, reducing the detection efficiency, using this procedure the spatial resolution (FWHM of the LSF as shown in figure 2(c)) has been improved further still to 25 µm. The improvement in the FWHM of the LSF does not, however, provide the full details of the improved image quality. The broader Gaussian profile contributing to the LSF shown in figure 2(c) is dramatically reduced, improving the resulting MTF in more ways than such an improvement in FWHM would imply. When considering the improvements in spatial resolution, one must carefully consider the requirements of the application such that a balance between the improved spatial resolution and the consequent reduction in detection efficiency can be achieved.

4 Conclusions

This study shows the potential for a high-energy, high-resolution hard X-ray/γ-ray imager with capabilities for energy discrimination. The influence of fluorescence cannot be ignored but may be accounted for. Further beam-line testing is required to more accurately determine the detector MTF which is expected to improve further still. Interest from synchrotron beam-lines for high-frame rate imaging will be explored in the coming months, particularly at lower energies (8-30 keV) where the fluorescence will no longer be an issue. The improvements in the FWHM of the LSF from 80 µm to 25 µm show how the analysis techniques used in this study can improve current technology and open the doors to a greater number of applications ready for exploration in the coming months.

Acknowledgments

With thanks to David Burt, Bill Bruns, Mark Robbins and Peter Pool of e2v technologies ltd. for general discussion, advice and for providing the CCD97 and CsI(Tl) used in the experimental work.

References

[1] e2v technologies, *CCD*97-00 *back illuminated* 2-*phase IMO series electron multiplying CCD sensordatasheet*, A1A-CCD97BI_2P_IMO, issue 3 (2004).

[2] D.J. Hall, A. Holland and D.R. Smith, *Imaging and spectroscopy using a scintillator-coupled EMCCD*, *Proc. SPIE* **7021** (2008) 70211Y.

[3] D.J. Hall and A. Holland, *High resolution X-ray and γ-ray imaging using a scintillator-coupled Electron-Multiplying CCD*, *Proc. SPIE* **7449** (2009) 74491G.

[4] D.J. Hall, A. Holland and D.R. Smith, *The use of automatic scale selection to improve the spatial resolution of a scintillator-coupled EMCCD*, *Nucl. Instrum. Meth.* **A 604** (2009) 207.

2011 JINST 6 C01022