Development of EM-CCD-based X-ray detector for synchrotron applications

Journal Item

Development of a new EM-CCD based X-ray detector for synchrotron applications

J.H. Tutt, D.J. Hall, M.R. Soman, A.D. Holland, A. Warren and T. Connolley

We have developed and successfully demonstrated a high speed, low noise camera system for crystallography and X-ray imaging applications. By coupling an EM-CCD to a 3:1 fibre optic taper and a CsI(Tl) scintillator it was possible to detect hard X-rays. This novel approach to hard X-ray imaging takes advantage of the low equivalent readout noise performance at high pixel readout frequencies of EM-CCD detectors with the increase in imaging area that offered through the use of a fibre-optic taper. Compared to the industry state of the art, based on CCD camera systems, we were able to achieve a high frame-rate for a full-frame readout (50 ms) and a lower readout noise (<1 electron rms) across a range of X-ray energies (6 keV to 18 keV).

Introduction: Many X-ray imaging detectors, from medical diagnosis to synchrotron research, use scintillator-coupled CCD detectors. However, CCD systems have performance limitations such as an increase in noise at higher readout speeds. Recently, we completed a lab-based, STFC-funded, concept study on a novel photon-counting detector [1][2]. The Electron-Multiplying (EM) CCD was designed for low light level imaging such as night-time surveillance and differs from the standard CCD through the addition of a "gain register" [3]. By multiplying the signal by thousands, the effective read noise of the device can be dramatically reduced, allowing operation at very high speeds with sub-electron read noise, offering high resolution centroiding and energy discrimination [4][5].

As part of an STFC-funded IPS grant in collaboration with e2v technologies, we have developed a high-speed (24 fps full-frame), large area X-ray detector module, using high-speed electronics provided by XCAM ltd [6]. This project aims to transfer this technology and expertise to applications in synchrotron research through the use of a proof-of-concept camera module. The main applications for this camera in synchrotron research are powder diffraction, macromolecular crystallography and larger area X-ray imaging.

By coupling a fibre-optic taper to a larger EM-CCD, an increase in the area of the detector is possible over previous studies, with arrays possible for increased area [7]. In comparison to previous CCD-based systems, the expected performance of the module will give a faster readout speed (increasing beamline throughput), higher effective dynamic range through higher maximum flux before saturation and higher detection efficiency, higher signal to noise and operation at higher temperatures.

This experiment was designed to maximise the stopping-power of the system and so uses a thicker scintillator than is typically used in state-of-the-art detectors (see Table 1). The thicker scintillator increases the detection efficiency; however, this comes at the expense of spatial resolution. Here, we summarise the experiment performed using the B16 beamline at the Diamond Light Source and compare the results to the current state-of-the-art CCD based detectors.

The camera system: The XCAM CCD 6200 camera system is designed for the purpose of driving EM-CCDs with a high pixel readout frequency. The camera system is based on an ARM microprocessor which handles all communications between the electronics and the initialisation program. In order to be able to run the EM-CCD at a high pixel frequency of 25 MHz with low noise and low pick-up, the electronics need to be as close to the EM-CCD headboard as possible. The camera system was provided by XCAM ltd with headboard, vacuum interface, electronics and custom Thermo-Electric Cooler (TEC) system as seen in Figure 1.

The EM-CCD (CCD201[8]) was provided by e2v directly coupled to a 1:1 fibre optic window. This window is then directly coupled to a 3:1 fibre optic taper. The surface of the fibre optic taper is directly coupled to a CsI scintillator doped with thallium that emits optical photons with wavelength of approximately 550 nm when placed in an X-ray beam [9]. The EM-CCD needs to be cooled to reduce dark current and increase the effect of multiplication gain and so the camera must be held under vacuum. An X-ray transmissive window fits on the end of the system and creates a vacuum tight seal. The window is 73% transmissive at X-ray energies greater than 5 keV (the transmission is not 100% due to the support structure needed to maintain the integrity of the window in the current prototype).

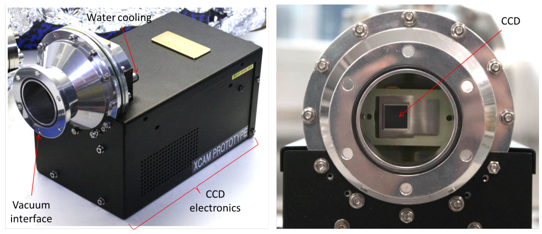

Fig. 1 *The EM-CCD camera system provided by XCAM showing the whole system with vacuum interface, water cooled heat exchanger and electronic (left) and the CCD201 mounted inside the vacuum chamber (right).*

The B16 beamline at the Diamond Light Source: B16 is a test beamline designed to be a versatile, hard X-ray testing facility with both white beam and monochromatic X-ray capability. The beamline can operated in the 4 keV-45 keV energy range and is typically used for the characterisation of optics, detectors and other instrumentation.

Experiments performed: The EM-CCD camera was placed in the monochromatic X-ray beam after attenuation with Al and after shutters had been used to confine the beam into a rectangular projection. The centre of the fibre-optic tape was partly covered with a piece of tungsten to form an edge in the image that would allow spatial resolution measurements to be made. The beam was moved across the scintillator surface to locations where part of the beam was obscured due to the tungsten edge and the support structures in the X-ray window. The gain of the system was variedd to see the effect of the increasing gain on readout noise and image quality. When the multiplication gain was increase too much, surface channel effects were seen in the images [10]. The energy calibration of the system (electrons/ADU) was found from Photon-Transfer Curve measurements [11] and this allowed the readout noise to be found from the regions of serial overscan in the images.

Readout noise and frame rate: The EM-CCD was read out with a constant pixel frequency of 25 MHz. The CCD201 has an image area of 1024 x 1024 pixels and therefore a frame rate of 24 Hz (full-frame). At gain levels greater than 150× the device readout noise falls to sub-electron levels and the multiplication registers have not entered surface-channel mode. This shows that the EM-CCD can be operated at high speed with sub-electron readout noise (rms). The shadows caused by the window support frame and tungsten edge were used to analyse spatial resolution. By plotting the signal across the edge and differentiating the resulting error function, it was possible to record the spatial resolution (FWHM) of the EM-CCD camera, found to be sub 200 μm across the device with a best performance of 168 μm. The spatial resolution performance is comparable to the state-of-art detectors found in industry as it is expected that the use of a scintillator with a higher stopping power (thicker) would have a lower spatial resolution performance. Rayonix quote the spatial resolution of a 40 μm thick scintillator to be 100 μm compared with a 25 μm thick scintillators' spatial resolution being 65 μm [12]. The stopping power of CsI scintillators is show in Figure 2.

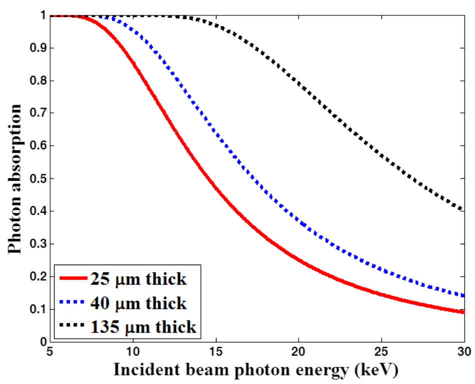

Fig. 2 *X-ray photon absorption for three thicknesses of CsI scintillators. The red (solid) line is for a 25 μm scintillator, the blue (dotted) line is for a 40 μm scintillator and the black (dot-dashed) line is for a 135 μm scintillator [13].*

Signal-to-noise ratio: The Signal-to-Noise Ratio (S/N) for EM-CCD and CCD detectors was calculated based on their readout noise and incident signal (to determine shot noise). The EM-CCD also has an additional $\sqrt{2}$ component of shot noise due to the excess noise factor [14]. Two CCD based camera systems were compared to the EM-CCD: the ADSC Quantum 315 [15] and the Rayonix SX85-HS [12], with 18 e^- rms and 8 e^- rms readout noise respectively [12][15].

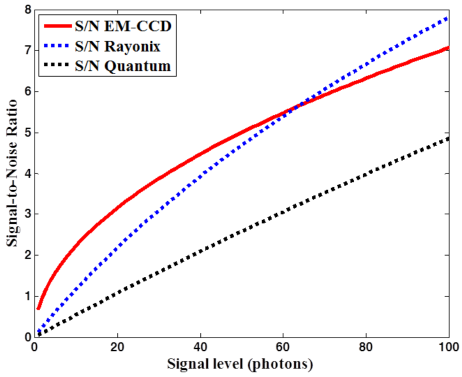

Fig. 3 *S/N at varying signal is shown for the Quantum, Rayonix and EM-CCD camera systems. The red (solid) line is for the EM-CCD, the blue (dotted) line is for the Rayonix camera and the black (dot-dashed) line is for the Quantum*

Figure 3 shows that the EM-CCD system has a better S/N than the Quantum system at all signal levels and performs better than the Rayonix system at signal levels below 60 optical photons. At low signal the readout noise dominates the S/N performance, but with increasing signal, the shot noise in the system starts to dominate.

Table 1: Comparison of different X-ray detectors used for high energy X-ray detection at synchrotrons

$Parameter$	$ADSC-Quantum315$	$Rayonix-SX85-HS$	$EM-CCDtaper$
Number of detectors	9	1	1
Detector type	CCD	CCD	EM-CCD
Active area (mm)	315 x 315	85 x 85	40 x 40
CCD pixel size (μm)	14 x 14	44 x 44	13 x 13
Number of pixels	3144 x 3144	1920 x 1920	1024 x 1024
Pixel at scintillator (μm)	51 x 51	128 x 128	39 x 39
Spatial FWHM (μm)	90	100 or 65[1]	<200
Taper ratio	3.7:1	2.92:1	3:1
Operating temp. ($^\circ$C)	-50	-50	-40
Full-frame readout (s)	1	0.4	0.05
Readout noise (e^- rms)	18	8	<1[2]
FWC (ke^-)	270	400	80
Cooling type	TEC[3]	Closed-cycle refrigeration	TEC[3]
Detection efficiency (400, 650 and 800 nm)	0.15, 0.5, 0.37	0.8 @ 650 nm	0.54, 0.9, 0.67

[1]100 μm with the 40 μm and 65 μm with the 25 μm scintillator.
[2]The EM-CCD was always operated at 25 MHz; therefore, the readout noise at 1 MHz is unknown.
[3]Thermo-Electric Cooler (TEC) or Peltier cooler.

Conclusion: The camera developed and tested during this experiment was designed to offer higher speed with lower readout noise than the current state-of-the-art CCD cameras and to be an effective detector across a large range of X-ray energies while still having sufficient resolution performance. Through the use of multiplication gain, the EM-CCD camera is able to operate at much higher pixel frequencies than is currently possible with CCD technology (at low readout noise levels) available and with a much lower effective readout noise (Table 1). This allows the EM-CCD to be read out very quickly and used in higher flux applications without becoming saturated. The EM-CCD has a high S/N ratio than its CCD counterparts, making it an ideal detector for low flux applications. The thicker scintillator gives the camera system a better stopping power making it a more efficient system for X-ray energies above 20 keV (Figure 2); however, this degrades the system spatial resolution. The degradation is at a level that is expected from using a thicker scintillator; therefore, spatial resolution can be improved with a thinner scintillator.

The EM-CCD has smaller area than the CCDs that make up the other camera systems and having a large imaging area is a key specification of this technology. The EM-CCD is a relatively new detector type in comparison to the CCD and developments are being made in devices with large imaging areas which will make them even more desirable in X-ray detection applications. It is also possible to tile them in a similar way to their CCD-based counterparts; therefore, their smaller size should not be a limiting factor in their use as X-ray detectors in synchrotrons.

This experiment has shown the EM-CCD based systems can be effective alternatives to existing CCD based cameras in X-ray detection at synchrotron facilities.

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