CCD Readout for the IXO Off-Plane Grating Spectrometer

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ABSTRACT

The International X-ray Observatory (IXO) project is the result of a merger between the NASA Con-X and ESA/Jaxa XEUS mission concepts. The IXO mission outline has an X-ray grating spectrometer operating in the 0.3-1 keV band. CCDs are the ideal detector for the readout of the grating spectrometer instrument and have been flown in similar functions on XMM and Chandra. Here we review the Off-Plane X-ray Grating Spectrometer concept for IXO and discuss the optimization of CCD technology for detection in the 0.2-2 keV X-ray band. We will discuss improvements to the existing technology previously flown, and the use of new technology such as electron multiplying CCDs which can provide enhanced signal to noise at these soft X-ray energies, together with radiation hardening measures and methods of reducing sensitivity to optical stray light. We will also end by discussing alternative CMOS-based technology which may be developed in future years to replace the CCD technology, offering benefits of higher system integration and radiation hardness.

Keywords: CCD, X-ray, spectroscopy, IXO, XMM, photon counting

1. INTRODUCTION

In 1999 the XMM and Chandra X-ray observatories were launched bringing in a new era in astronomy in the 0.3-10 keV region with focussing telescopes having large collecting area, high spatial resolution and providing spectroscopy of X-ray sources. For the last decade studies have been underway to consider the follow-on to these missions. In 2008 the ESA/Jaxa XEUS and NASA Con-X mission concepts were merged into a single project named the International X-ray Observatory (IXO)[1]. The mission baseline concept carries a large focussing X-ray optic operating up to ~50 keV, with an unprecedented 3 m^2 effective area at 1 keV to provide spectroscopy of the early universe. Three core instruments occupy the focal plane; a Wide Field Imager using silicon and CdTe imagers providing imaging and medium spectral resolution R_{1keV}~10, a cryogenic imaging spectrometer using an imaging Transition Edge Sensor (TES), with limited spatial resolution but with higher spectral resolution R_{1keV}~400, and a non-imaging grating spectrometer with high spectral resolution, R_{1keV}~3000. In addition to these core instruments, the baseline mission concept includes other instruments that provide high count rate with timing capability, and polarization sensitive imaging.

Here we describe one design concept for the X-ray grating spectrometer (XGS) on IXO, using reflection gratings in the off-plane mode, referred to as the Off-Plane XGS, or OP-XGS instrument. A schematic of the telescope concept is given in Figure 1 having a 20 m focal length, and thereby requiring a deployable instrument platform to enable accommodation within the shroud of a launch vehicle. The other instruments require positioning at the telescope focus and are mounted on a translation platform to enable one to be selected for an observation. In the current OP-XGS instrument concept the grating array is mounted on the spacecraft platform at 13.5m from the focal plane. The dispersed X-rays lie out of the main focussed field of view, and a camera is located away from the other main instruments to measure the dispersed beam. The current goals for the XGS instrument are;

- To cover an energy band of 0.3-1 keV
- To achieve an effective area of 1000 cm^2 at 1 keV for point sources
- To have a spectral resolution, R>3000 over the energy band.

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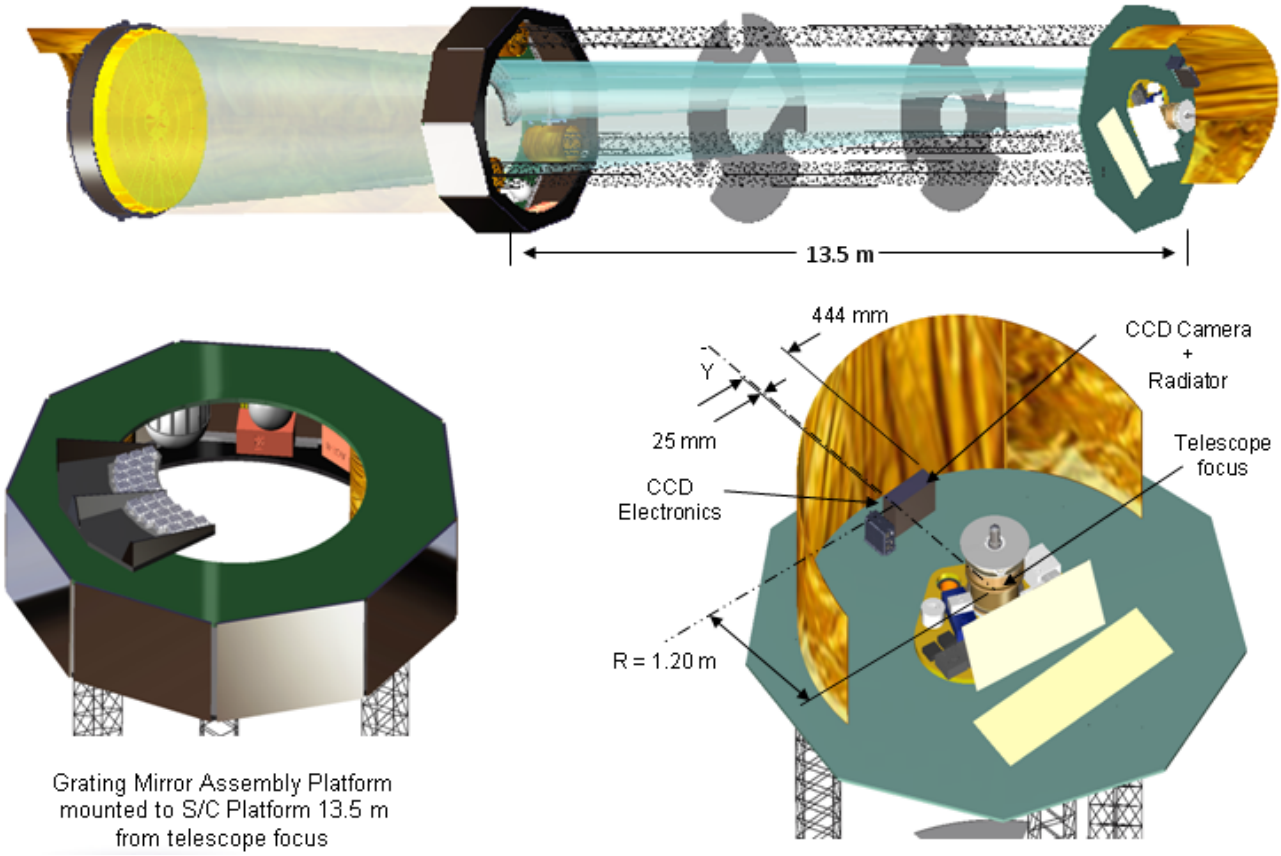

Figure 1. Concept for the OP-XGS on IXO, with the gratings mounted at the 13.5m service module, and the dispersed X-ray spectrum being detected by a CCD array at the instrument platform.

Both the IXO spacecraft and instruments are currently in a Phase-A design process, and therefore exact details of configuration and performance will evolve in coming years. In the current XGS configuration, the gratings lie permanently in the beam, and operate all the time, whilst the other instruments are configured for the observations. An important aspect of the gratings is that by only intercepting a sector of the annular X-ray beam, the angular resolution can be improved, since the gratings intercept the beam from mirror segments over a limited range. This is referred to as "sub-aperturing" and results in the grating PSF being narrower in the dispersion direction than the telescope PSF on-axis.

The effective area at the gratings has a design goal of 1000 cm^2 at 1 keV. This is a factor 10x increased area from the XMM RGS instrument. Thus, the averaged X-ray throughput needs to be 10x that for XMM. However, in addition, the angular resolution of both the telescope, plus the sub-aperturing, provides a line spread function which is ~10x narrower than that for XMM. Therefore specific emission lines may be up to 100x more intense than when measured in XMM. The readout camera may therefore have to be capable of handling up to 100x higher flux than the XMM RGS system.

The off-plane gratings are discussed in another paper [1]. In this paper we review the baseline concept for the spectrometer readout which uses an array of X-ray optimised CCD detectors. As CCD detector technology is quite mature, and is already performing similar functions on XMM and Chandra, we can define a baseline solution using existing technology. In addition, the performance of the instrument can be further improved through some modest technical developments and these will be discussed in Section 3. Finally, new detector technology is being developed which may supplant CCD technology, and we will discuss the future developments in CMOS technology which are occurring and which may be of relevance to the application.

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2. INITIAL DETECTOR ARRAY CONCEPT

The focussed dispersion from the gratings lies along an arc at the instrument platform of the spacecraft. Being in the off-plane mode the zero order of the beam is not at the telescope focus, with reflection radial to the axis as in the XMM RGS, but also lies on the dispersion arc. This necessitates a zero-order beam monitor to provide a plate-scale calibration for the resultant measured dispersed spectrum. We have assumed that fully customised CCDs will be used for this application, and are confident that the use of a custom design does not pose a technical risk to the project, given the large number of customised flight devices in use today. In the baseline configuration we have considered relatively small devices, by today's astronomical CCD standards, which are similar in scale to those used for the XMM RGS [2] and which will have a high manufacturing yield. The baseline array concept is depicted in Figures 2 and 3, showing the locations of the CCDs for the zero order monitor, and the dispersed spectrum array, plus a solid model of the proposed array concept.

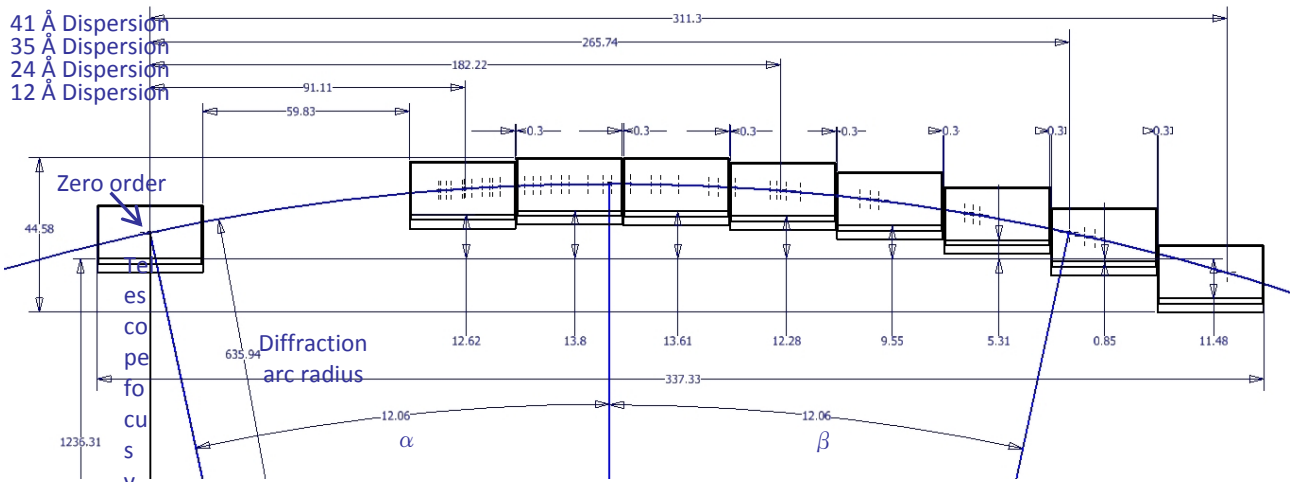

Figure 2. Dispersion of the X-ray spectrum together with the zero order monitor CCD. The dispersed spectrum is along an arc and in this baseline configuration the centre of the outer CCDs cover 1keV (closest to zero order) and 0.3keV (furthest from zero order)

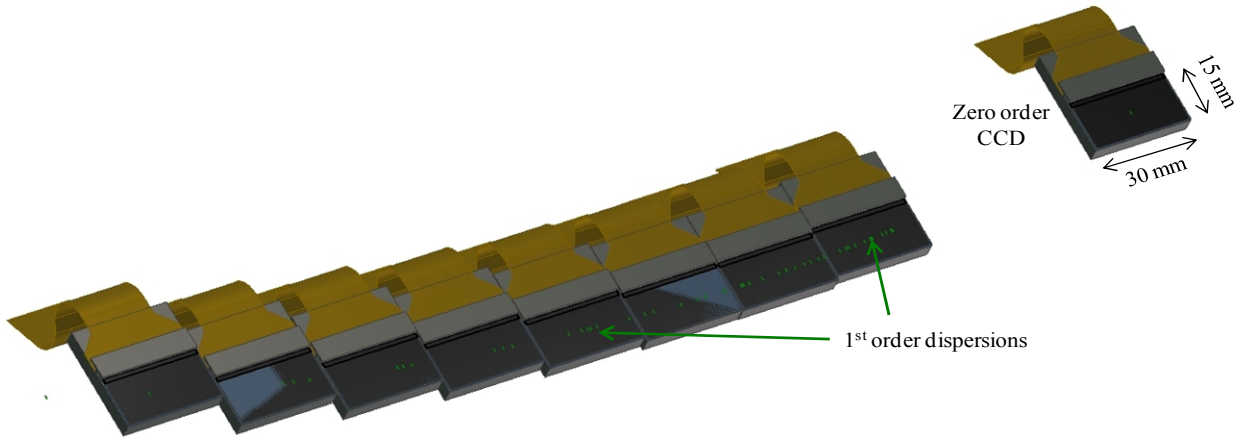

Figure 3. Solid model of the baseline CCDs and array concept

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The array consists of 9 identical CCDs, with 8 CCDs used for the spectrum readout. The array has been configured so that 1 keV (12.4 Å) lies approximately in the centre of the CCD closest to the beam monitor, and 0.3 keV (41 Å) lies approximately in the centre of the CCD furthest away. These CCDs have the following design details:

- Frame transfer architecture, with 10:1 reduction in pixel height at image:store boundary
- Back illumination with integral light shield having high efficiency over the 0.3-2 keV region
- Image size 30 x 15 mm^2 (15 mm height is required to account for telescope alignment and spacecraft pointing)
- Image pixel dimensions 30 μm along dispersion and 100 μm across dispersion
- Image size 1000 x 150 pixels
- 4 low noise/high speed amplifiers per CCD, each running at 1 MHz [3]
- System noise <8 electrons rms.
- Frame time 40 ms (approx. $1/100^{th}$ the XMM RGS frame time)
- Operating temperature -80°C

The requirement for high throughput for the readout system, formed from a combination of 10x increase in collecting area over XMM RGS and a 10x increase in resolution, necessitates a high frame rate. Using conventional CCD technology, this is achieved by a combination of having multiple readout nodes per CCD, each running at a higher frequency. The system noise requirement is determined by the ability to separate orders from the gratings, and this places an equivalent noise charge (e.n.c.) specification on the system of ~8 electrons rms. This can be achieved at readout speeds of up to 1 Mpix/s. Through four output nodes, with the baseline image size results in a 40 ms frame time, which is more than 100x faster than the XMM RGS system. To retain the imaging integrity one must transfer the image into the store section in approximately $1/100^{th}$ of the image integration time; i.e. in ~ 400 μs, or at a line rate of ~2.7 μs/row. This speed is just achievable using conventional polysilicon electrodes. A faster transfer speed would require the addition of aluminium tracks over the polysilicon electrodes; this "metal buttressing" reduces the sheet resistance of the polysilicon electrode and enables much faster transfer speeds.

The array will be fabricated onto a cold finger and maintained at a temperature of approximately -80°C. This is much warmer than the CCD temperatures on XMM and Chandra and can be accommodated due to the much higher frame rate. In XMM and Chandra, the operating temperature is determined by the release time constant of the dominant E-centre formed after radiation damage. The higher frame rate, combined with electronic charge injection will help ensure that the traps which degrade charge transfer efficiency will remain filled at warmer temperatures. This higher operating temperature will also provide a relaxed specification on the spacecraft water vapour partial pressure, although it will not significantly affect the hydrocarbon specification to avoid device contamination.

The technology readiness level (TRL) of technology being proposed for space instruments is particularly important as it can determine timescales to launch opportunities, or whether a particular technology is adopted for flight due to perceived risks of incorporating it in an instrument design. The CCD technology baselined here is similar to that flown before, and whilst the customized solution for IXO will be unique, the technical solution will have a high intrinsic TRL of ~7-8 which will help ensure that the readout solution for the gratings is achievable to budget and timescale.

3. FUTURE DETECTOR DEVELOPMENTS AND IMPROVEMENTS

The baseline detector solution described in Section 2 offers a conservative solution to the readout of the grating spectrum and zero order, but could limit the performance, or be improved upon. We have therefore identified several technical developments which can be undertaken to improve the instrument performance beyond that of the baseline. These technical developments fall broadly into two main themes;

- Improvements which benefit the low energy cut-off, enabling detection down to 200 eV to enable better measurements of carbon processes, and of red-shifted objects. This can be achieved using thinner light blocking filters, which can be tolerated since the increase in optical transmission is compensated by the higher frame rates compared to XMM and Chandra
- Improvements to the radiation hardness of the detectors which will provide lower instrument mass through reduced instrument shielding. This can be achieved through a combination of design changes to the CCDs, including use of electronic charge injection methods, and possibly through the development of p-channel CCDs to a high TRL. In addition, developments in CMOS detectors in the X-ray region could provide significant improvements to radiation hardness.

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These developments are discussed below.

3.1 Optical Blocking Filter

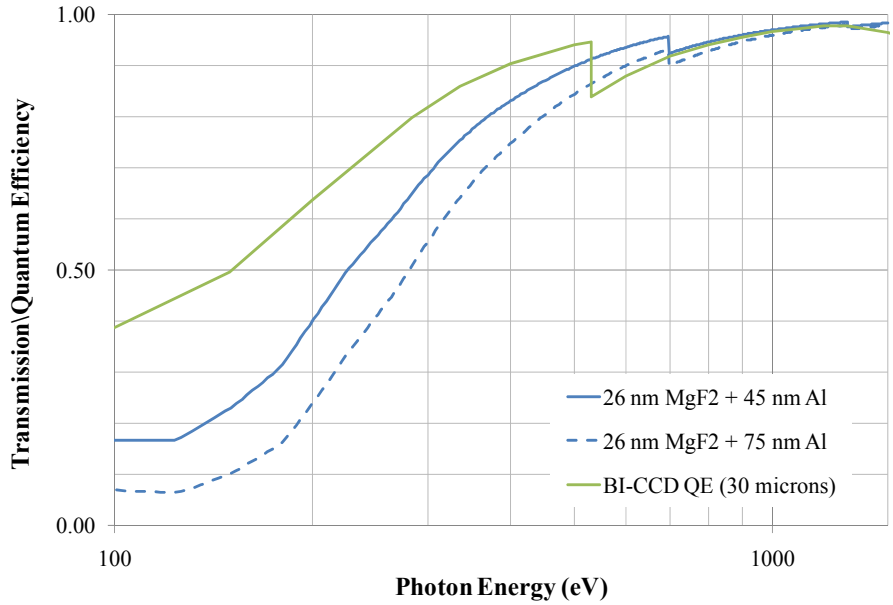

Figure 4. Detection efficiency of a back-illuminated CCD, together with the X-ray transmission of two different optical blocking filters used in the XMM RGS

Figure 4 depicts the detection efficiency of the XMM RGS back-illuminated CCDs, together with the transmission efficiency of the light blocking filters. In the RGS instrument, these filters were directly deposited onto the back-illuminated CCD surface, and had a range of aluminium thicknesses from 45-75 nm, decreasing in thickness with distance from the X-ray beam. As can be seen from the figure, the transmission of the optical filters dominates the overall performance, compared to the CCD detection efficiency. The required thickness of an optical blocking filter and the stray light specification placed on the spacecraft directly trade against each other. However, if one were to use a similar specification to that for XMM, the increased {frame rate x pixel area} product of the baseline design would be ~25x more tolerant to stray light before affecting the system noise specification. This increased tolerance to stray light can be used to enable use of thinner light blocking filters. To achieve a better understanding of this parameter space, an experiment is planned to explore thinner filters than used on XMM, together with their X-ray and optical transmission properties.

3.2 Electron Multiplying CCDs

One of the limitations to detectors operating at these soft X-ray energies in a photon counting mode is the energy re-distribution of the detection process, where signal charge can be lost in "dead" zones where the charge collection efficiency (CCE) is less than unity. These phenomena lead to "partial events", where only a fraction of the generated signal is measured in the device. The recovered fraction can be between 0-100%, and the proportion of X-ray events which undergo this loss process is dependent upon the details of the top surface layers (<0.1 μm). In addition to these partial events, charge from a single X-ray can be split between two or more pixels, further reducing the signal to noise ratio. These factors combine to modify the intrinsic device quantum efficiency, into the "detected" quantum efficiency; DQE. The DQE can be significantly reduced from the QE particularly for X-ray energies <400 eV.

Electron multiplying CCDs were originally demonstrated commercially in the late 1990's, however to-date have not been adopted for use in space instrumentation, partially due to concerns over radiation damage where protons might

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cause "hot pixels" in the avalanche regions of the device, and also due to the lifetime issues where the EM gain can reduce slightly over time. We have conducted studies into both these effects demonstrating that proton damage is not a concern for the use of EM CCDs in space [4] and the change in EM gain over lifetime is also not a serious concern for the use of the technology.

With these potential issues resolved, the EM CCD technology can offer significant benefits to *some applications* in space instrumentation, particularly when measuring small signals. Figure 5 shows the modelled FWHM resolution in photon counting mode as a function of energy for several systems with 8, 30 and 100 electrons rms. noise, and EM gains of 1x, 10x, and 100x. The first case represents that for a standard non-EM CCD and shows the cross-over where the resolution changes from system-dominated to being dominated by Fano statistics on the signal generation. When the EM gain is applied, the e.n.c. is reduced, however, shot noise also occurs on the signal. This indicates that above ~2 keV, the EM CCD technology would yield degraded resolution over standard technology, whilst below 2 keV the EM CCD could offer significant improvement to the noise and photon counting resolution of the device. This could provide the additional benefit of enabling recognition of events whose signal is split between several pixels, resulting in an increase in the DQE of the detectors.

The significance of modelling relatively high system noise components is that 30-100 electrons rms. can be achieved in systems running at video rates of up to 15 Mpix/s, and would indicate that CCDs with only a single readout amplifier could both achieve a low e.n.c. when using on-chip EM gain, resulting in the 100x increased throughput required over XMM RGS, and could result in increase detection efficiency to split events.

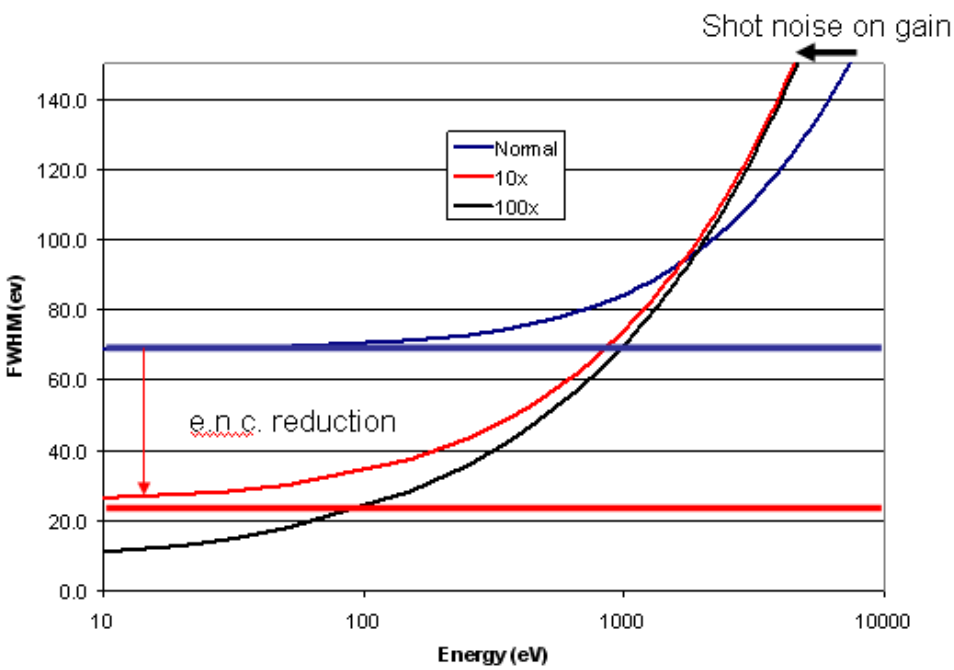

Figure 5. Predicted FWHM resolution of a CCD in photon counting mode as a function of energy in a system with 8 electrons rms. with no gain, and in devices with 30 and 100 electrons rms. with on-chip gains of 10 and 100 respectively. The predicted improvement in resolution below 2 keV is evident

Figure 6 demonstrates the detection of soft X-rays at 250 and 450 eV where the signals have been deliberately spread over several pixels (in this case to provide improved spatial resolution using event centroiding techniques). The device was operated at 1 Mpix/s already demonstrating 10x increase over XMM RGS. Figure 7 shows a series of isolated event spectra from a Cu X-ray target illuminated by an X-ray tube, and taken for different EM gains between 1-5x. The predicted increase in FWHM with the onset of the avalanche process is evident, together with the reduction in the 5σ event detection threshold linked to the reduction in system e.n.c.

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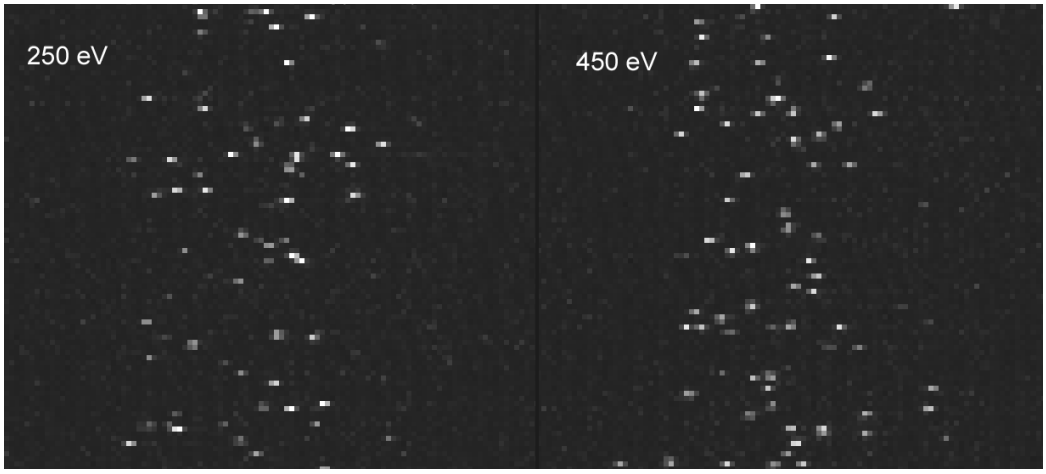

Figure 6. Soft X-ray photons imaged in an EM CCD with a gain ~30x showing that even for events split over several pixels the signal is significantly above the noise enabling high detection efficiency

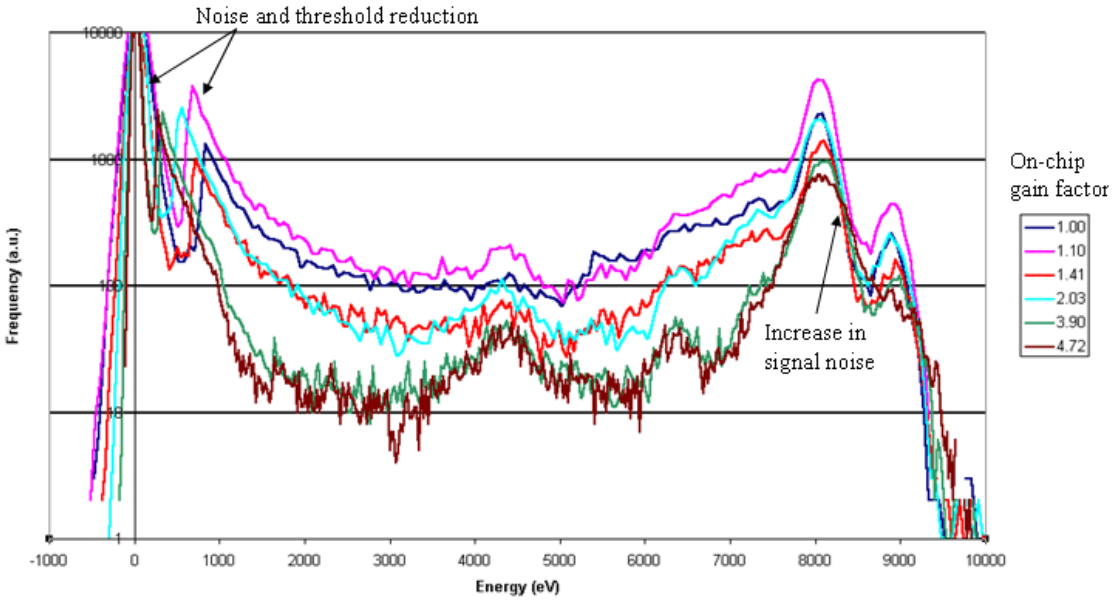

Figure 7. The responsivity map of the CMOS imaging sensor

New EM CCDs are being developed without the conventional anti-reflective coating for evaluation for the IXO XGS readout. These will be evaluated over the coming year, particularly with respect to order separation as a function of EM gain.

3.3 Improved Radiation Hardness

Radiation damage is a concern for the detectors in many space instruments. In the case of the CCDs for XMM and Chandra, the performance of the detectors has been maintained through a combination of shielding of the instrument and low device operating temperature. In the case of XMM/EPIC up to 3 cm of explicit aluminium shielding was used, in addition to the structures of the camera and spacecraft to reduce the non-ionising dose received by the detectors to an

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acceptable level. This shielding introduces additional mass to the instrument, which is undesirable. Furthermore, the low operating temperatures (-130°C in the case of XMM EPIC), place additional challenges for the thermal design of the instrument. Detectors having improved radiation tolerance can therefore bring benefits to the focal plane cooling solution, plus the overall mass of the instrument. We are currently exploring the use of electronic charge injection structures which provide sacrificial signal to fill proton-induced traps in the silicon [5,6]. The benefits of the charge injection technique form a complex operating regime where device operation modes, temperature, and signal, combine in a non-simplistic way, requiring detailed study for the particular applications concerned. Depending upon the application, charge injection can result in improvement to the radiation hardness by factors between 2-20x beyond normal device operation, although other operational details such as non-uniform background also need to be taken into account when considering overall applicability.

In addition, new results indicate that the use of p-channel CCD technology can lead to improvements in radiation hardness of between 3-10x over the more conventional n-channel CCDs [7]. The TRL of this technology is relatively low and these initial results require further work to establish yield and improved initial device performance but show promise for future instrumentation.

3.4 X-ray CMOS Sensors

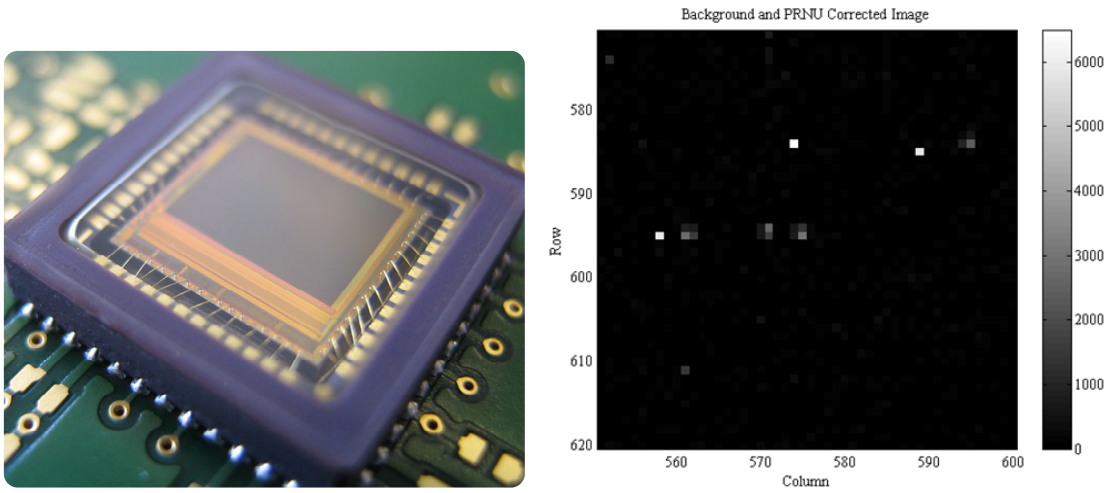

Figure 9. Photograph of a CMOS sensor which is currently being evaluated for space applications, together with an image of 6 keV photons detected in the 5 micron pixels.

The CCD technology is quite mature, enabling performance extrapolation for new design architectures with relatively low risk, and hence is baselined for the XGS readout. However, other technologies are being explored as X-ray detectors including hybrid technology, where an array of diode/pixels is hybridized to a readout IC (ROIC), plus CMOS imaging sensors. We are also exploring the development of CMOS imaging technology for use in the 0.2-2 keV band, where low noise, large detection area, large pixels are combined with back-illumination having high soft X-ray QE and good DQE. Some initial results of this work are discussed in [8] and a development programme is underway to improve the device performance for soft X-ray detection. Devices have been proton and gamma tested to $>10^{10}$ cm^{-2}(10MeVp) and >100 krads which show promise for future use in space instrumentation.

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4. CONCLUSIONS

In this paper we have introduced the IXO Off-Plane X-ray Grating Spectrometer instrument concept, and have described the baseline configuration for the CCD detector array to be used for the readout of the spectrometer. The baseline CCD technology is quite mature, providing a high Technology Readiness Level (TRL) to the instrument, and thereby a low development risk. However, further improvements to the technology are also possible which can improve the optical light rejection, extend the low energy cut-off, and improve the X-ray throughput. The possible use of Electron Multiplying (EM) CCDs may also yield improvements in signal-to-noise in the 0.2-2 keV energy region and developments are underway to assess this. Also, since the launch of Chandra and XMM, already-demonstrated and future developments in device radiation hardness may allow the detectors to withstand more radiation damage which could bring about savings in instrument mass through reduced shielding.

REFERENCES

1. McEntaffer R. L., Murray, N. J., Holland, A. D., Lillie, C., Casement, S., Dailey, D., Johnson, T., Cash, W., Oakley, P., Schultz, T., Burrows, D. N., "Off-Plane Grating Spectrometer for the International X-ray Observatory", Proc. SPIE, 7437, (2009)
2. Verhoeve P., de Korte P., Boggende A.J.F., Brinkman B., Jansen F.A., Burt D.J., Holland A.D. and Castelli C.M., "CCDs for the XMM Reflection Grating Spectrometer", Institute of Physics Conference Series, 121 (1991) 25-32
3. Murray N., Holland A.D., Jeyasundra G. and Waltham N., "High throughput video processing ASICs for X-ray CCDs", Proc. SPIE, 7435, (2007)
4. Smith D.R., Ingley R. and Holland A.D., "Proton irradiation of EM CCDs", IEEE Trans. Electron. Devices, 53, (2006) 205-210
5. Smith D.R., Holland A.D., Hutchinson I.B., Abbey A.F., Pool P., Burt D.J. and Morris D., "Low noise charge injection in the CCD22", Proc. SPIE, 5501, (2004) 189-196
6. Murray N.J., Holland A.D., Pool P., "CCD considerations for the visible focal plane on Euclid", Proc. SPIE, 7439A, (2009)
7. Gow J., Murray N.J., Holland A.D., Burt D.J.and Pool P., "A comparative study of radiation damage in p- and n-channel CCDs", Proc. SPIE, 7435, (2009)
8. Dryer B., Murray N.J., Holland A.D., , X-ray photon counting with a CMOS imaging sensor", Proc. SPIE, 7435, (2009)

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