Development of Pixel Detectors for X-ray Space Science and use in terrestrial applications

Andrew Holland[1,2]

1. Centre For Electronic Imaging, Open University, UK
2. XCAM Ltd., Northampton, UK

Summary of Topics

- Group introductions
- X-ray detection in general
- Photon Counting X-ray Detection
- Development of CCDs for XMM
- X-ray Background
- EM CCDs for soft X-rays
- SMILE
- X-ray detection in CMOS sensors
- Spinout Applications
  - Imaging for XFELs
  - Improvements to RIXS applications

<u>This talk will discuss :</u>
CCDs, CMOS

<u>This will not discuss:</u>
Hybrids, SOI, DEPFET, pn-CCD, Cryogenic, …..

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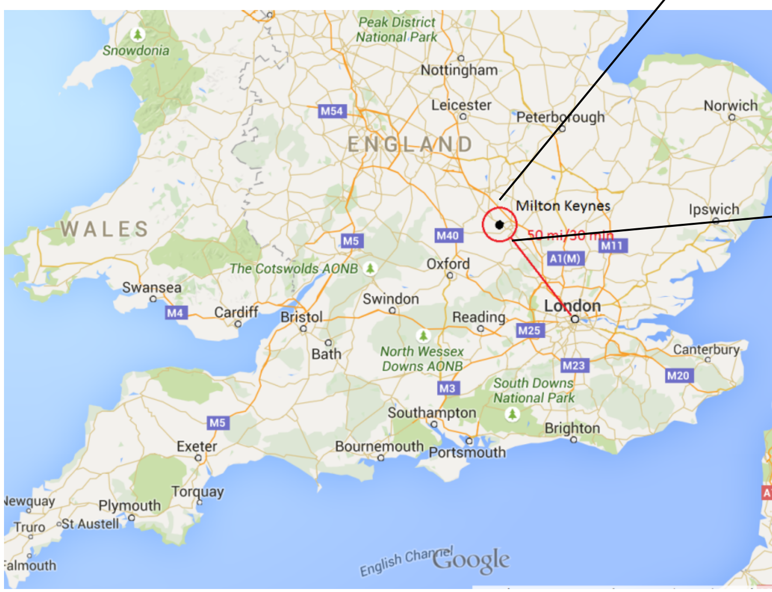
The Open University

- The UK's largest university
- >250,000 students, turnover ~$600M/year
- Sited at Walton Hall, Milton Keynes
- The CEI is located in the School of Physical Sciences (SPS)



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Centre for Electronic Imaging

Group Overview

- **Formed in 2004**
- **Sponsored by e2v technologies ltd.**
- **~20 People led by Prof. Andrew Holland**
- **Detector Research and Application Development**
  - Advanced CCD and CMOS research
  - Development of space instrumentation
  - Development of new measurement techniques
- **Training Engineers and Scientists**
  - Training PhD students, plus continued training of PDRAs
  - Training of professionals through 3-day residential workshops
  - Creating a significant pool of highly-skilled people
- **Knowledge Exchange**
  - An exemplar in knowledge exchange between university and industry
  - Recently celebrated 10 year relationship with e2v technologies

90% of the activity is in Space Science!

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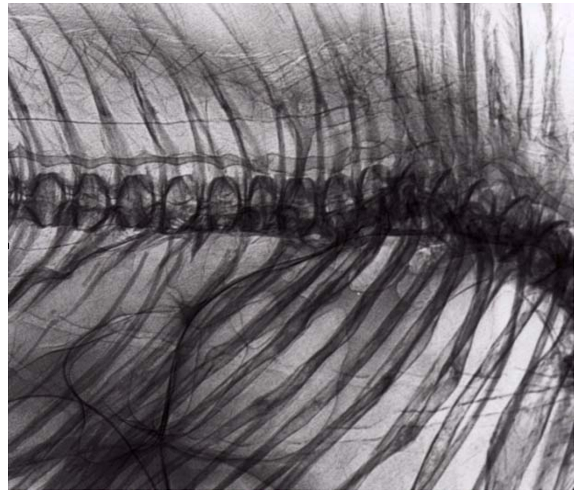
XCAM Outline

- Founded in 1995 – has just celebrated 20 years
- XCAM stands for "X-ray Cameras"
- Has 14 FTE staff across ~20 people
- Moved to new 7000 sq. ft. factory in 2012
- Offices, Class 1000 cleanrooms + development and production laboratories
- Specialises in scientific and industrial camera systems for optical, EUV and X-ray applications
- http://www.xcam.co.uk/

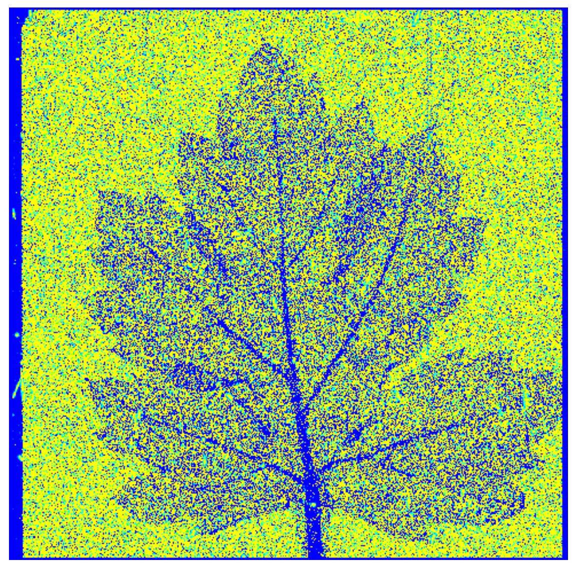
Photon Counting vs. Imaging

- Imaging mode – accumulating many
  photons per pixel
  before readout



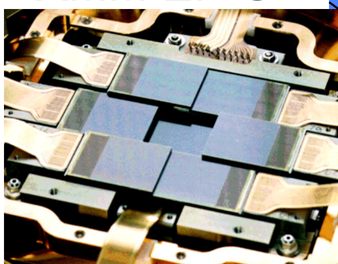
PCR Image

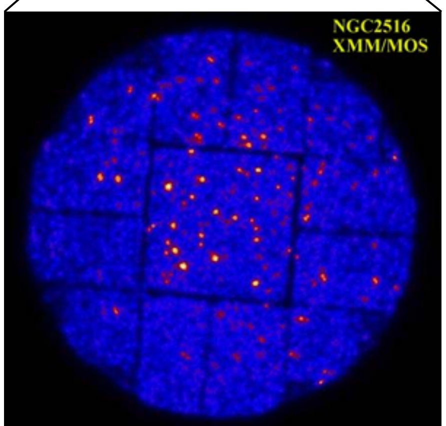
- Photon counting - <1 X-ray/pixel
  - Image accumulated
    in digital domain
  - Spectroscopy

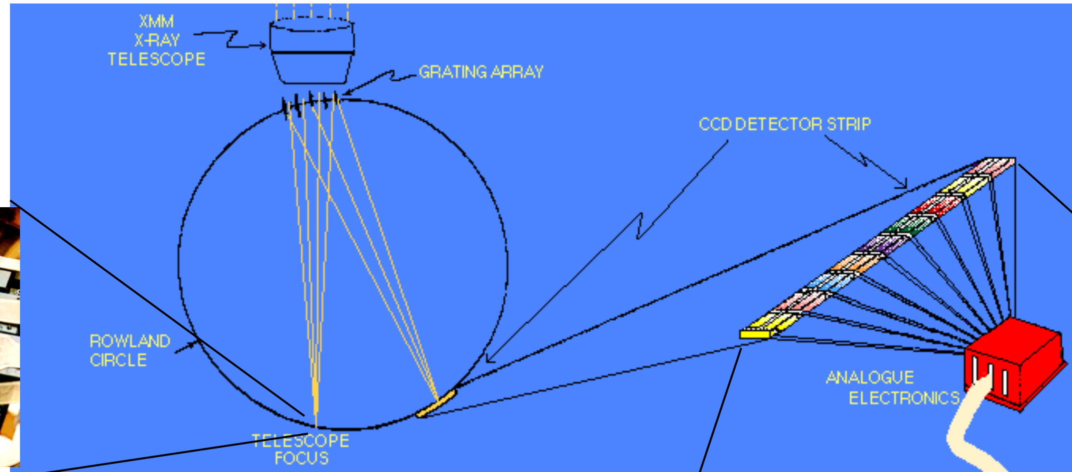


Imaging vs. Dispersive Spectrometer

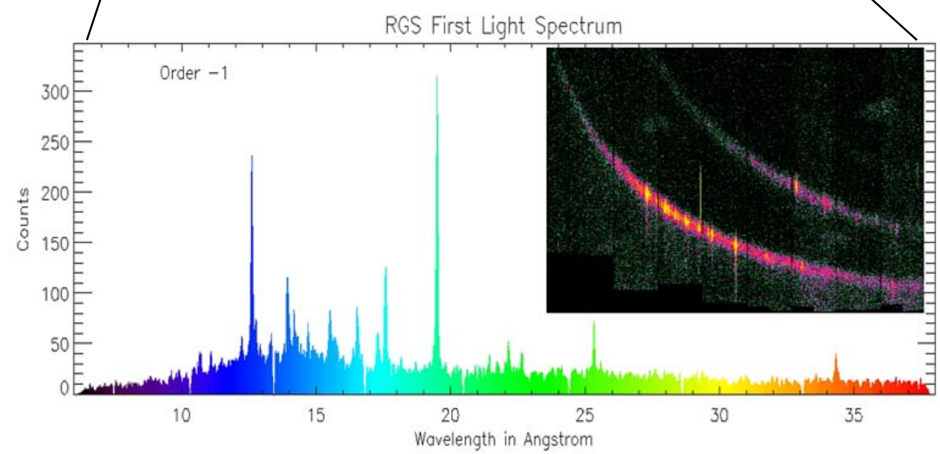
XMM EPIC







XMM RGS



Signal Generation

- X-ray absorption in silicon liberates electron-hole pairs
- Number of carriers generated

$$\mathbf{n = E/\omega}$$

where E is the photon energy in eV, and
$\omega \approx 3.65$eV/e-h pair is the mean ionisation energy

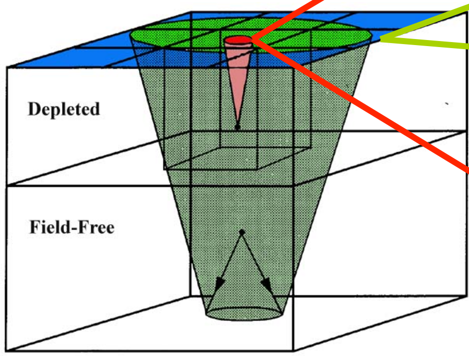
- Variance on carriers generated

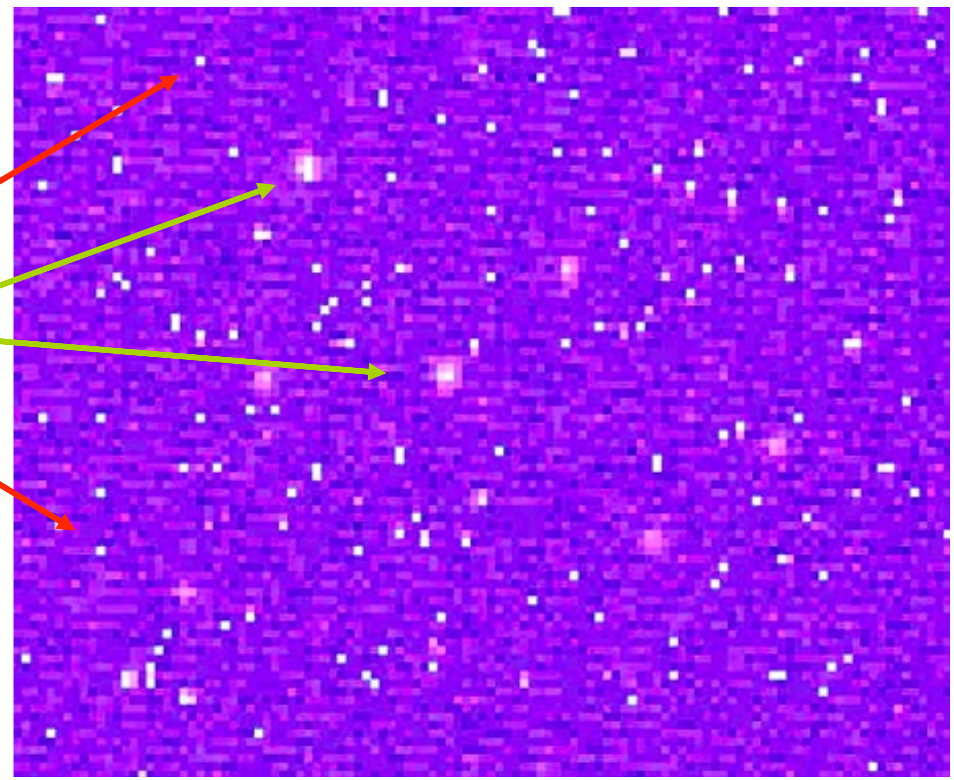
$$\mathbf{v = FE/\omega}$$

where F~0.12 is the Fano Factor in silicon

X-ray Photon Events in Pixel Detectors

- Absorption in depletion region leads to be isolated single/double events
- Absorption in field-free region leads to multi-pixel spread events

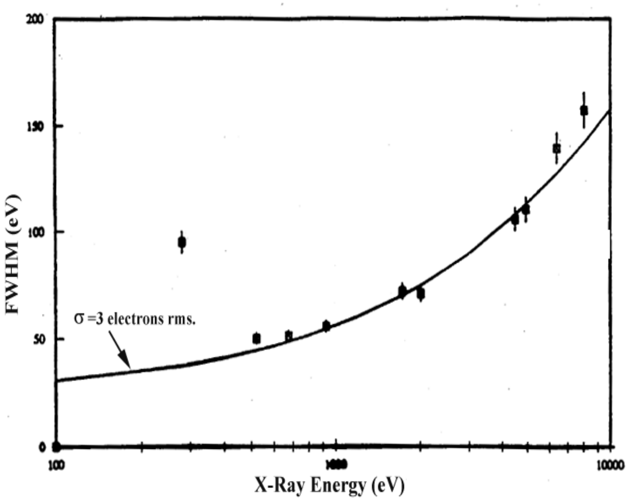


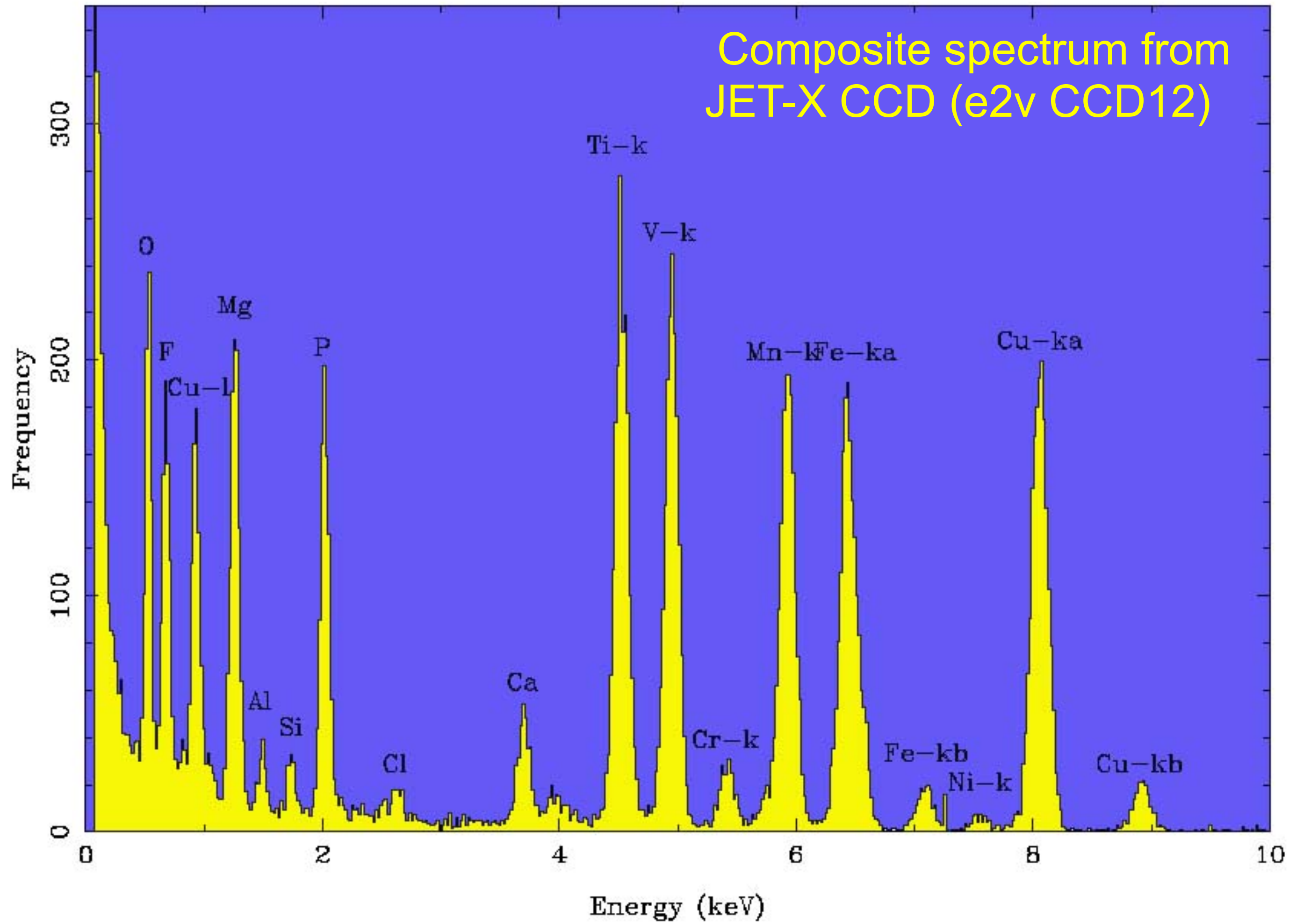


High Resolution Spectroscopy using a CCD

$n_{electrons} = E/\omega$

variance $= FE/\omega$





Timeline for XMM EPIC Developments

In the past, working on one space project was enough…

- 1987-1992 ESA funded various developments toward XMM,
  - significant performance enhancement
- 1989 ESA adopts XMM as a "Cornerstone" Mission for launch in 10 years
  - Radiation damage becomes "re-discovered"
- 1990 EPIC consortium created – Lead from Milan
- 1994 EOBB demonstrates the key performance characteristics of EPIC at Panter
- 1996 AH leaves the project…… (after essentially 10 years ..)
- 1999 Launch of XMM in December
- 2016 ~16 years of blissful operation

~10 year build phase

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CCD Developments for XMM

- In the late 1980's ESA funds a series of activities under it's TRP programme to support the two X-ray instruments
  - EPIC The imaging camera 0.3-12 keV, R~30, Imaging
  - RGS Dispersed X-ray grating 0.3-2keV, R~300, Non-Imaging
- Technical Development Activities

Parameter	State of Art	Target	Technology
Noise	~10e- rms.	<5 e- rms.	Lower node capacitance
Area	~1x1 cm^2	2x3 cm^2	Developing "stitching"
Depletion (QE)	5 μm	>30μm	High resistivity epi
Dead Layer	~1 μm	50 nm	Back-illumination
Serial CTE	0.99998	>0.99999	SBC (also helps with radiation)

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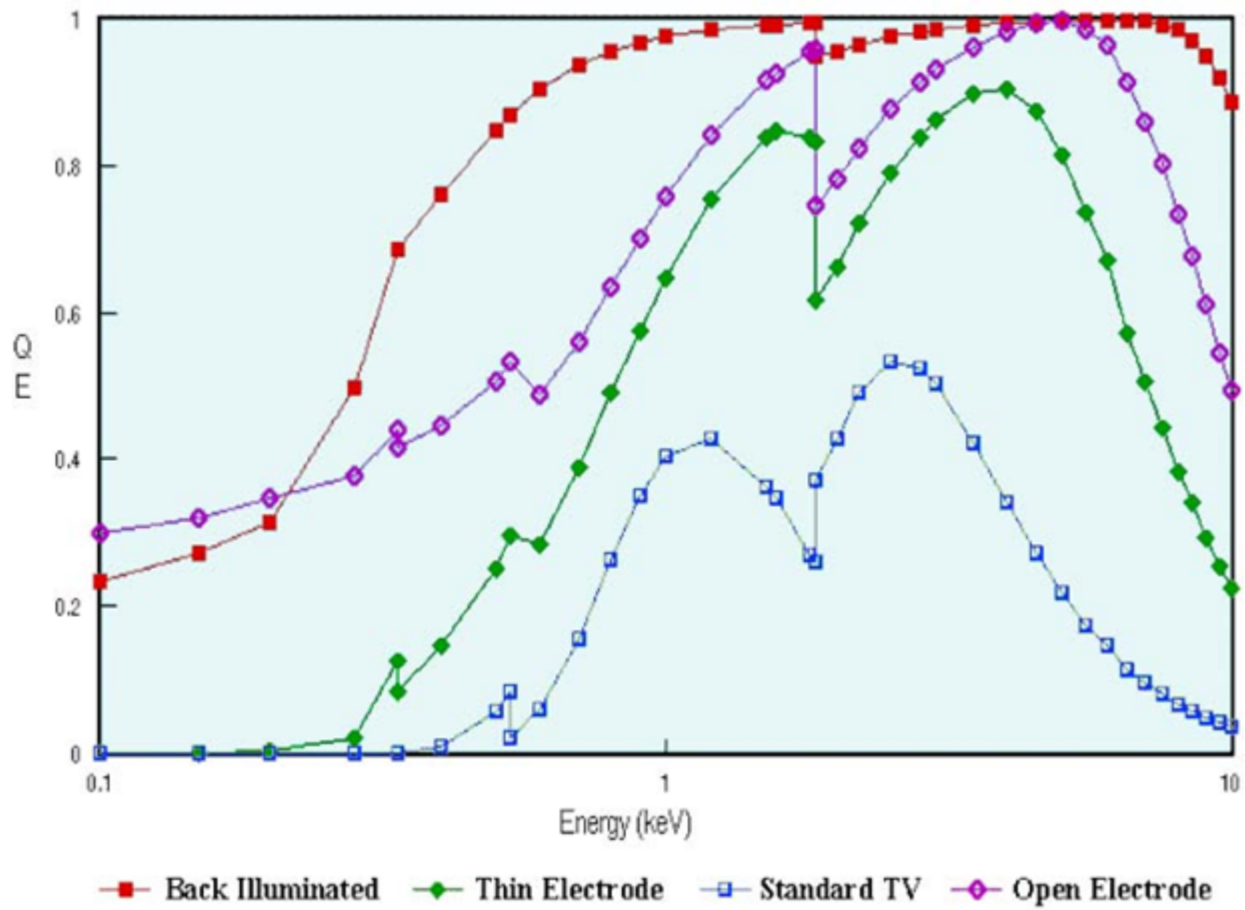
CIS now following many of the same trends

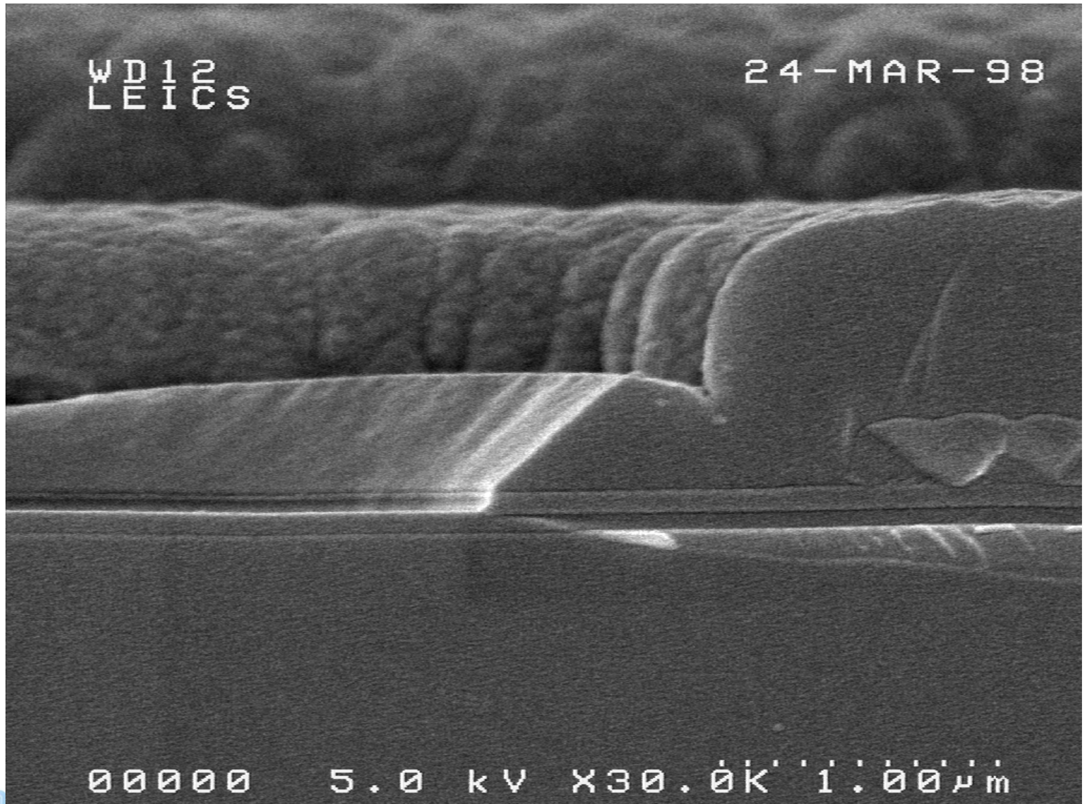
Quantum Efficiency

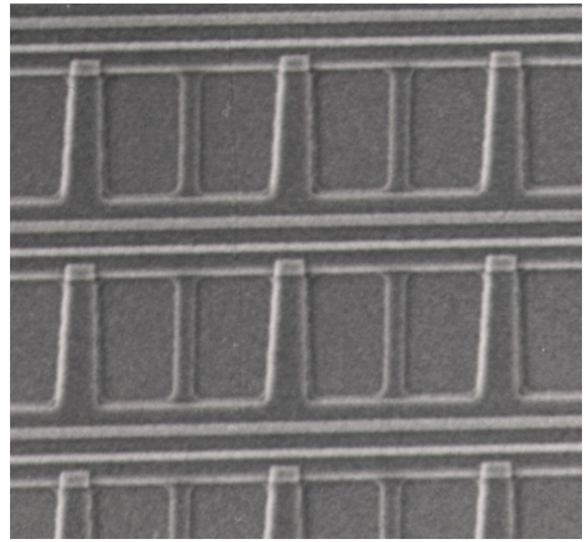
- Increase from 5 microns to 30-50 micron depletion
- Epitaxial layer from 20 microns to 50, 80 and 100 microns
- Back-illumination
- Open Electrode

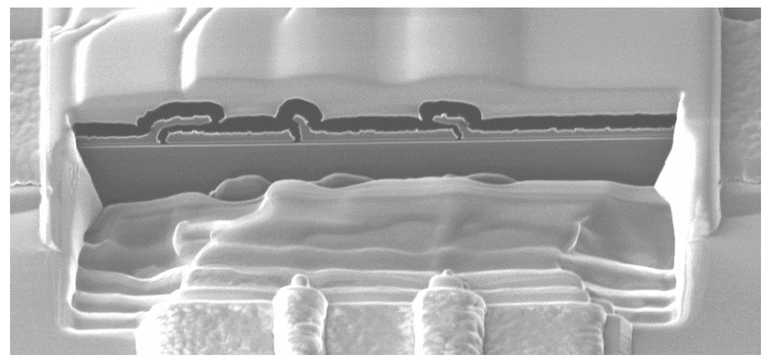


CCD22 Open Electrode Structure

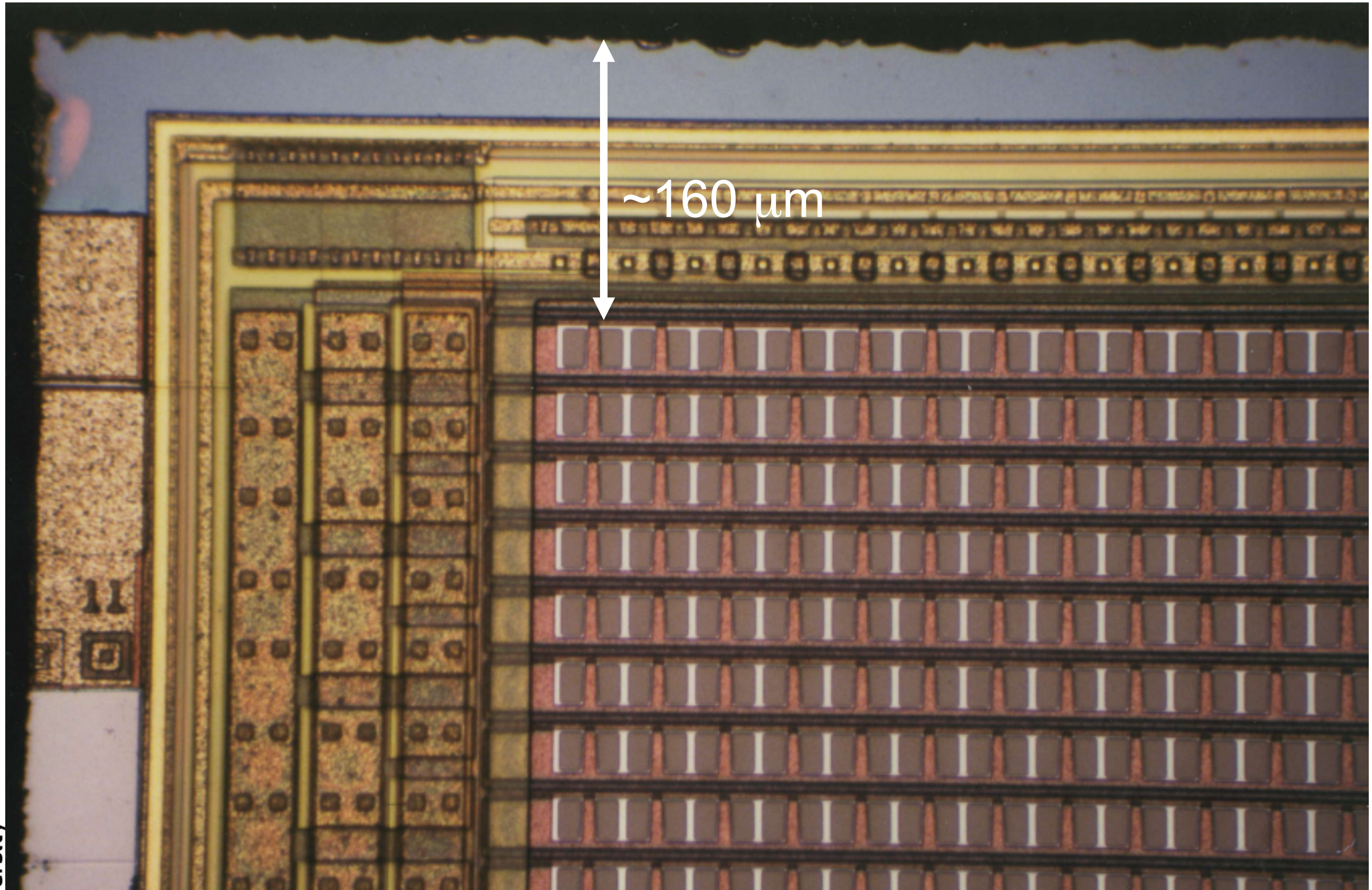
- 50% of pixel has open area
- Thinned to oxide layer in open region







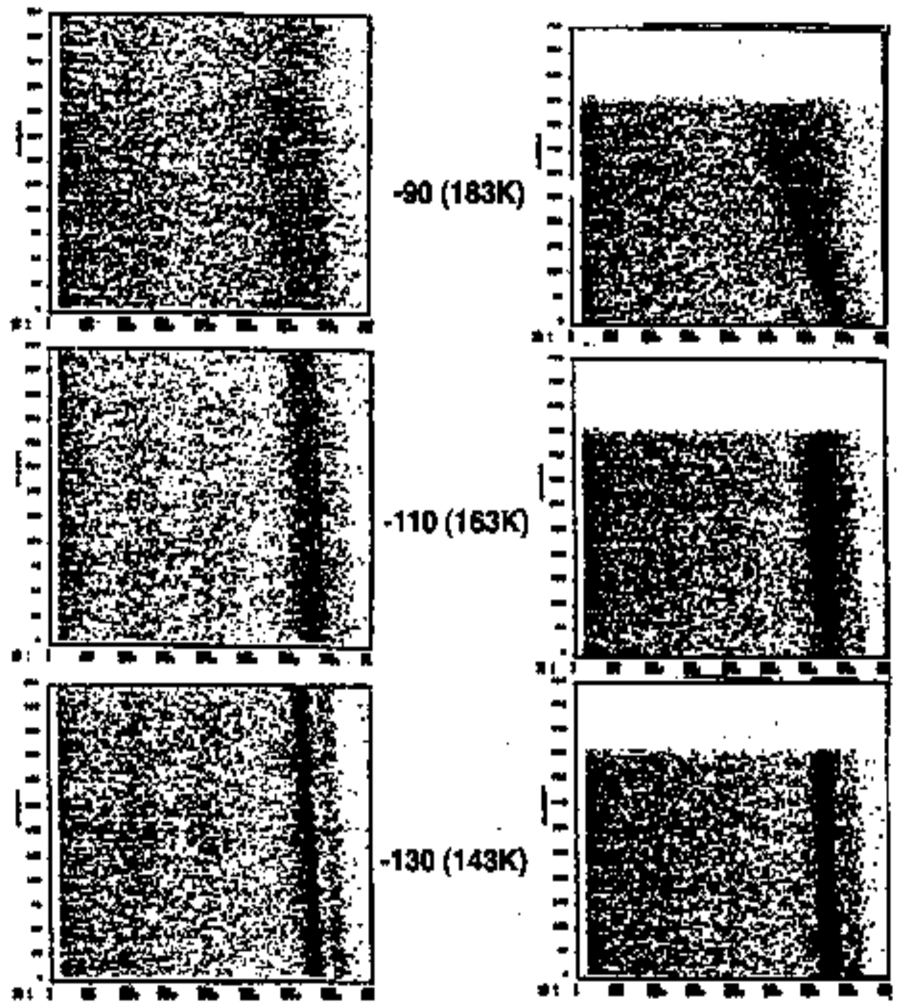
CCD22 – Sawn Edge of CCD



Then, radiation damage is re-discovered

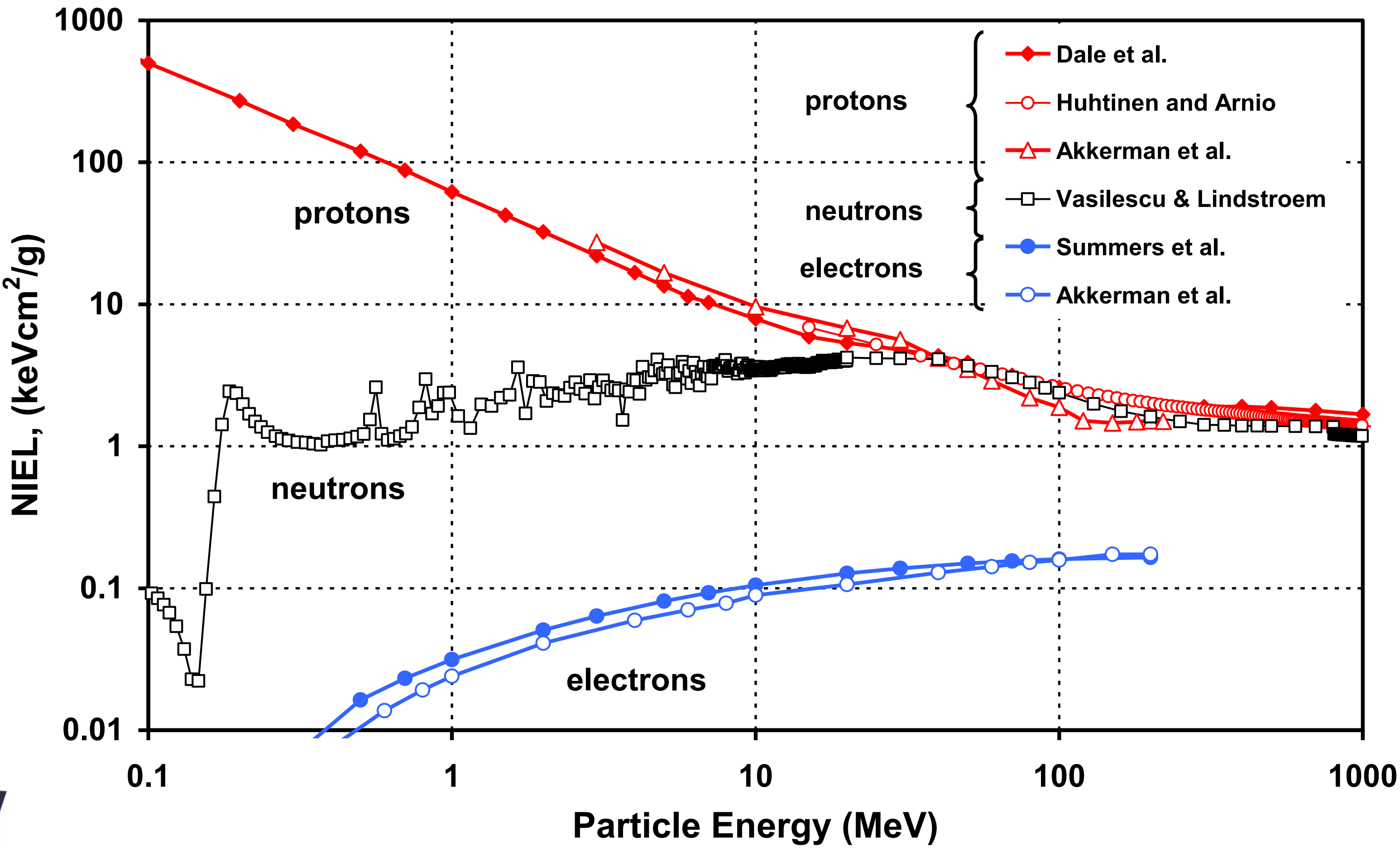
- After spending many years improving CCD performance, with large areas and good CTE of 0.999999
- Proton testing demonstrated much of this could be thrown away with CTEs in the 0.999 region

- The results provided many new insights into the damage mechanisms
- Proton radiation damage research (and qualification) is still a hot subject today for space instrumentation



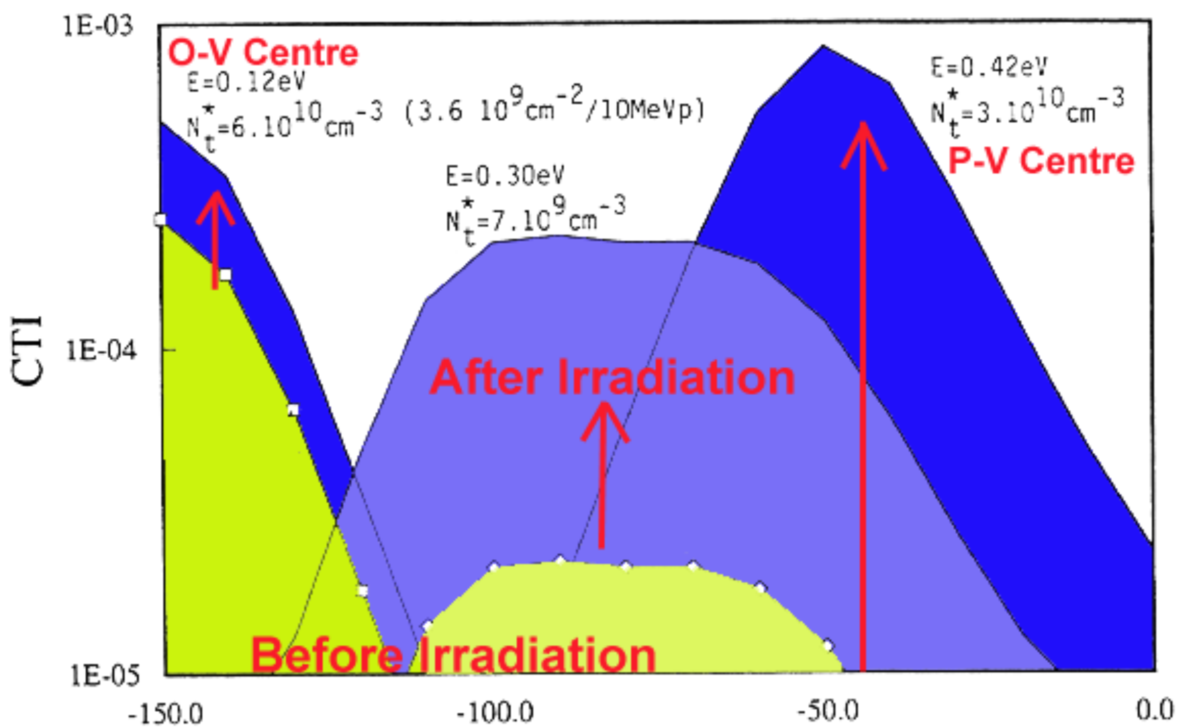
NIEL

- Began to explore the experimental and theoretical relationship between particles/energies



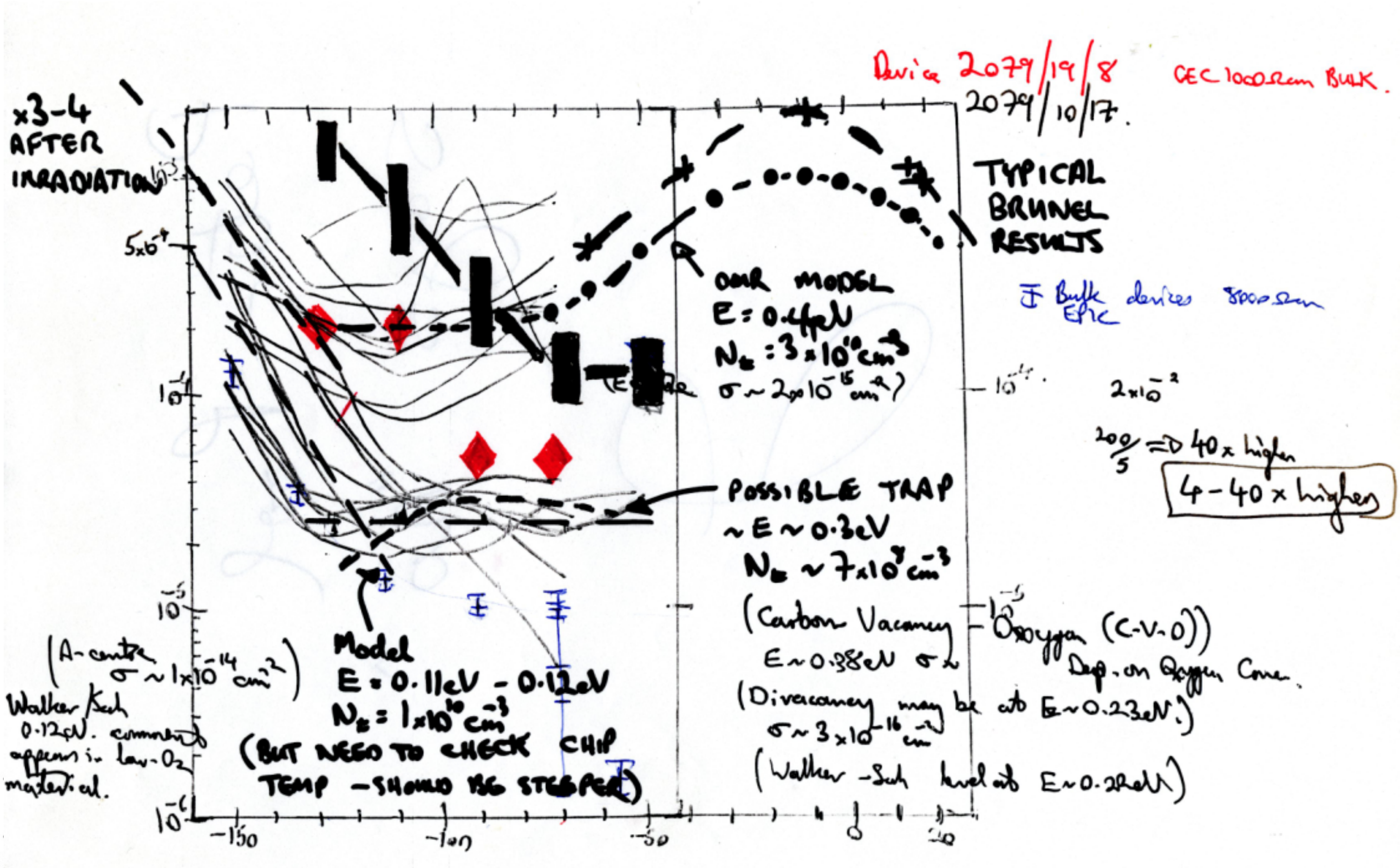
The work lead to models of trap species in the CCD

- Led to the identification of several key trap species
  - Deep/slow 0.42 eV P-V (V-V) complexes Parallel around -80°C
  - Mid-band 0.3 eV "Unknown defect" Parallel around -120°C
  - Shallow/Fast 0.12eV O-V complex Serial



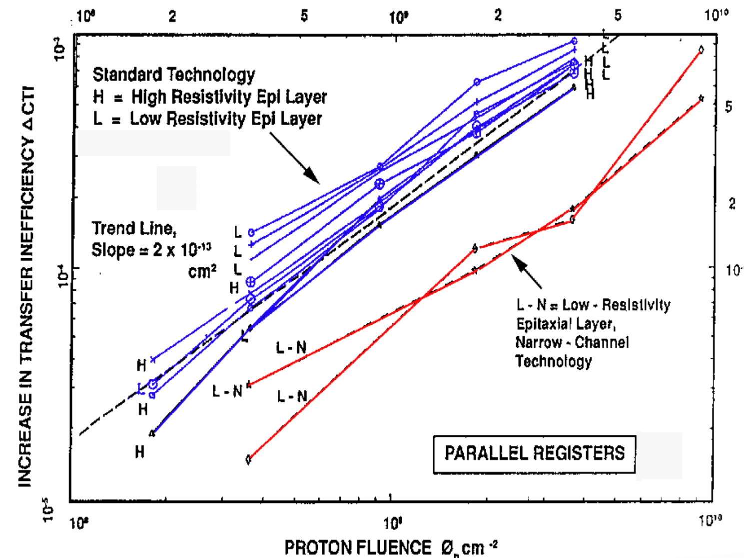
Parallel CTI Measurements

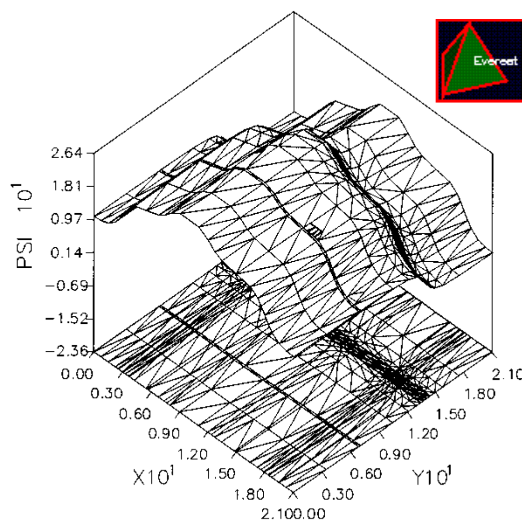
Despite simple models, excerpts from the early labbooks indicate huge scatter

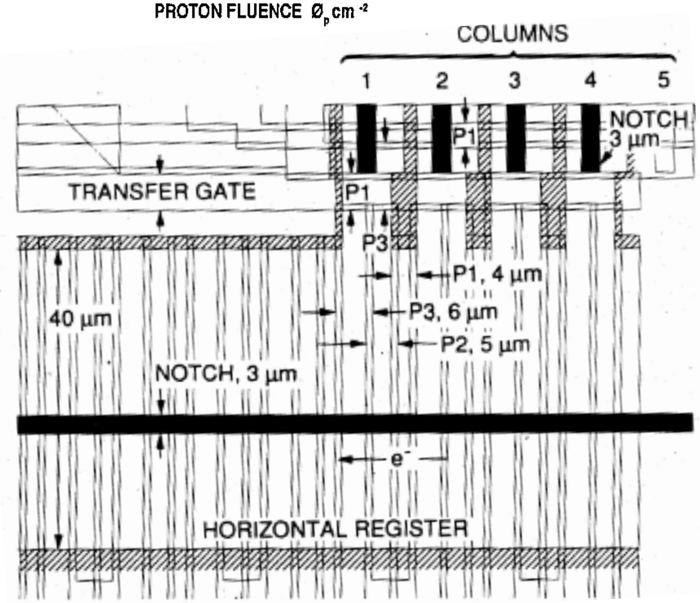


Supplementary Buried Channels (or "Notch")

- For small signals (e.g. X-ray photons) the charge can be confined during transport using a narrow channel
- To maintain full well handling, normally a supplementary channel is implanted creating a "notch"
- Effective confinement widths of 3-5 μm can be achieved producing a factor ~4 improvement over standard devices with 22 μm pixels



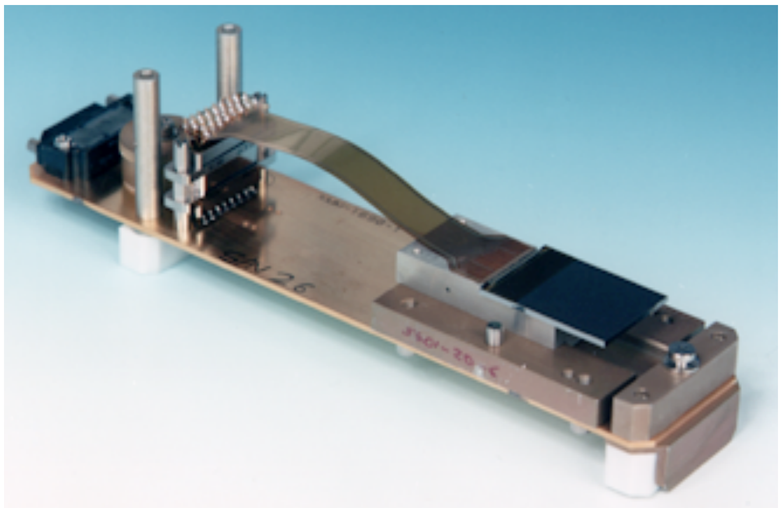


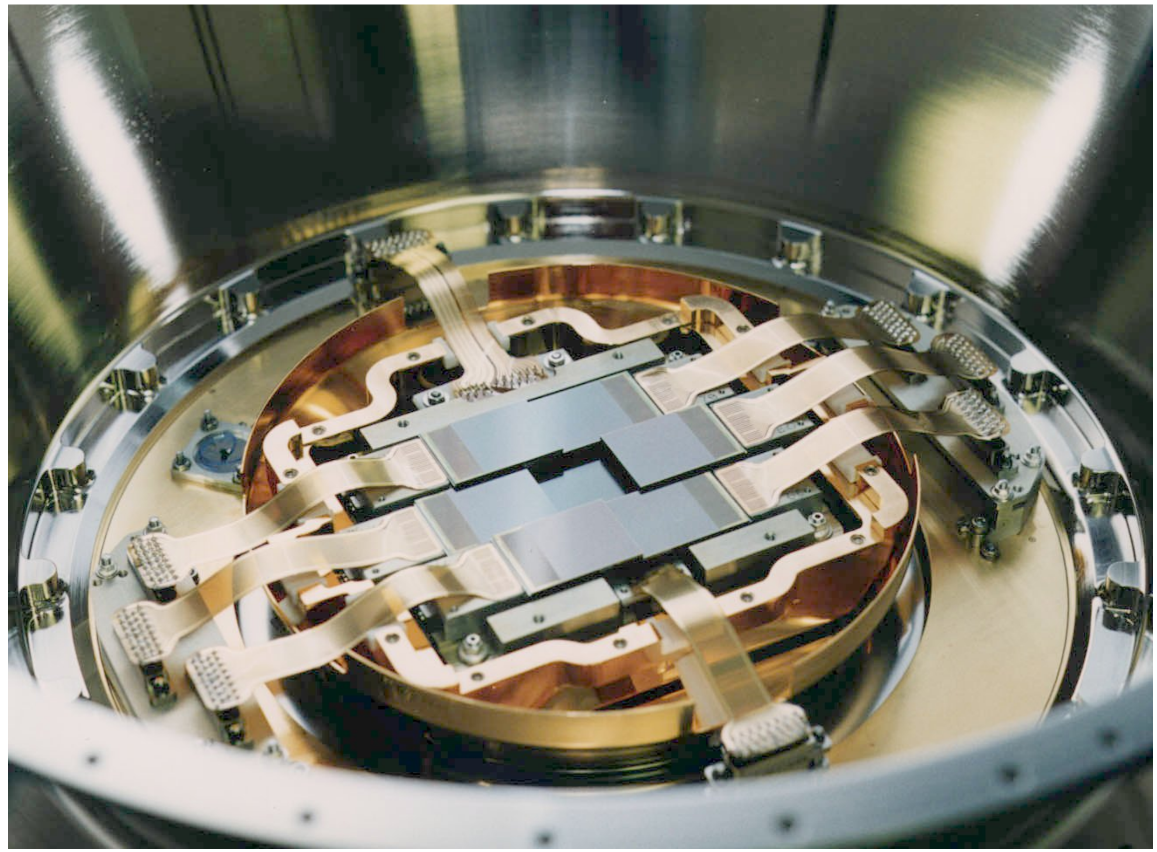


EPIC MOS Camera Radiation Mitigation Measures

- >3cm Al shielding over 4π using forward baffle approach
- Filter wheel with thick "blocking" filter *Became important for soft protons*
- Ability to cool the FPA down to operating temp of -130^{o}C
- Supplementary buried channels
- First use of Charge Injection structure *Never used in practice*
- Ability to anneal P-V centre at +130^{o}C *Never used in practice*

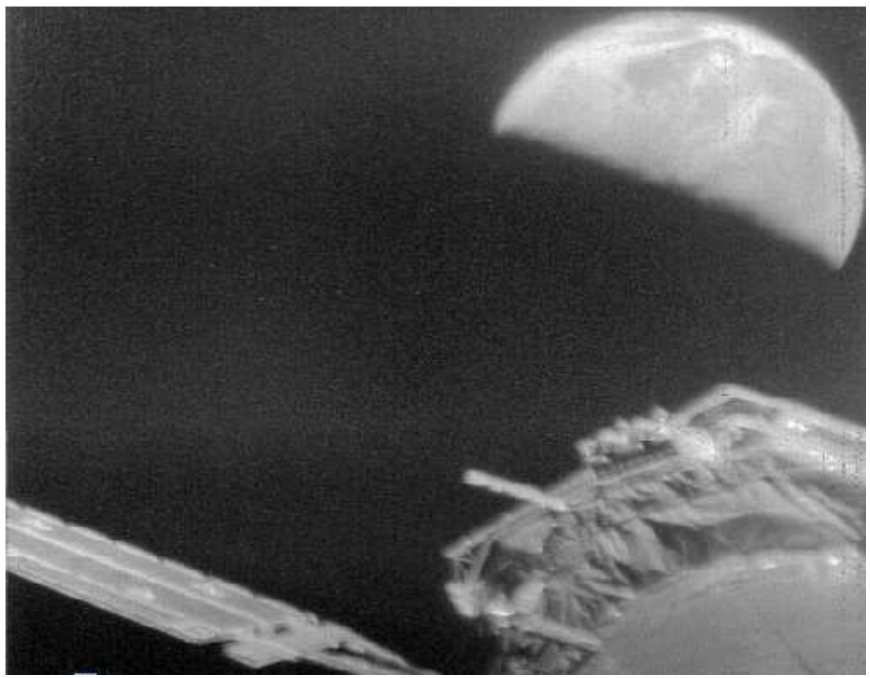
EPIC CCD Packaging and Focal Plane Array





December 1999 – XMM Launch

XMM is a cornerstone observatory of ESA's horizon 2000 programme. It was successfully launched in Dec 1999.



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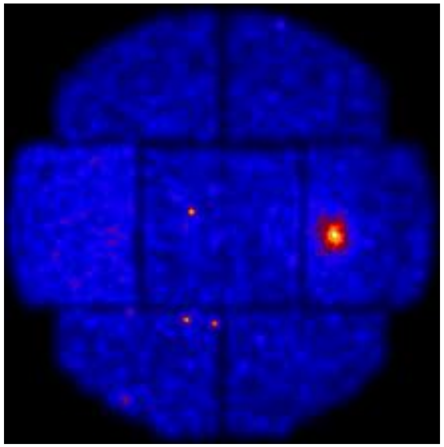
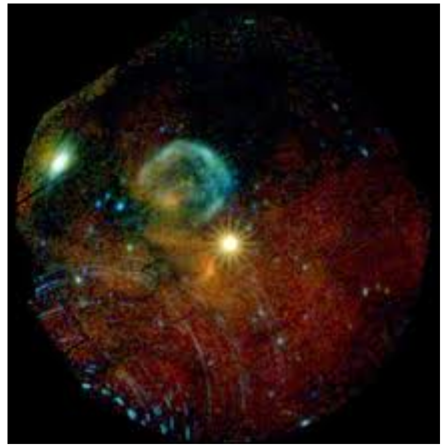
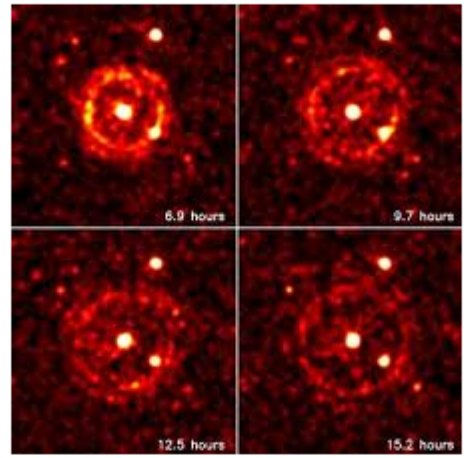
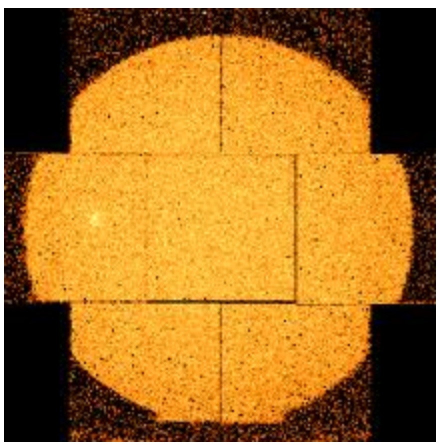
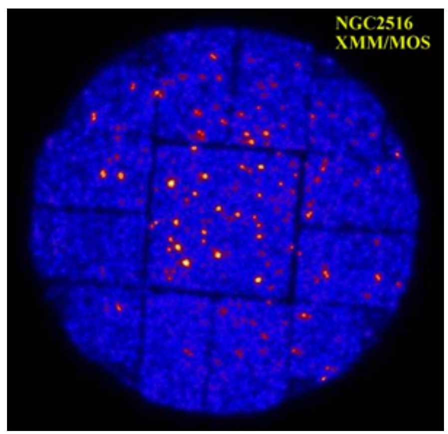
16 years of fruitful operation

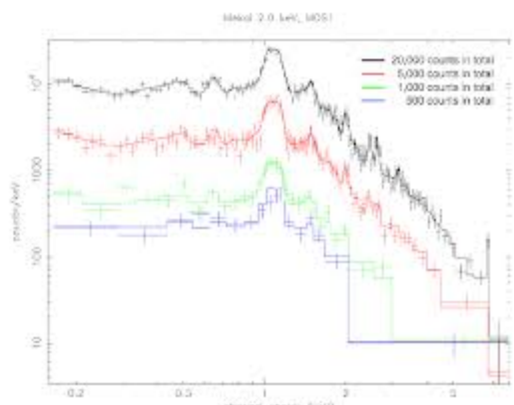












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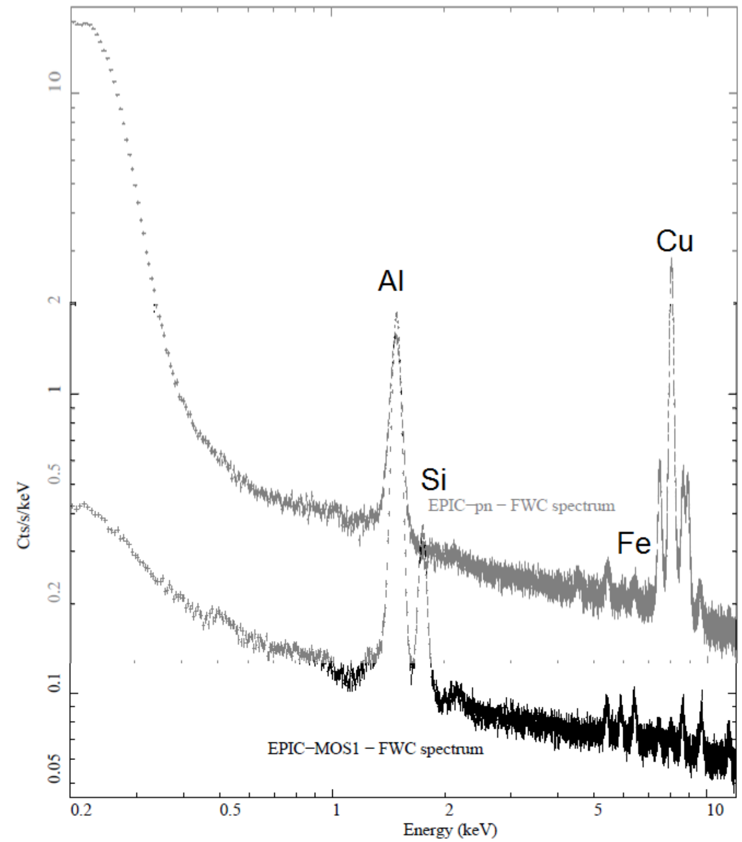
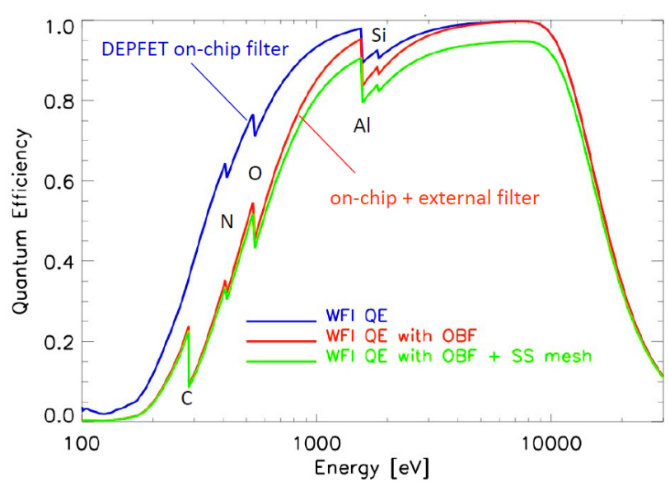
Instrument Background

- In-orbit instrument background from XMM was >5x greater than original predictions
- For weak sources, $S:N=S/(S+BG)^{0.5}$
- Degraded background can dominate over improvements to QE
- Background comprised of :
  - Elemental fluorescence lines
  - Majority of background comes from soft electrons stimulated by protons emitted from inner surfaces



XMM-SOC-CAL-TN-0018



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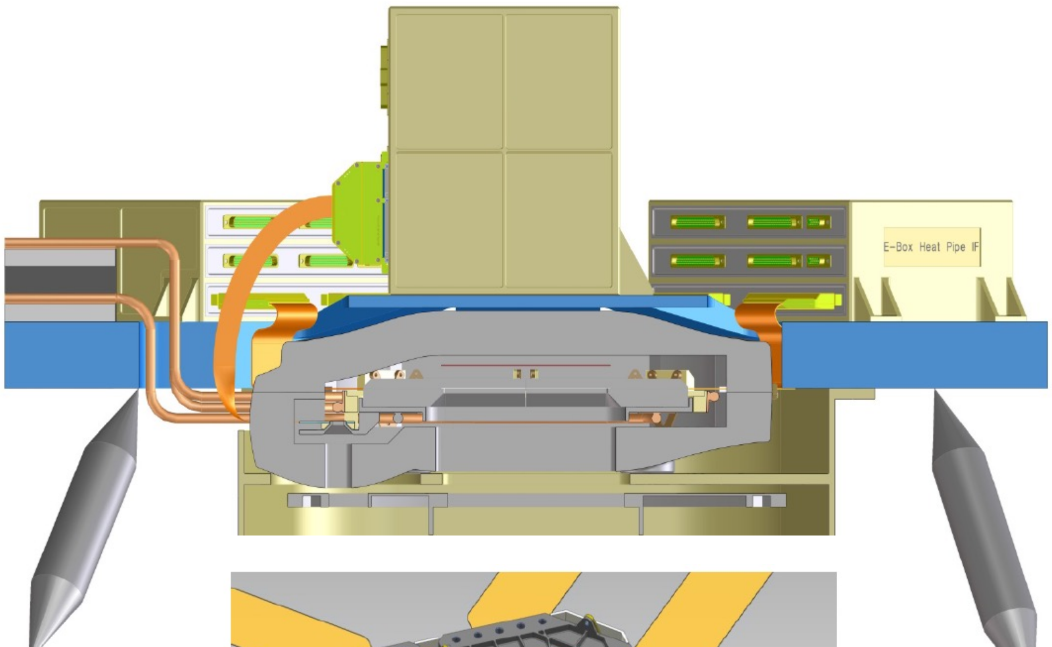
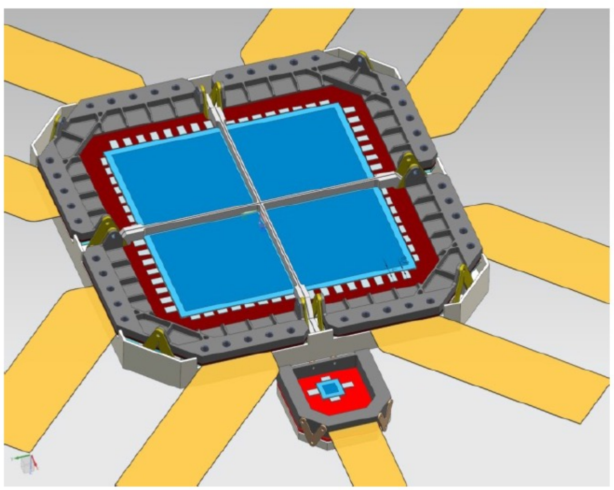
Athena WFI Graded-Z Shield





- The Graded-Z Shield is the final surface that a particle or photon sees before hitting the detectors.
- This surface layer determines the final level of instrument background experienced.
- It is vital that this detector-facing layer provides the necessary reduction in background.
- **Complex surface geometries both for the proton shield and the detector support structure.**
- Both a physics and an engineering problem.

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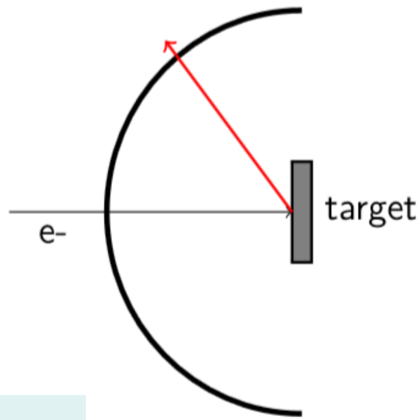
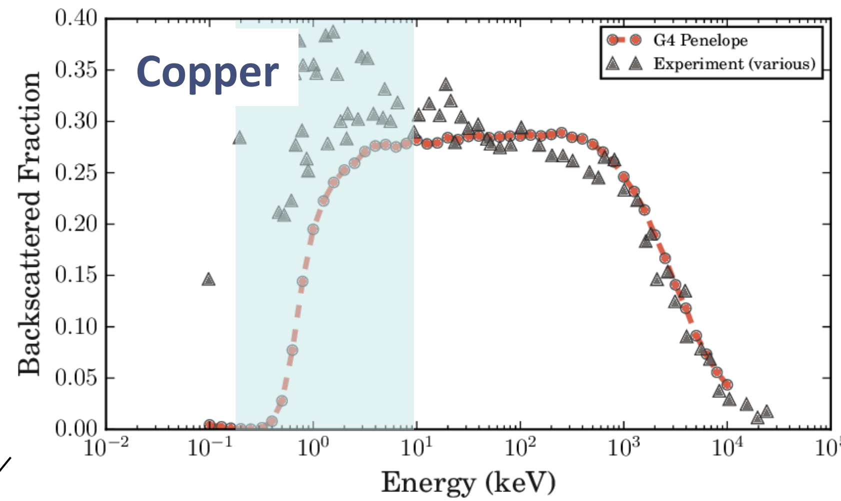
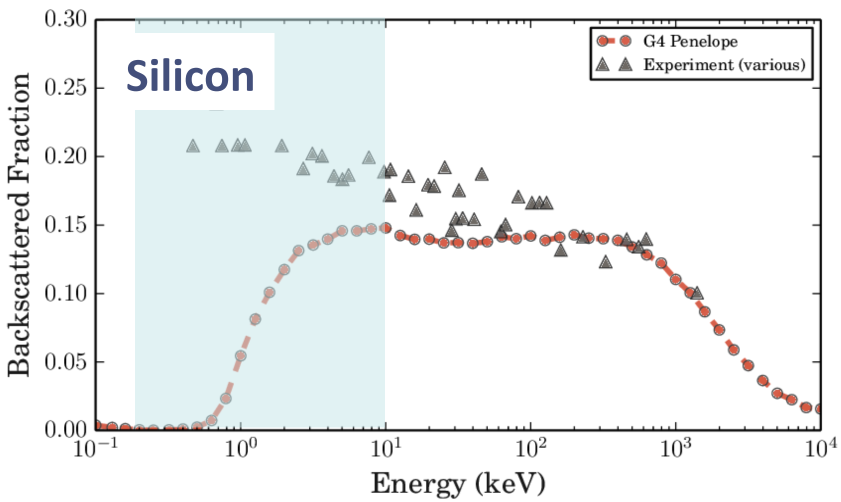
Electron Backscattering

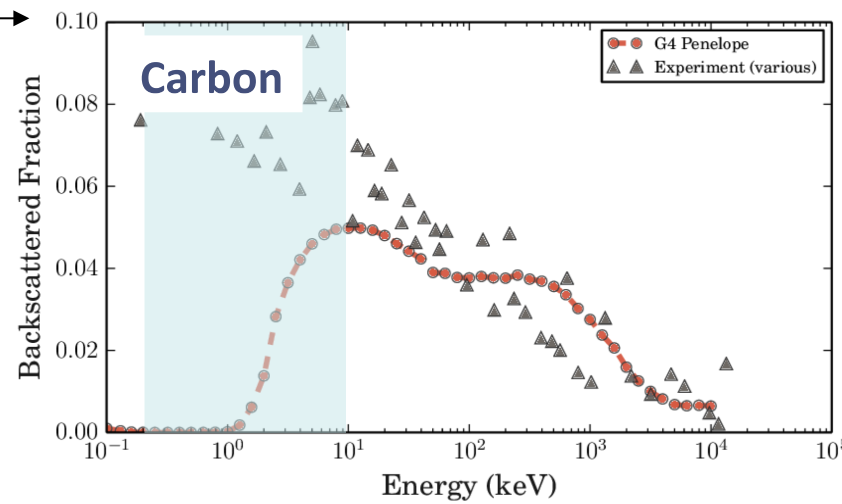
- Underestimation of the pre-launch background can be caused by either high e- backscattering on the detector materials or low back-scattering on the inner shielding surfaces.



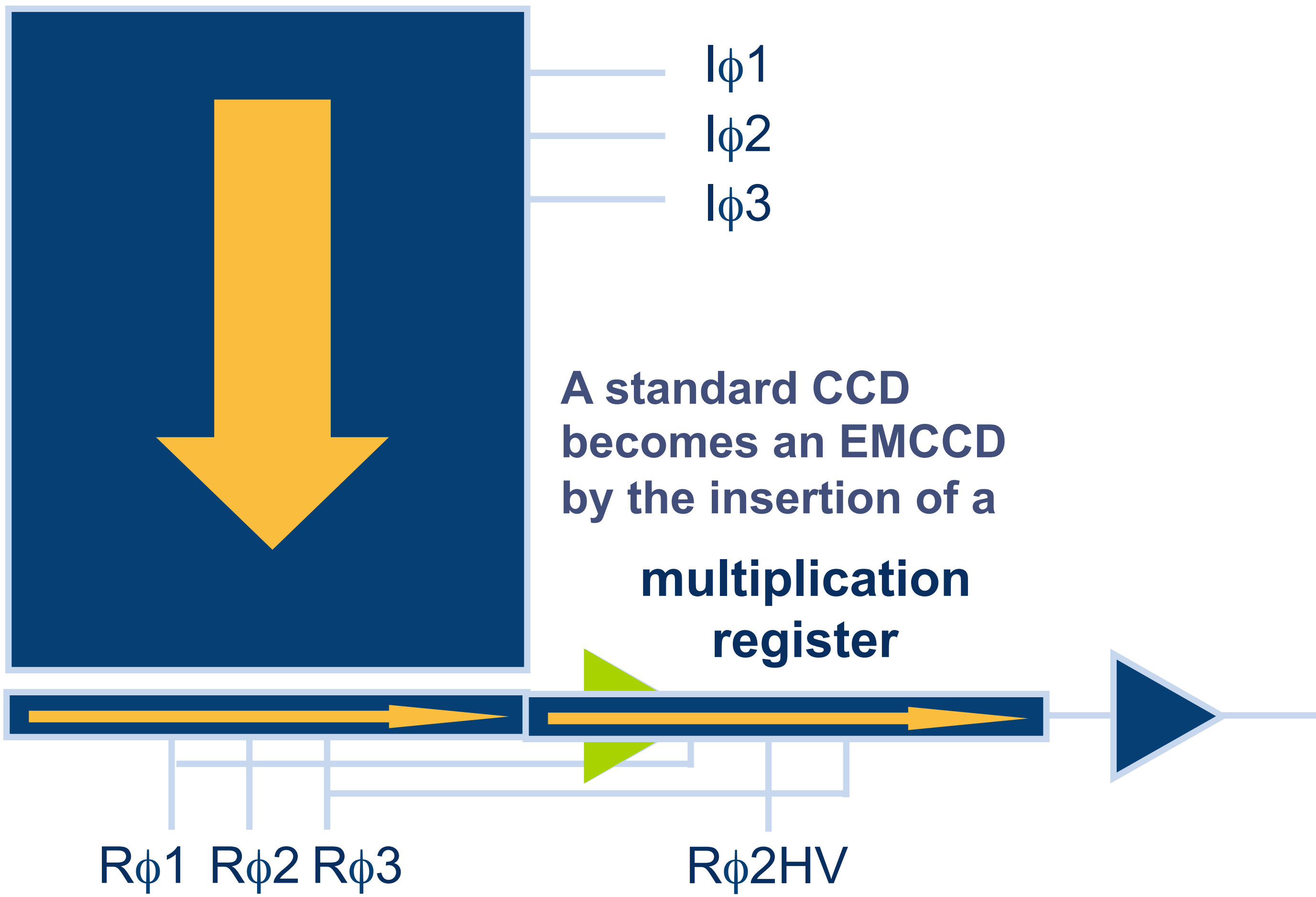


Efficient energy band of the WFI





The EM CCD

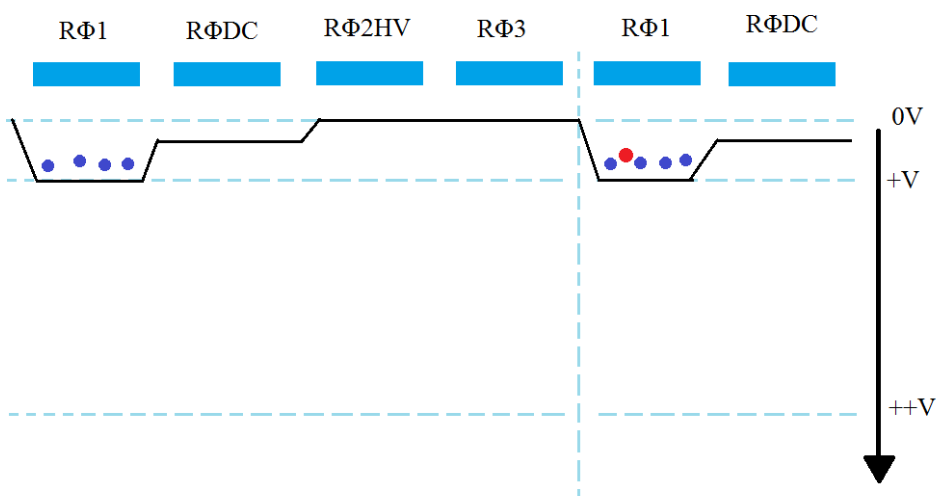


A standard CCD becomes an EMCCD by the insertion of a

multiplication register

EM CCD Gain

- The multiplication register utilises impact ionisation in 536 multiplication elements with each electron having a small chance of increasing the charge in each element.
- A common issue with faster readouts is larger readout noise. EM-CCDs supress this larger noise due to the multiplication register increasing the signal sufficiently high enough allowing for faster reads.



Gain=(Gain/stage)$^{\text{Nelements}}$

Eg $(1.01)^{536} = 207$x.

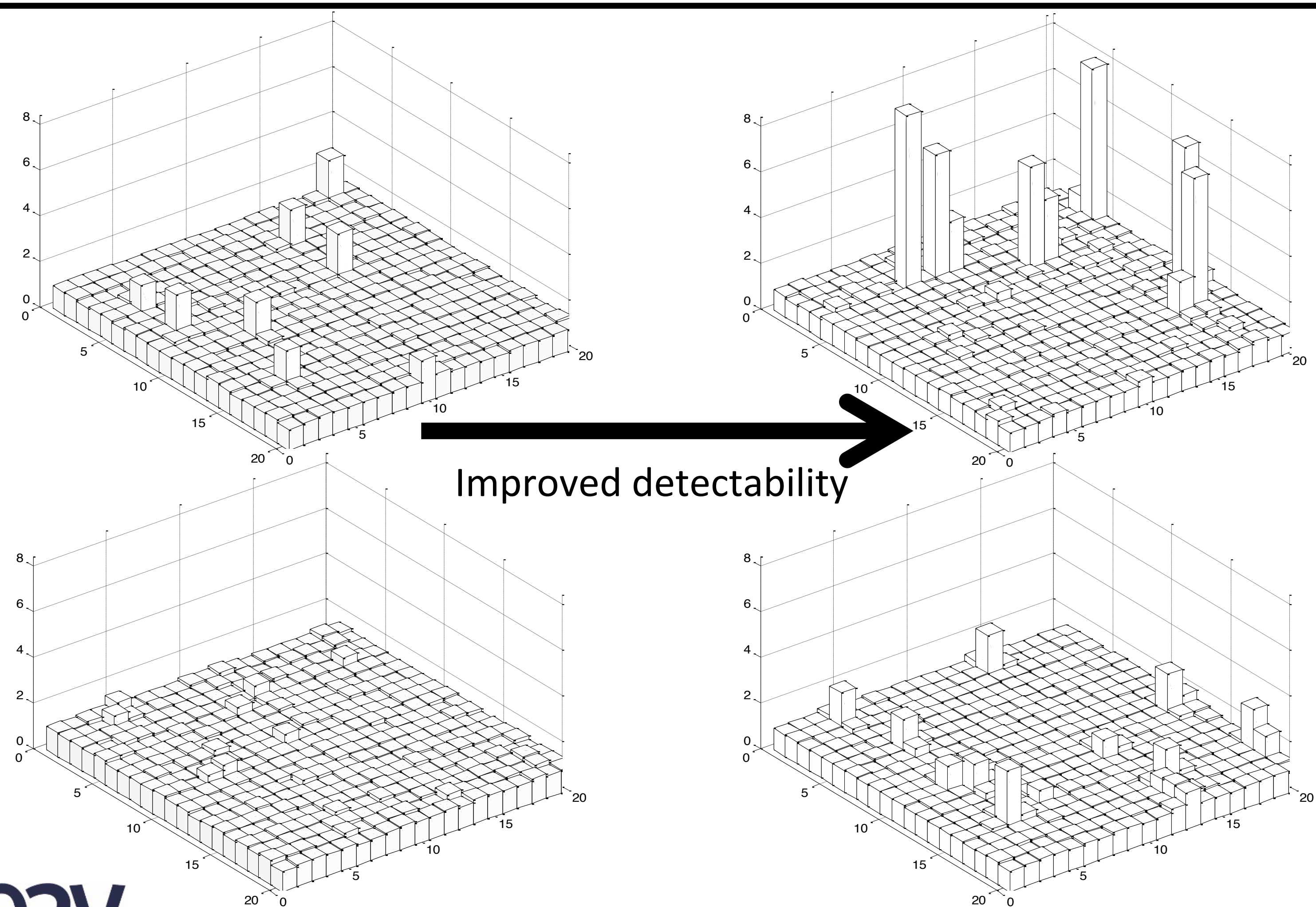
If the noise is σ=50 e- rms.
e.n.c.=50/207 = 0.24 e- rms.

EM-CCDs giving increases SNR

Gain = 1 | Gain = 7

1.0 keV

0.3 keV



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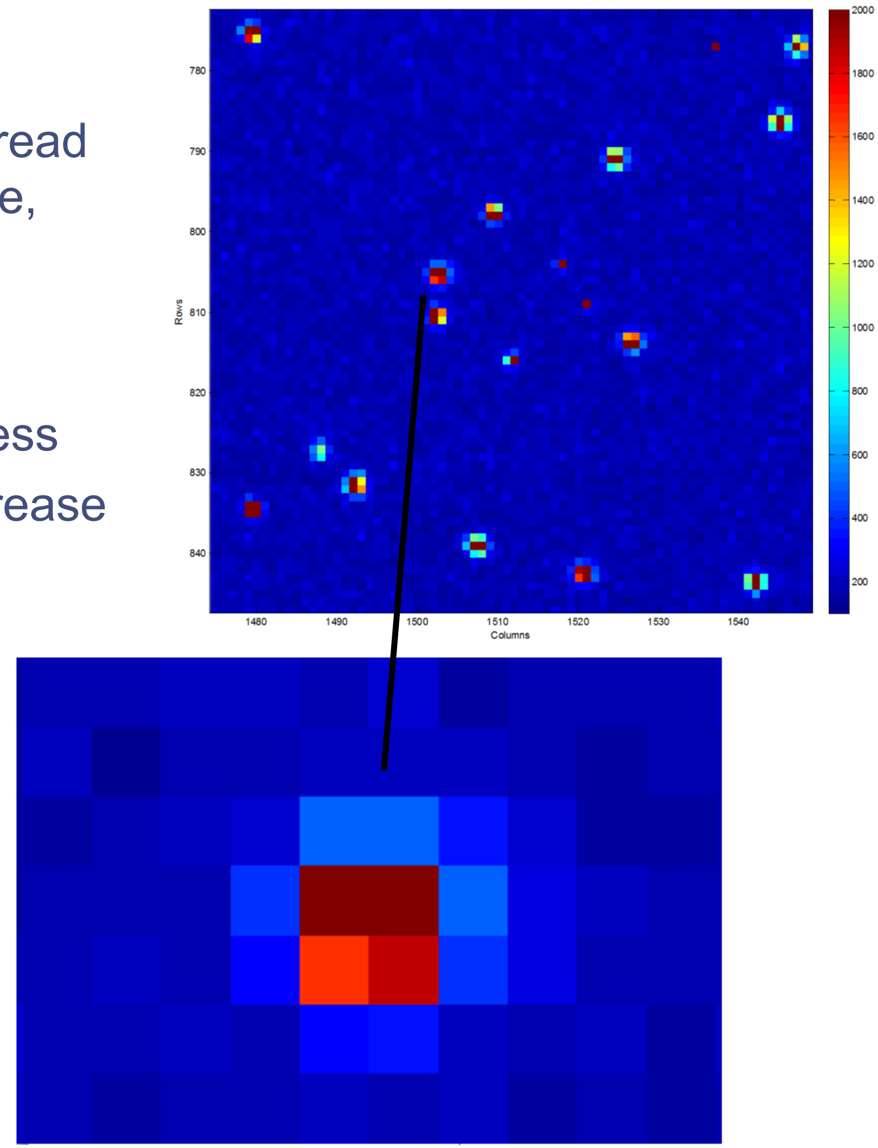
X-rays in an EM CCD

- EM gain can enable the CCDs to be read out with at high speed, with high noise, yet with low e.n.c.

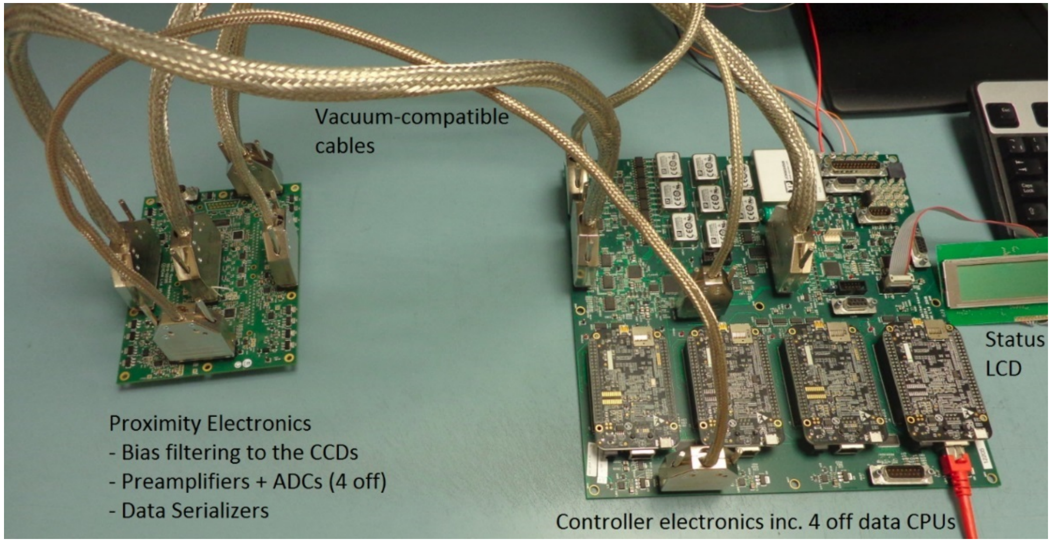
- Modified Fano factor - $v = (1+F)E/\omega$ due to shot noise on avalanche process
- Sub-pixel charge centroiding can increase spatial resolution

- Example of an Mn-K X-ray
  - Signal occupies ~12-16 pixels
  - S/N~1000:1
  - Enables centroiding to ~1 μm



OGRE Sounding rocket

- Testing a high resolution (R~3000) grating spectrometer
- Launch (currently) scheduled for Nov. 2018
- XCAM-OU responsible for developing the X-ray camera to read out the spectrum.
- Aimed at raising the TRL of the system components



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XCAM

Soft X-ray Imager on SMILE

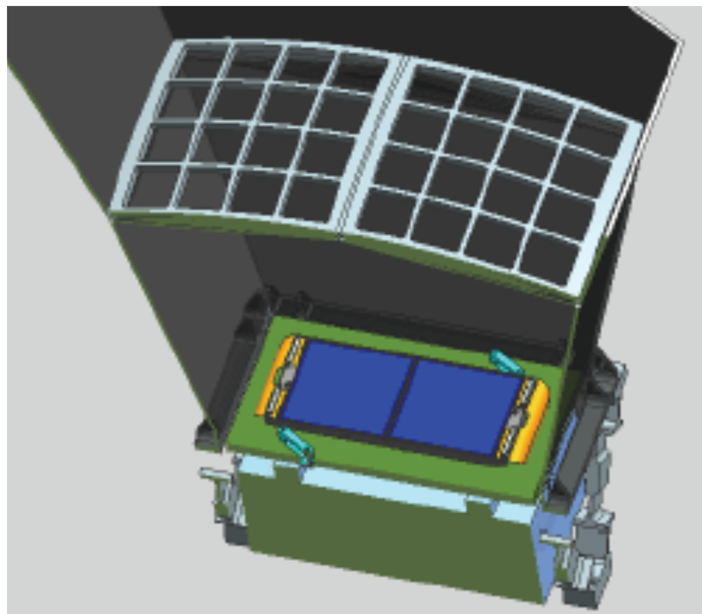
Lobster-eye Micropore Optic

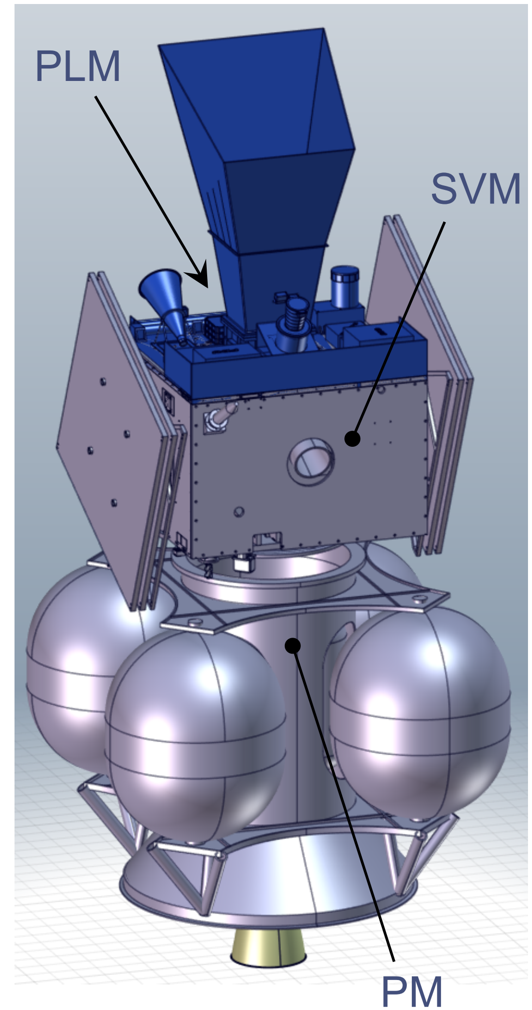
Ultra-wide field of view
~16° x 27°

Focal length 30 cm

Optic Mass < 1kg

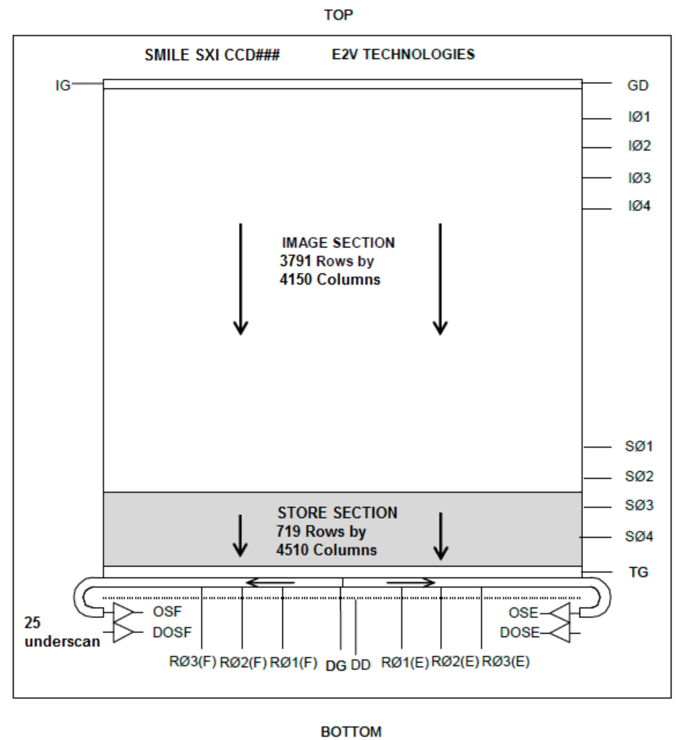
Instrument ~ 26 kg

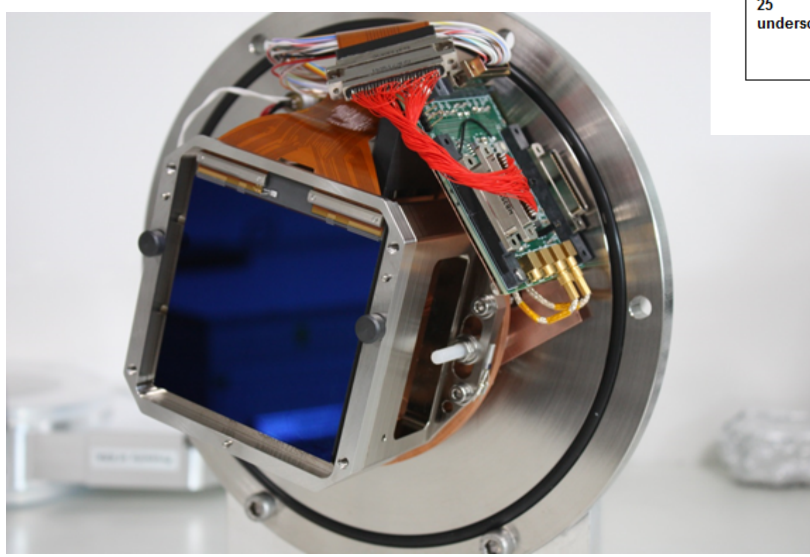




SXI CCD Configuration

- Based on the PLATO CCD270 mask set
- Optimised as an X-ray detector and not an optical imager
- Image 3791 rows
  - 6x binned at store IF
  - 631 rows
  - 5 CI rows
- Store 719 rows
  - 87 spare rows





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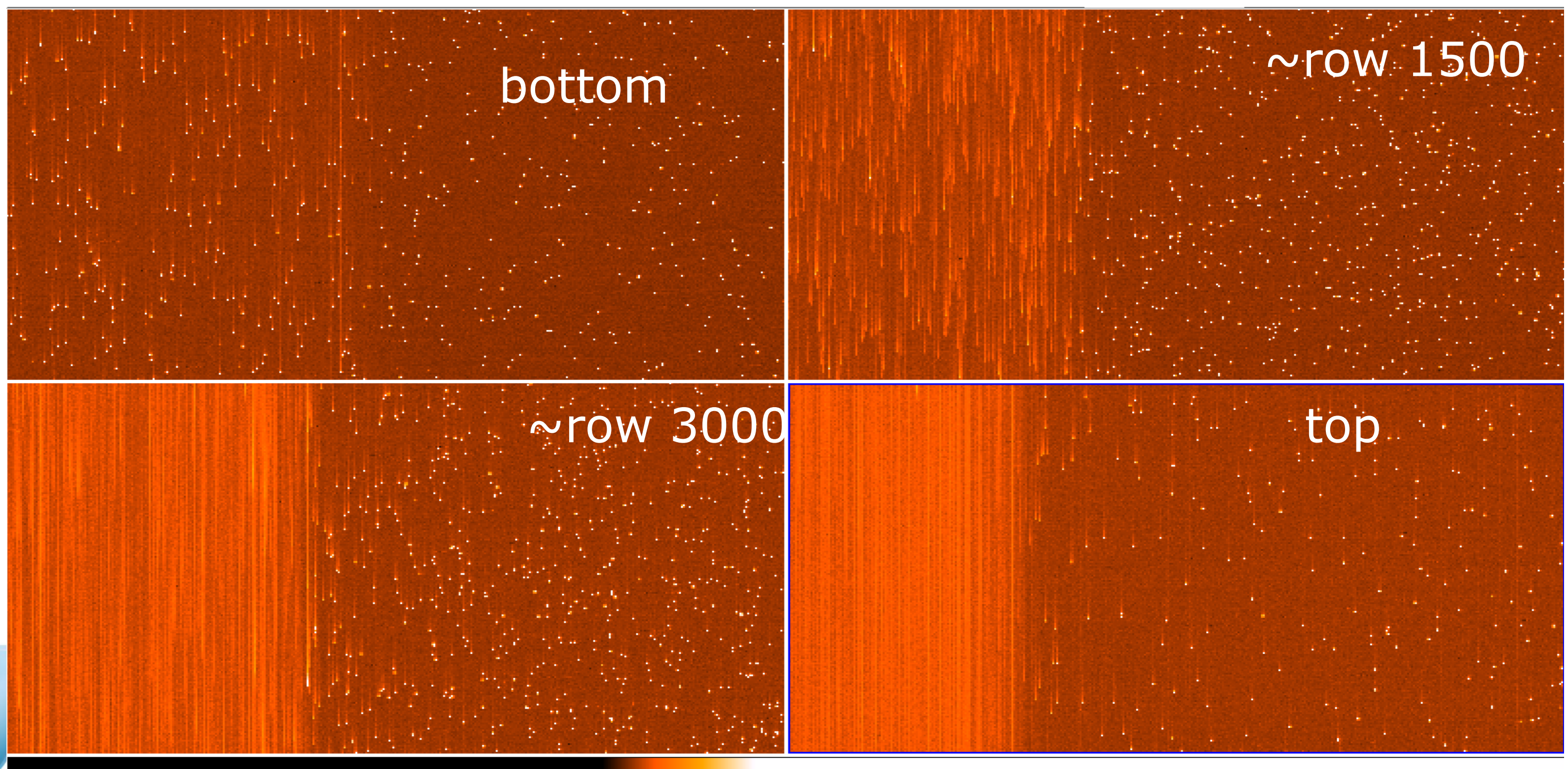
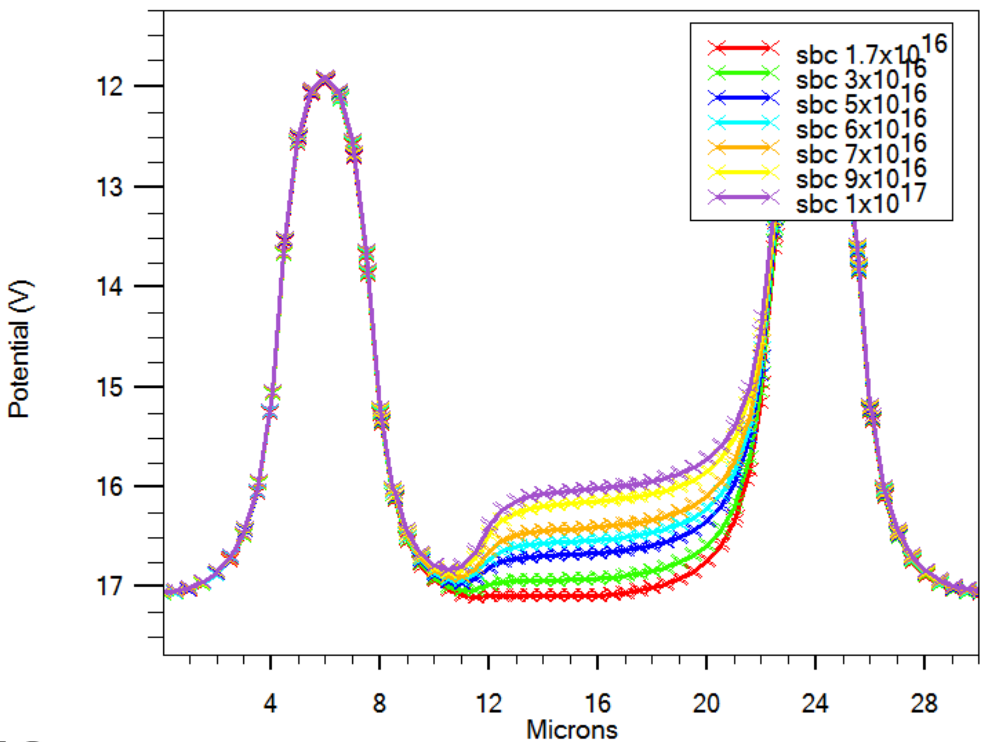
Radiation Damage in CCD270s

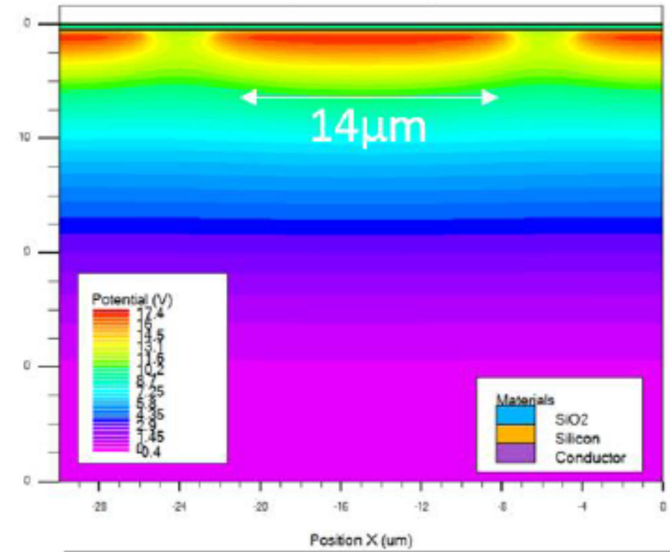
- Once again, radiation damage is becoming a concern in the CCD270 for SMILE
- A combination of limited radiation shielding and large CCD area compounds the problem
- Radiation damage modelling and characterisation will need to be improved to meet the mission requirements

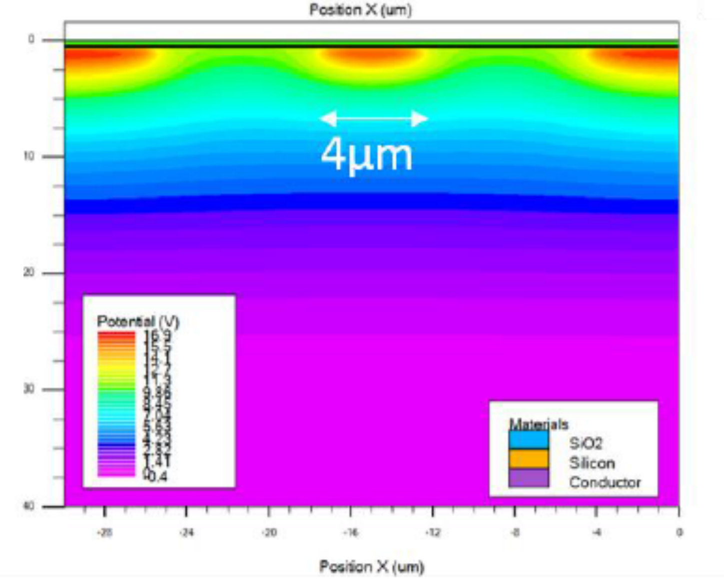


Silvaco Modelling

- Suggested SBC with 4 um width in the parallel direction for improved radiation hardness







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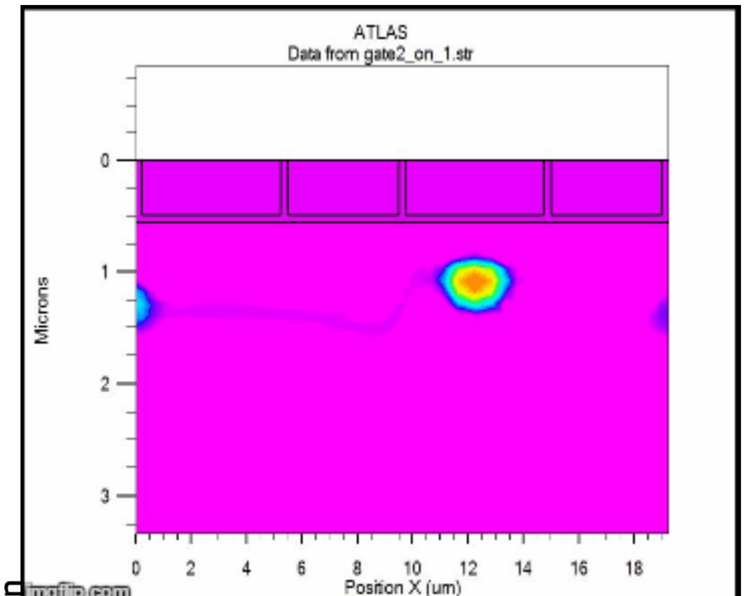
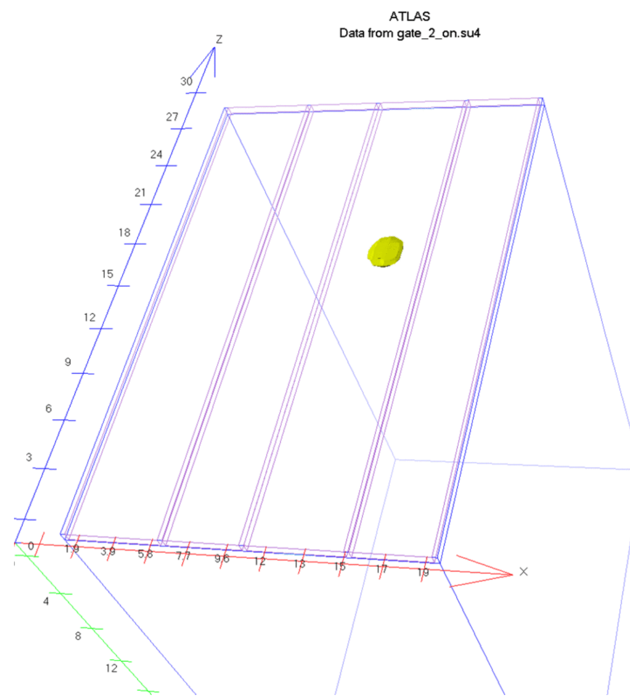
Dynamic Modelling of the SBC

- We have recently created dynamic simulations of charge flow in the proposed SBC for the SXI CCDs
- Concerns that the charge may "balloon" beyond the SBC confinement into the normal channel seem un-founded
- Indicates that the improved radiation hardness will be maintained during transfer





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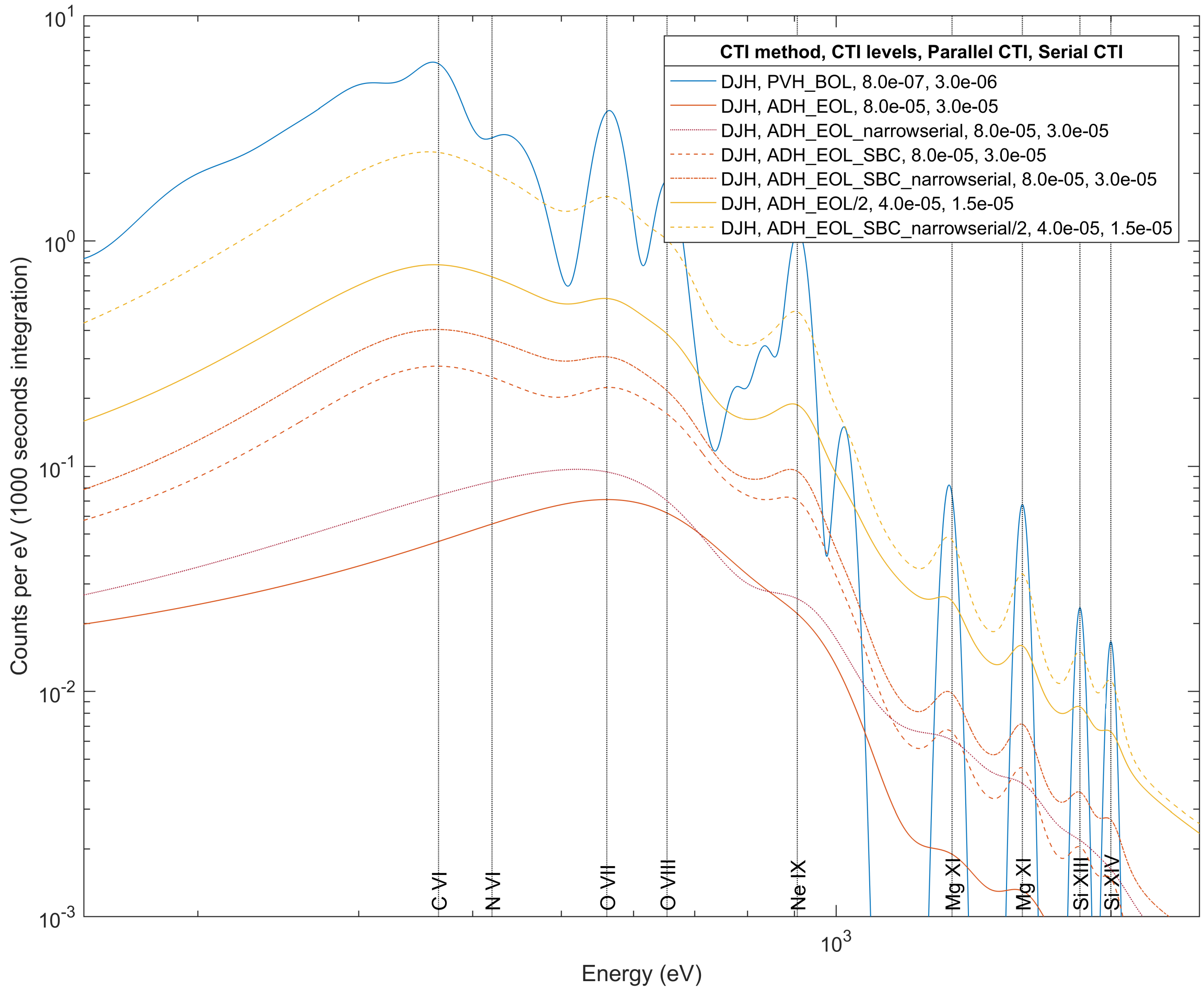
SXI Performance Modelling over Time



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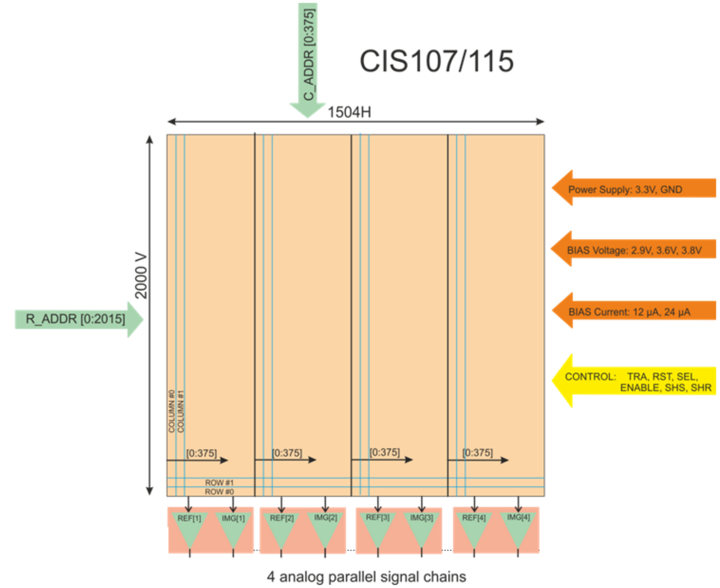
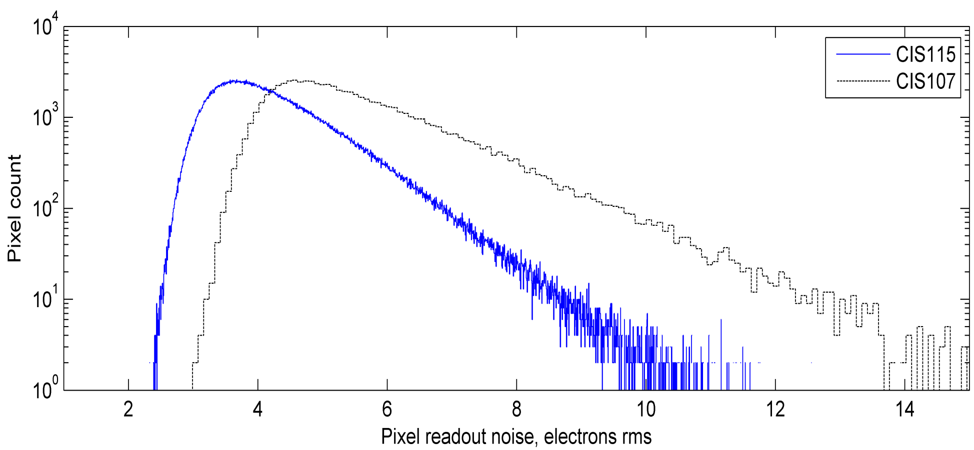
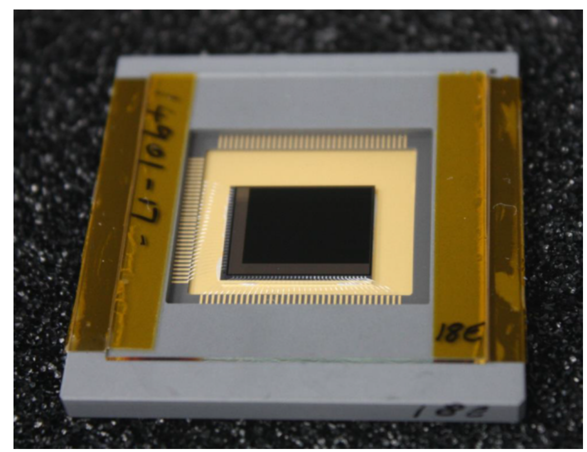
CMOS Image Sensors for X-ray Detection

- e2v CIS115 is being developed for JUICE for visible imaging of Jupiter's moons
  - Back-illuminated, 9-12μm thick
  - 3 Mpixel, read through 4 blocks
  - 7 μm pixel pitch
  - Area = 1.4 cm^2
  - R=48μV/e-
  - Noise 4-5 e- rms.







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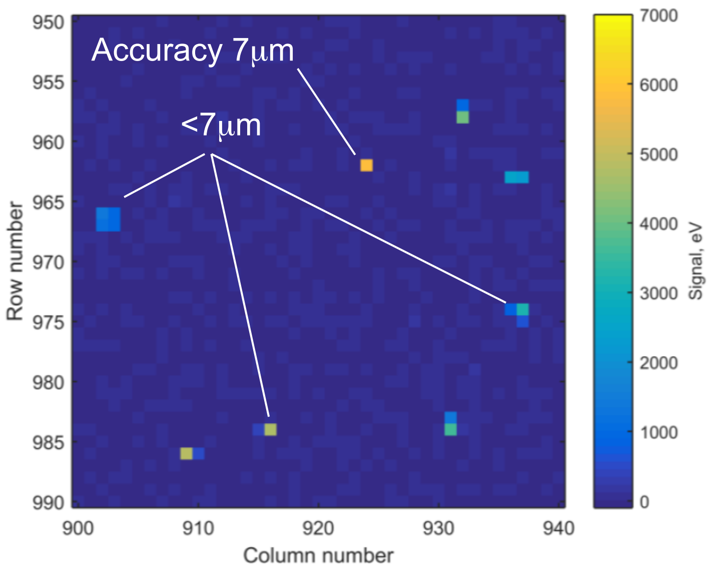
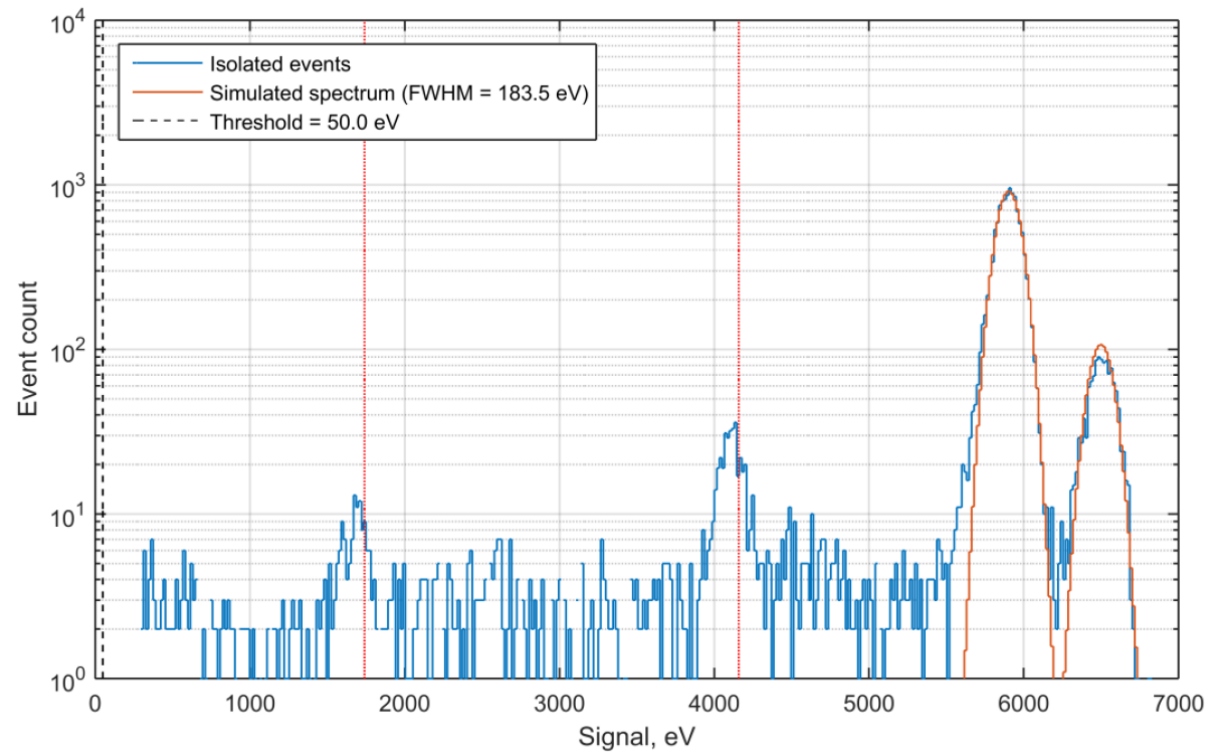
X-ray spectroscopy with CIS115

- Recent results using Fe-55 from the calibration data of Matt Soman
- Will enable 7μm and below spatial resolution
- Around 60% of events could undergo centroiding to increase resolution further
- Probably all sub-keV X-rays may be split
- QE is currently low (device thickness) and no samples without AR coating





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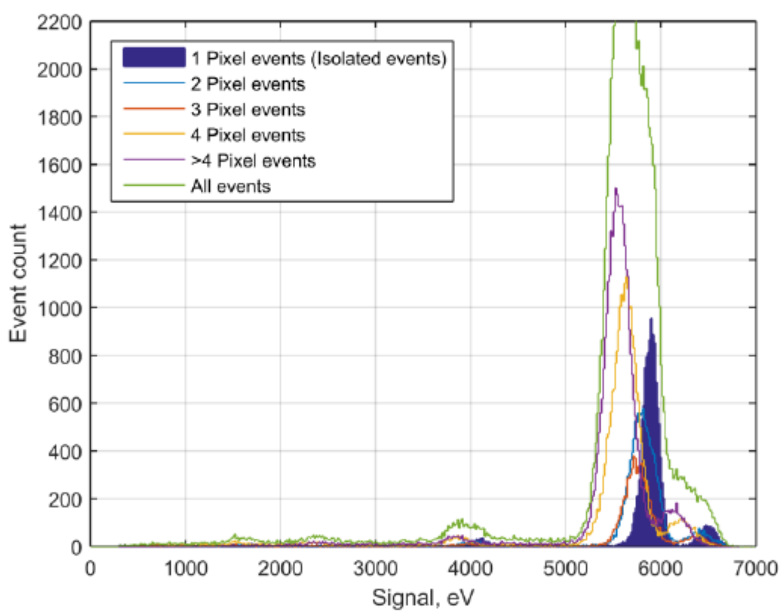
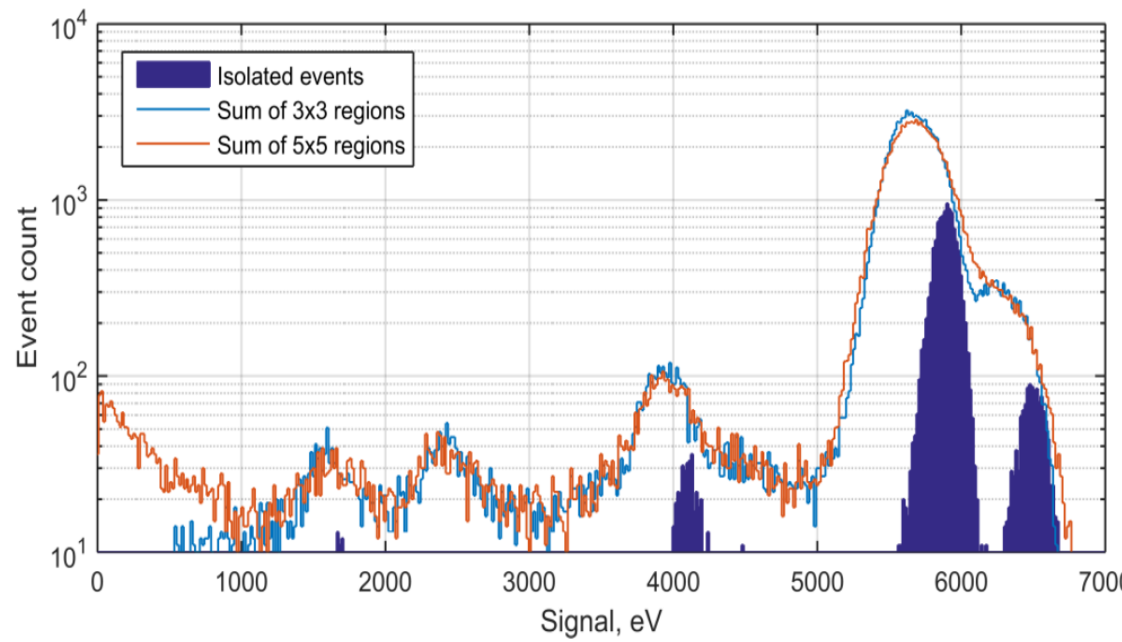
CIS115 Split event fractions

- With this sensor variant, the majority of photon events are split (note @6keV)
- This enables event centroiding and hence higher resolution than the pixel size
- However, this also degrades non-dispersed photon counting spectroscopy





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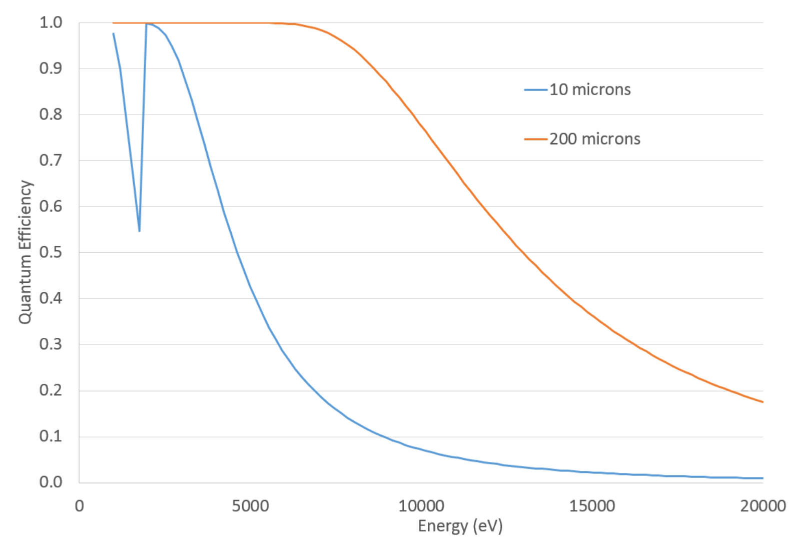
CMOS QE Improvement using Full Depletion

- JUICE CIS115 sensors have ~5 μm depletion on 10 μm BI structure
- Restricted efficiency for X-ray use

- Can obtain up to ~40μm BI devices from epi-Si
- Test structures have been developed at OU and fabricated by ESPROS
- Device are currently being evaluated under a PhD studentship



- This development may go part-way toward making a useful X-ray detector using a standard CMOS process

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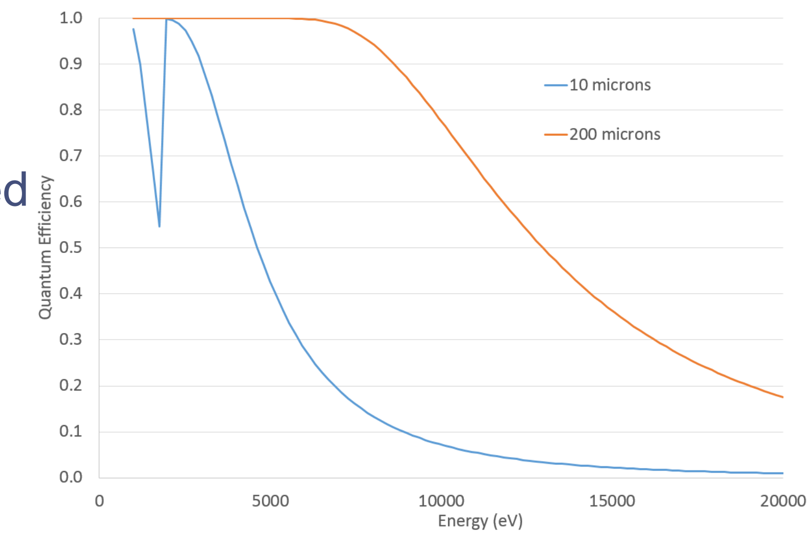
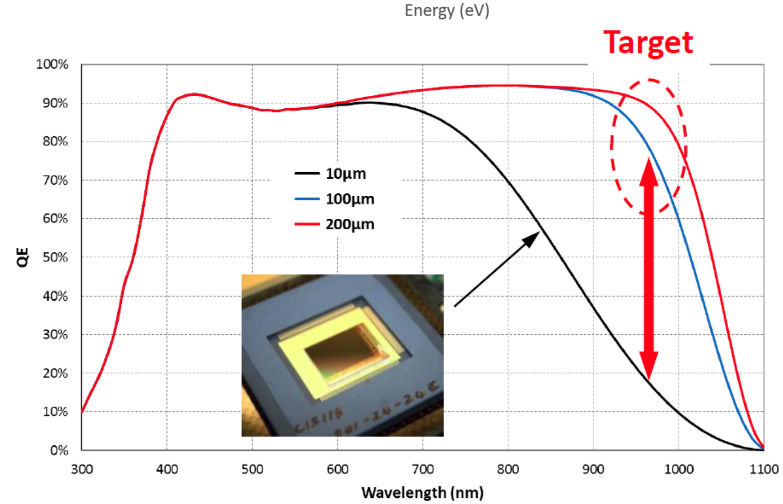
CMOS QE Improvement - toward Full Depletion

- To make significant improvements need to use bulk FZ silicon
- & use reverse bias for full depletion
- There is a problem with conduction from pixel to back substrate, but a design has been created to overcome this enabling 200 μm thickness
- Supported by patent
- First prototypes received from Tower-Jazz and are being tested in the laboratory



- Complementing established CMOS properties
  - Pinned photodiode for low noise
  - High speed and low power readout
  - Radiation hardness
- Will improve both X-ray and IR QE



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Spin-out into Photon Science Applications

Giving a few examples of spin-out based on CCD technology (noting CMOS for X-ray applications is less mature)

- Imaging in XFELs
  - FLASH
  - SACLA

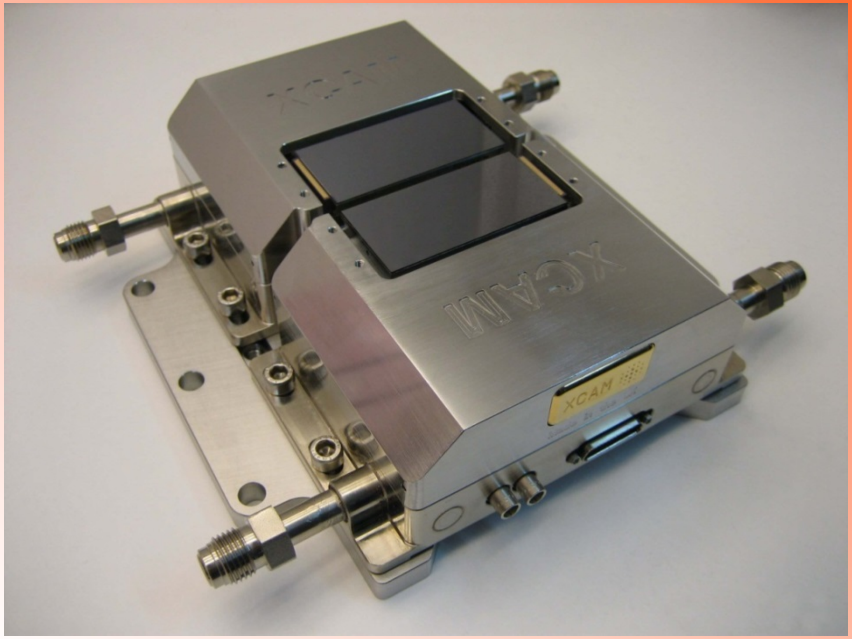
- Spectroscopy readout for RIXS
  - SAXES

XCAM DESY FLASH Triple Camera system

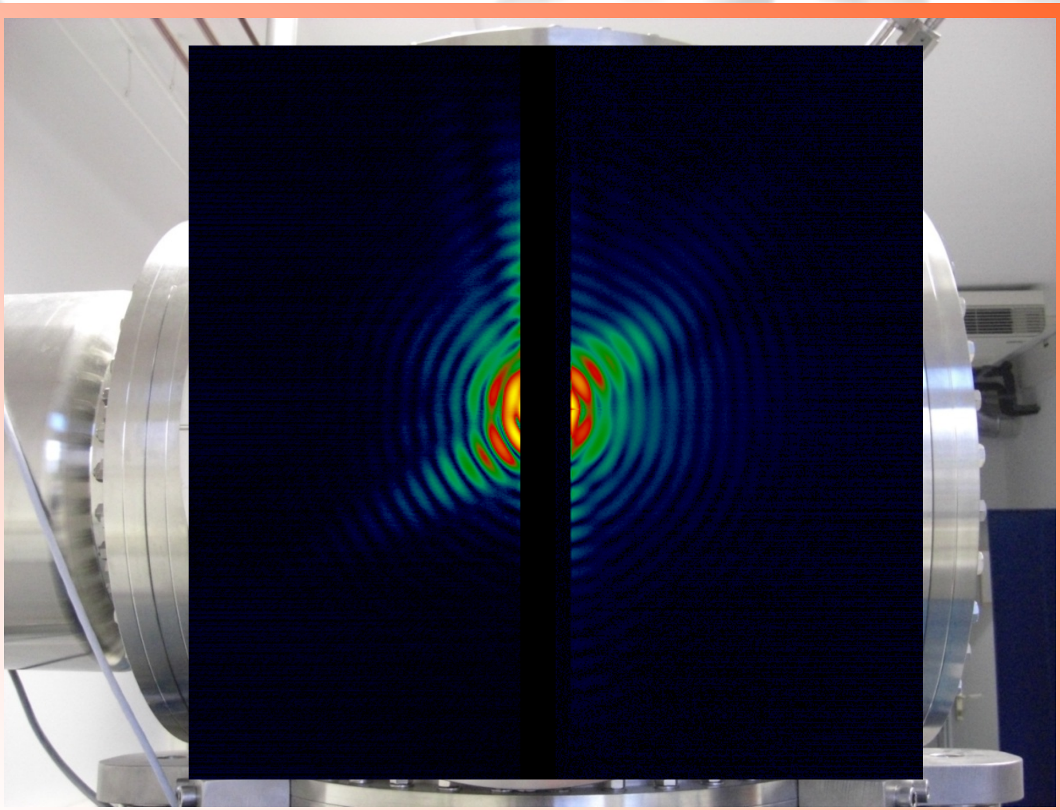
XCAM

Uses large area astronomical CCD44-82s

Two of the three cameras supplied to work at 100 eV on FLASH



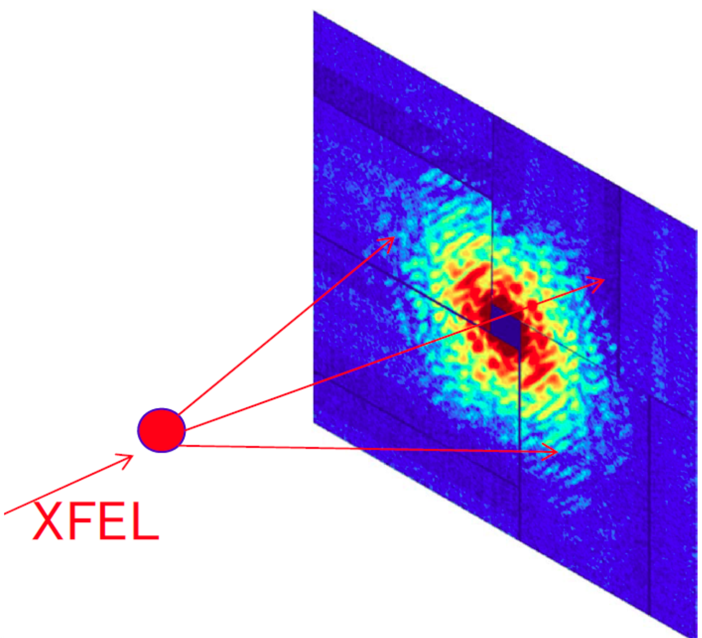
Dual Unit camera undergoing commissioning in the vacuum chamber at DESY

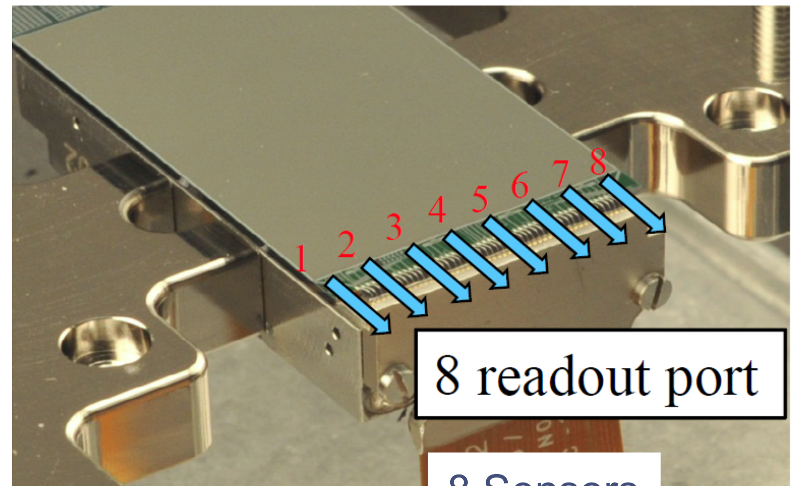


MP CCD development for SACLA

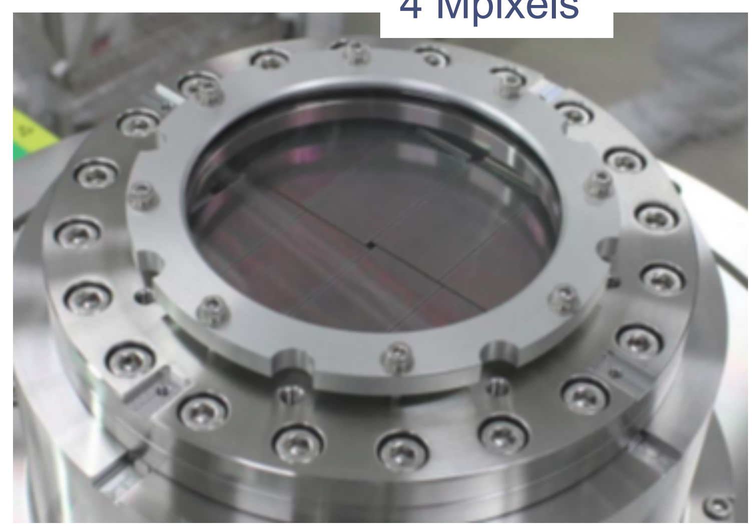
Kameshima et.al., Rev. Sci. Instrum. 85, 033110 (2014).

- Using knowledge amassed on CCD X-ray detectors a custom CCD was designed and developed for use at SACLA



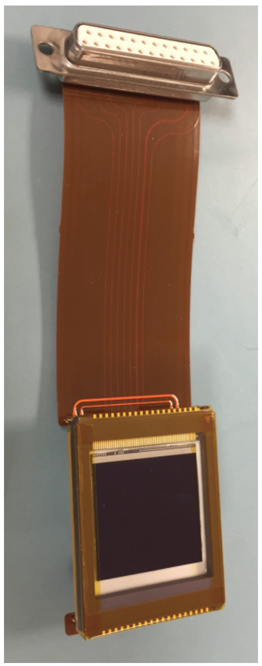


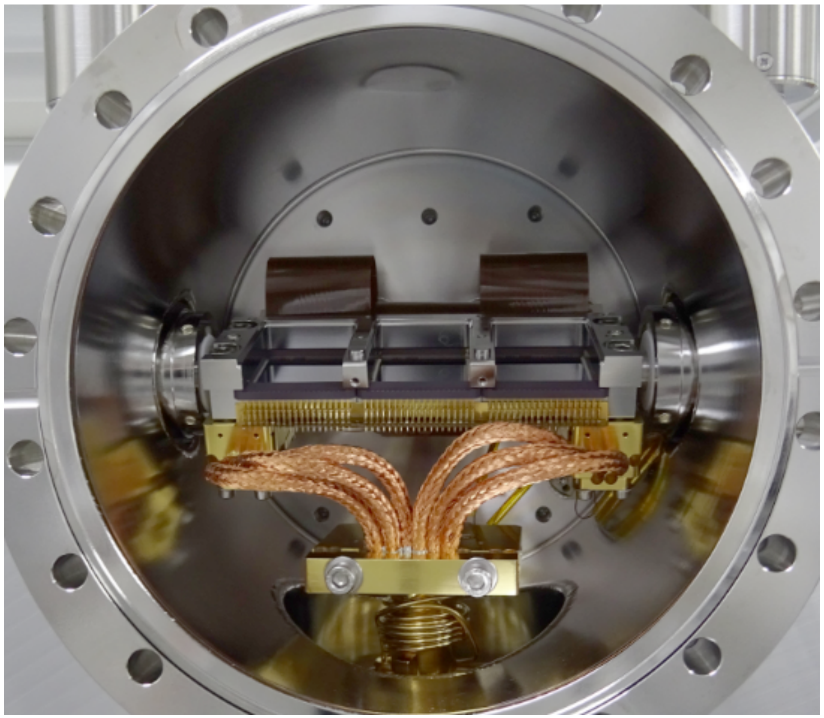
8 Sensors
4 Mpixels

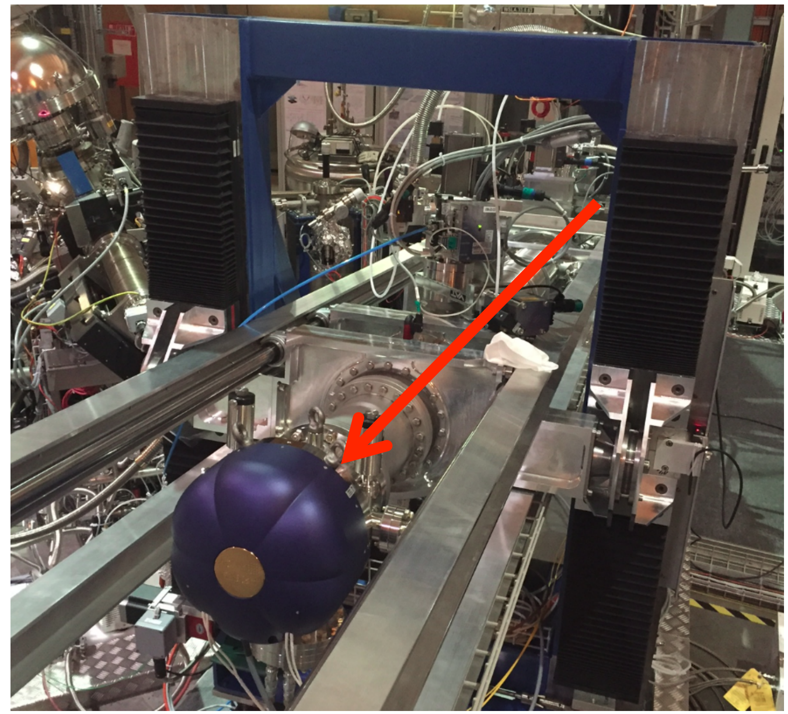


RIXSCam During Assembly & Test

- For improved readout of dispersed X-ray grating spectrometers
- XCAM has developed a camera system for RIXS using EM CCDs & event centroiding
- Triple-CCD camera system during assembly
- Is fabricated as 3 independent camera systems, but with a master clock for synchronisation







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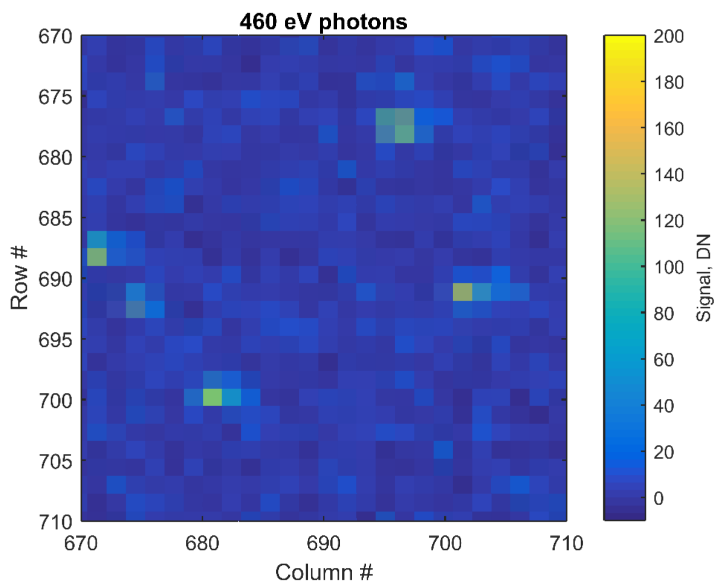
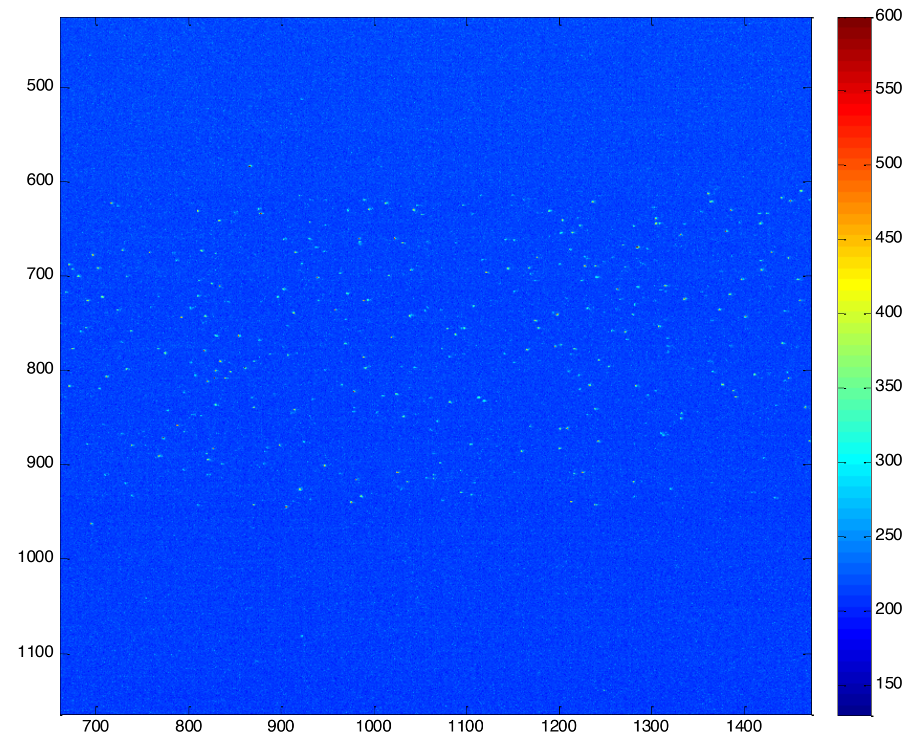
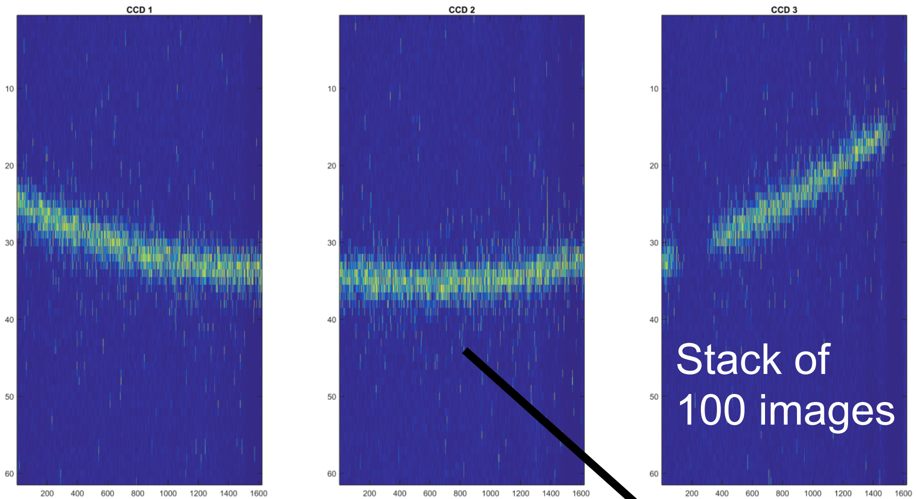
Soft X-rays

- For soft X-rays in BI device photons are absorbed close to the entrance window
- Majority of X-ray events undergo lateral diffusion during drift to potential wells
- Recent results from SAXES for a de-focussed line
- 460 eV photons with high S:N

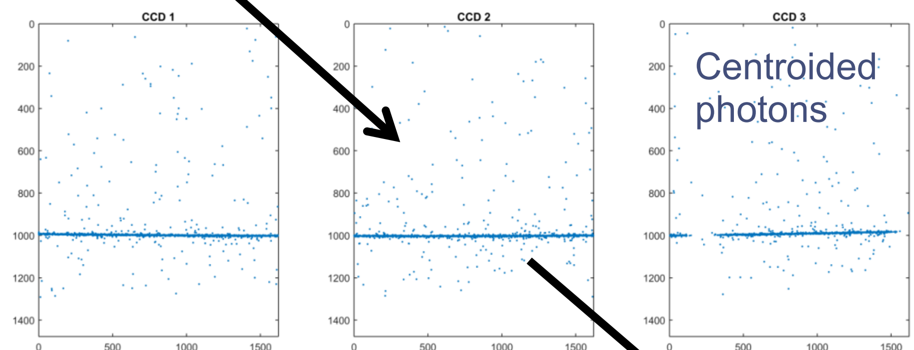




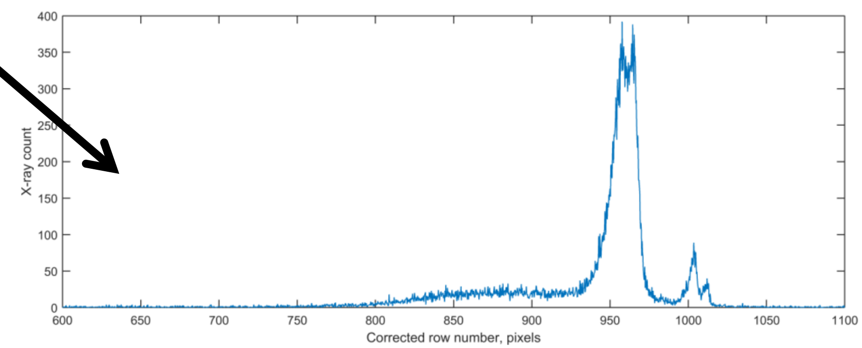
Early commissioning results



- The RIXSCam™ includes the RIXS dll which performs the on-the-fly event centroiding and eta-correction to give the high spatial resolution
- Integrates into EPICs



Example of accumulated spectrum



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Talk Summary

- CCDs continue to be, developed for X-ray science:
  - Size, Speed, Energy range,
- In space science, radiation damage is a key concern, and TRL must be high before adoption
- EM CCDs are now being used for soft X-ray detection down to 50eV
- CMOS image sensor technology is following the development steps of CCDs
- Development of such CMOS technology will require deep(er) pockets to produce
- The ultimate in low energy detectability and spatial resolution will probably remain with the EM CCD for the next 5-10 years (without a “BIG” (i.e. $$) programme)
- The technology is finding uses in many applications; including industrial, Synchrotron research & XFELs

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