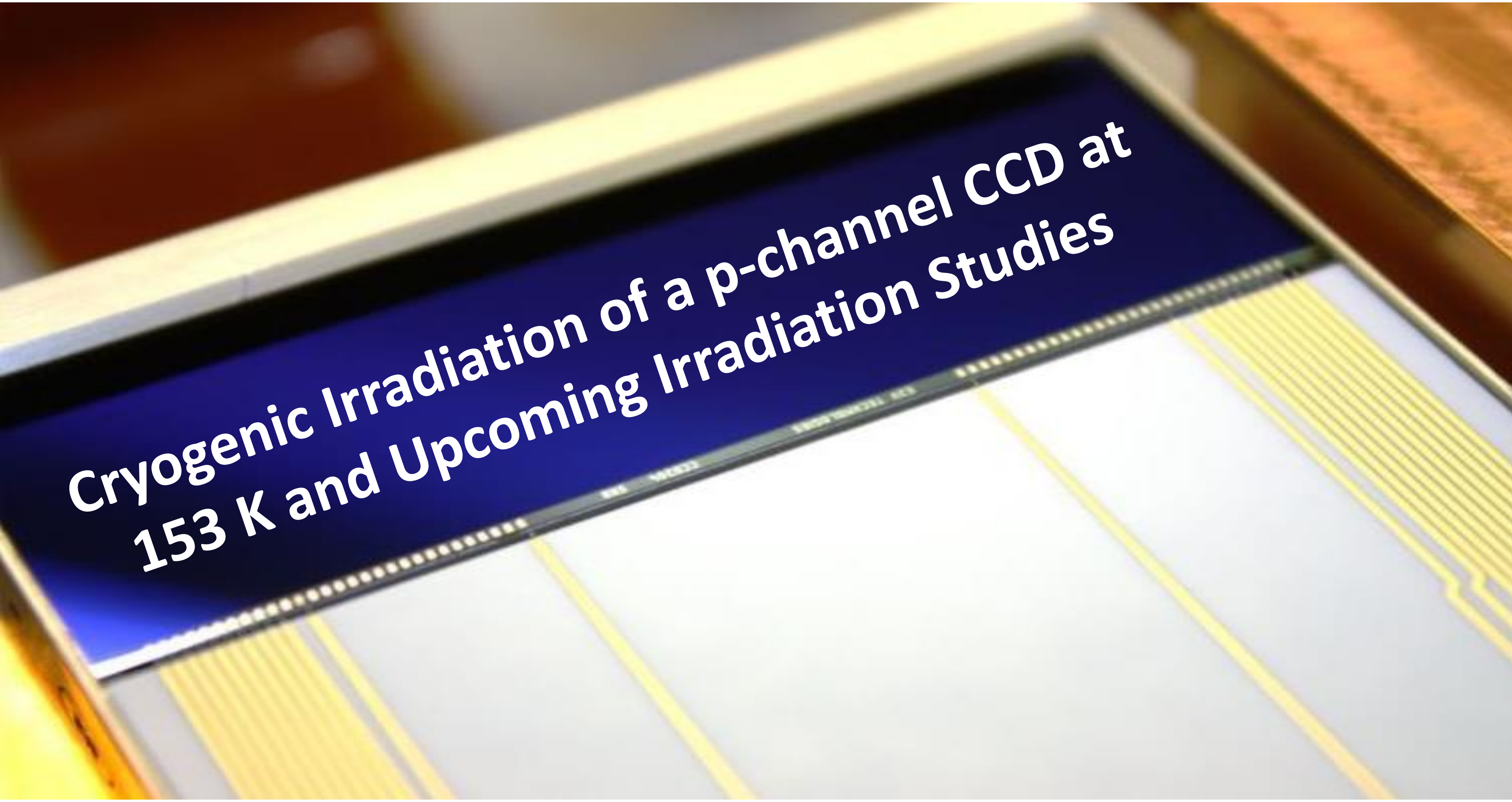
Centre for Electronic Imaging



Cryogenic Irradiation of a p-channel CCD at 153 K and Upcoming Irradiation Studies

The Open University

Jason P. D. Gow

Daniel Wood, Neil Murray, Ben Dryer, David Hall and Andrew Holland

Overview

- Why Cryogenic Irradiations?
- Experimental Arrangement
- Experimental Technique
- Proton Irradiation
- Initial Results
- Summary
- Future Work

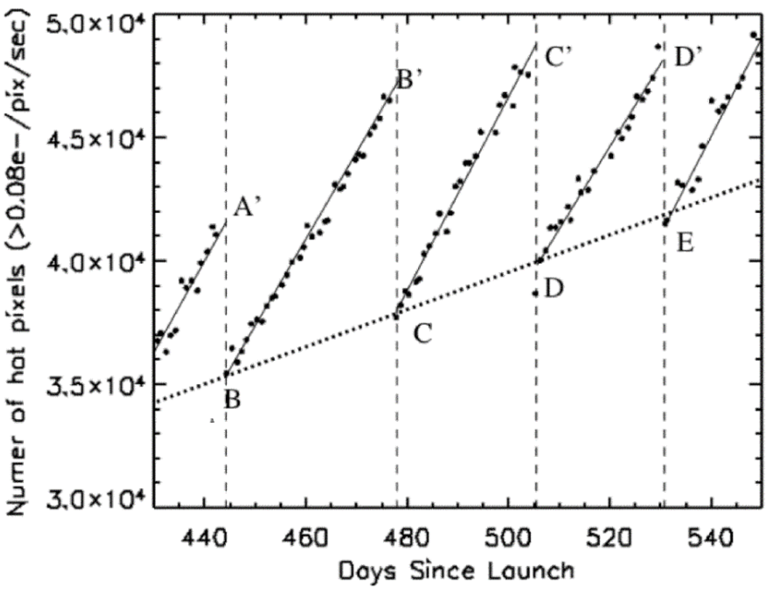
e2v technologies CCD204

- 4k × 1k × 12 µm square pixels
- 49.2 mm × 12.8 mm image area
- Two output nodes, split register
- 4.5 µV/h+ or 1.5 µV/h^+ amplifier responsivity
- High resistivity bulk n-type silicon thinned to ~70 µm
- Parallel hole-injection structure

Why Perform Cryogenic Irradiations?

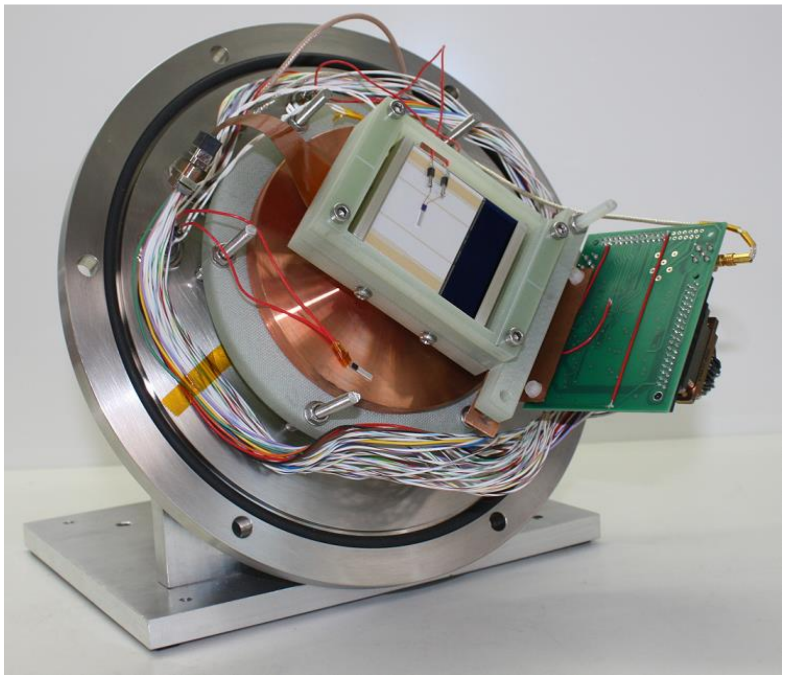
- M. Bautz *et al*., "**Anomalous Annealing of a High-Resistivity CCD Irradiated at Low Temperature**", IEEE Trans. Nucl. Sci, vol. 52, no. 2, 2005
  - Irradiated a device at -100 °C with 120 keV protons, then warmed to -60 °C
  - Warming the device further to +30 °C for 8 hours resulted in a factor of ~2.5 increase in CTI, with a trap identified with an emission time of 40 μs
  - Further annealing at +30 °C saw the conversion of these traps into a trap species with a longer emission time

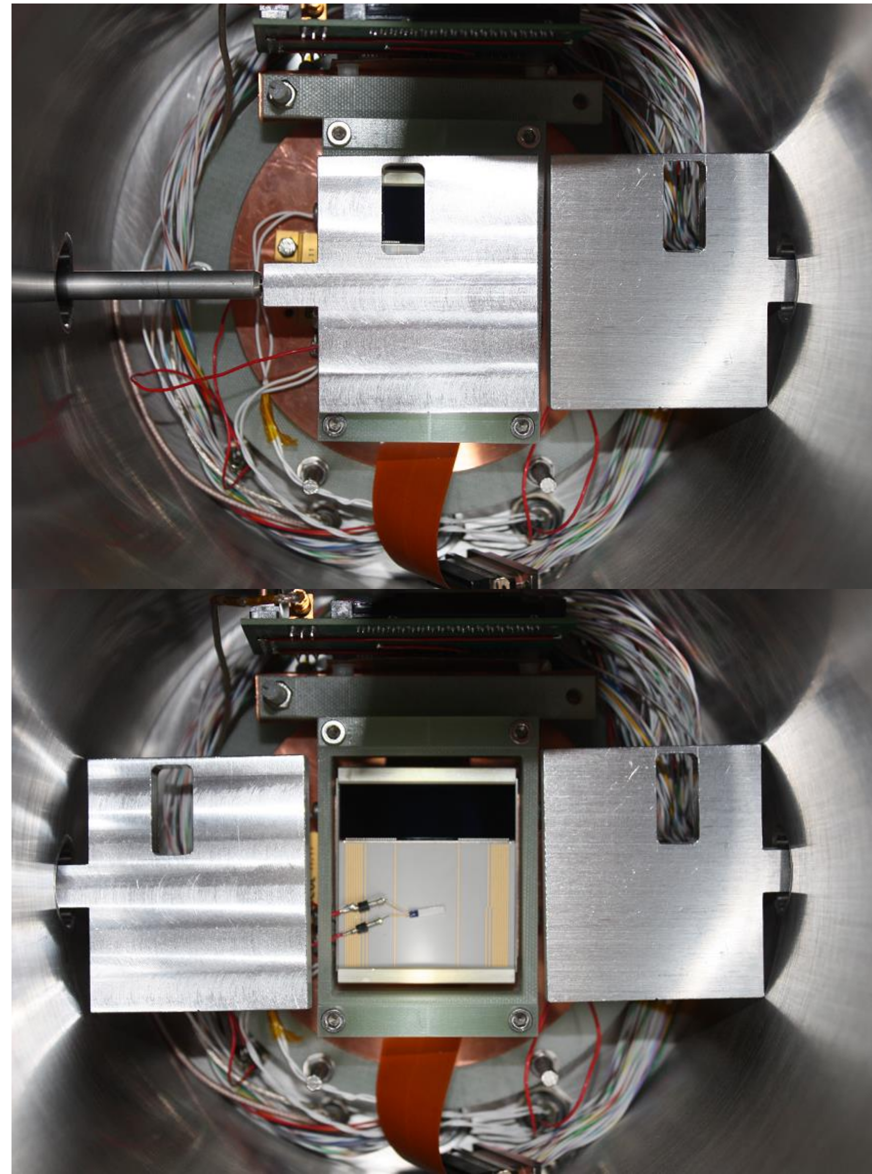
- M. Sirianni *et al*, "**Radiation Damage in Hubble Space Telescope Detectors**", Radiation Effects Data Workshop, 2007
  - Hubble's camera's undergo a monthly anneal to +20 °C
  - A room temperature irradiation would result in these bright defects not being identified



The Open University

Experimental Arrangement



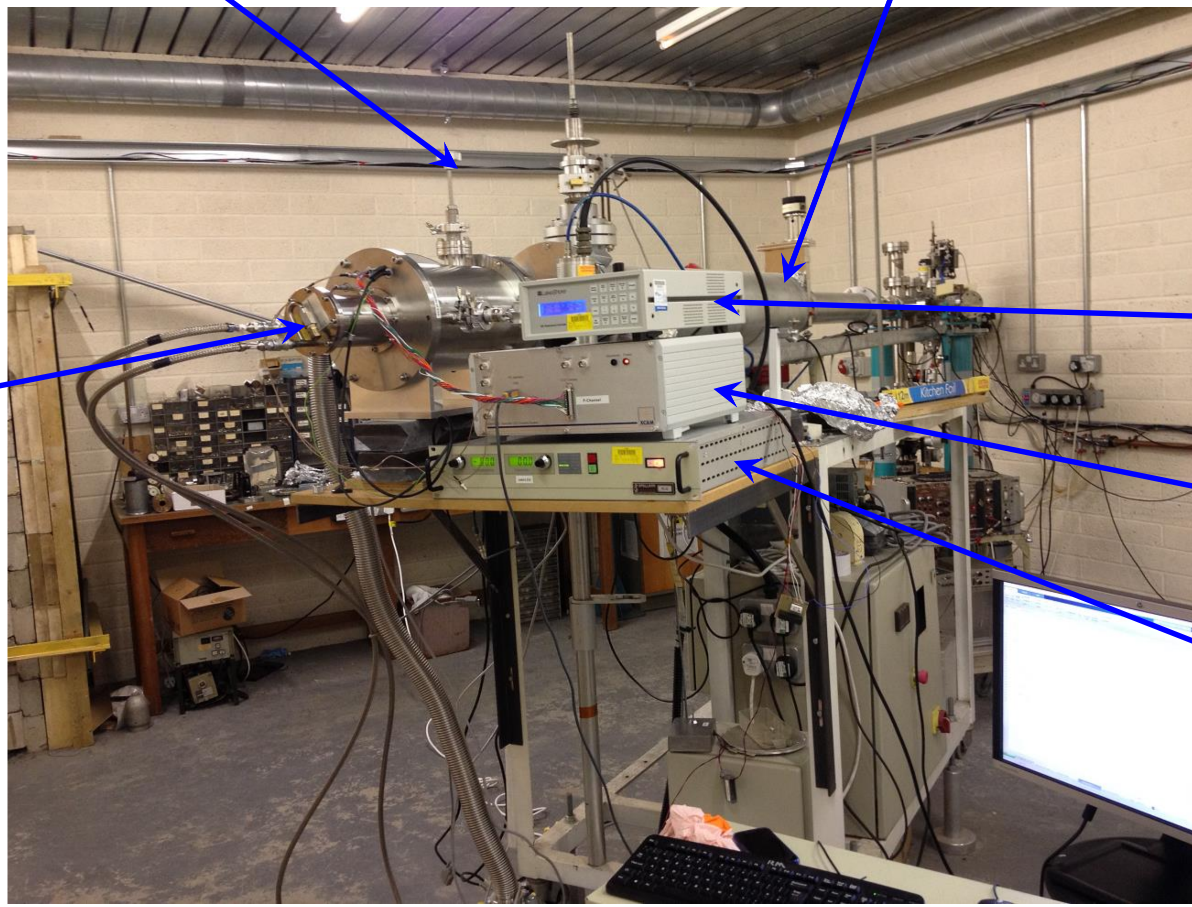


CCD204 mounted on the camera head and inside the chamber showing the radiation shields, this setup was used to perform all irradiations

Cryogenic Irradiation

Rotational target wheel

Proton beamline



Cold End

Temperature control

CCD Drive electronics

X-ray tube power supply

Experimental Technique

- Aim to monitor a number of variables over a period of time after the irradiation and after the devices have been at room temperature for 26 hours, 1 week and 4 weeks, etc.
- Including
  - Dark Current
  - Bright defects
  - Noise
  - Full Well Capacity in the image region
  - Charge injection uniformity
  - Charge Transfer Inefficiency
    - First Pixel Response
    - Extended Pixel Edge Response
    - ^{55}Fe X-rays
  - Defect identification by trap pumping

The Open University

Experimental Technique

- Aim to monitor a number of variables over a period of time after the irradiation and after the devices have been at room temperature for 26 hours, 1 week and 4 weeks, etc.
- Including
  - **Dark Current**
  - **Bright defects**
  - Noise
  - **Full Well Capacity in the image** region
  - Charge injection uniformity
  - Charge Transfer Inefficiency
    - First Pixel Response
    - Extended Pixel Edge Response
    - ^{55}Fe X-rays
  - **Defect identification by trap pumping**

The Open University

Experimental Technique

A flat-field of charge packets are clocked forwards and backwards by 1 (or more) elements for a number of cycles. During this time a signal is trapped from one element and released into another, resulting in a larger signal in one and a lower signal in the other, manifesting as the characteristic bright and dark pixel pairings observed in 'pumped' images.

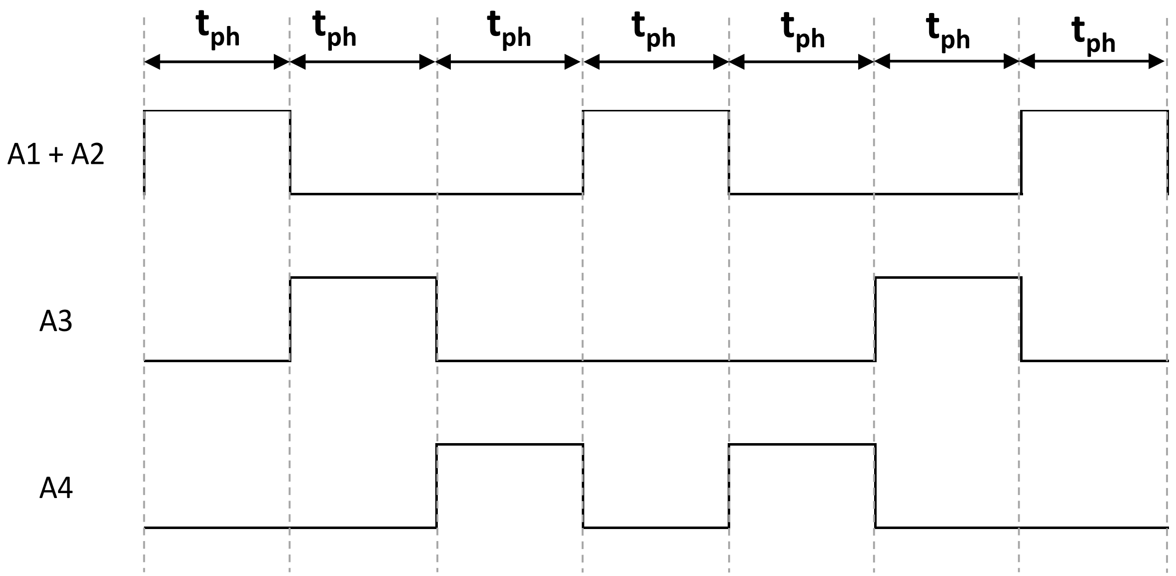
The efficiency of transfer between charge packets is dependent on the location of the trap and the trap species (emission time and temperature).

Note, the charge packet needs to be of sufficient size to encounter the trap and there needs to be signal to pump, so you must have a background signal.

Serial register elements can be pumped similarly.

Experimental Technique

- Trap Pumping, for defect identification



- t_{ph} is varied to explore different trap species

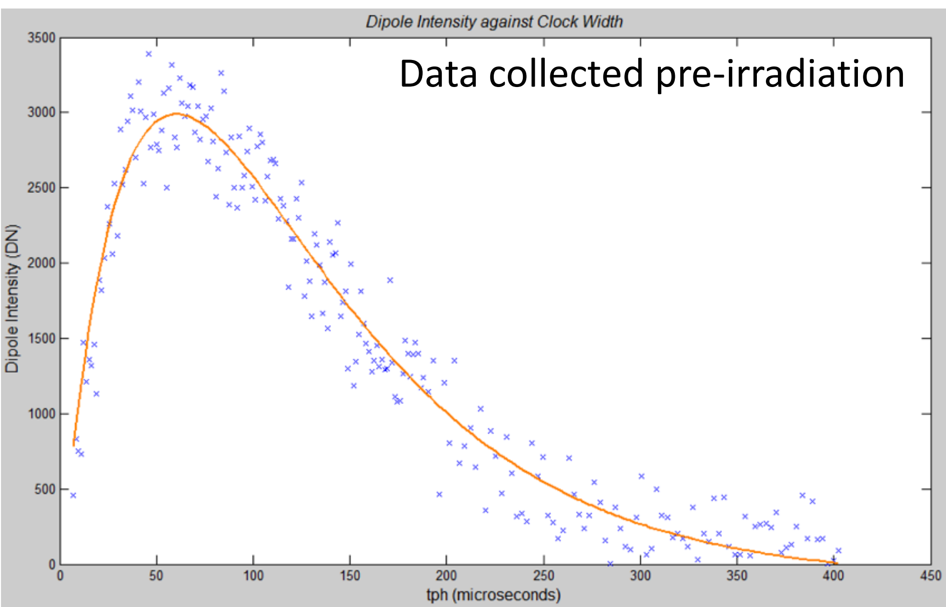
$$Dipole\ Amplitude = NP_C\left(exp\left(\frac{-t_{ph}}{\tau_e}\right) - exp\left(\frac{-2t_{ph}}{\tau_e}\right)\right)$$

where N is the number of pumping cycles (4,000), P_C is the probability of capture and τ_e is the emission time constant

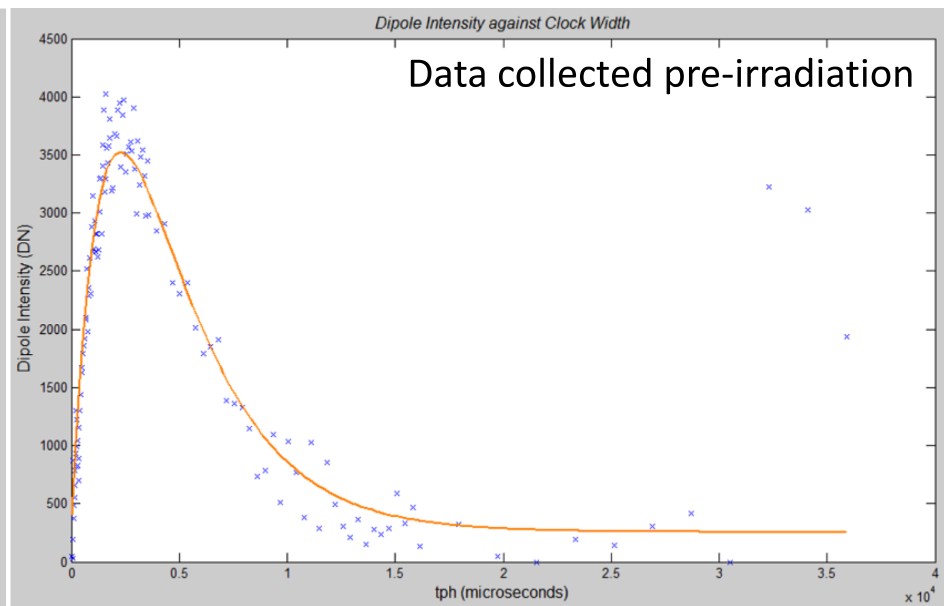
The Open University

Experimental Technique

- **Trap Identification** (Typically ~8 hours to complete)
  - Traps that will be explored at 153 K will include those assumed to be VV and Ci
  - Achieved by varying the clock width during trap pumping using the method described by Hall *et al* "**Determination of In Situ Trap Properties in CCDs Using a "Single-Trap Pumping**" Technique" IEEE Transactions on Nuclear Science, 61(4), pp. 1826–1833.



VV

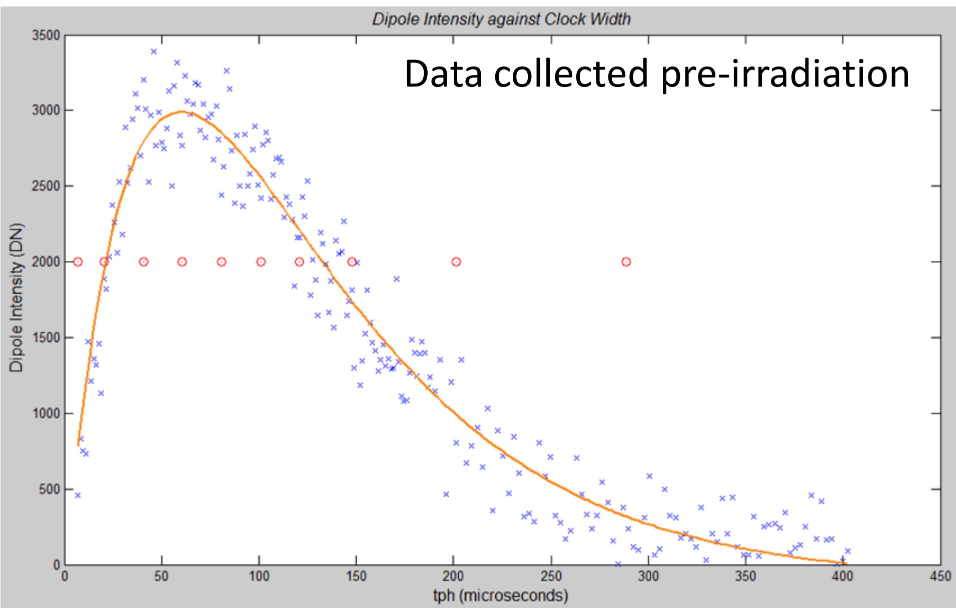


Carbon Interstitial

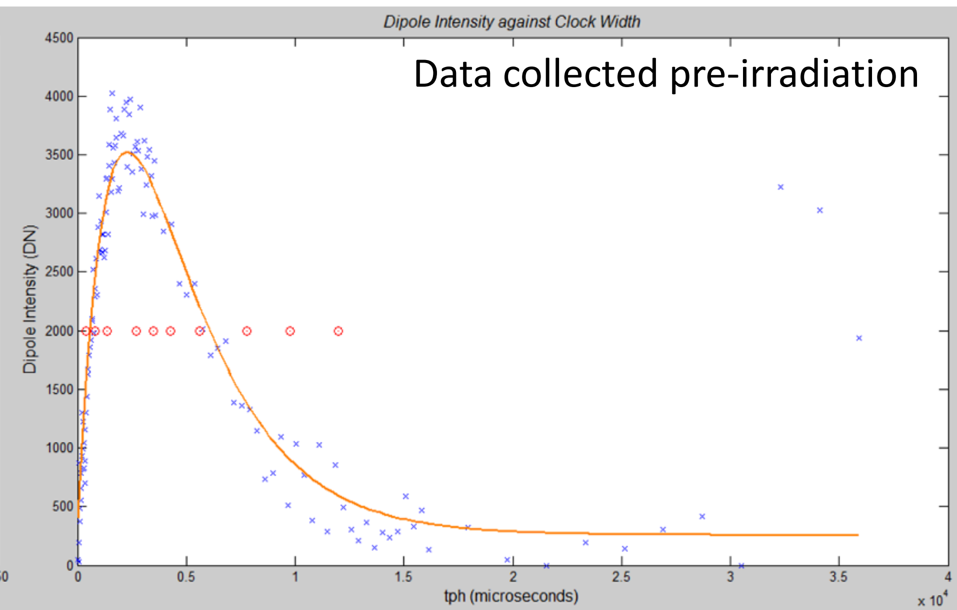
The Open University

Experimental Technique

- **Trap Sweeping around VV** (~20 minutes to complete)
  - Looking at points between 7 and 290 µs
- **Trap Sweeping around Ci** (~40 minutes to complete)
  - Looking at points between 400 and 1,200 µs
- Trap sweeping was performed by targeting key locations on the trap efficiency plots



VV



Carbon Interstitial

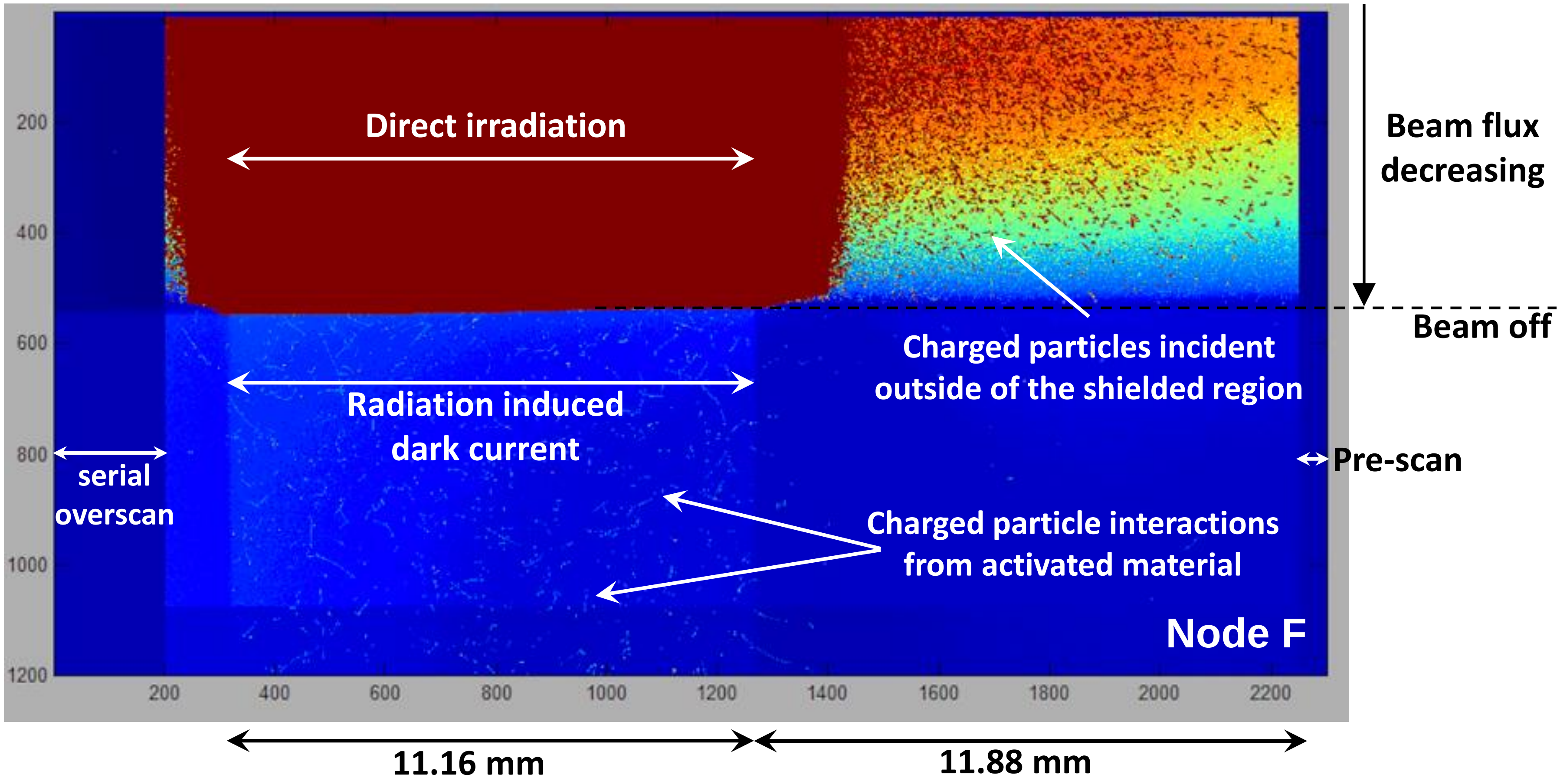
Proton Irradiation

- The irradiations were performed over two days, after one day of setup
  - Room temperature irradiations
  - Cryogenic irradiations at 153 K
- The cryogenic irradiation was performed while the device was acquiring images
- The radiation levels delivered are shown below

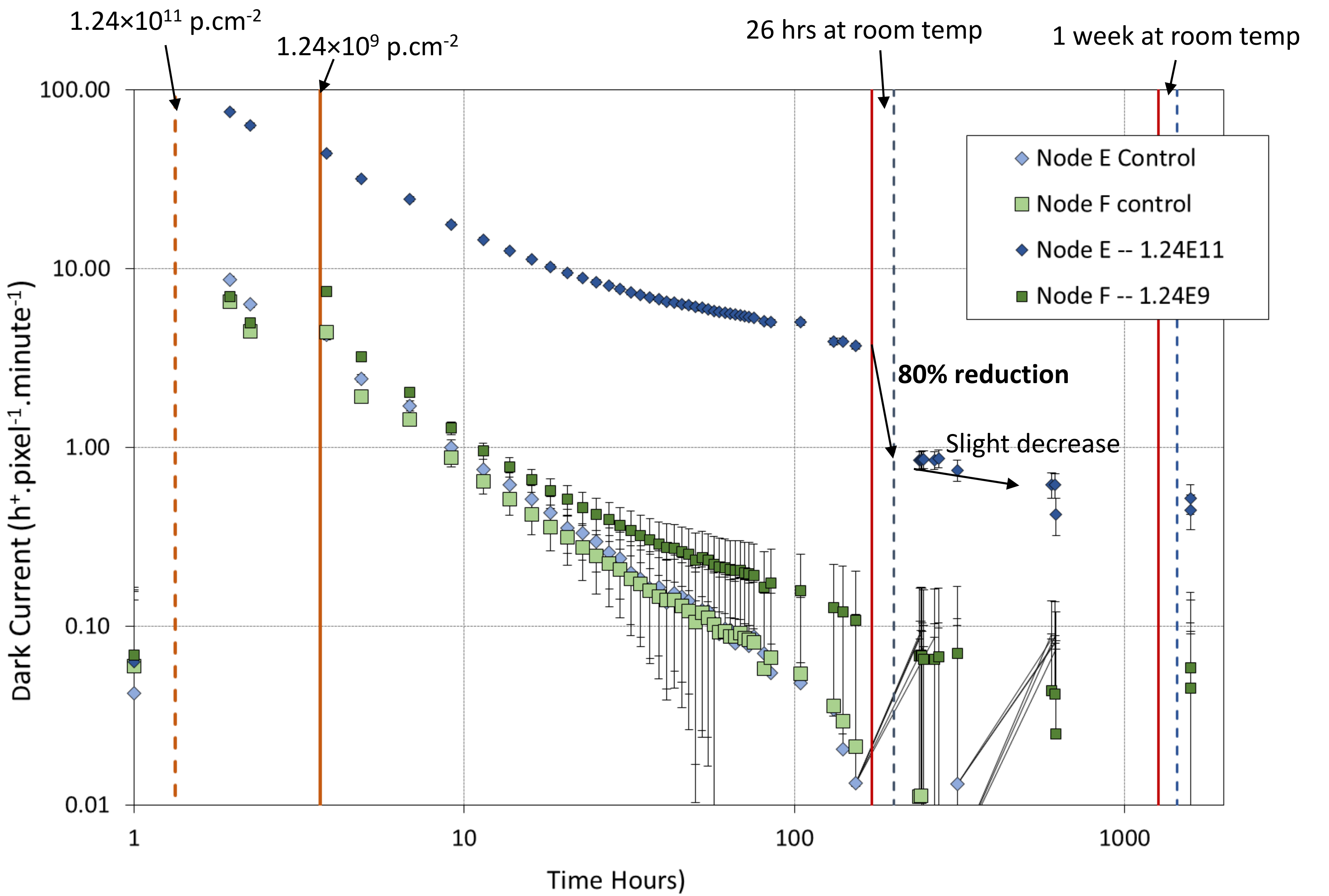
Device	Details	Image Region	7.5 MeV proton fluence (protons.cm^{-2})	7.5 MeV flux (protons.cm^{-2})	10 MeV equivalent proton fluence (protons.cm^{-2})
10092-04-03	Control	AE	Control Device		
		AF			
10092-06-02	Room Temp	AE	1.53×10^{9}	2.0×10^{7}	2.0×10^{9}
		AF	3.07×10^{9}	2.0×10^{7}	4.0×10^{9}
10092-01-04	Room Temp	AE	1.23×10^{10}	2.0×10^{7}	1.6×10^{10}
		AF	7.66×10^{10}	2.0×10^{7}	1.0×10^{11}
10092-04-05	Cryogenic	AE	9.50×10^{8}	2.5×10^{7}	1.24×10^{9}
		AF	9.50×10^{10}	2.5×10^{7}	1.24×10^{11}

Proton Irradiation (RHS image)

- This lucky image was taken as the beam was powered down at the end of the irradiation of node F, all images acquired during the irradiation were fully saturated!
- Shield was held at a distance of around 3 mm from the surface of the detector, typical room temperature irradiations use 0.5 to 1 mm.



Dark Current evolution post irradiation measured at 153 K



Reduction in Image area FWC

- There was a clear reduction in the image area full well capacity in the area irradiated with a 10 MeV equivalent proton fluence of 1.24×10^{11} protons.cm^{-2}
- Based on the total ionising dose deposited by the 7.5 MeV protons, ~65 krad, and the relationship between image clock voltage and full well capacity, initial estimates of the flat band voltage shift are around **30 mV per krad**
- This compares well to the standard gate n-channel CCD which experiences a flat band shift of between 100 to 200 mV per krad
- The reason for this improvement is currently under investigation.

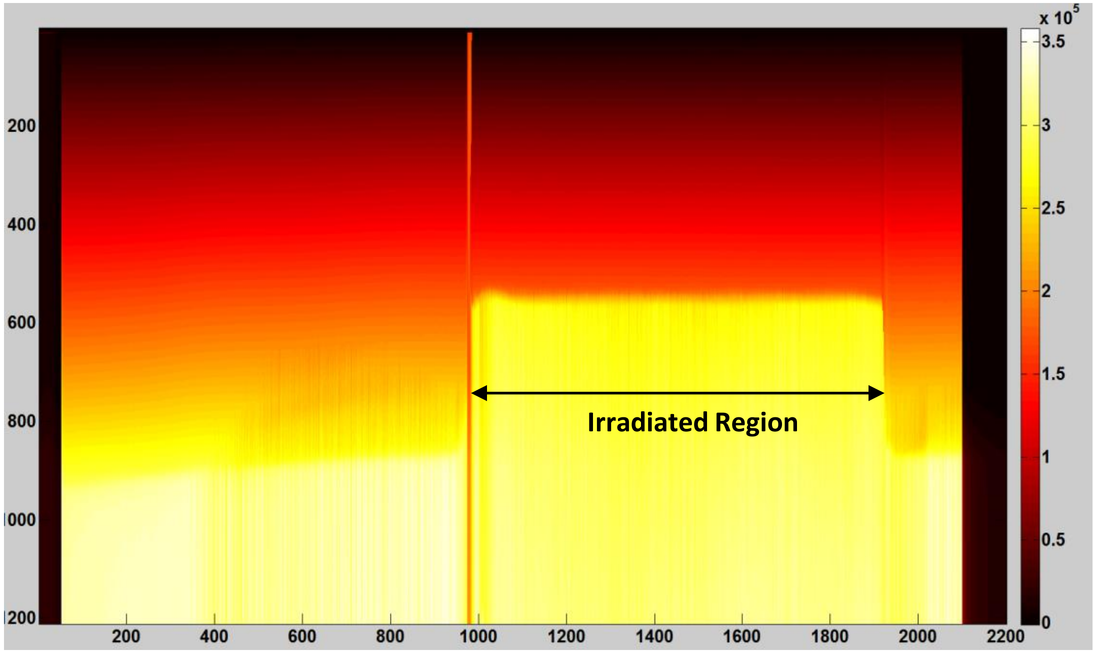


Image produced with an LED on during readout

Edge effects of the irradiation

- The two bands at the edges of the irradiation are believed to be the result of the preferential movement of charge towards a region of increased potential, resulting brighter charge on the outside.

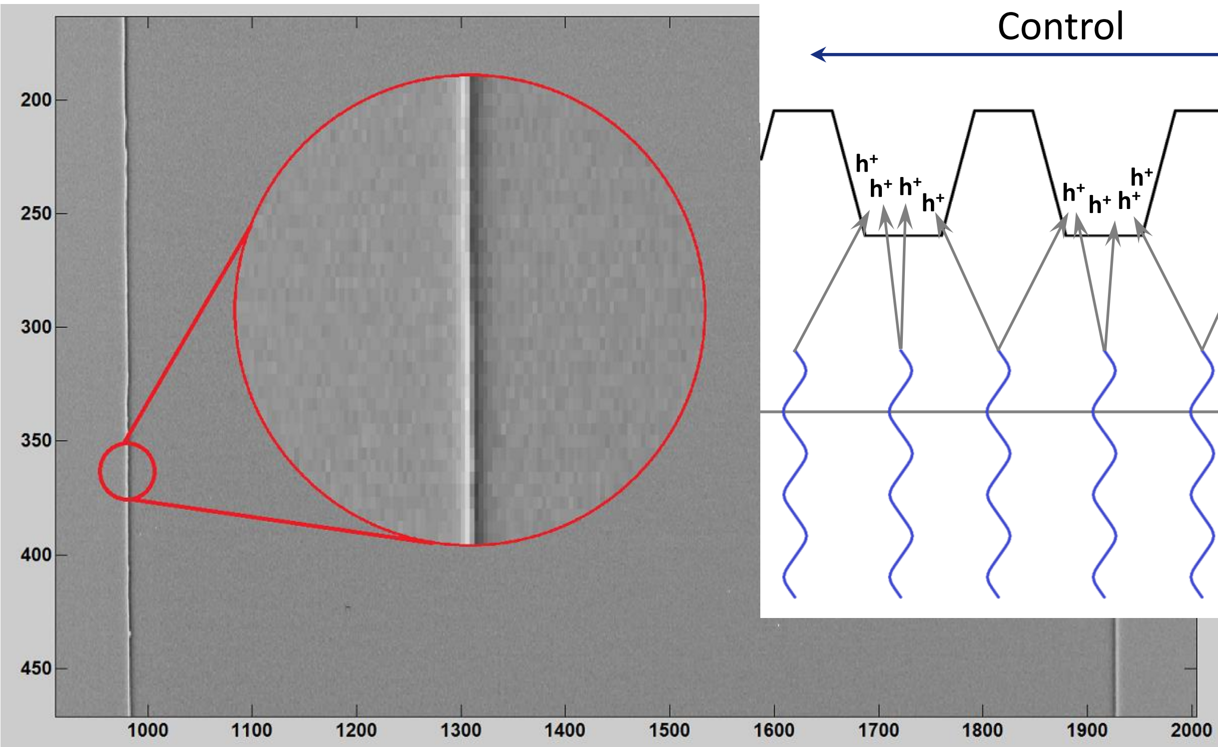


Image taken using a flat field of 20,000 holes

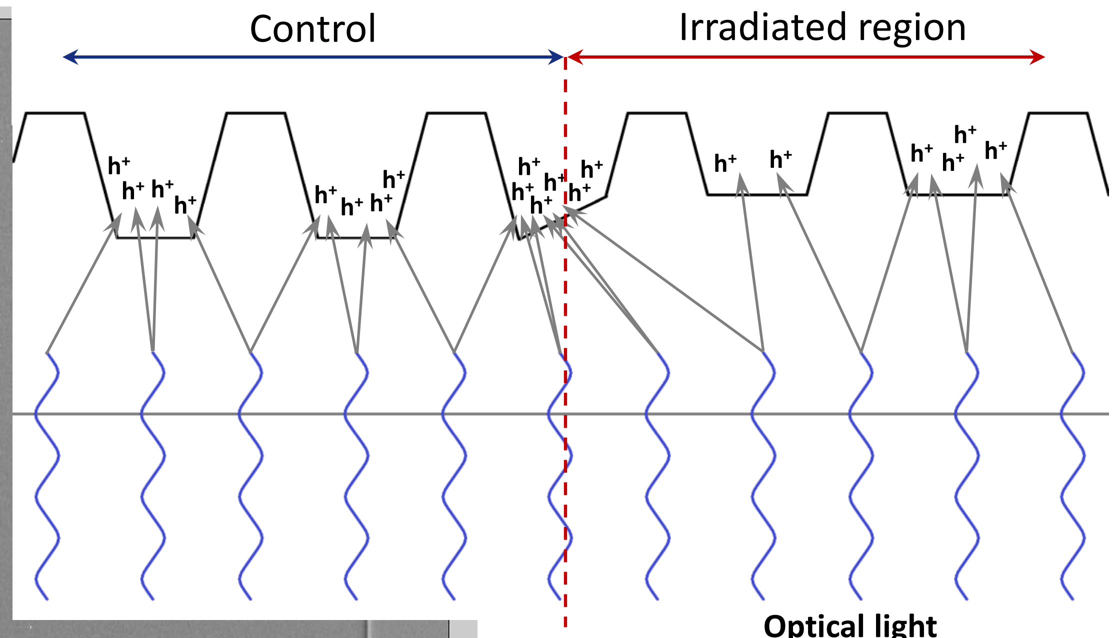
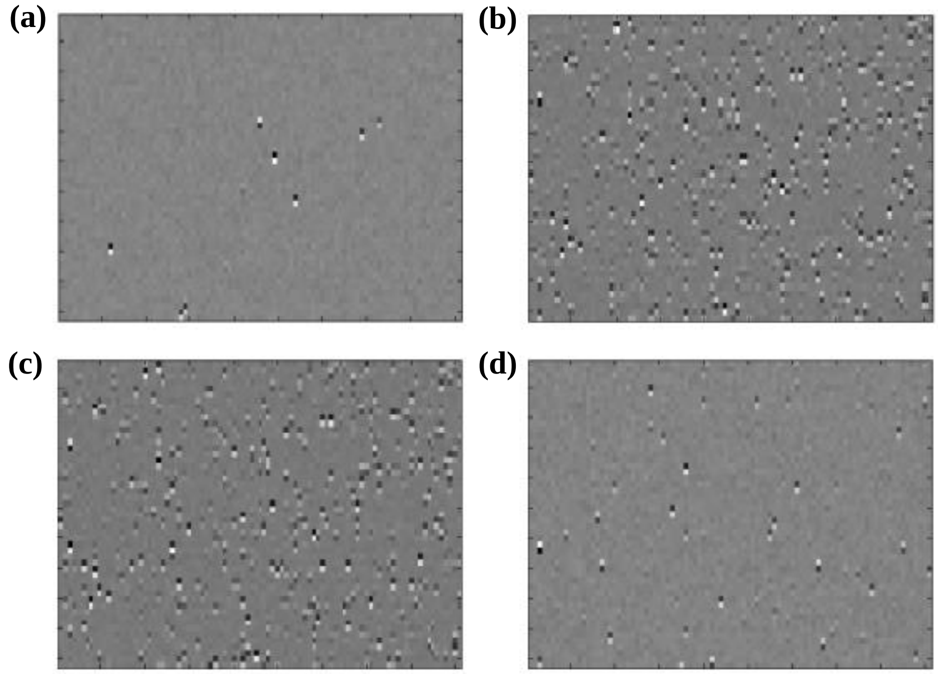


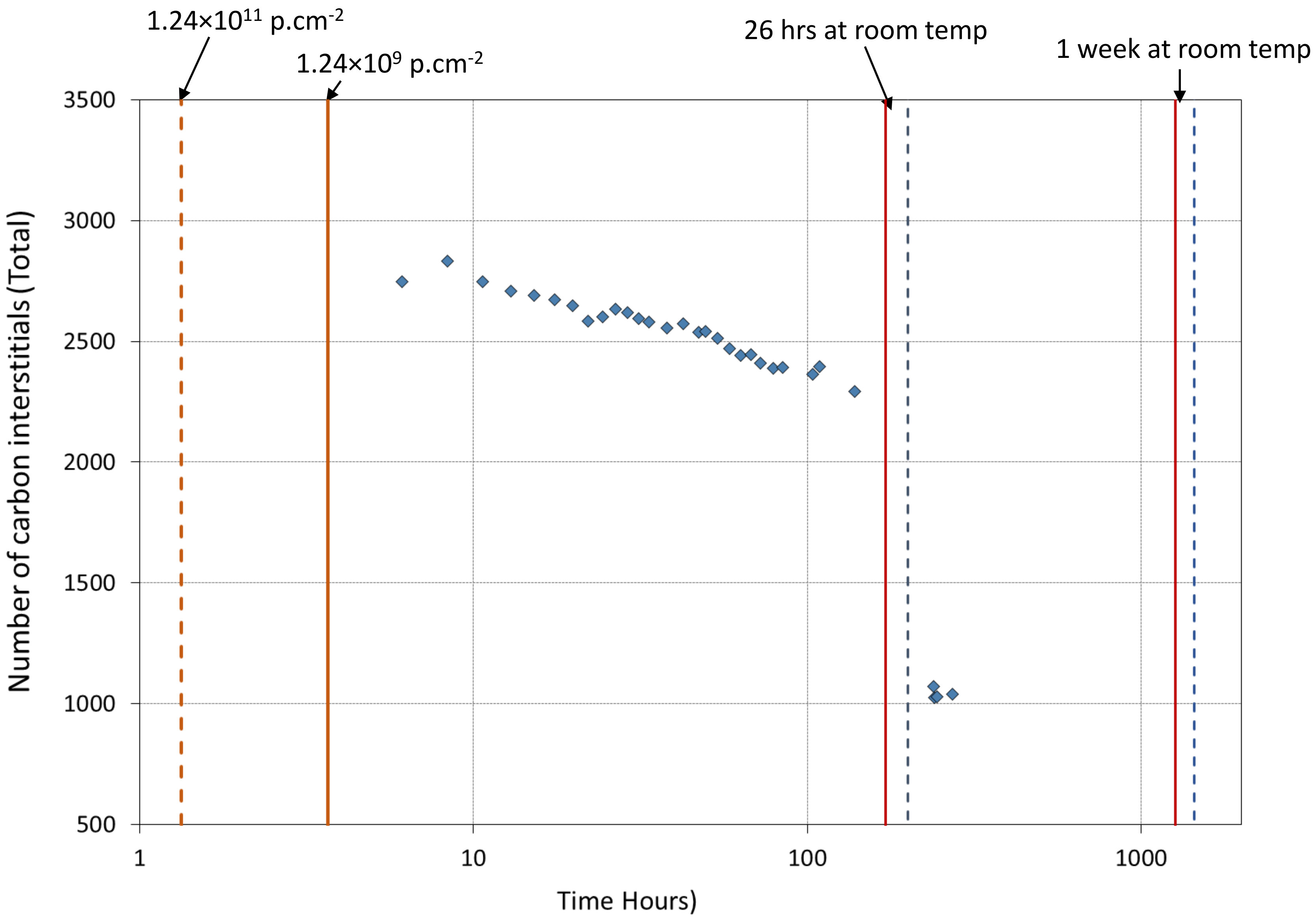
Diagram showing charge redistribution at the boundary of the irradiation

Defect evolution post irradiation

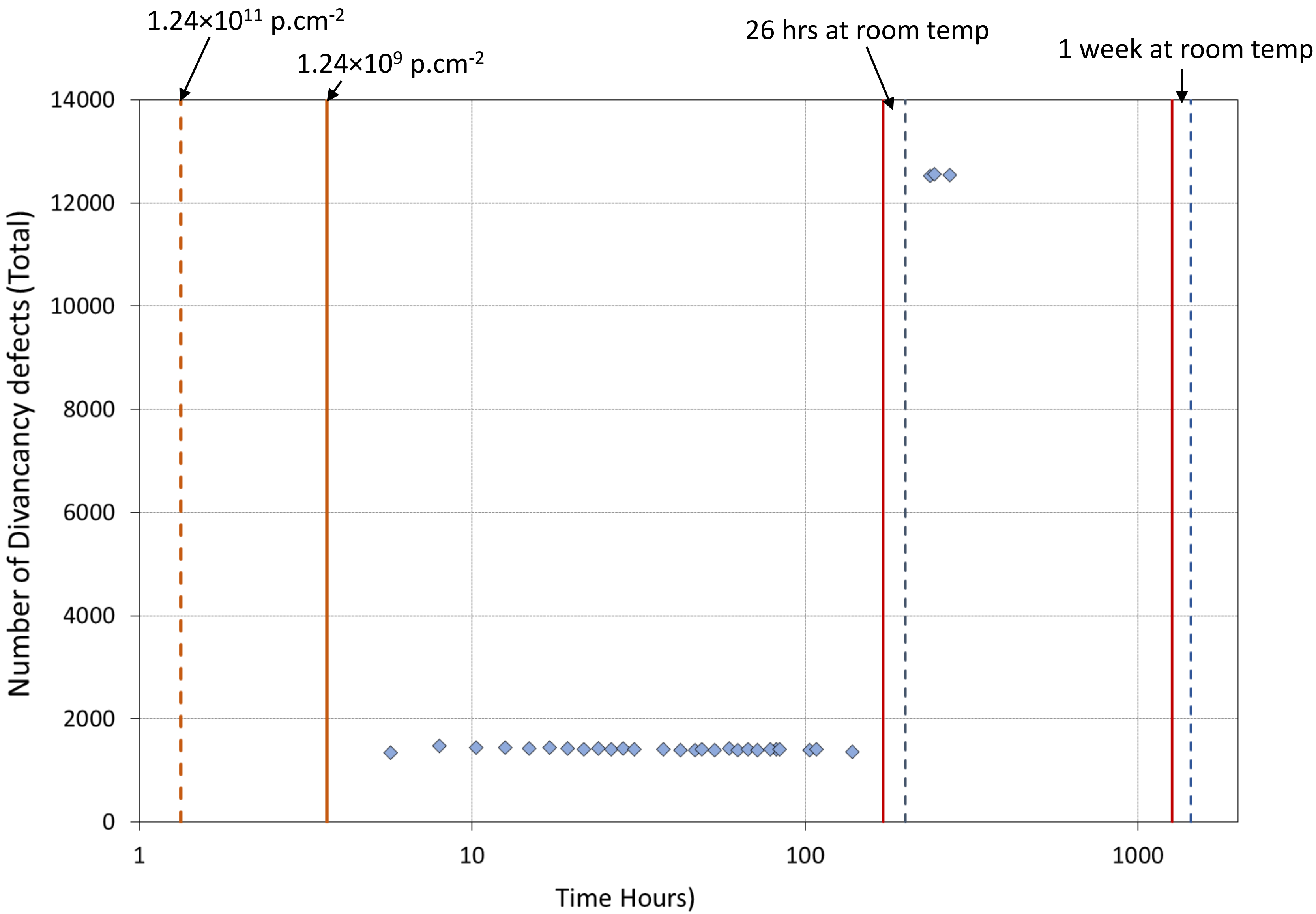
- Image showing the results of trap pumping in a section of the device pre-irradiation (a),
- 6 minutes after the irradiation was complete (b),
- 18 minutes after the irradiation was complete (c)
- and a difference image (d) showing the change over a period of 12 minutes.



C_i defect evolution post irradiation



Divancancy defect evolution post irradiation



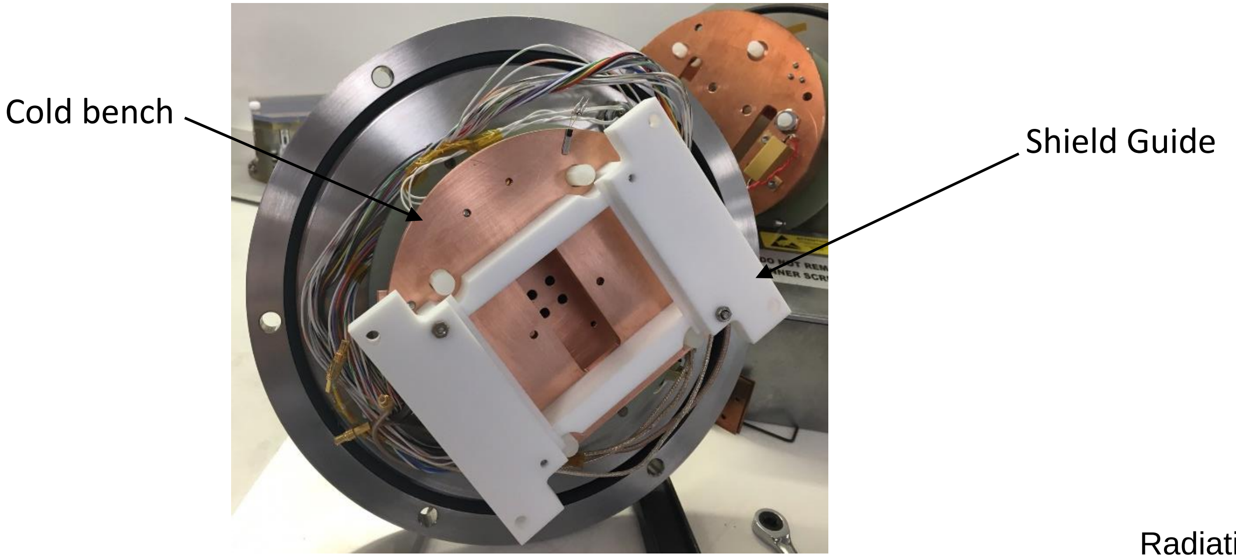
Summary

- ESA funded study into the performance of a p-channel CCD irradiated at 153 K under a Technology Research Programme
- The post irradiation behaviour of a number of parameters is dynamic
  - In particular the number of defects varies considerable immediately after the irradiation
  - Monitoring everything rapidly is challenging
- The behaviour of traps after the anneal stage is important to understand in order to select the optimal transfer timings
  - An optimisation at room temperature would indicate timings to avoid the divacancy but that could be comparable to the C_i.
  - A cold optimisation would clearly indicate avoiding the C_i and, subject to mission requirements could allow for faster transfer timings as the divacancy experience a significant increase.
- CTI measurements are not as straight forward as in previous campaigns, where only stable and unchanging operation was being considered.
- Data will continue to be collected with the cryogenically irradiated device after increasing periods at room temperature
  - Looking at CTI over time and the continued evolution of the different trap species (for submission to RADECS 2016)

The Open University

What's next …

- **P-channel**
  - Planned ESA funded study to look at a side by side study of an n-channel and p-channel CCD204 with both devices **irradiated simultaneously**.
  - Devices would be irradiated at 153 K and monitored for an extended period of time to look into defect evolution, dark current and CTI.
  - The temperature would then be increased to 173 K and performance monitored for an extended period of time
  - Devices would then be irradiated again at 203 K, with further monitoring.
  - Annealing at room temperature and around 100 °C would then be performed, again with continued monitoring for each level.



What's next …

- **Euclid CCD273 study**
  - In support of the Euclid visible imager, working alongside MSSL, ESA, CEA and Durham University.
  - A cryogenic irradiation will be performed on a device and the results compared to a room temperature irradiation to ensure optimal operating conditions.
  - A second device will be irradiated cold, and **kept cold for an extended period of time (years)** to allow for a long term assessment of cryogenic operating conditions.