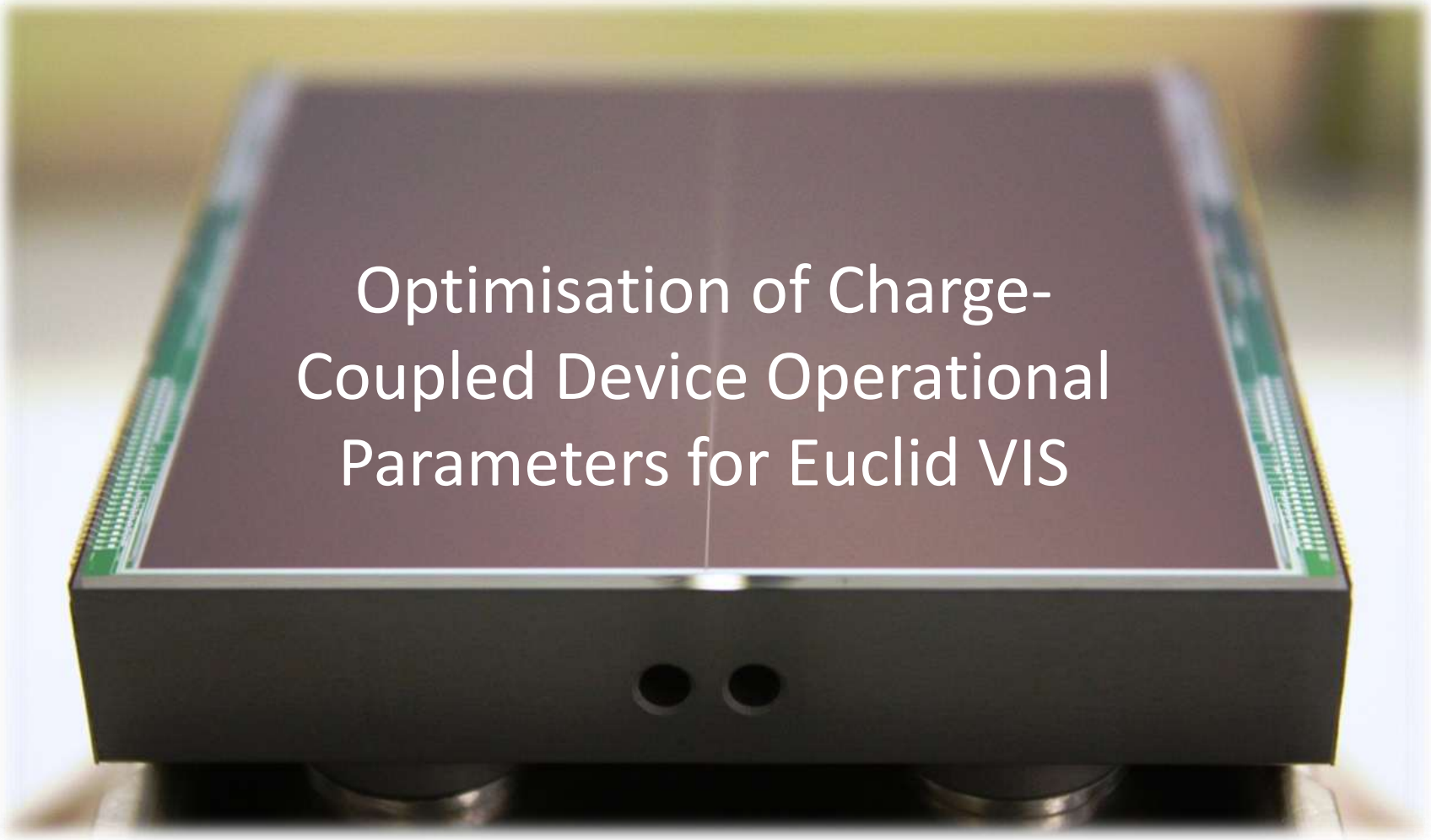
centre for electronic imaging



Optimisation of Charge-Coupled Device Operational Parameters for Euclid VIS

The Open University

Neil Murray

13th December 2012

Overview

- **Introduction to group and facilities**
- **Charge Transfer Optimisation**
  - The CTE Problem for galactic shear measurements
  - Trap Pumping
  - Line Transfer Optimisation
  - Further Improvements – Tri-State
  - Serial register
  - On-orbit calibrations
  - Ground Based Correction
- **On-going and future work**
- **Optical PSF facilities**
- **Remanence following optical overload**

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The centre for electronic imaging

Andrew Holland
Professor
Radiation Effects in CCD X-ray Detectors (1990)

Konstantin Stefanov
Reader
Experimental Particle Physics (2001)

Neil Murray
Research Fellow
Improvements to MOS CCD Technology for future X-ray Astronomy Missions (2008)

David Hall
Research Fellow
Exploring the Impact of Detection Physics in X-ray CCD Imagers and Spectrometers (2010)

Thomas Greig
Research Fellow
Development of CMOS Active Pixel Sensors (2008)

Ross Burgon
Research Fellow
Manoeuvre Planning Architecture for the Optimisation of Spacecraft Formation Flying Reconfiguration Manoeuvres (2010)

Jason Gow
Radiation Damage PDRA
Radiation Damage Analysis of the Swept Charge Device for the CIXS Instrument (2009)

James Tutt
EM-CCD PDRA
Development of CCD and EM-CCD Technology for High Resolution X-ray Spectrometry (2012)

Ben Dryer
GAIA PDRA
Radiation Effects in CMOS Image Sensors

Calum MacCormick
PDRA
Atomic Physics (2002)

Anthony Evagora
Ageing Effects in EM-CCDs
University of Reading

Phillipa Smith
Radiation Damage Effects in SCDs
University of Reading

Edgar Allanwood
Evolution of the Euclid VIS PSF
University of Liverpool

Richard Harriss
Development of Space Flight Electronics
University of Oxford

Andrew Clarke
Modelling of Charge Storage and Transfer
University of Liverpool

Daniel Weatherill
X-ray Detection in CMOS Imagers
University of Cambridge

Matthew Soman
Improving Spatial Resolution with EM-CCDs
University of Warwick

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Laboratory Facilities (CCD)

Cooling

4 × CryoTiger with temperature control (138K to 233K)
1 × Free Piston Stirling Cooler (193K to 293K)
2 × Water Cooled Thermo-Electric (223K to 313K)
1 × Fan Cooled Thermoelectric (223K to 313K)
1 × LN2 (77K to 293K)

X-ray sources

2 × W-target X-ray tubes (1.2 keV to 25 keV)
2 × Cu-target anode X-ray tubes (1.2 keV to 25 keV)
4 × ^{55}Fe isotopes (6 keV)
1 × Manson Source (0.3 keV to 9 keV)

Camera Electronics

7 × XCAM USBREM2 racks
1 × XCAM PCI card
2 × P-channel inverters

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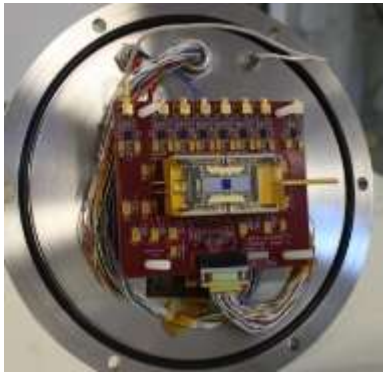
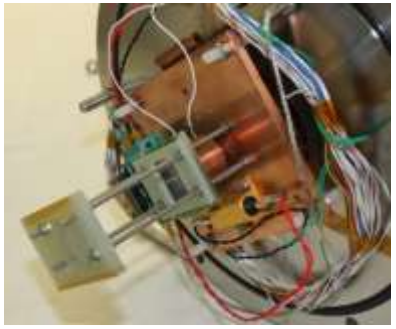
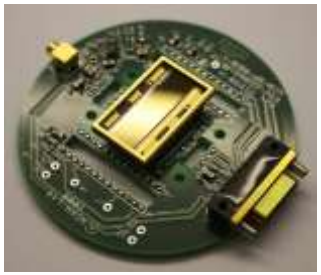
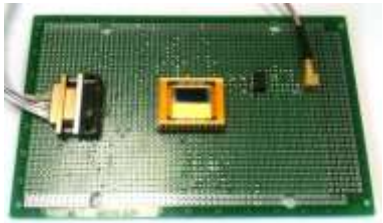
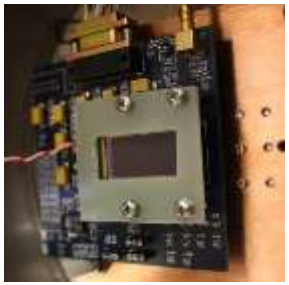
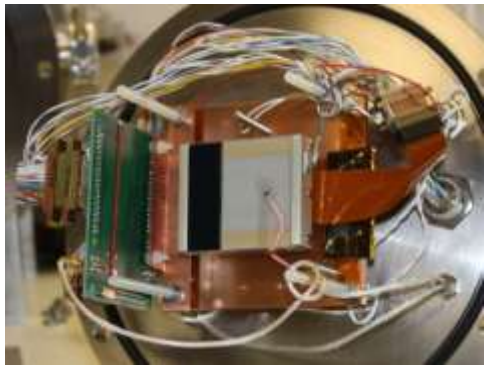
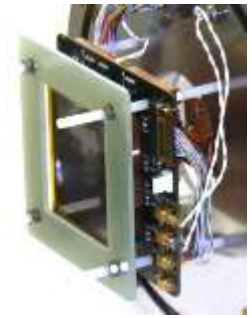
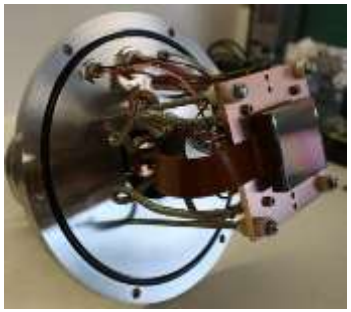
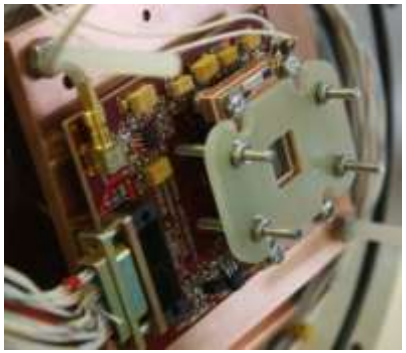
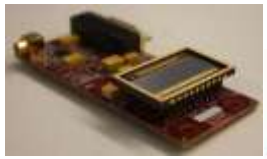
CCD Experience







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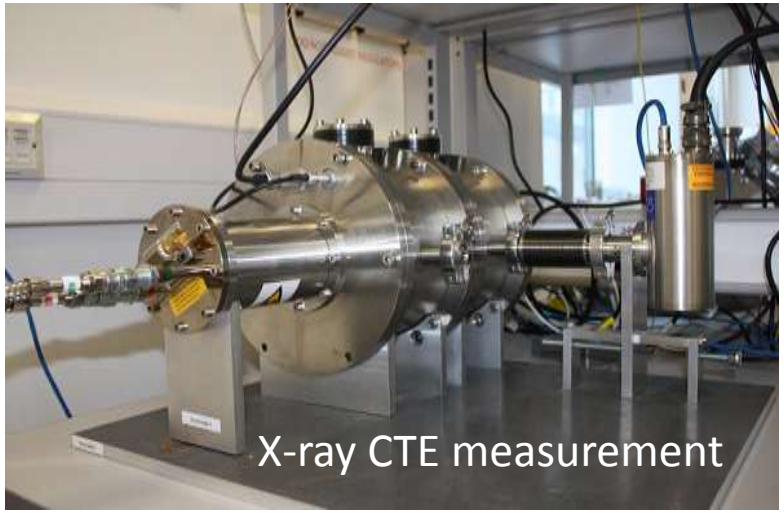
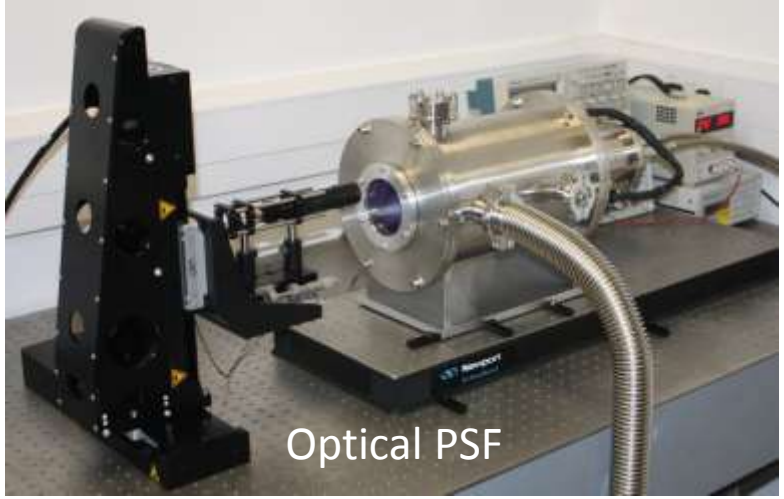
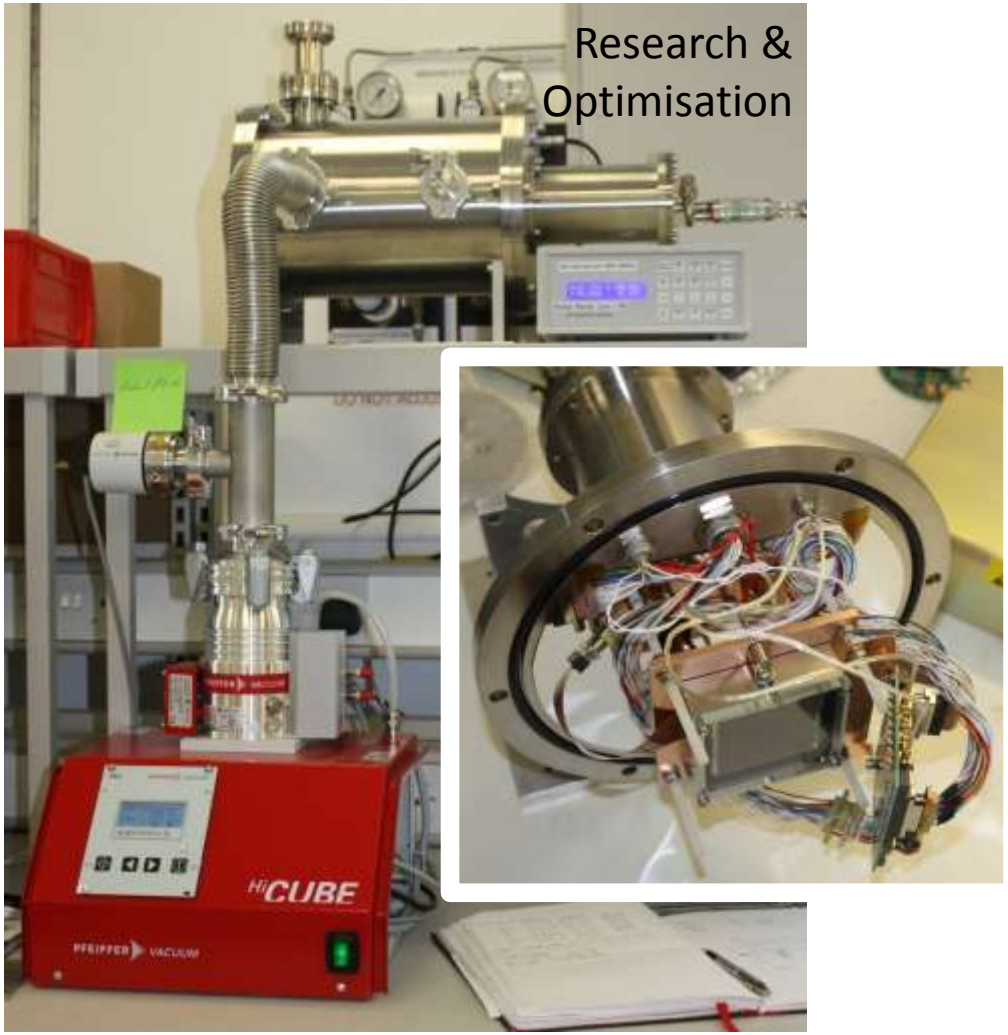
Current Euclid CCD273 Cameras







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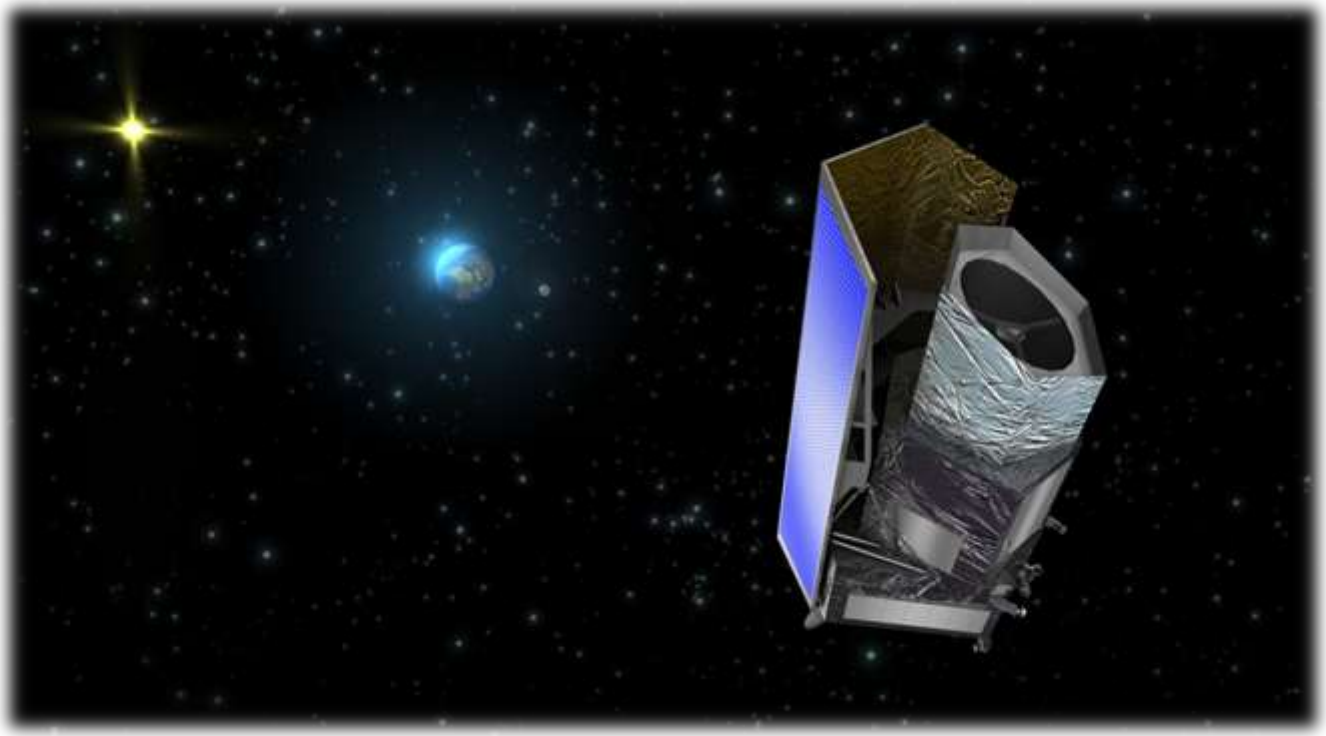
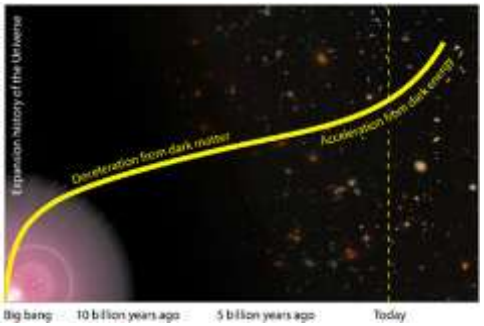
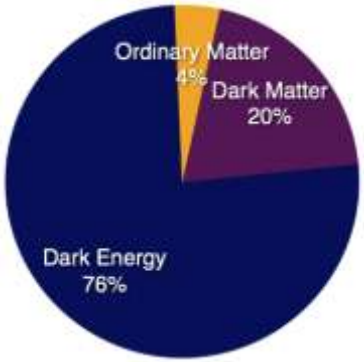
Euclid

Euclid Visible Imager (VIS)







Euclid aims to map the geometry of the dark Universe, measuring the distance-redshift relation and the growth of structure by using two complementary dark energy probing methods, baryon acoustic oscillations and weak gravitational lensing.

Euclid is an ESA M-class mission, due for launch in 2020 with a 6 year duration at L2.

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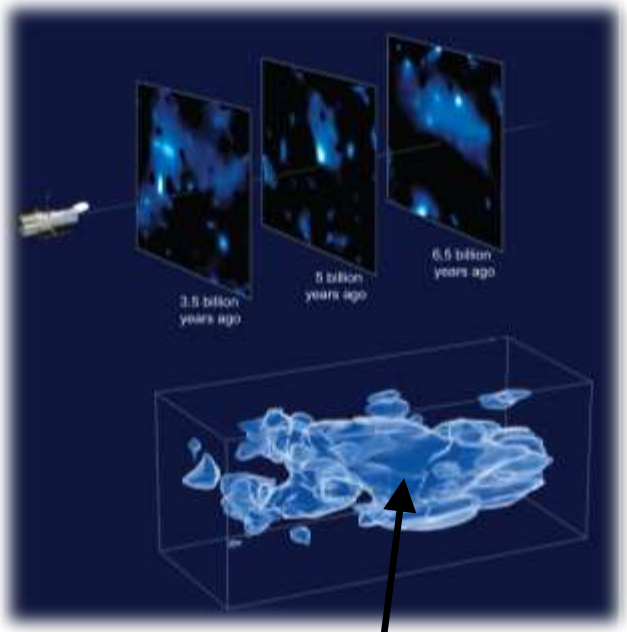
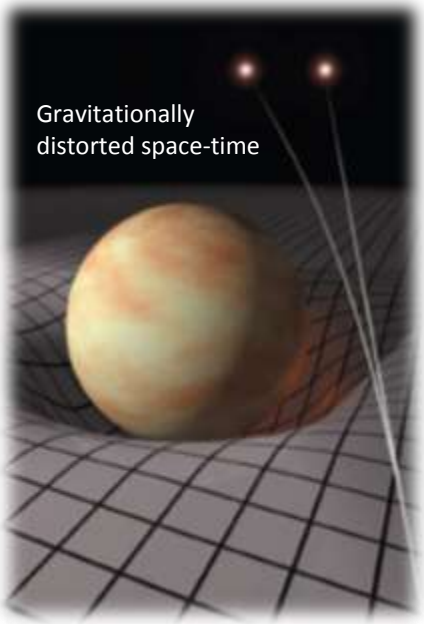
Gravitational Lensing

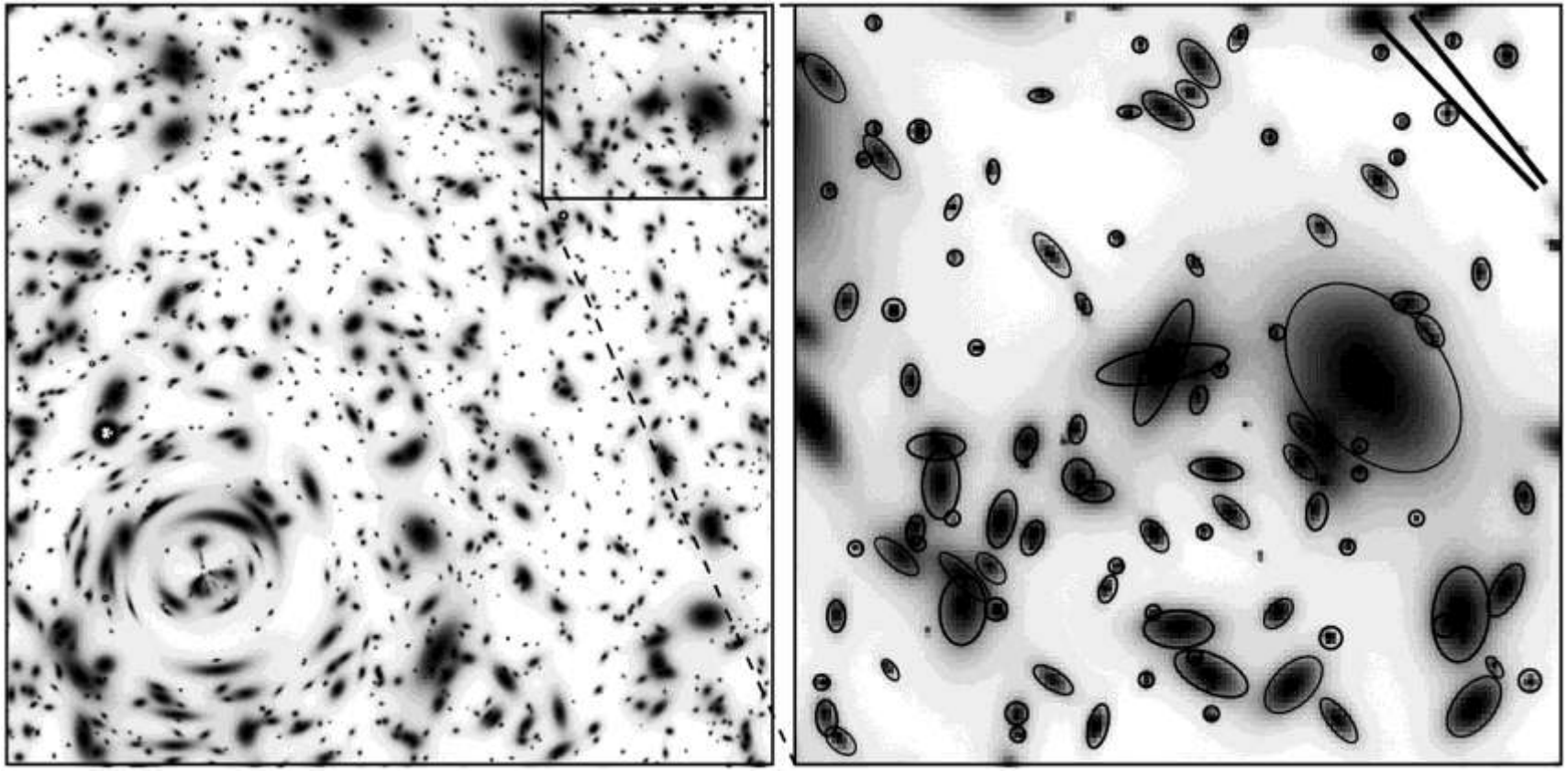
As distant galaxies are observed the presence of dark matter distorts space-time curving the light's path





The distribution of dark matter measured from the HST COSMOS survey using weak gravitational lensing. This survey covers an area about 8 times the size of the Moon. Euclid will produce higher resolution 3-D dark matter maps over the entire sky.

Weak Gravitational Lensing



http://www.cita.utoronto.ca/~hoekstra/lensing.html

- *Strong* lensing around galaxy clusters produces *strong* effects (multiple images, arcs, rings)
- *Weak* lensing produces *weak* but statistically measurable effects

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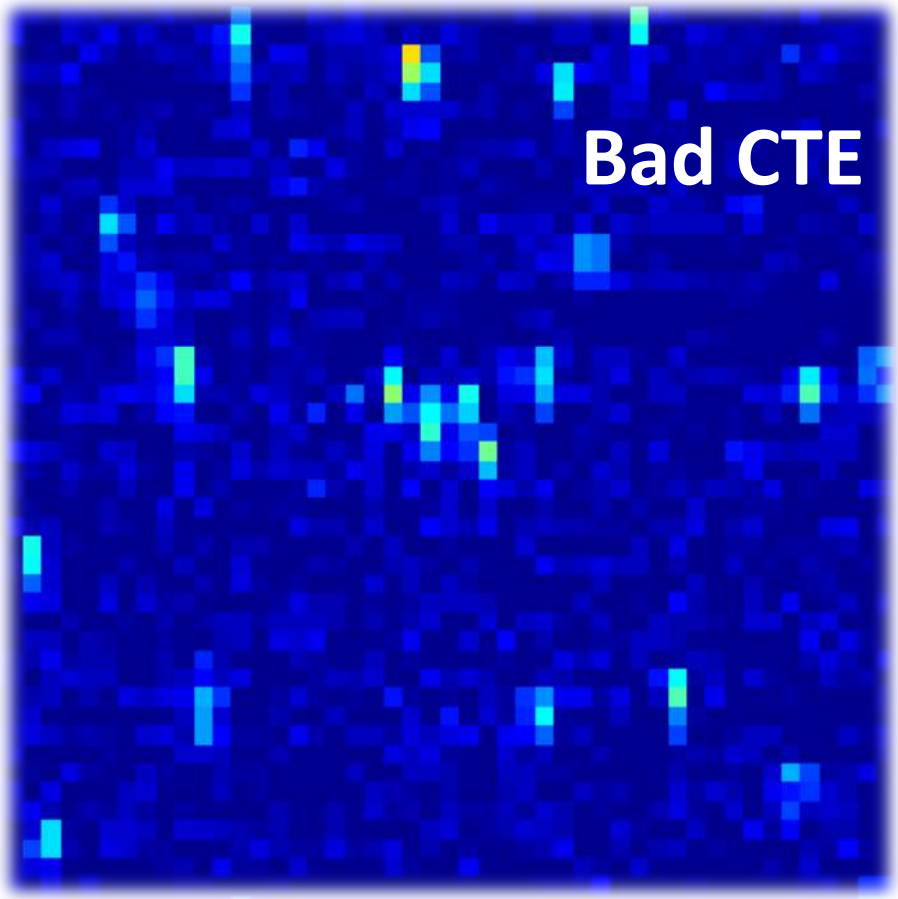
Weak Gravitational Lensing

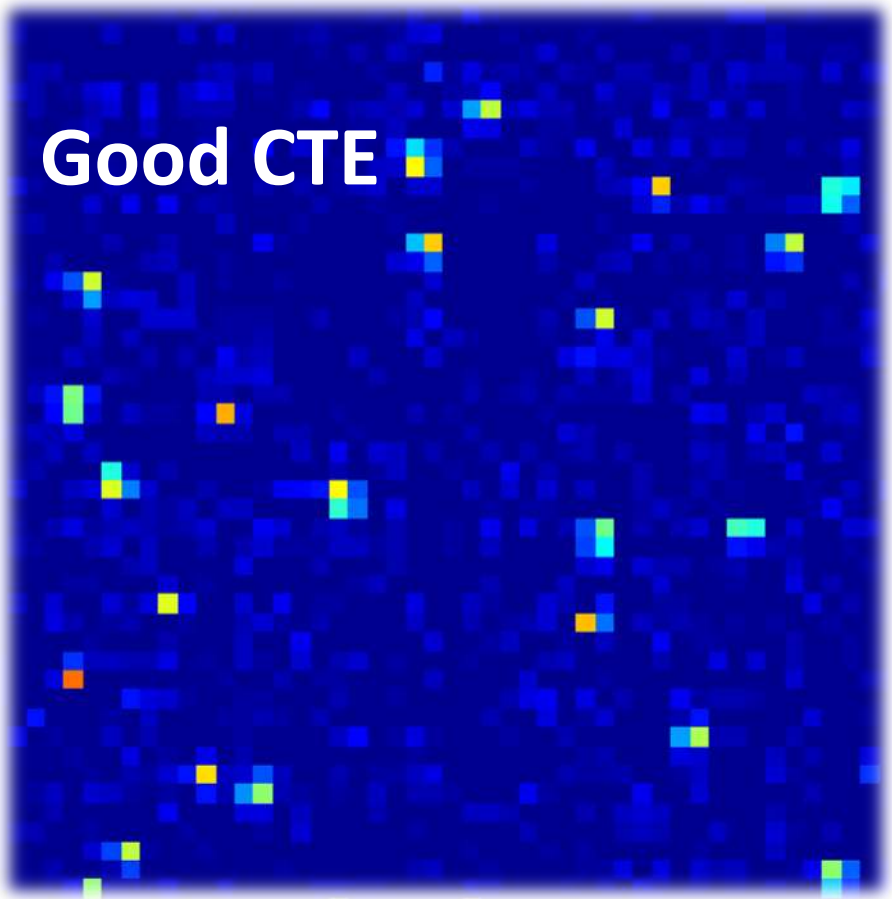
How do we know if a galaxy has been weakly lensed, or is it just a degradation in the charge transfer efficiency of the CCDs?

Proton damage on-orbit will certainly cause a problem. We need to fully understand this and operate under optimal parameters for the very best science

Fix the problem then explain it!

Fe55 events after ~1000 transfers (after 1E11 p.cm-2) – 153K, P-channel CCD204





n-channel parallel timings t_{oi} = 14.4 µs

t_{oi} increased to 1,000 µs

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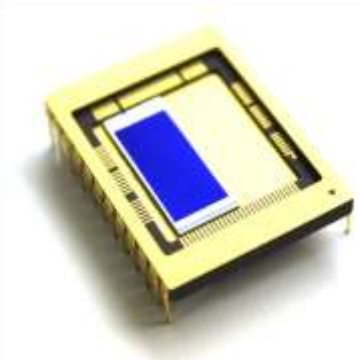
Recent history

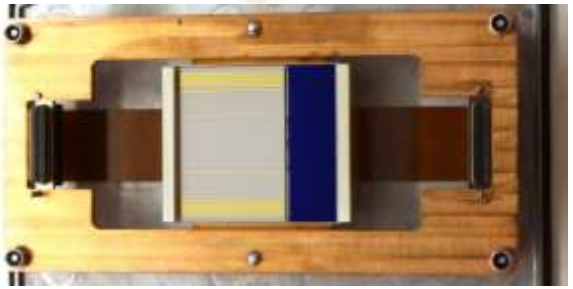
August 2011

Asked to try and replicate Ralf Kohley's GAIA trap-pumping results with the radiation test structure CCD221 for G.M. Seabroke's GAIA SBC paper.



October 2011

Noticed changes to the pumping transfer rate (amongst many other parameters) and pause between transfers could have a significant effect on the efficiency of the 'pumped' signal.

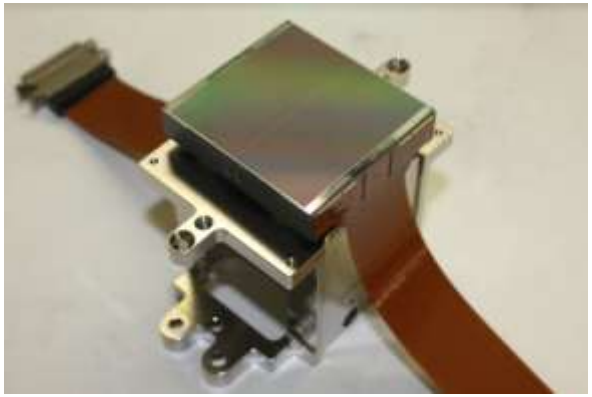


November 2011

Techniques applied to earliest available CCD, p-channel CCD204.

November 2011

Diagrams produced to explain trap-pumping aid in the understanding of the fast-release traps that cause deferred charge tails .
Investigating clocking schemes and timings to increase CTE for Euclid.



December 2011

Techniques applied to earliest available CCD, n-channel CCD204.

2012 - onwards

Optimisation of parallel and serial clocking schemes for very best CTE for the CCD273.

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How is a trap ‘pumped’

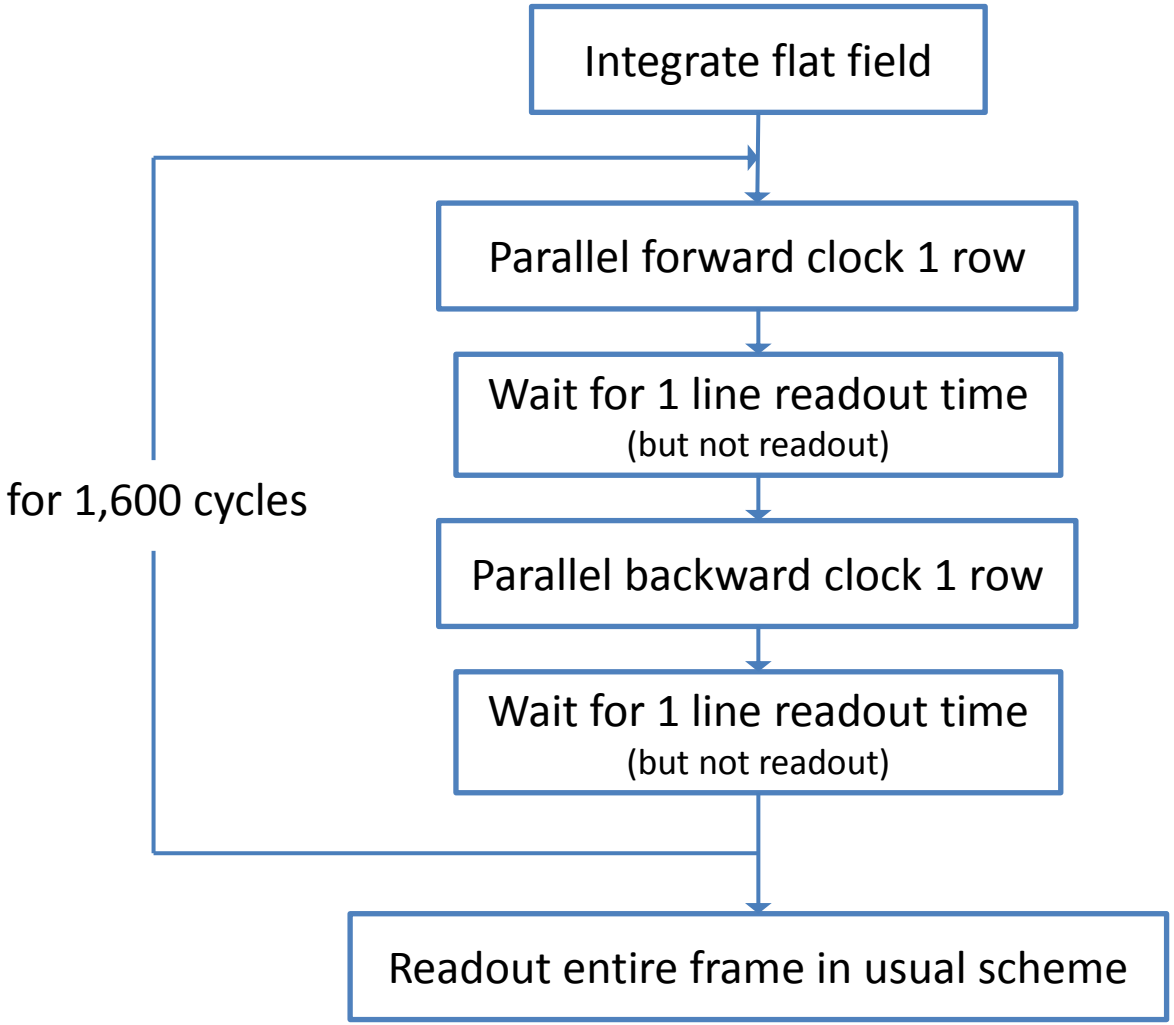
A flat-field of charge packets are clocked forwards and backwards by 1 (or more) elements for a number of cycles. During this time a signal is trapped from one element and released into another, resulting in a larger signal in one and a lower signal in the other, manifesting as the characteristic bright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

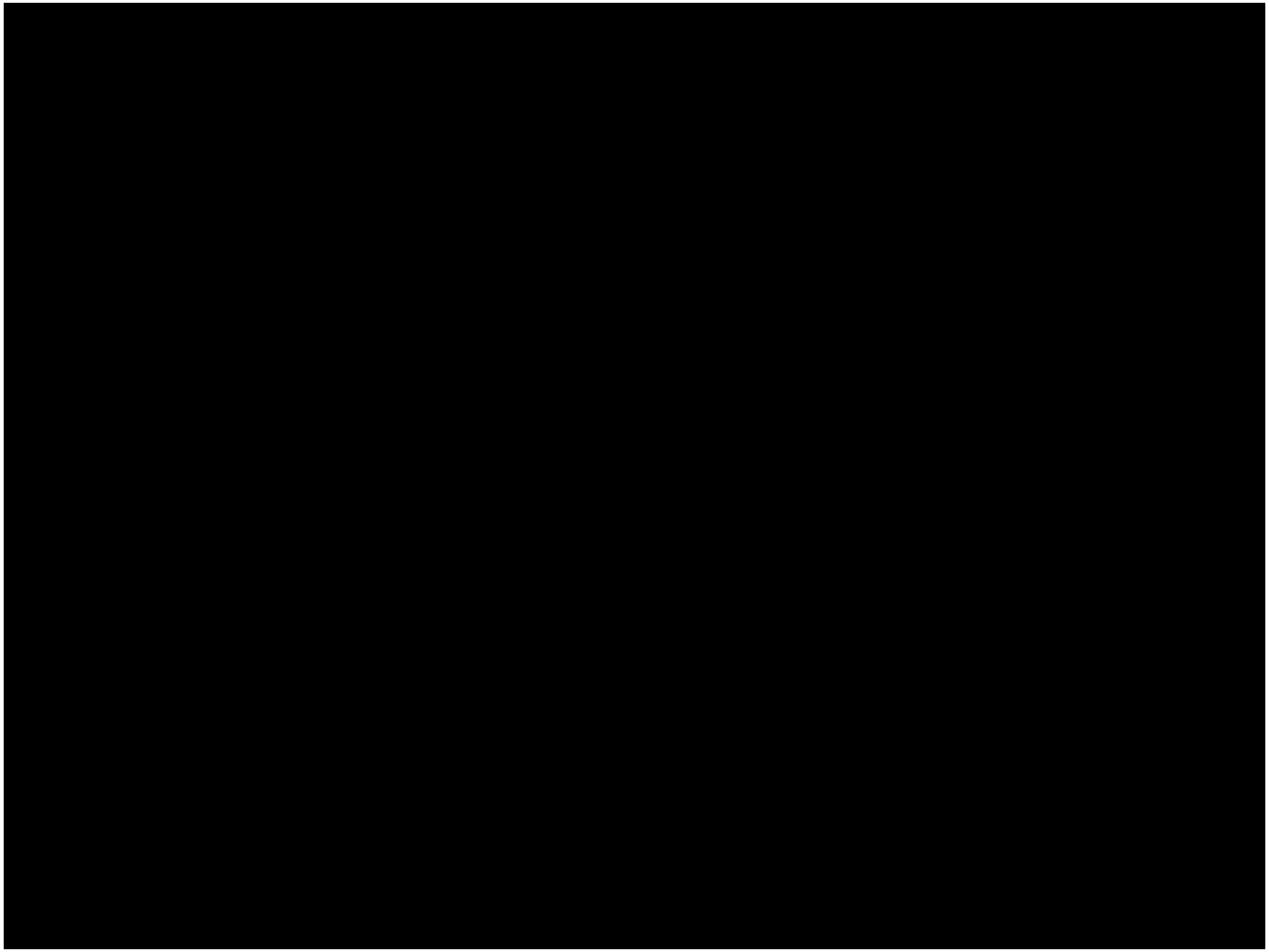
Note, the charge packet needs to be of sufficient size to encounter the trap and there needs to be signal to pump, so you must have a background signal.

Serial register elements can be pumped similarly.

Typical trap pumping sequence



Animation of trap pumping sequence

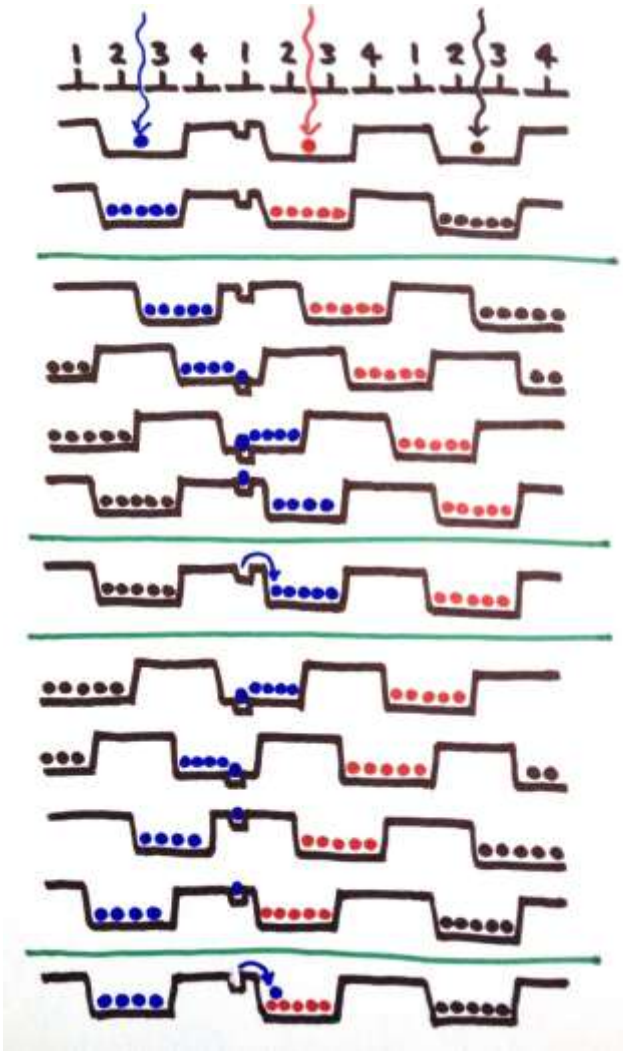


Ed Allanwood

The Open University

Single pumping sequence example: Trap under the barrier phase electrode 1

Pumped



①

Step 1 – A flat field of photo-generated charge, dark current or charge injection is stored in the potential wells in the CCD array formed by the collecting phase electrodes.

Step 2 – Charge packets are transferred forward by 1 array element using the typical clocking sequence for readout. During this time an electron may be captured by a trap under phase 1.

Step 3 – After some dwell time the electron releases and is captured in the nearest potential well. In this case the original charge packet.

Step 4 – Charge packets are transferred backward by 1 array element using the reverse clocking sequence. During this time an electron may again be captured by the trap under phase 1.

Step 5 – Again, after some dwell time the electron releases and is captured in the nearest potential well. This time the preceding charge packet in the array, pumping 1 electron.

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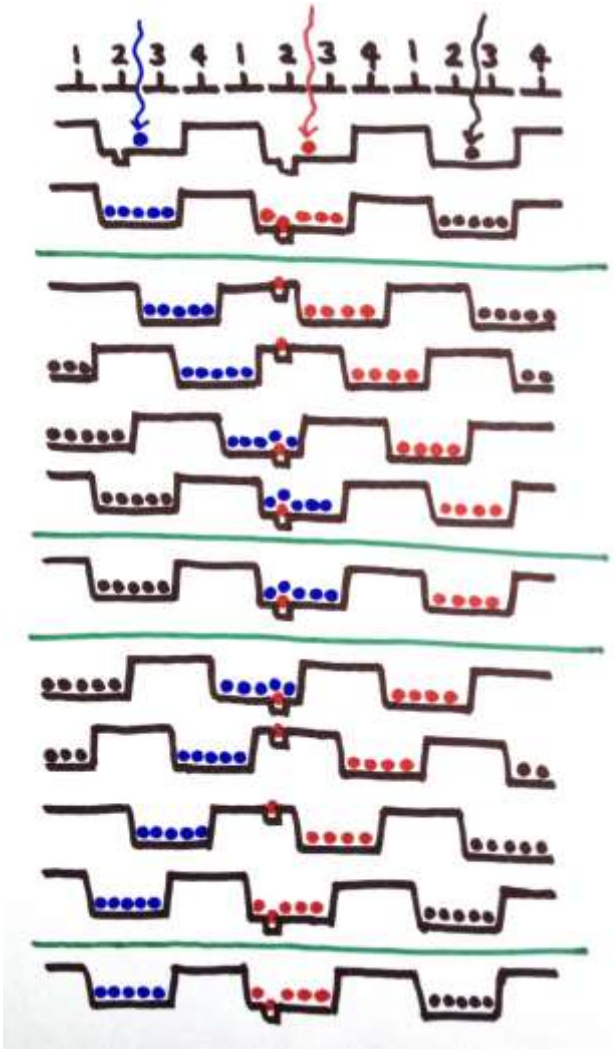
Single pumping sequence example: Trap under the collecting phase electrode 2

Not Pumped



②

Step 1 – A flat field of photo-generated charge, dark current or charge injection is stored in the potential wells in the CCD array formed by the collecting phase electrodes.

Step 2 – Charge packets are transferred forward by 1 array element using the typical clocking sequence for readout. During this time an electron remains captured by a trap under phase 2.

Step 3 – After some dwell time the electron releases and is immediately re-captured in the same potential well. In this case the proceeding charge packet.

Step 4 – Charge packets are transferred backward by 1 array element using the reverse clocking sequence. During this time an electron again remains captured by the trap under phase 2.

Step 5 – Again, after some dwell time the electron releases and is immediately re-captured in the same potential well. This time the original charge packet in the array and hence no electron is pumped.

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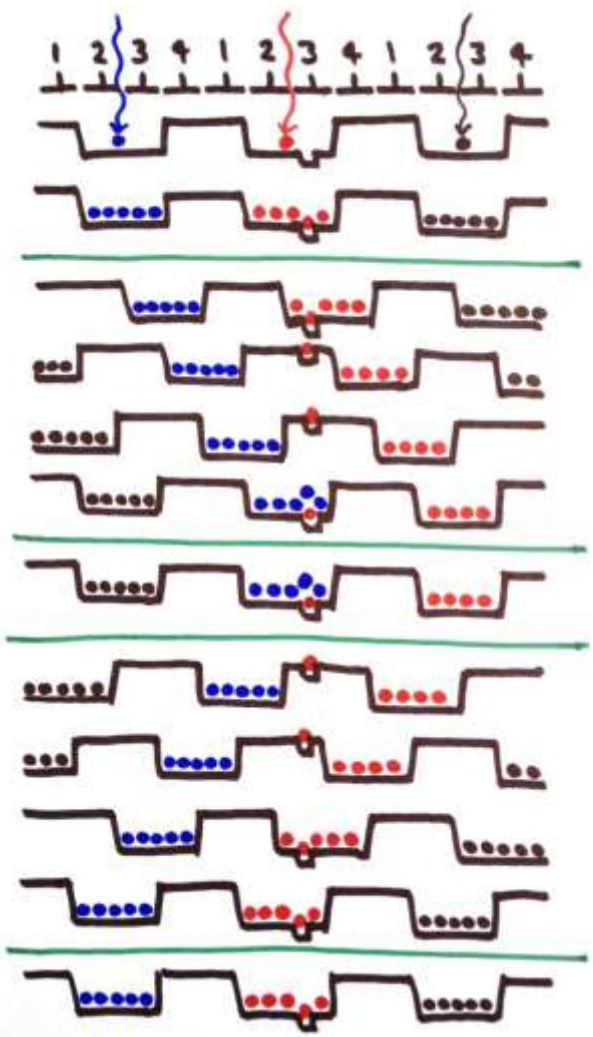
Single pumping sequence example: Trap under the collecting phase electrode 3

Not Pumped



3

Step 1 – A flat field of photo-generated charge, dark current or charge injection is stored in the potential wells in the CCD array formed by the collecting phase electrodes.

Step 2 – Charge packets are transferred forward by 1 array element using the typical clocking sequence for readout. During this time an electron remains captured by a trap under phase 3.

Step 3 – After some dwell time the electron releases and is immediately re-captured in the same potential well. In this case the proceeding charge packet.

Step 4 – Charge packets are transferred backward by 1 array element using the reverse clocking sequence. During this time an electron again remains captured by the trap under phase 3.

Step 5 – Again, after some dwell time the electron releases and is immediately re-captured in the same potential well. This time the original charge packet in the array and hence no electron is pumped.

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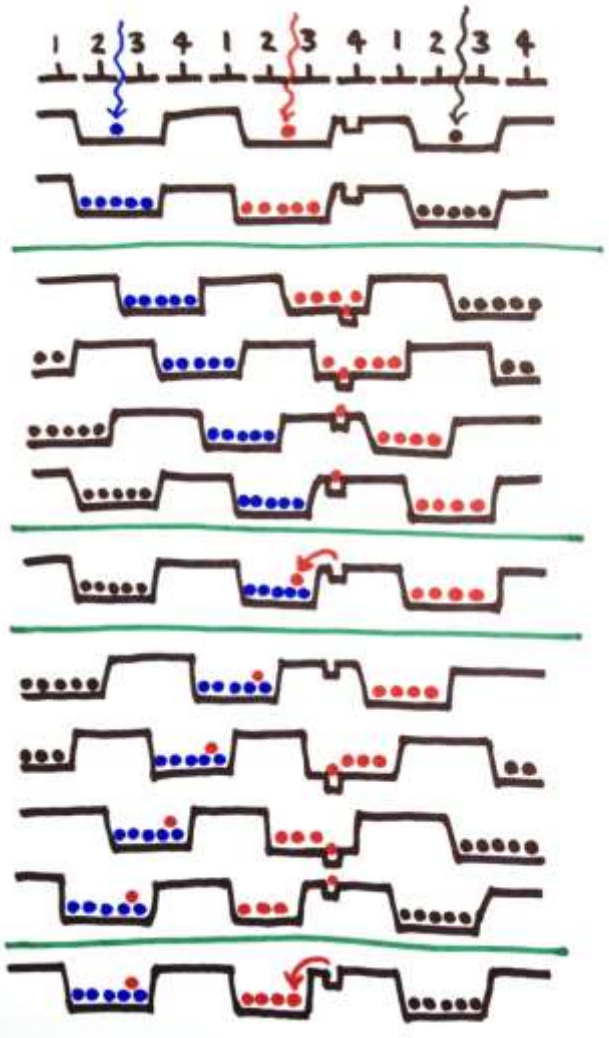
Single pumping sequence example: Trap under the barrier phase electrode 4

Pumped



4

Step 1 – A flat field of photo-generated charge, dark current or charge injection is stored in the potential wells in the CCD array formed by the collecting phase electrodes.

Step 2 – Charge packets are transferred forward by 1 array element using the typical clocking sequence for readout. During this time an electron may be captured by a trap under phase 4.

Step 3 – After some dwell time the electron releases and is captured in the nearest potential well. In this case the proceeding charge packet, pumping 1 electron.

Step 4 – Charge packets are transferred backward by 1 array element using the reverse clocking sequence. During this time an electron may again be captured by the trap under phase 4.

Step 5 – Again, after some dwell time the electron releases and is captured in the nearest potential well. This time the original charge packet.

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Trap pumping parameters

- Signal level – is the charge packet volume being transferred of sufficient size to encounter the trap during transfer?
- Transfer time – will the trap release before the complete transfer by 1 element? Leading to an inefficient pumping sequence.
- Dwell time – will the trap release before the second cycle? Leading to an inefficient pumping sequence.
- Temperature – will the trap even release close to the dwell or transfer time?

The latter three parameters can be examined to probe the species of a particular trap and will be discussed later.

Over-pumping the background

Only signal that exists in the original flat field can be pumped.

Once the number of efficient pumping cycles is equal to the signal in the flat field the graph levels off.

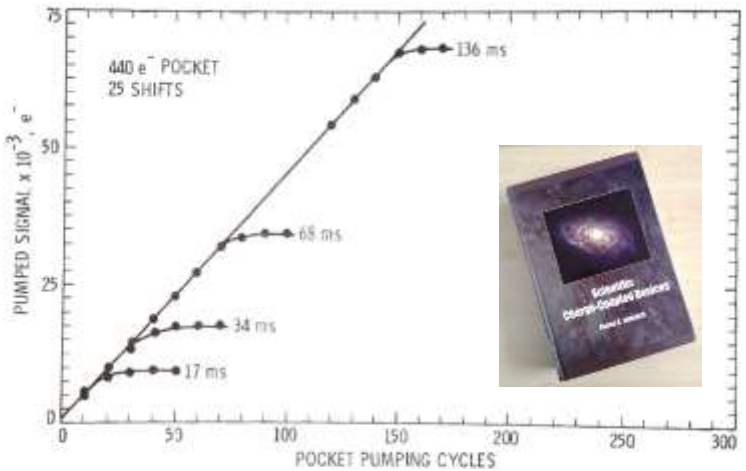
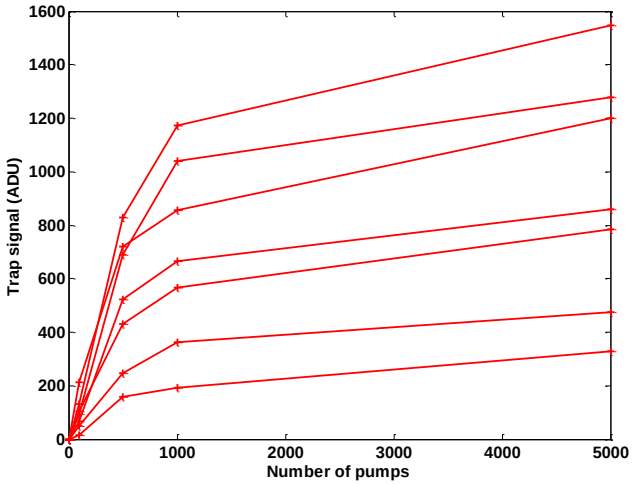
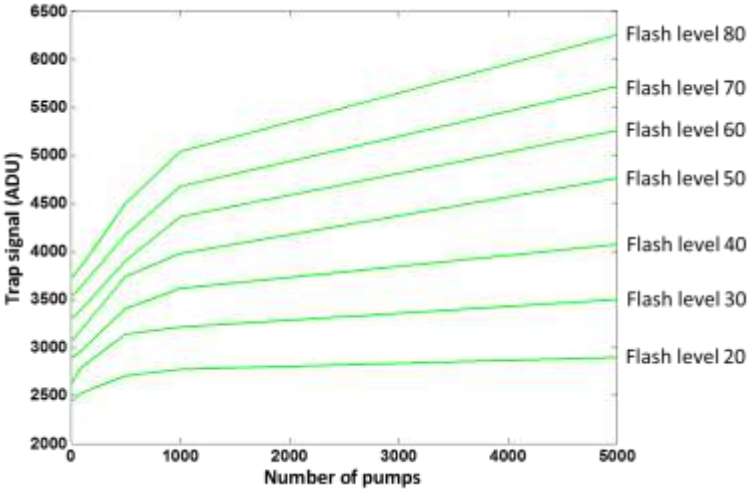


Figure 5.29(b) Charge taken from a trap as a function of pumping cycles.

CCD204 data



CCD204 data – not background subtracted



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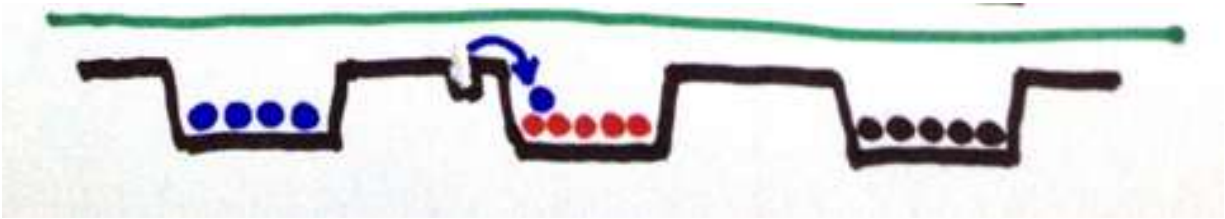
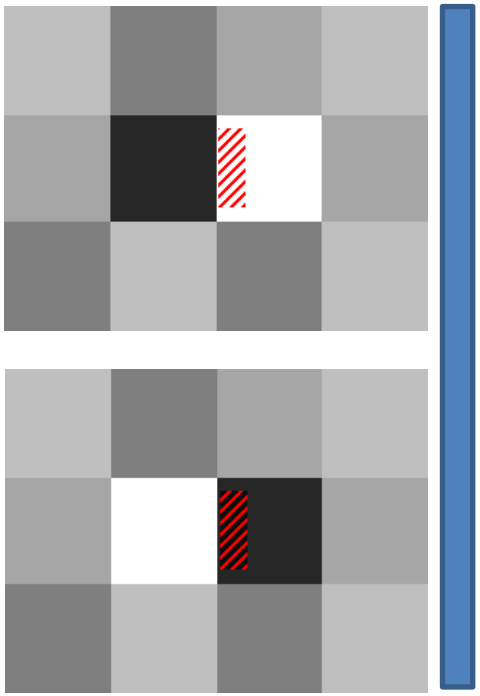
Trap locations – Sub-pixel location

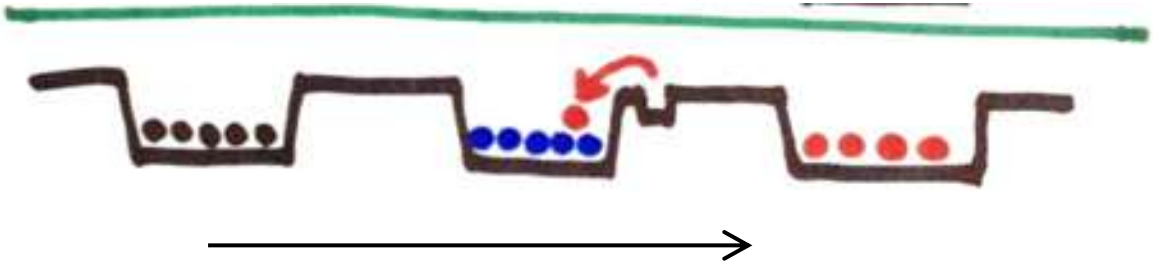
From sequence diagrams collecting phase traps are not pumped.

Phase 1 trap – trap is in bright pixel





Phase 4 trap – trap is in dark pixel



Readout direction

Trap pumping efficiency vs. temp

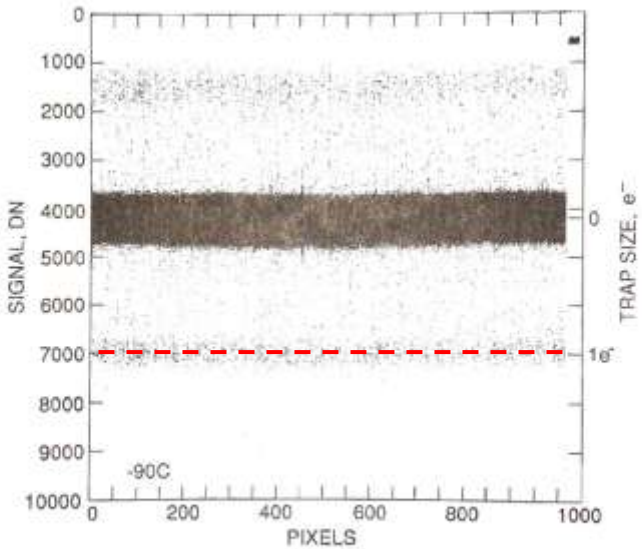


Figure 5.48(a) Pocket pumping response showing 1-e⁻ bulk state traps characterized at an operating temperature of −90°C.

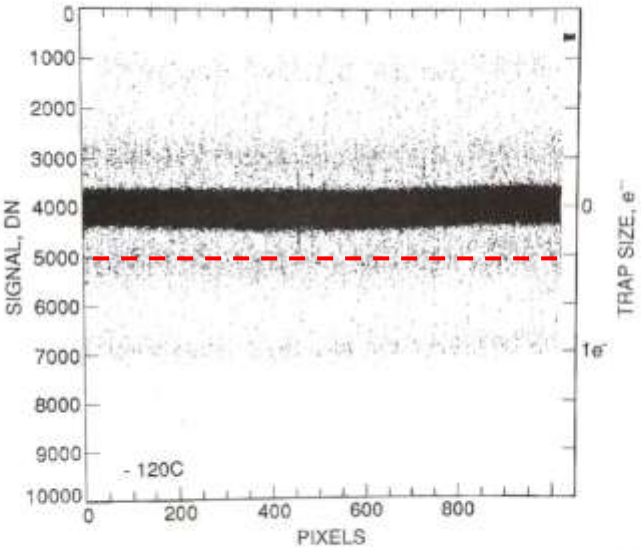


Figure 5.48(b) Pocket-pumping response at −120°C showing two different types of bulk traps.

Changing the device temperature will change the emission time constants of the traps. Are some of the traps at 7,000 ADU at -90°C just being less efficiently pumped when reducing the temperature from to -120°C?

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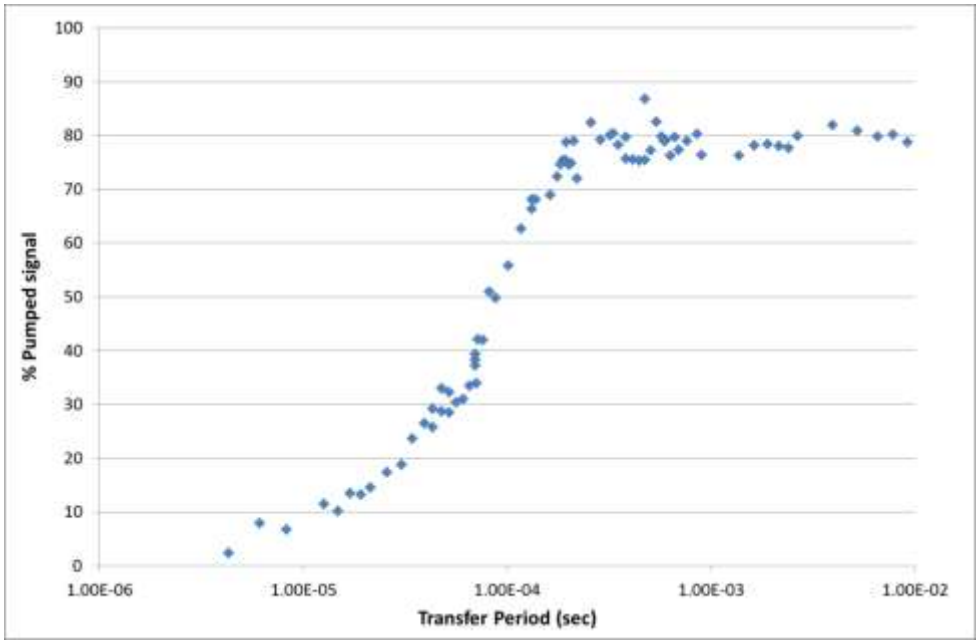
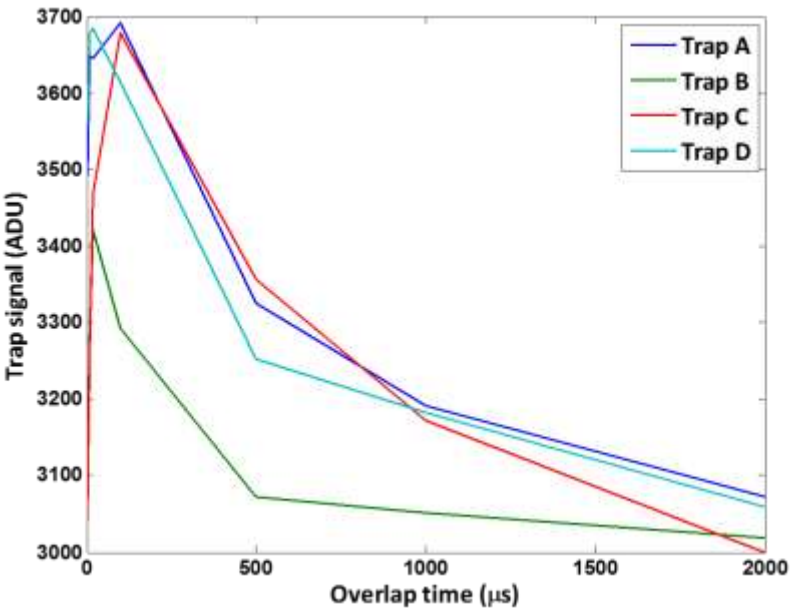
Trap pumping efficiency vs. emission time

Looking at the pumping efficiency of a trap when changing the transfer time between rows.

The trap species can be inferred from the knee of the curve, the device temperature and the known electron emission time constants.





James Tutt

Similarly 4 traps are compared in the same image at different parallel overlap times. Traps A, C and D are of the same species, whereas B has a shorter emission time constant.

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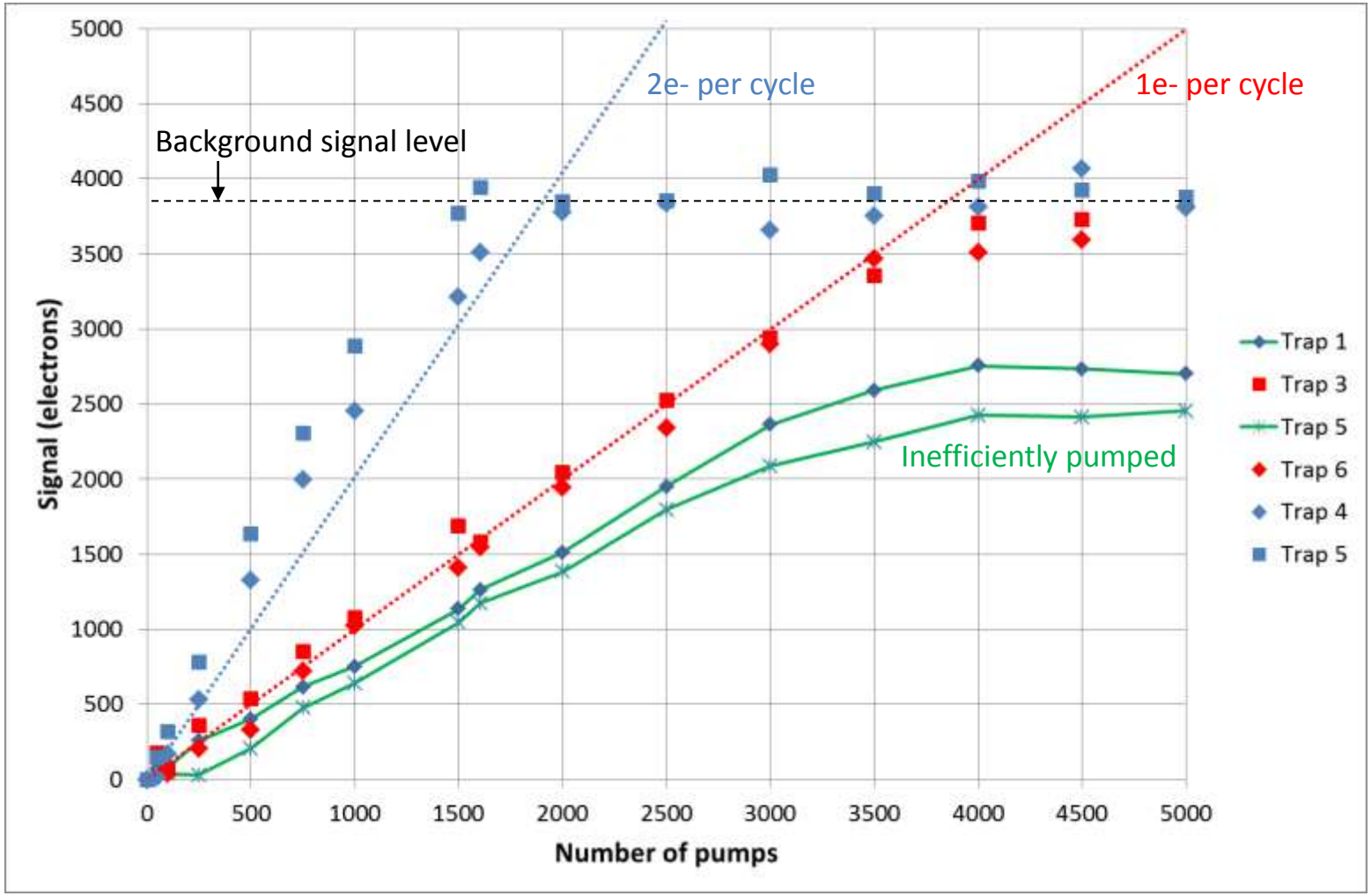
Pumped trap examples



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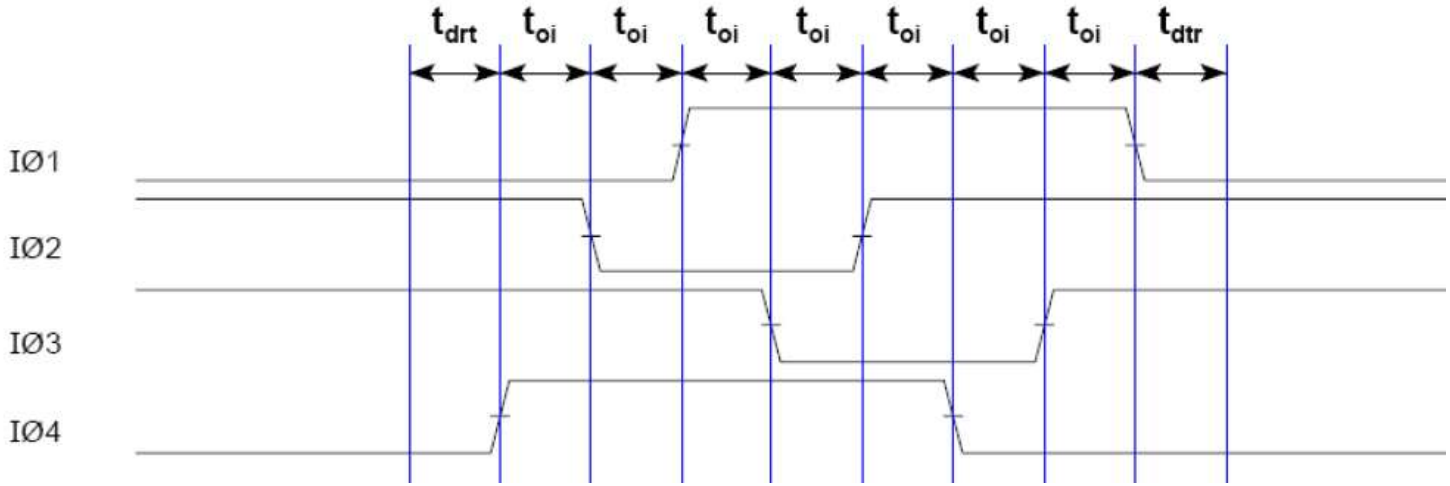
Identification of optimal transfer times

A realistic pumping scheme

- The trap species with a release time constant similar to the line transfer time (and the ones that will most effect the CTE, due to deferred charge) will be more efficiently pumped and show with greater contrast in the trap pumped image
- For optimising CTE it is necessary to consider all parameters including those which may be fixed such as device temperature or line read time (dwell time)
- Within these constraints, a pumping scheme needs to be devised as close to the operational mode of the CCD
- In the case of Euclid the key parameter with freedom is the parallel clocking overlap time that governs the line transfer time, referred to as t_{oi} in e2v literature

Parallel transfer timing – what is t_{oi}?



t_{oi} for OU n- and p-channel studies = 14.4 µs

Symbol	Description	Min	Typical	Max	Unit
T_i	Line transfer time (5)	90	90	100 (6)	µs
t_{oi}	Image clock pulse edge overlap	9	10	11	µs
t_{ri}	Image clock and transfer gate pulse rise time	0.5	1	0.5 t_{oi}	µs
t_{fi}	Imager clock pulse fall time	0.5	1	0.5 t_{oi}	µs
t_{tgf}	Transfer gate pulse fall time	5	6	t_{dtr} -2	µs
t_{drt}	Delay time, RØ stop to IØ rising	2	t_{oi}	11	µs
t_{dtr}	Delay time, IØ falling to RØ start	8	t_{oi}	11	µs
T_{rr}	Register clock period		5 (6)		µs

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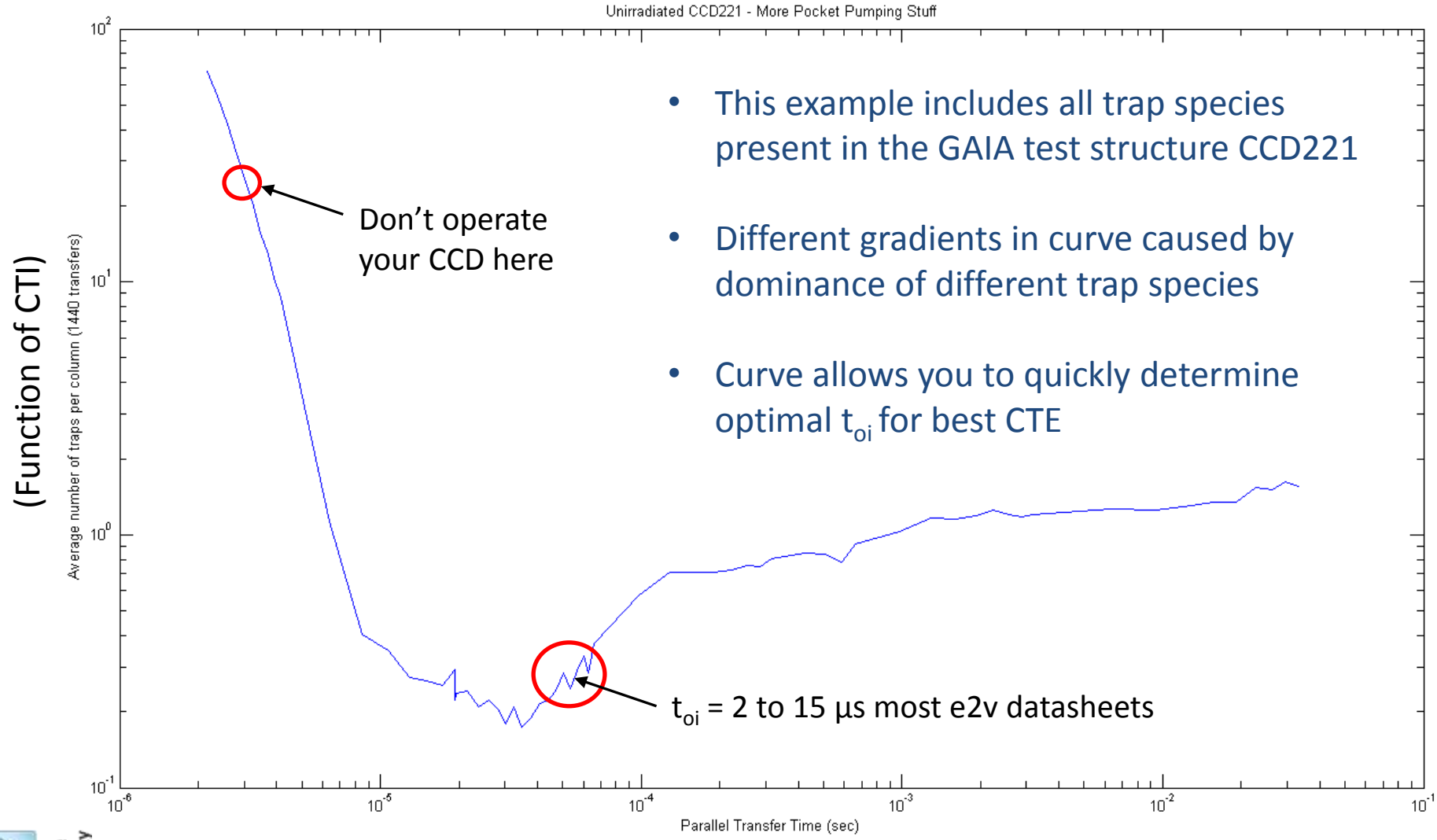
intrinsic traps vs. line transfer time



- This example includes all trap species present in the GAIA test structure CCD221
- Different gradients in curve caused by dominance of different trap species
- Curve allows you to quickly determine optimal t_{oi} for best CTE

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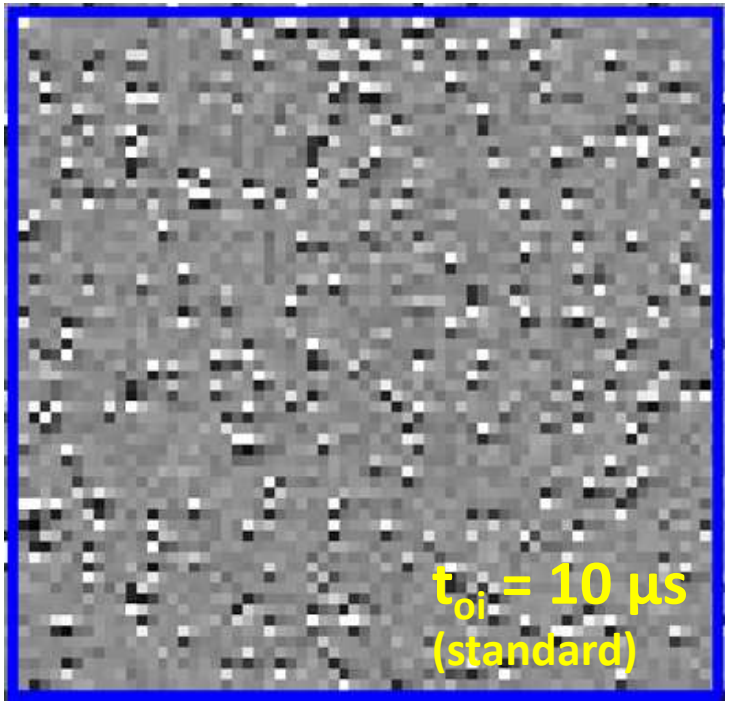
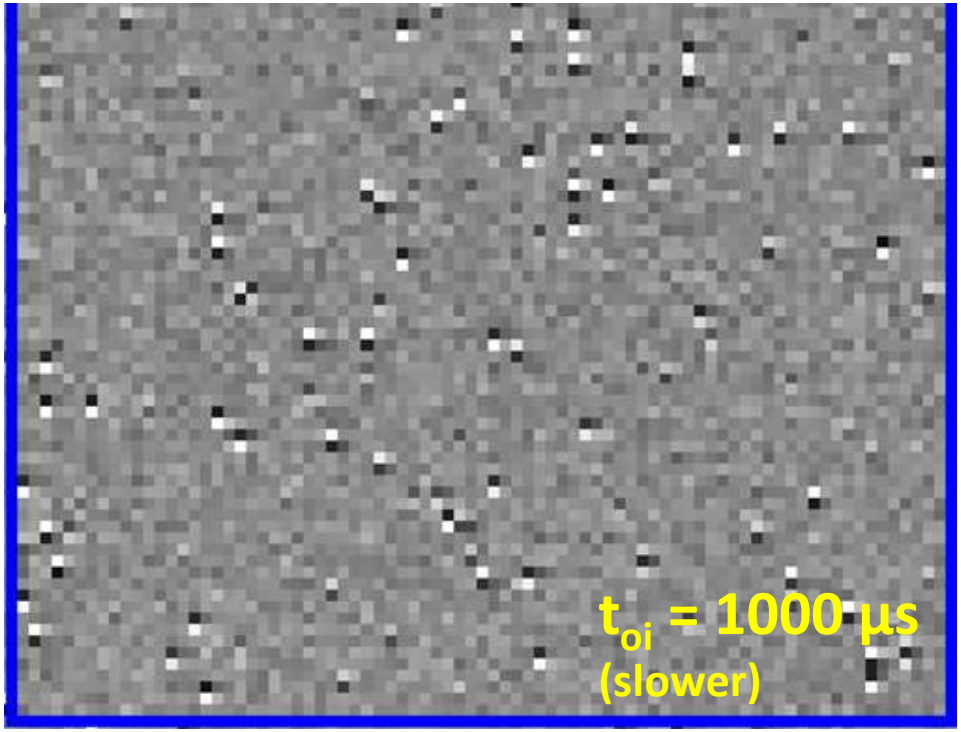
Trap pumped examples of an irradiated CCD204

- Trap pumped images with standard CCD line transfer time and 100 times slower.
- Dipoles observed indicate the trap sites and their contrast show their trapping efficiency.
- The lower the number of dipoles observed in such an image, the lower the CTI.
- Improvement shown right may improve CTI by factor ~2 at a cost of an extra 14 seconds to the readout of the entire frame.





T = 153K

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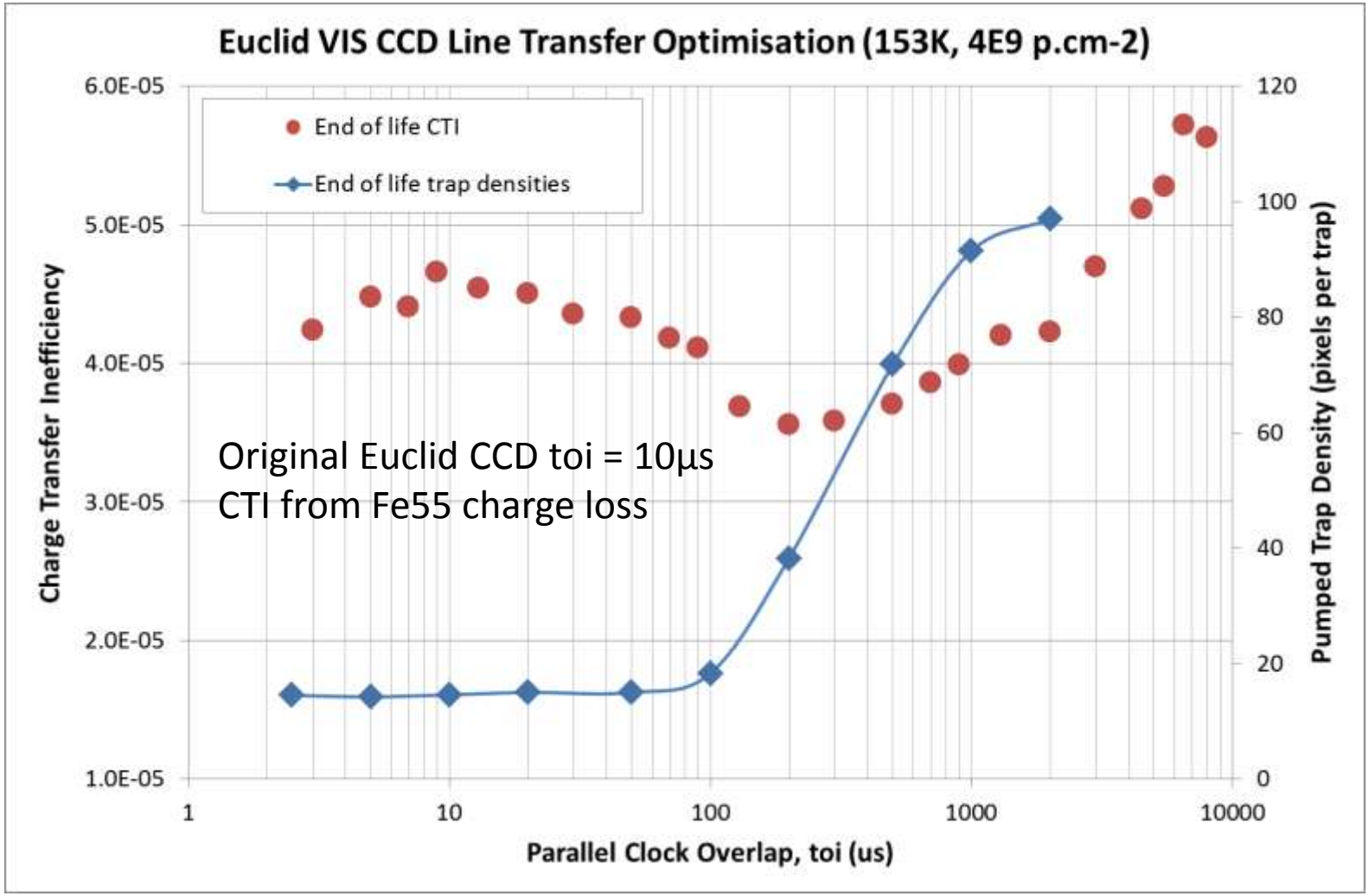
X-ray CTI measurement vs. parallel clock overlap



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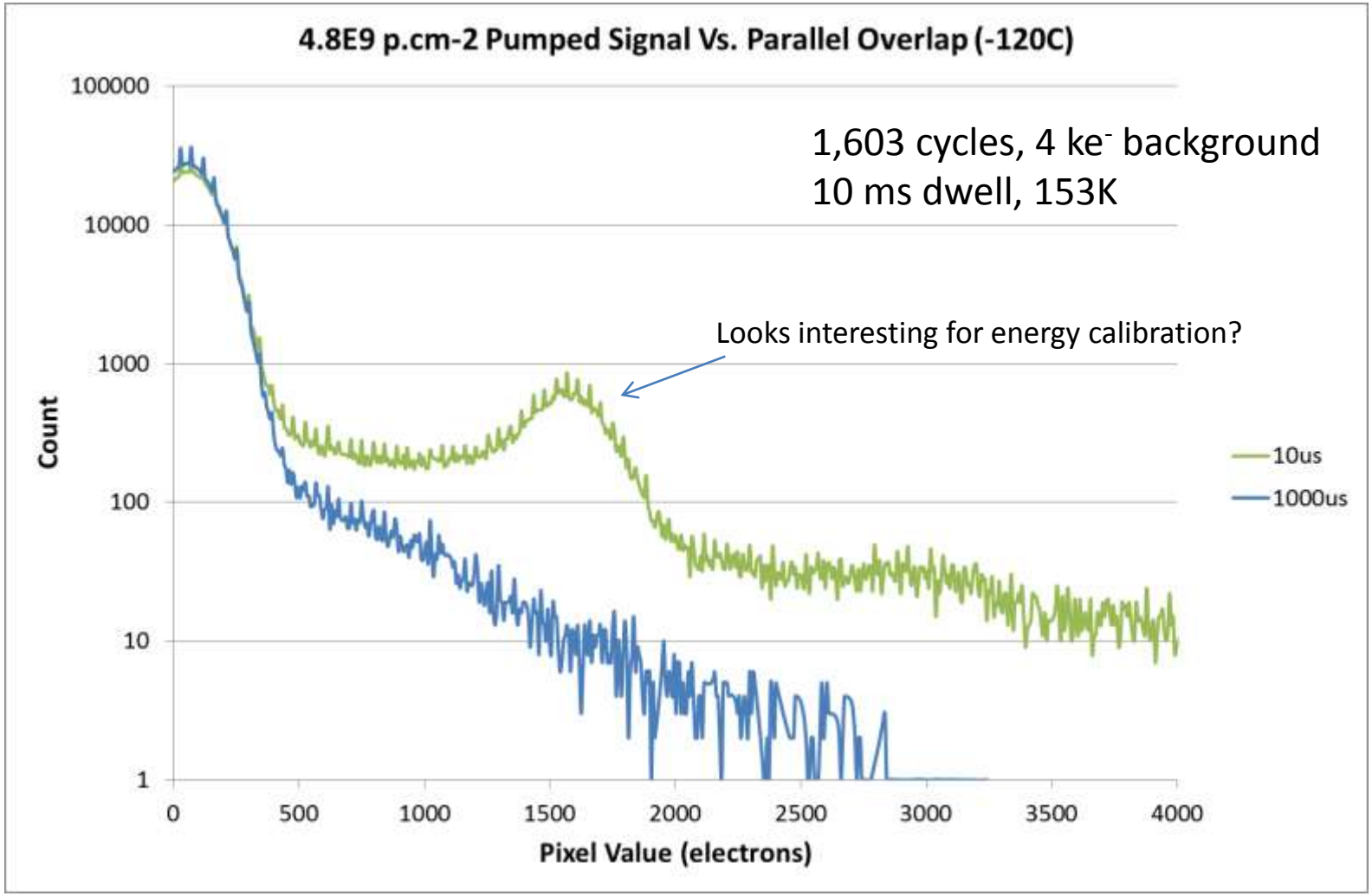
Euclid CCD273 trap efficiencies vs. clock overlap



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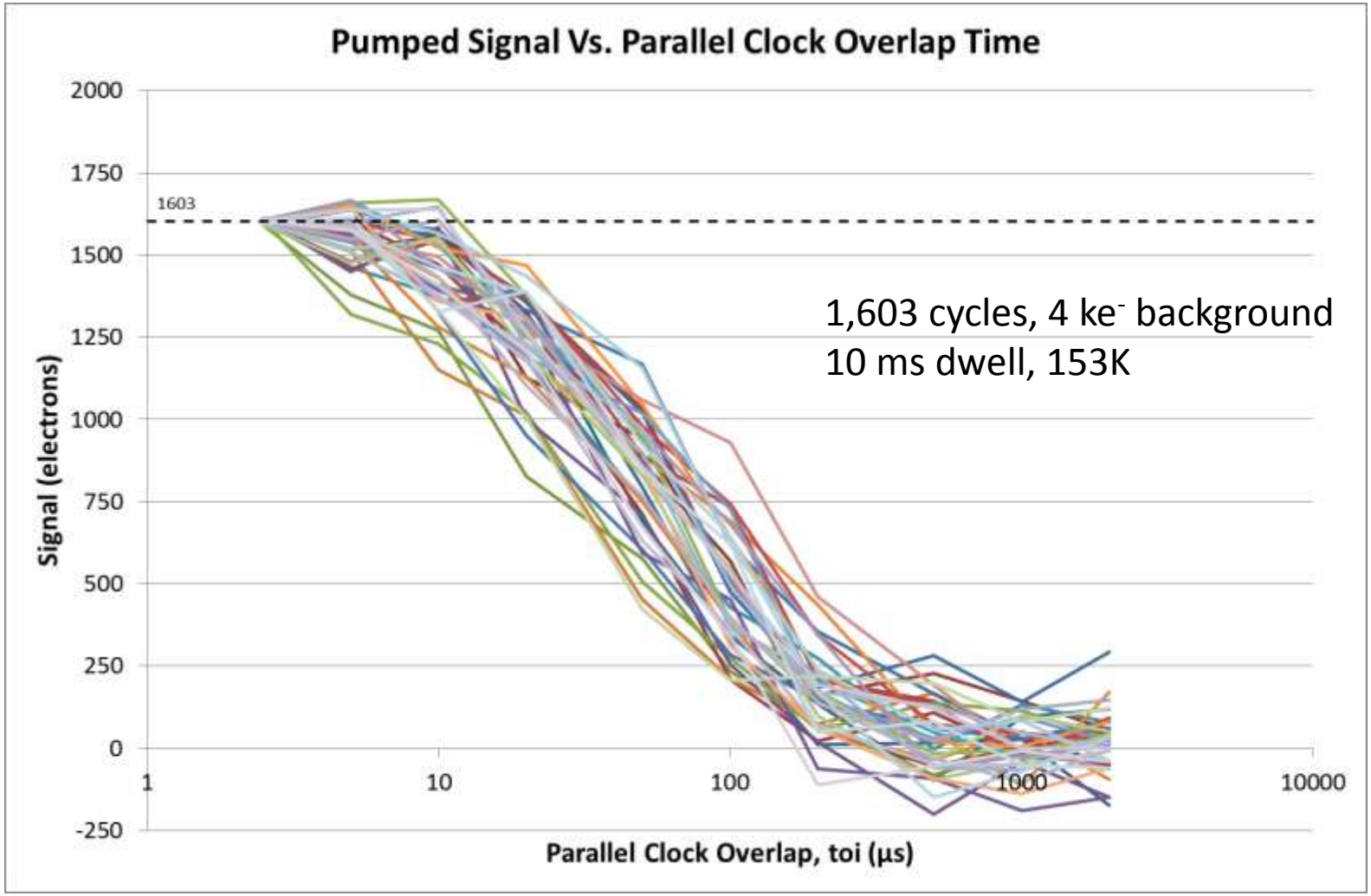
40 example traps, 100% efficiency at 2.5 µs



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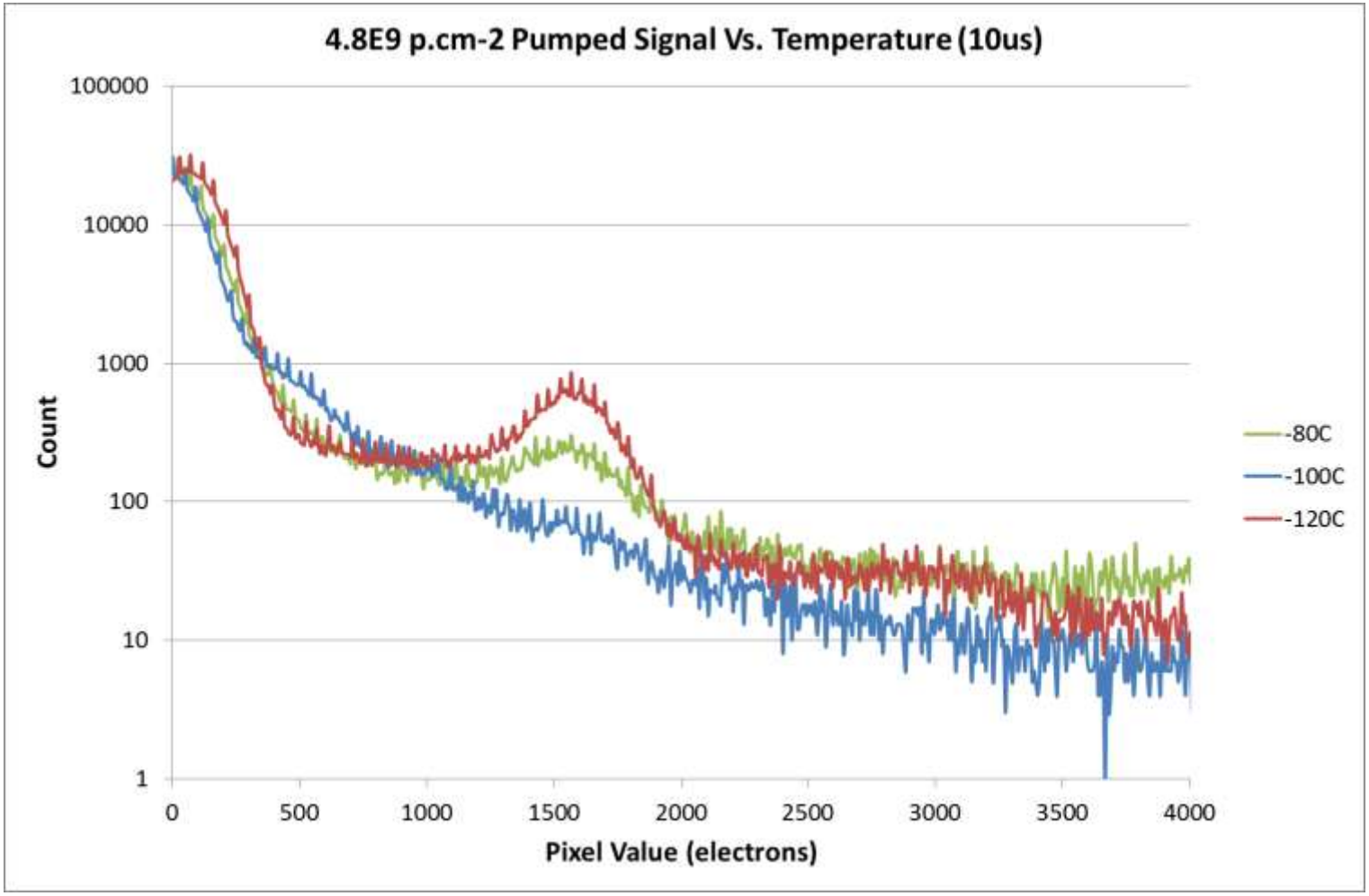
Euclid CCD273 trap efficiencies vs. temperature



(Nick J. Mostek, et. al, "Charge trap identification for proton-irradiated p+ channel CCDs," SPIE Vol. **7742**, 774216, July 2010)

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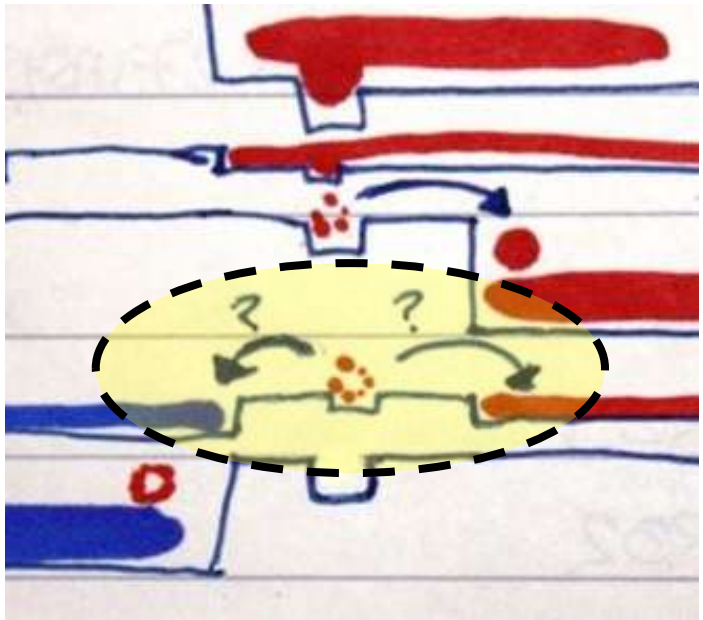
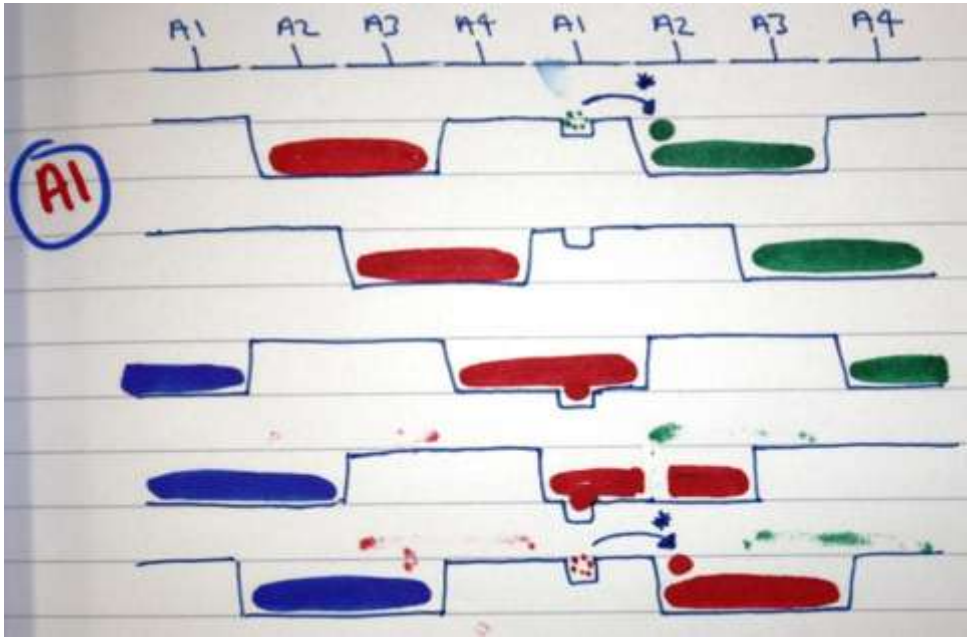
Further Improvement – Coincident Clocking

3-2-3-2-3-2-3-2 scheme allows conditions where escaping charge can go either way



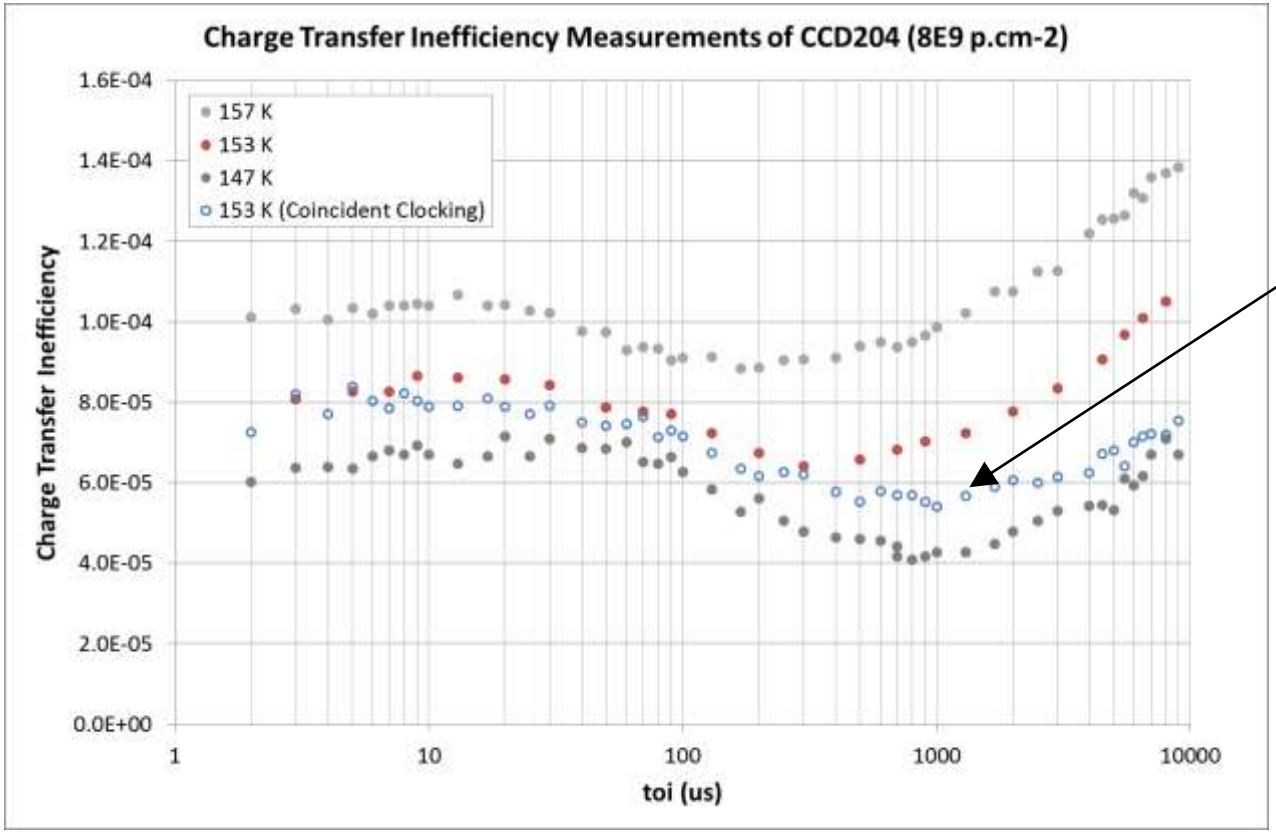
Sometimes only 1 barrier phase!

2-2-2-2-2 increase probability of charge re-joining original packet by 25%



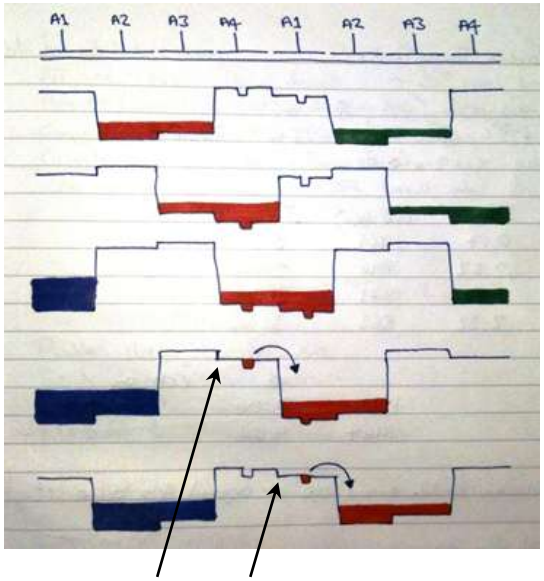
Always 2 barrier phases

Coincident clocking improvement



Forward biasing the row isolation phases gives a further 25% improvement by supressing the transfer traps at slower line rates

- Parallel transfer sequence



Additional potential gradient forces escaping electrons forward

Trough shifts to right at lower T as trap is freezed out

Fixed gradients only help 50% of the time!

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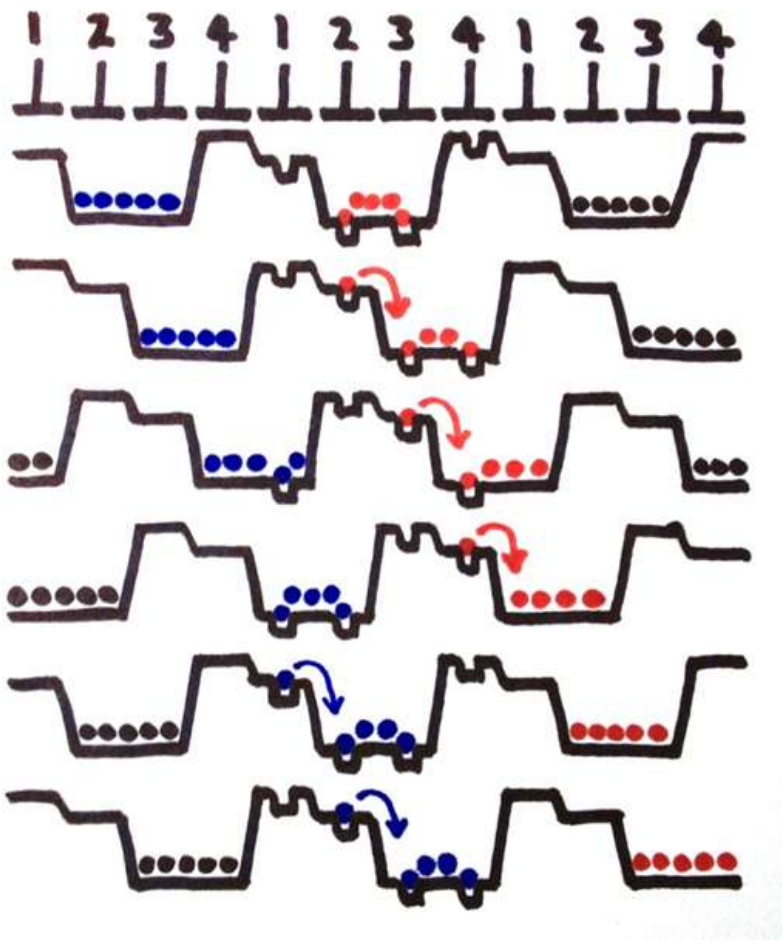
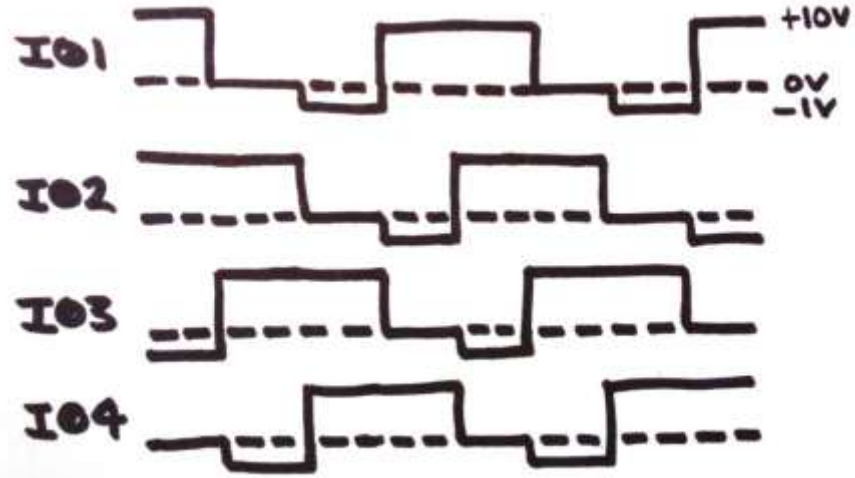
Tri-level Parallel clocking sequence





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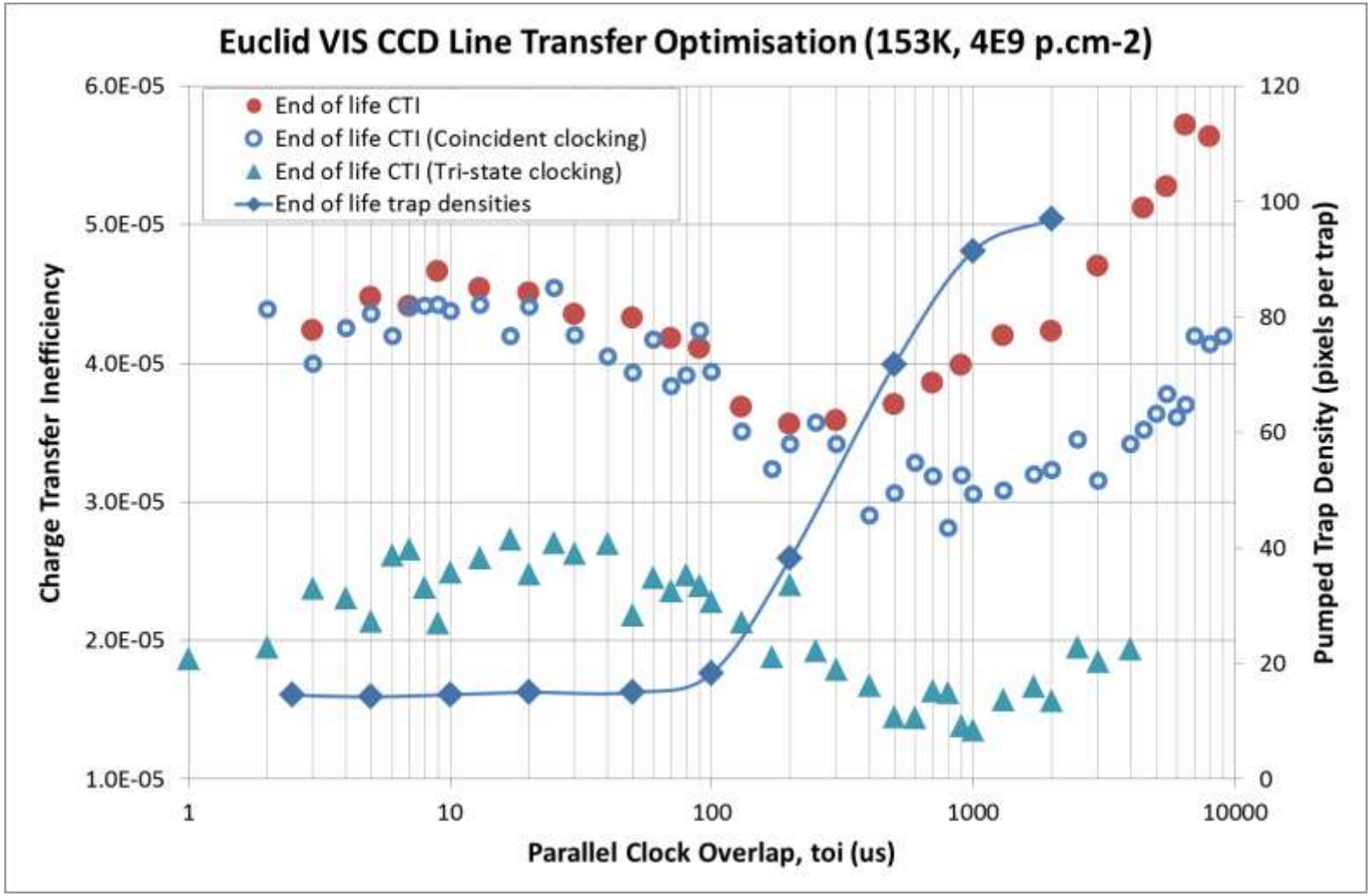
Animation for all trap locations

A third potential level defining the row structures applies a forward gradient across the barrier phase electrodes, inviting any trapped and released electrons back into their original charge packets (rather than deferring to the subsequent packet)

1st Results with Tri-level clocking



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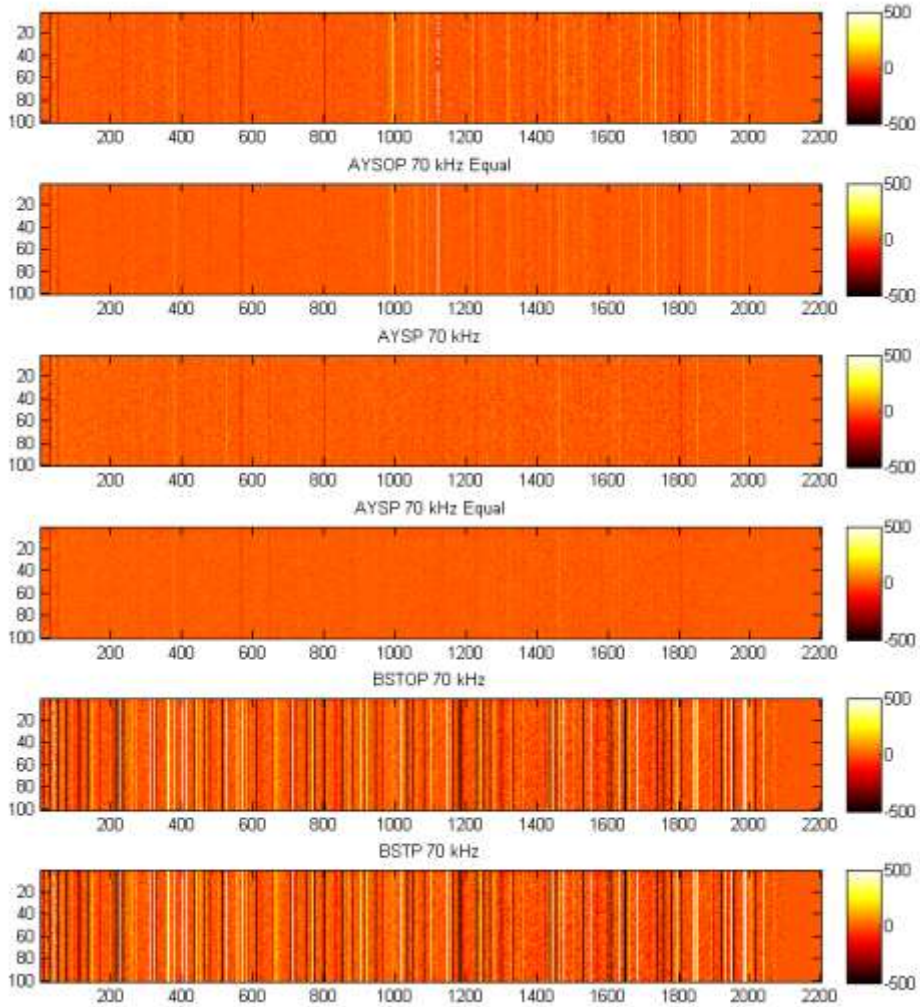
Euclid Optimal Serial Clocking Scheme

Pumped as a 70 kHz readout



	Register$_{FWC}$	Noise	CTE
Asymmetric video mode with 100 ns overlap			
Equal video mode with 100 ns overlap			
Asymmetric video mode 50% overlap			
Equal video mode 50% overlap			
Burst mode with 100 ns overlap			
Burst mode 50% overlap			

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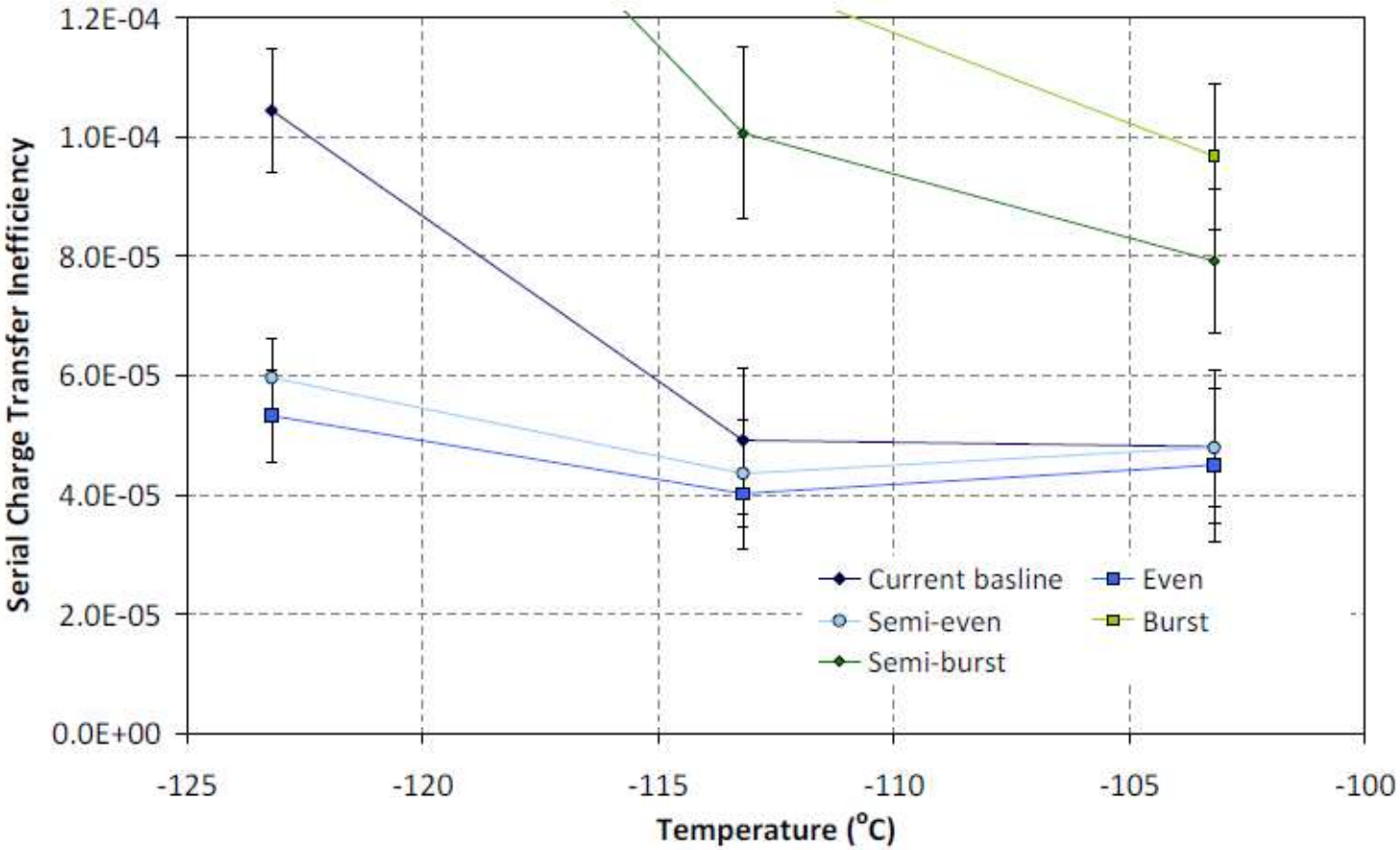
Euclid Serial CTI Measurements

- Serial CTI measured at -113 °C and 10 °C either side using the different serial clocking schemes



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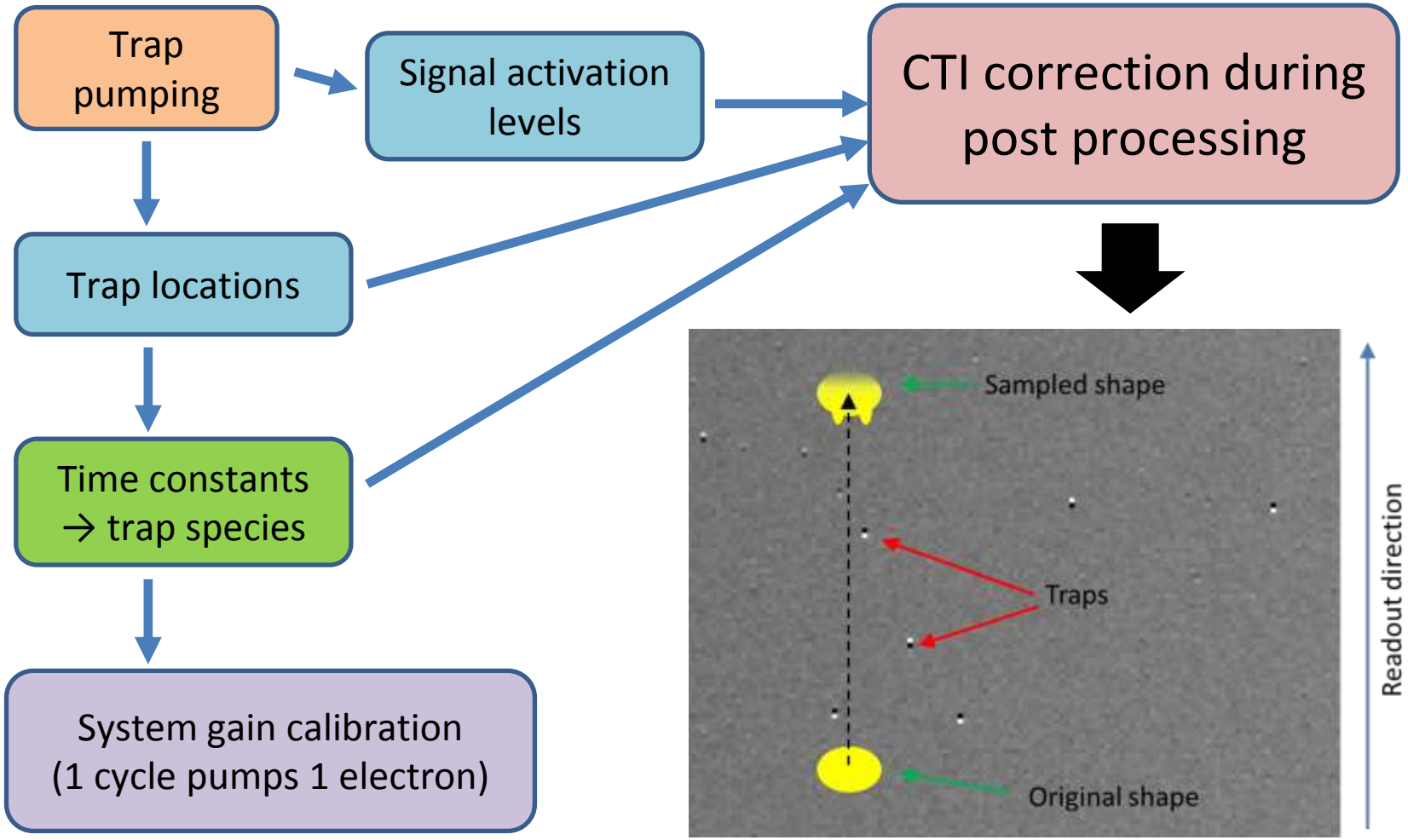
Trap pumping for on-orbit calibration

On-orbit trap pumping for calibration and ground correction algorithms



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The most useful pumping scheme

As we have seen, there are a number of parameters that can be explored to probe the efficiency trap pumping, leading to the identification of trap species.

However for on-orbit calibration we will assume that **changing temperature is impractical** and we would seek to minimise the amount of calibration data required in terms of spacecraft resources.

Intrinsic trap species can be fully characterised prior to launch and only an increase in radiation induced traps species are expected, so the pumping transfer rate should be set at the post-irradiation optimised line transfer rate discussed earlier.

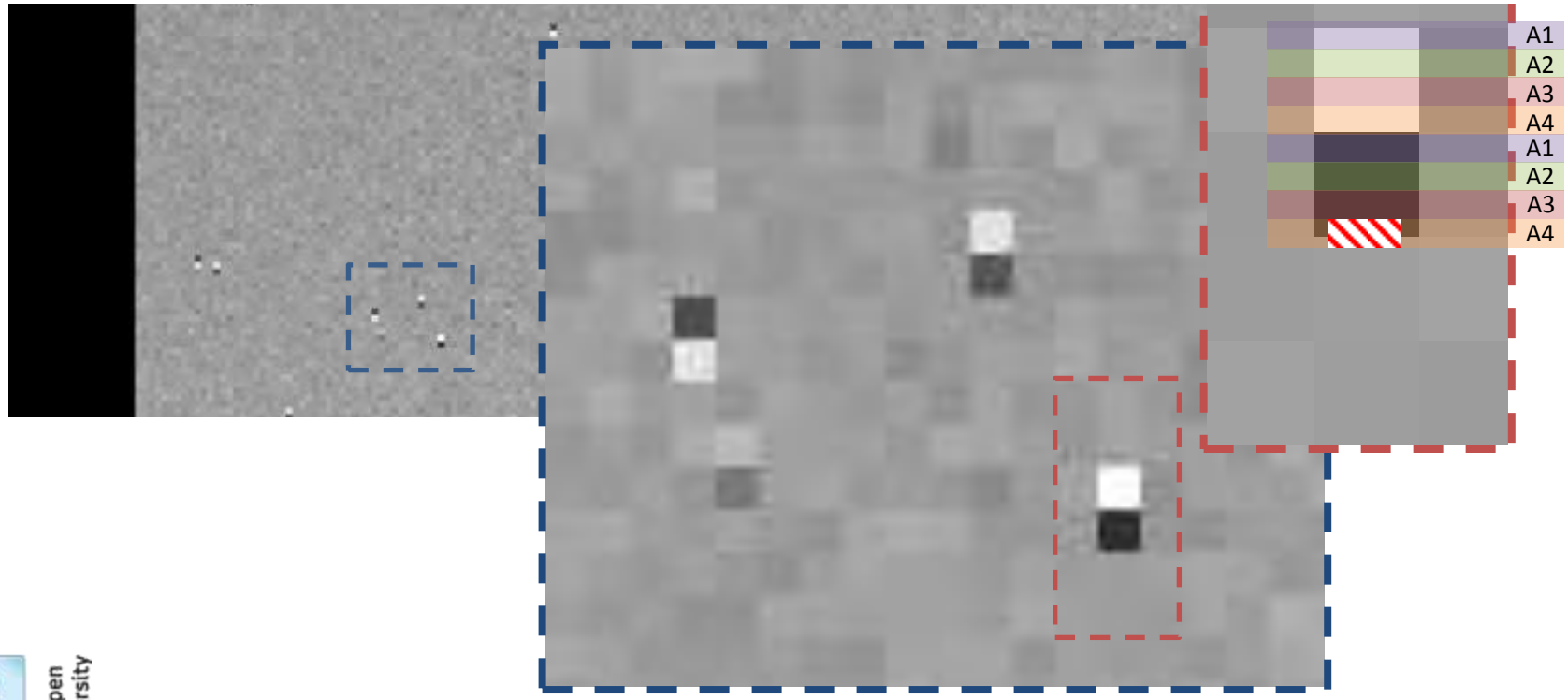
Also the dwell time between transfers should be equal to the line readout.

The remaining key parameter is the **signal activation level**. That is the level of signal during the mission that the greatest degree of accuracy will be required.

Location of traps

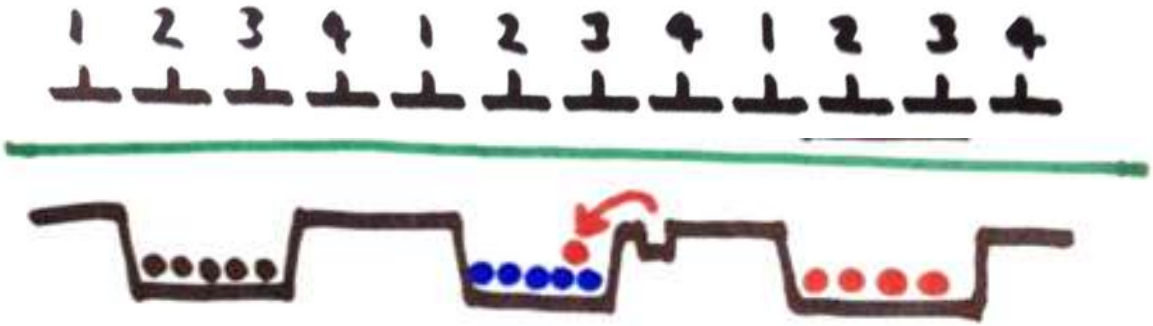
The simplest information to extract from a pumped image is the coordinates of all the trap sites by event thresholding. These will highlight traps that effect CTE under the barrier phases A1 and A4 in a typical 4-phase device.

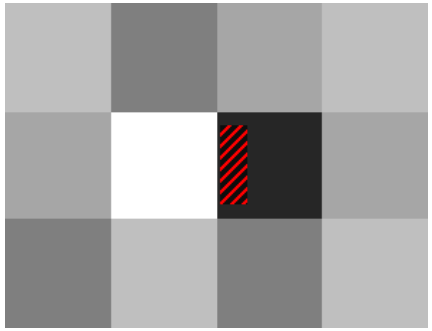
Collecting phase traps can be found in a similar way by modifying the sequence by two steps, so that charge is integrated under phases A1 and A4.



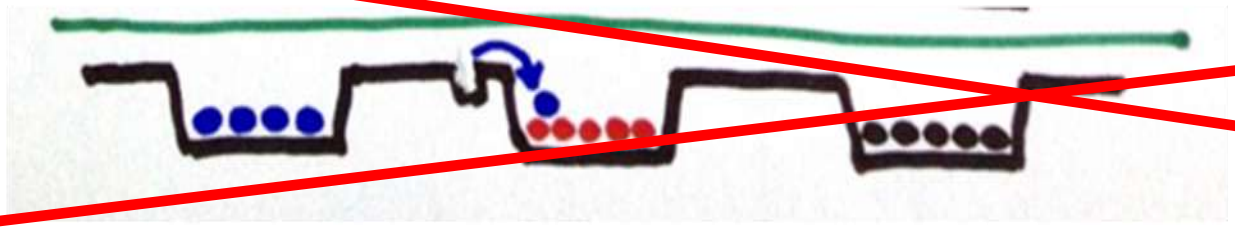
Which Trap dipoles are responsible for CTI?

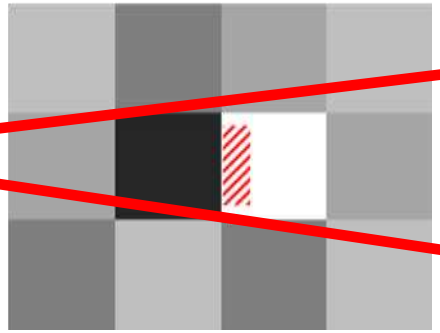
Traps in phase 1 will release with high probability into original charge packet during the long register read time so don't need worrying about.
Traps in phase 4 could cause CTI if $\tau_e > t_{oi.}$ These manifest as dark first dipoles.





Phase 1 trap – trap is in bright pixel





Readout direction

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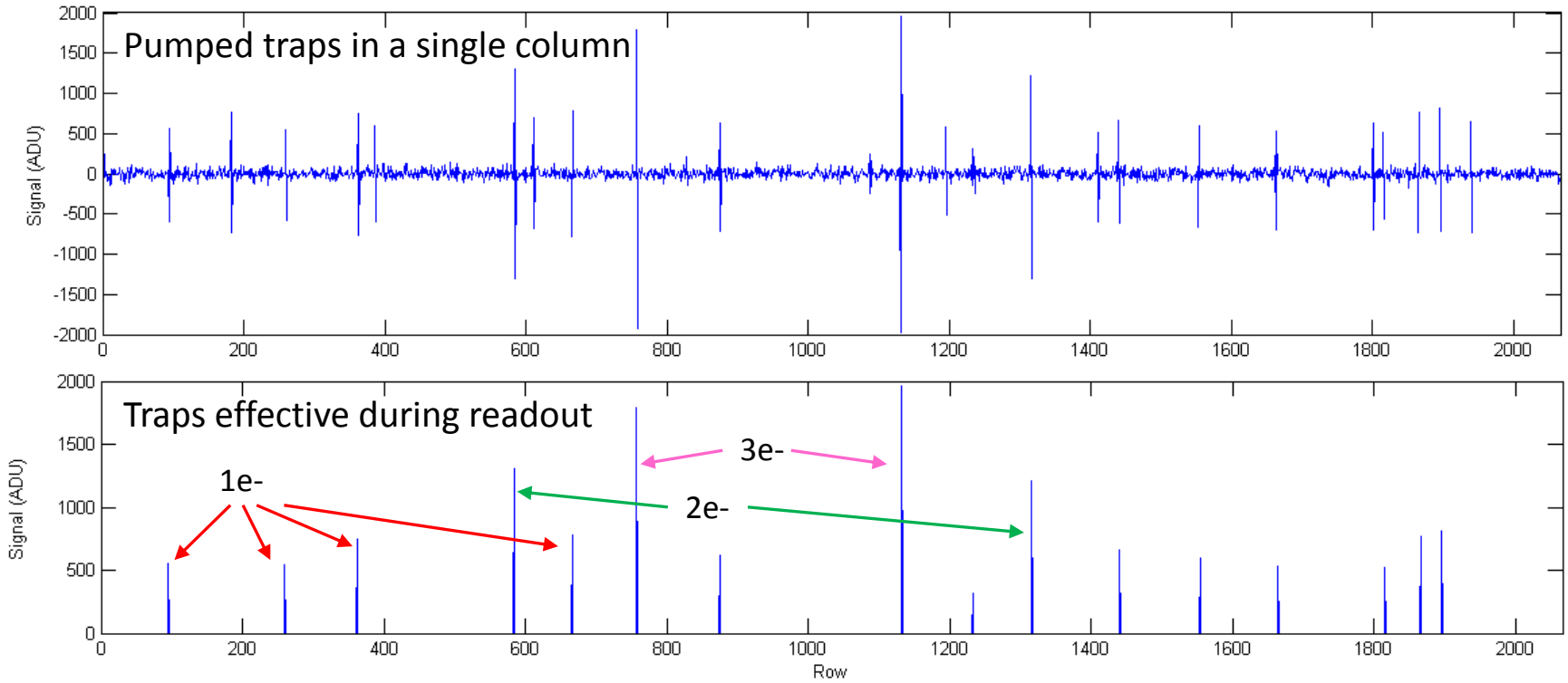
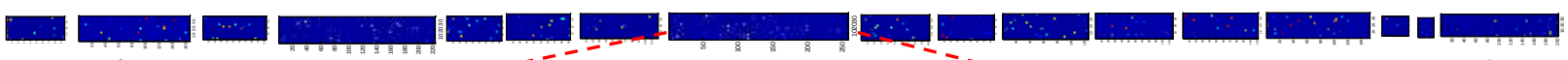
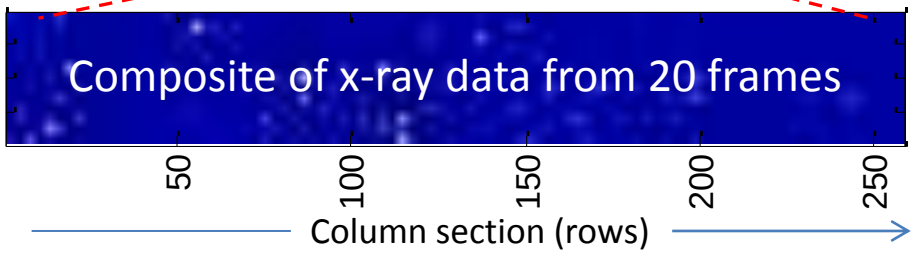
Pumped trap CTI correction algorithm





Add 1e- to leading signal, take 1e- from next



Add 22e- to leading signal, take 22e- from next

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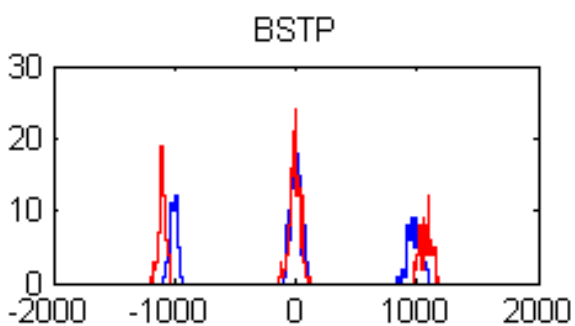
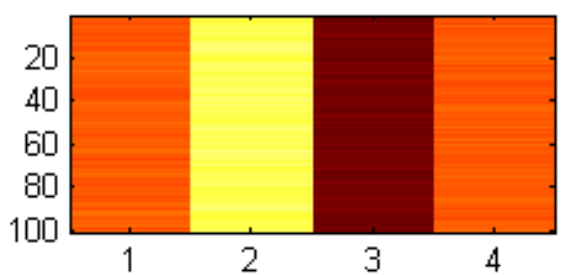
Gain calibration

A number intrinsic traps are present in any CCD. Pre-flight these can be calibrated in terms of pumping efficiency under the strict operating conditions for the mission (transfer time and temperature) to a known signal such as Fe55.

This then allows the pumped signal for the same number of cycles and similar background level to be converted into electrons.

Only at the point that additional radiation induced traps interfere with a known trap does its gain calibration become unreliable. However as there are many to use the probability of losing gain calibration for each device remains low.





Histogram of a multiple serial register trap samples pumped at 70 kHz and 200 kHz

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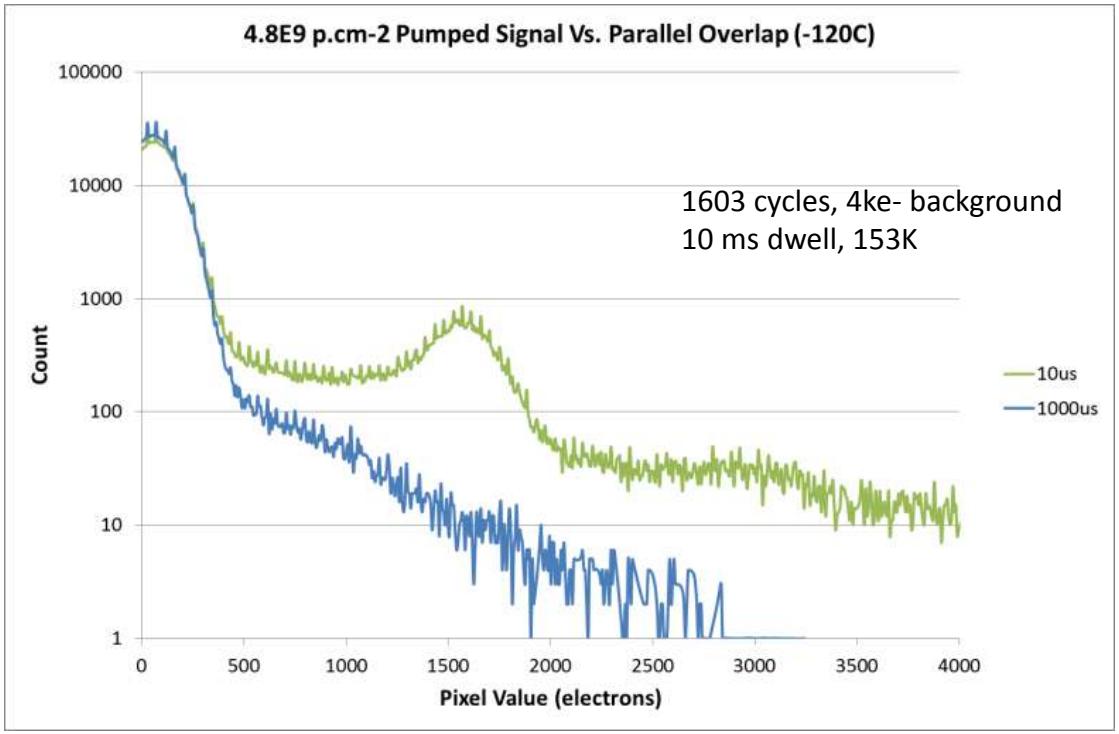
System gain calibration 1

Characterise the intrinsic traps pre-launch using the on-orbit pumping scheme, so that the pumping efficiencies are known for each trap.



During the mission these can be referred to determine the energy scale of each CCD using the peak, similarly to an X-ray calibration.

Intrinsic traps in 2×CCD273s were characterised in late August 2012 prior to proton irradiations to End Of Life (EOL), EOL/2, and EOL/4 expected fluences.

Changes to these traps are currently being investigated to estimate how long this technique could be employed on-orbit.

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Conclusions

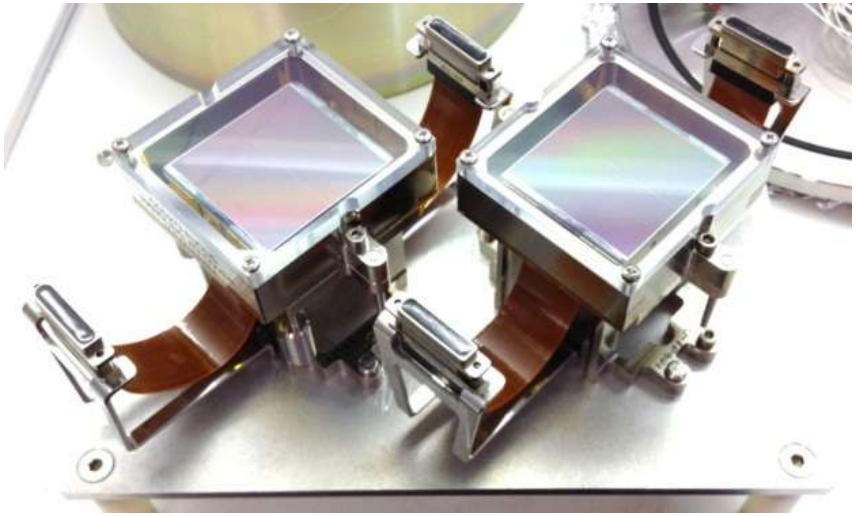
- Pocket/trap pumping can be used to quickly explore/evaluate clocking schemes
- Serial register can be pumped and optimised similarly
- Pumping efficiency is related to the temperature and emission time constant of the trap species
- Other parameters can be explored to fully characterise particular trap species
- Easy to implement as a daily calibration routine in spacecraft such as Euclid
- Wealth of information obtained for ground-based correction
- **Would provide a day-by-day measure of the radiation damage experienced by 36 CCDs at L2 – interest from solar physicists?**

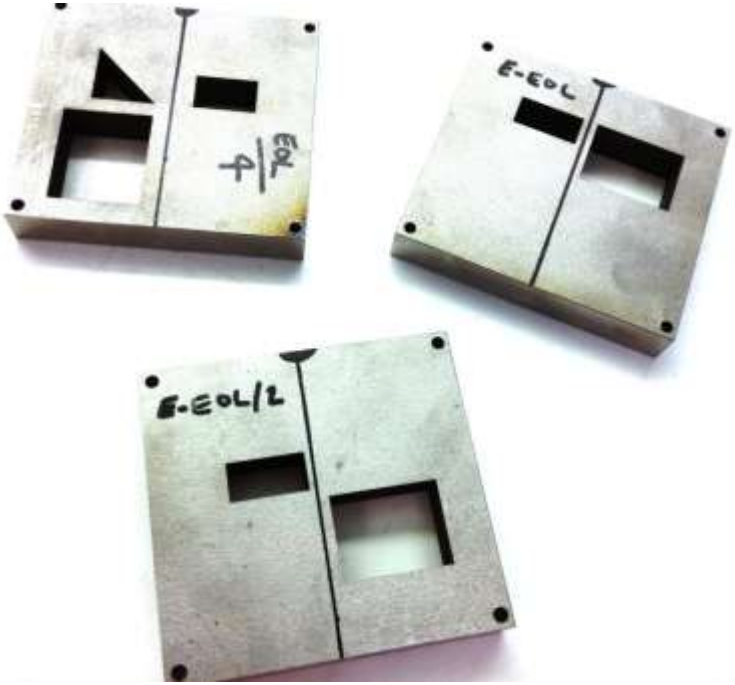
On-going and Future Work

September 2012 Proton Irradiation

Two additional CCD273s were irradiated to allow further investigation of:

- Parallel CTE improvement (no serial damage to consider)
- Longevity of an on-orbit energy calibration strategy (trap density vs. fluence)
- Potential neutron damage at KVI
- Pumped traps vs. CTI
- Optical PSF





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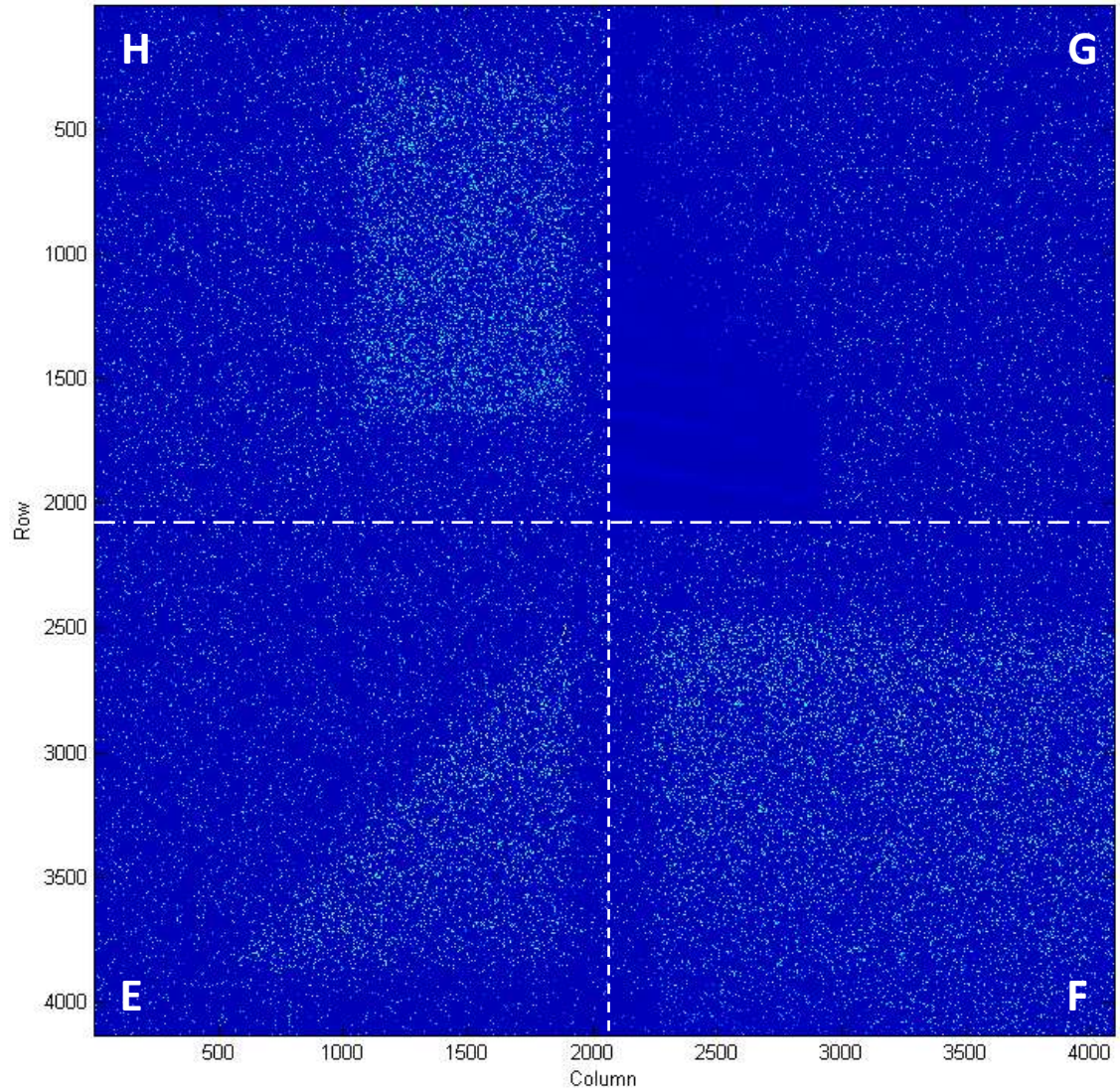
Device 11263-05-02 (Euclid ¼ EOL)

Three regions of device irradiated to 1.2E9 p.cm^2 (10 MeV equivalent)



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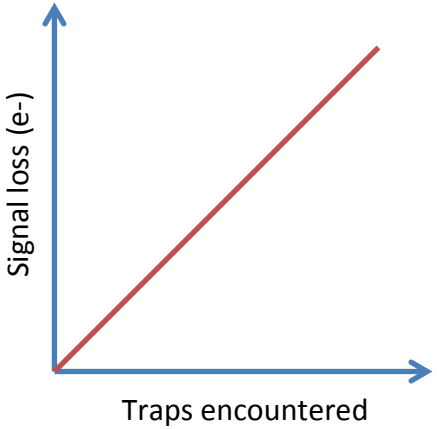
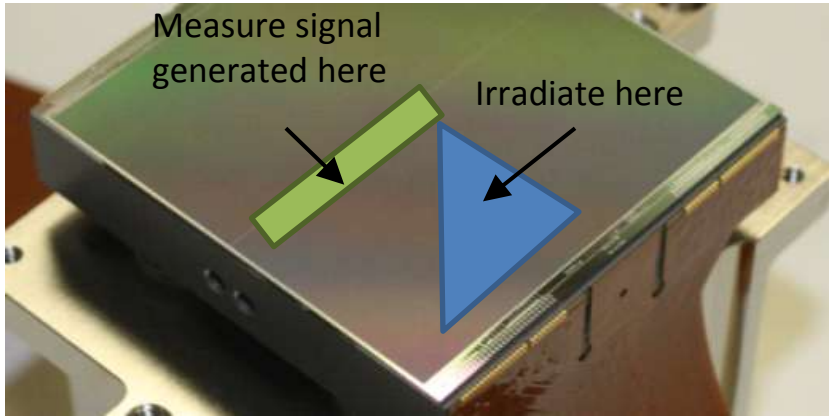
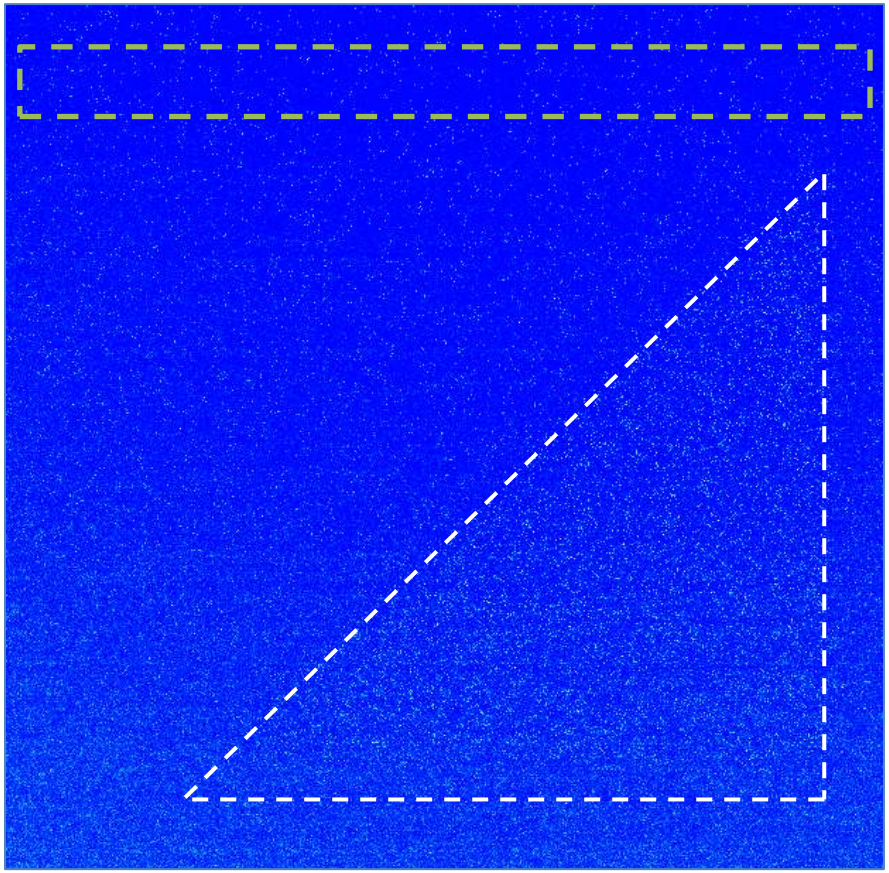
What proof traps cause CTI?







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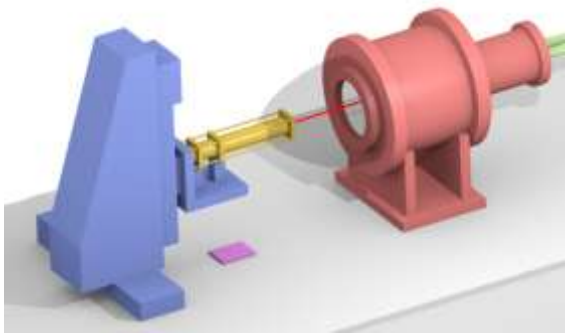
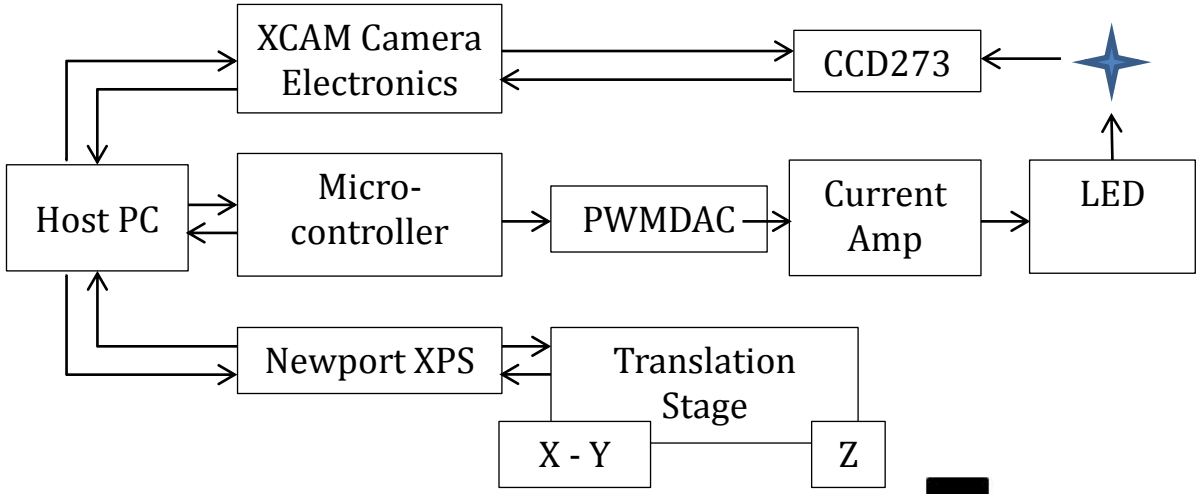
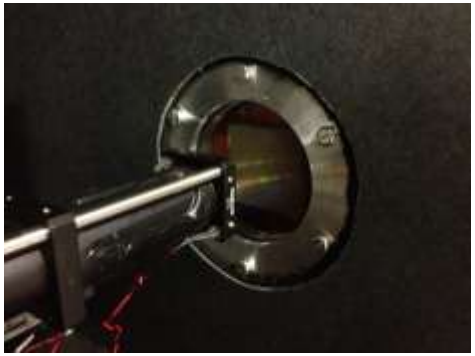
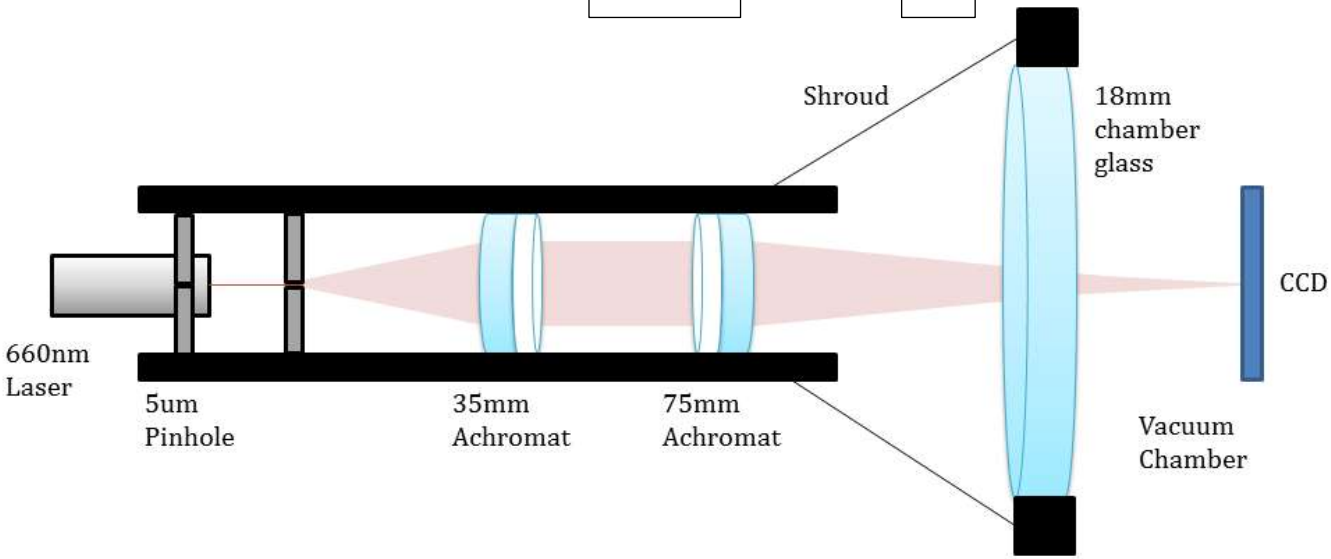
Optical PSF facilities

Classic optical projection system

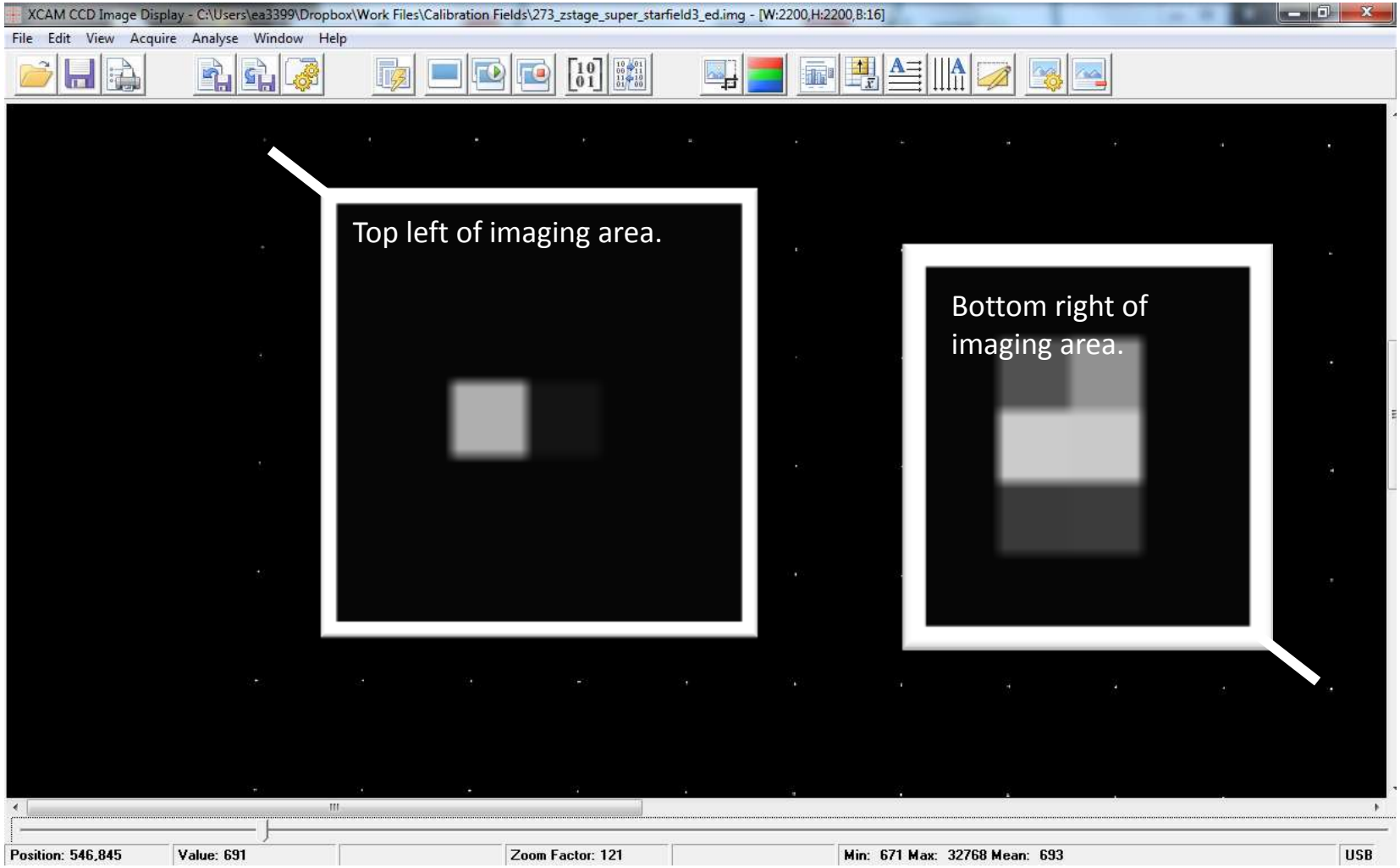








Region Autofocus (RA) Algorithm



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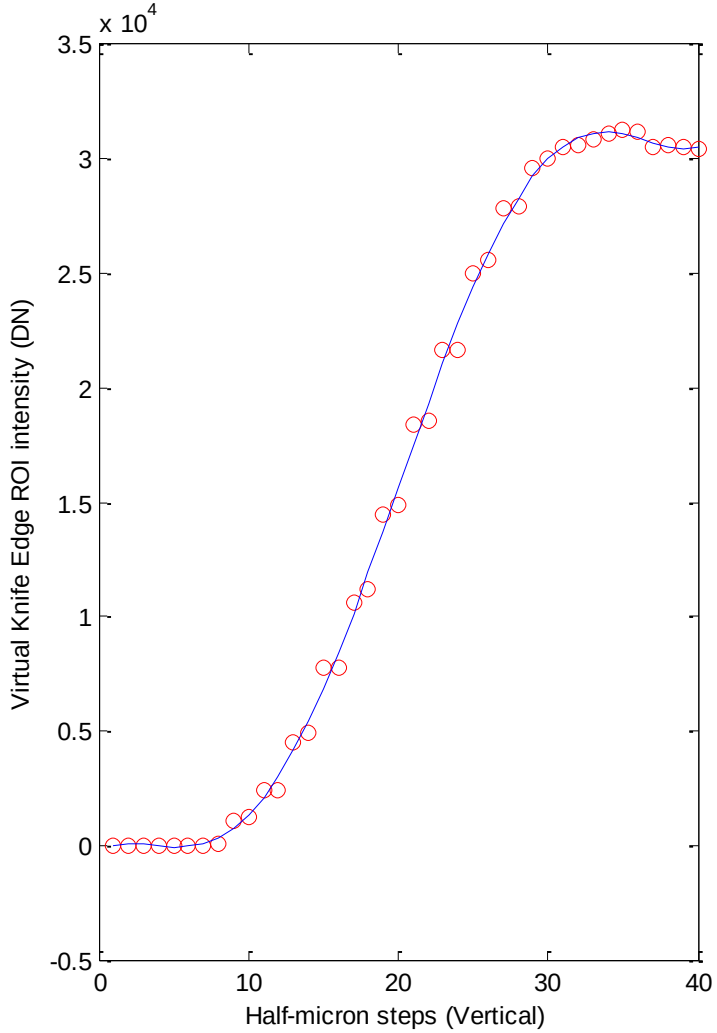
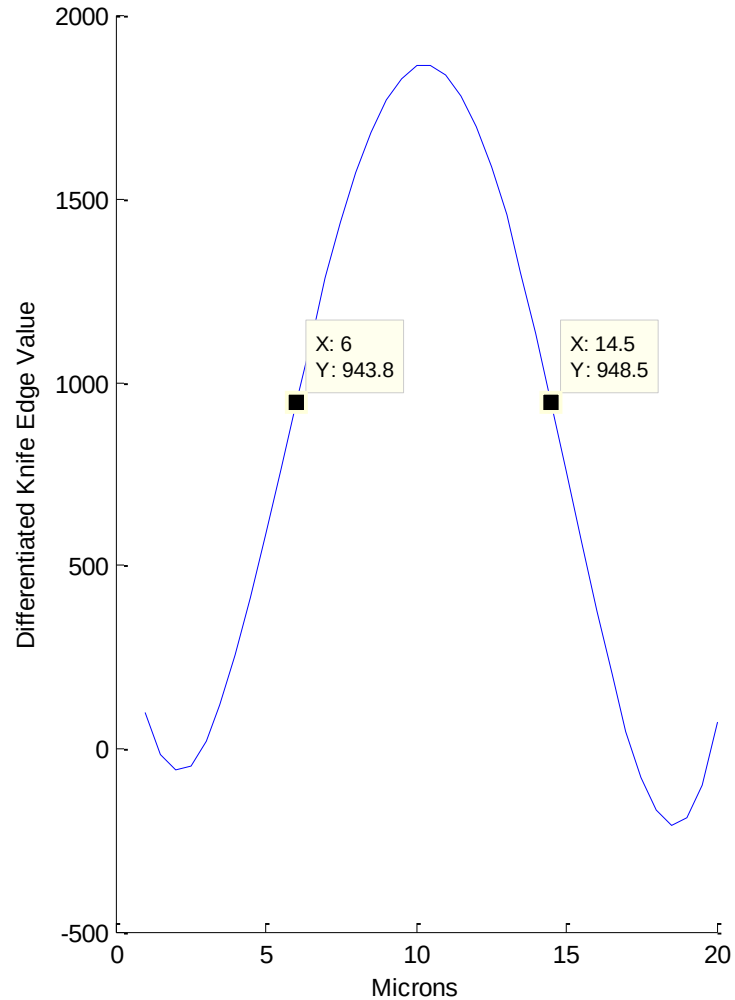
Virtual knife edge measurements





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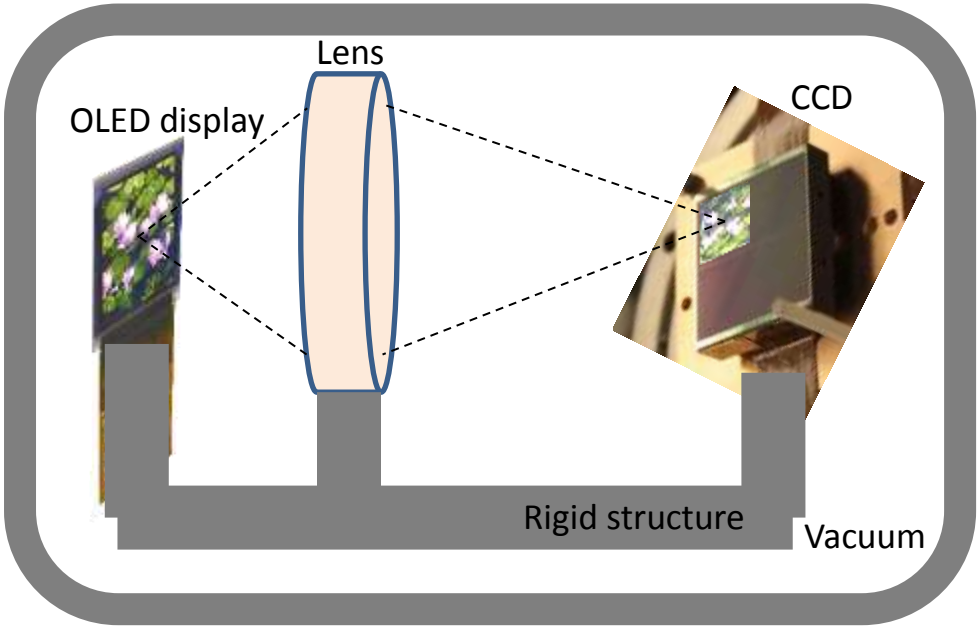
A simple low cost alternative using OLEDs?

- Can modern technology be used to simplify the design of an optical bench?
- Individual pixels in AM-OLED displays produce their own light, allowing superior contrast ratios.
- Could image single OLED pixels to provide point sources on CCD, or small ellipses to simulate galaxies in applications such as Euclid.
- Rather than moving the spot of light, individual pixels in the OLED display can be switched on and off to illuminate different regions of the imaging sensor, between or during integrations.



- Provided a suitably rigid structure the positional repeatability should be excellent.
- Could be entirely contained within the vacuum cryostat offering improved environmental stability over traditional systems.
- OLEDs appear to be vacuum safe, although will require some experimentation.
- A low cost (£80) proof of concept is currently being developed in the research laboratory.

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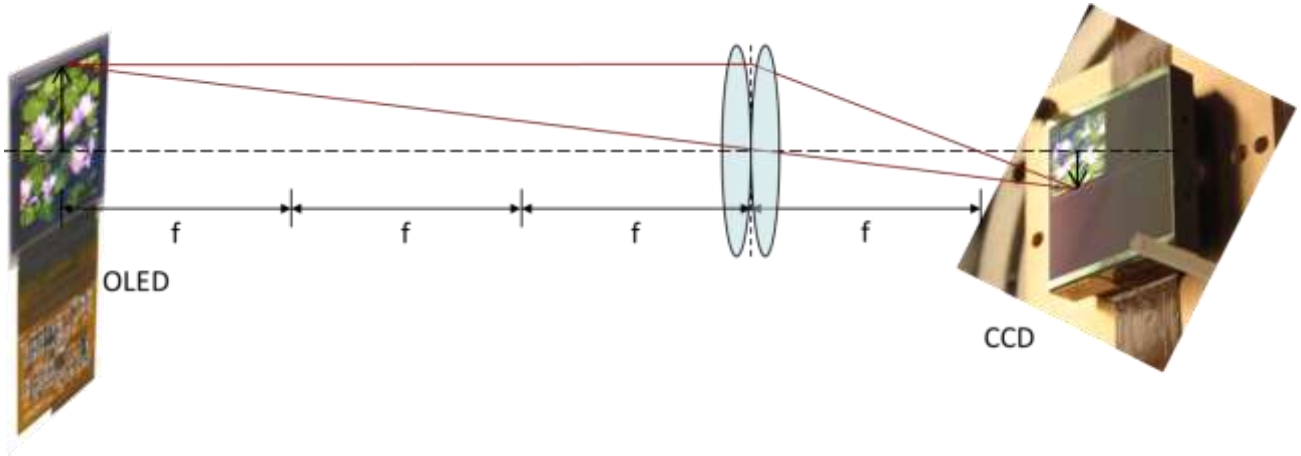
Optical Arrangement



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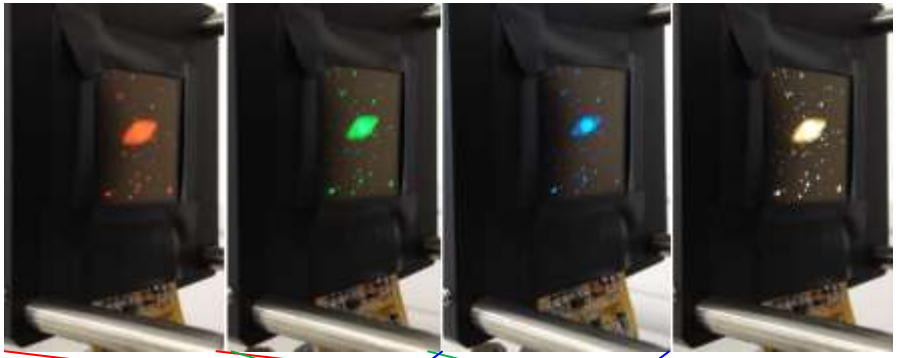
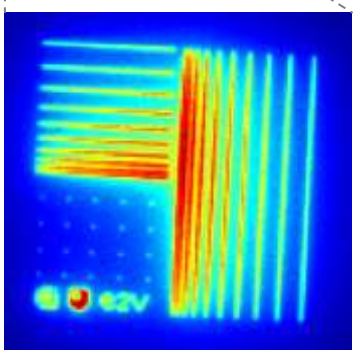
Input Stimuli

- 128 × 128, 8-bit colour depth RGB images
- Apply threshold to remove JPG artefacts
- Black out display during readout





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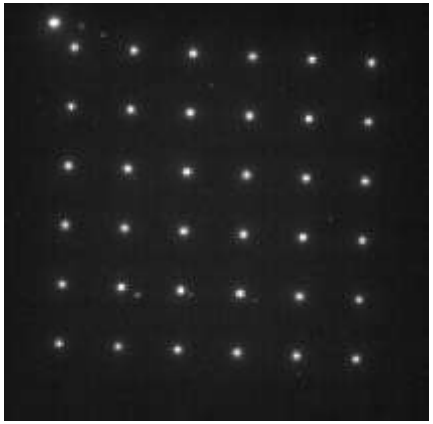
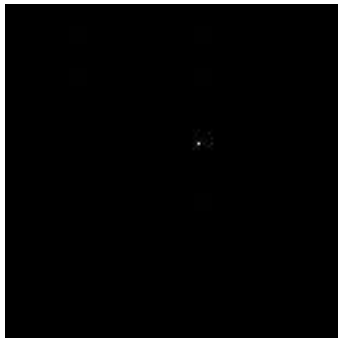
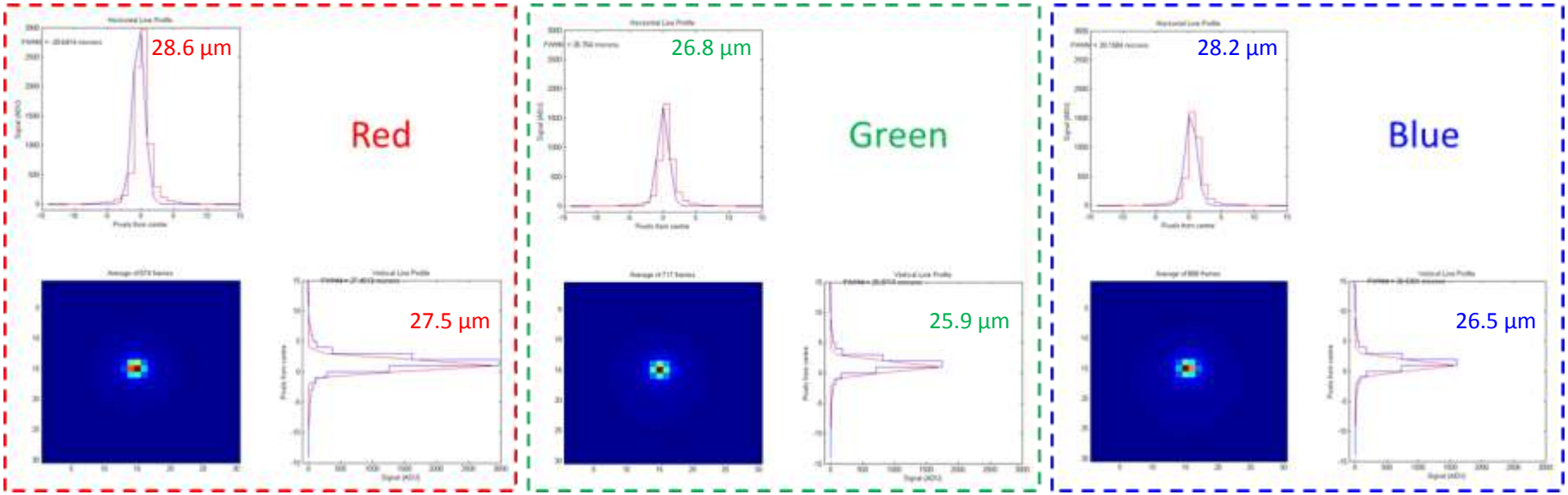
Initial PSF Measurements



- Find most centred spot in array (for green).
- Update OLED with best spot.
- Acquire 1,000 images and fit.
- As each RGB component is in a different position automatic routine is desirable for best fit at each wavelength.





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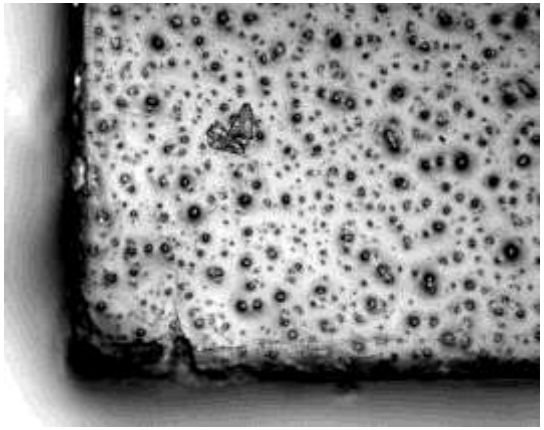
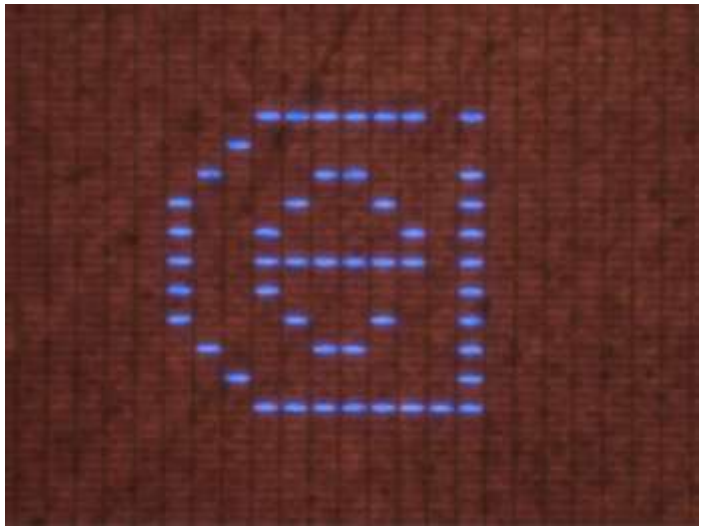
Current Limitation?

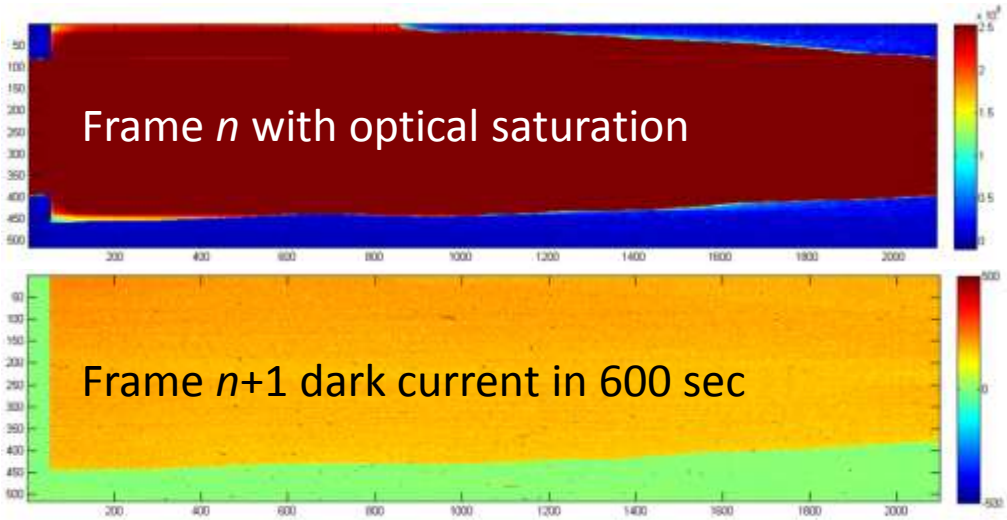


- Diffuser to blend RGB components
- Don’t want it, monochromatic displays shouldn’t have diffusers.

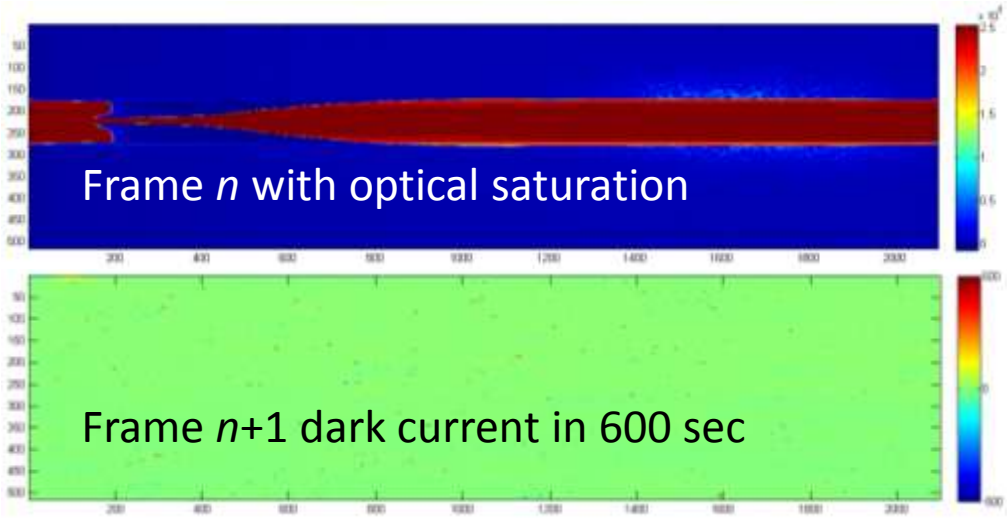


Remanence

Flushing Remanence between subsequent frames



Problem – Saturating objects (~100 per CCD per frame) allow electrons to contact and fill surface traps. These slowly release over time, causing localised increases in dark current during subsequent frames



Solution – Pin surface momentarily between frames by raising substrate potential. This floods the surface with holes that recombine with any trapped electrons. Could also clock barrier phases to negative potential.

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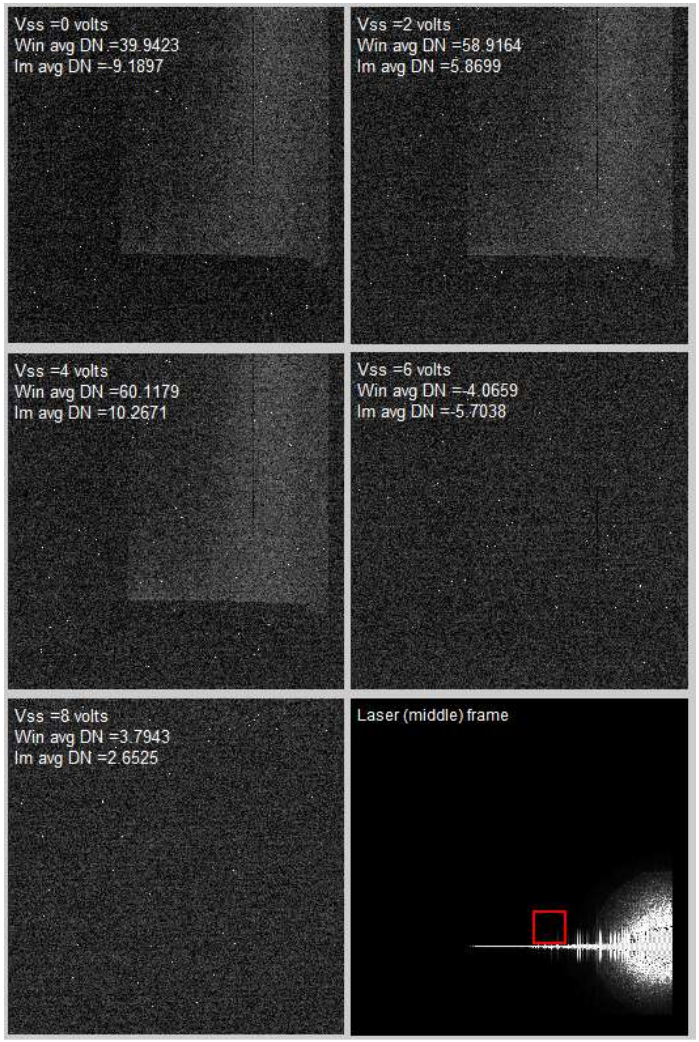
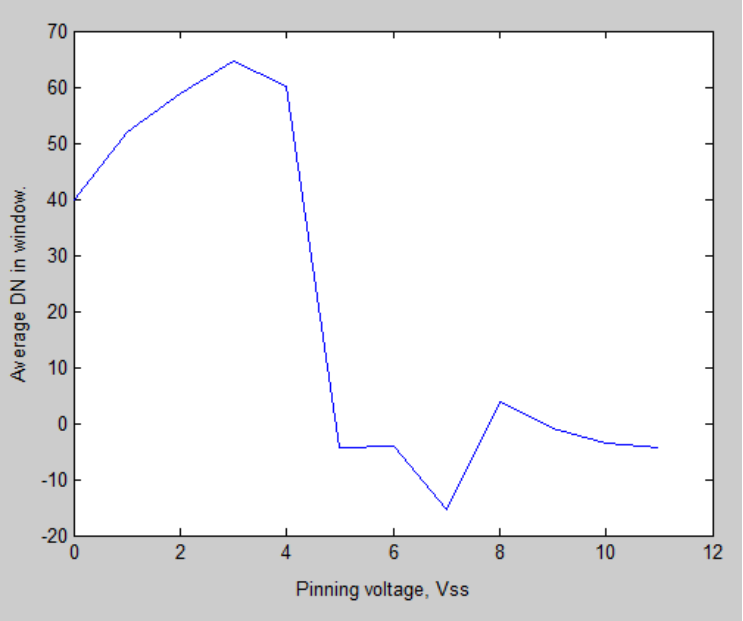
Remanence as function of pinning potential – 1



- 300 second dark, 3 second light, 300 second dark. Residuals are Frame 3 - Frame 1.
- Operated at IØH = 10 V to promote lateral blooming as it is easier to see!
- No surprises, pins and clears at Vss = (#barrier phases/total phases)*clock amplitude high



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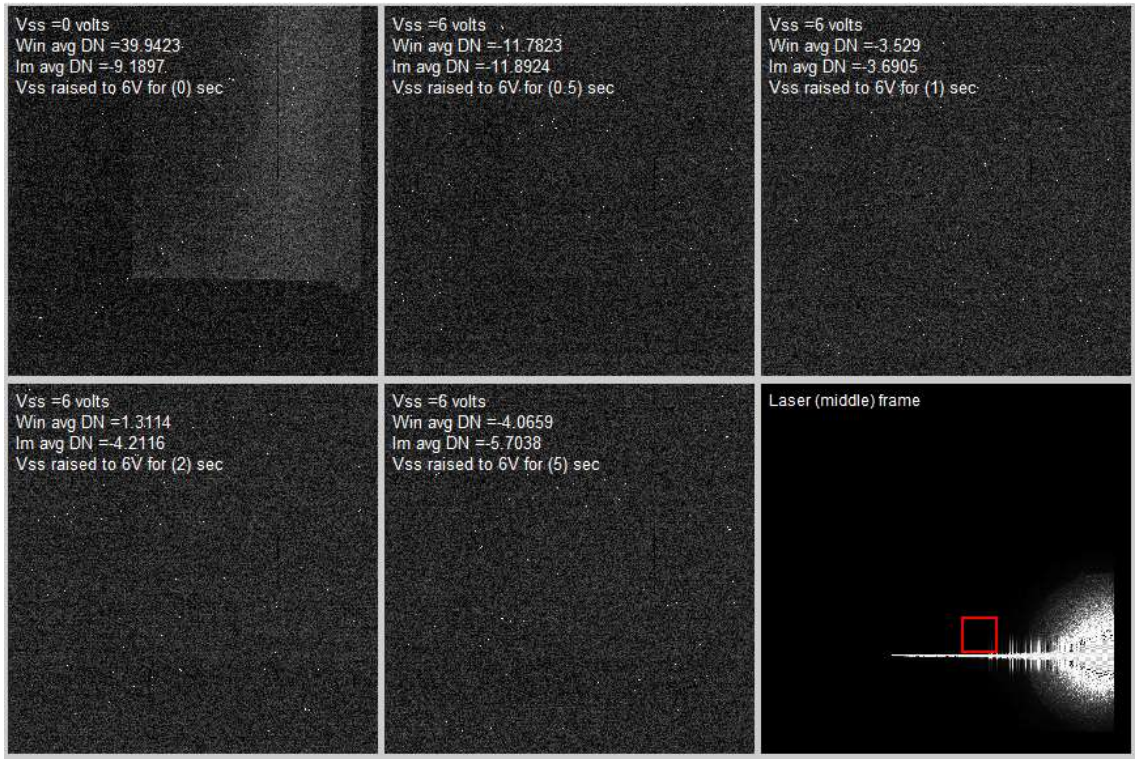
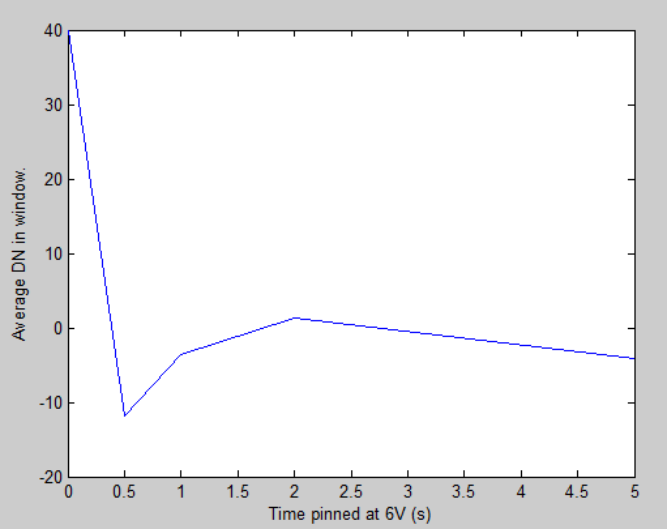
Remanence as function of pinning time – 2





- Holes move fast; not as fast as electrons, but fast!

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