WFIRST-AFTA Coronagraph EMCCD Cryo-Radiation Testing

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Outline

- Milestone EK-7 Background
- Cherng's radiation analysis summary
- Phase I summary
- Phase II Plan (defect populations depend on operating temperature)
- Phase II results
  - Dark current, RN, X-ray CTI, EPER
  - EM gain, CIC, output amplifier responsivity
- Conclusions

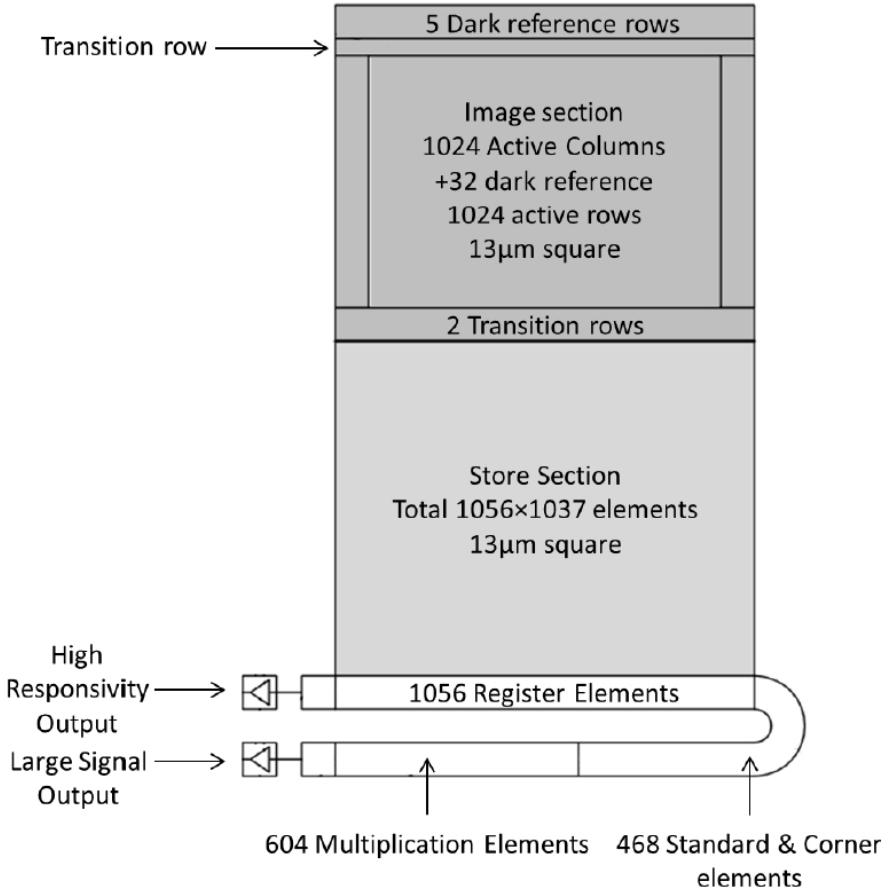
EK-7 Milestone

- Background
  - "Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e^-/pix/s and read noise less than 1 e^-/pix/frame."
  - EMCCD BOL testing at JPL passed these requirements; In addition, CIC, linearity and photon transfer curves measured
  - Working toward proof of actual performance necessary for CGI science (imaging, IFS)

Specification	Goal	Requirement	Measurement	Unit	**Notes**
Effective read noise w/gain	0.2	0.2	<0.2	e^-	With EM gain
Dark current	1×10^{-4}	5×10^{-4}	1.01×10^{-4}	e^-/pix/sec	165K, IMO
Clock induced charge (CIC) @ 5.5σ threshold	0.0010	0.0018	0.0017	e^-/pix/fr	10 MHz serial freq 1 MHz parallel freq EM gain = 1000

e2V CCD201-20 Architecture

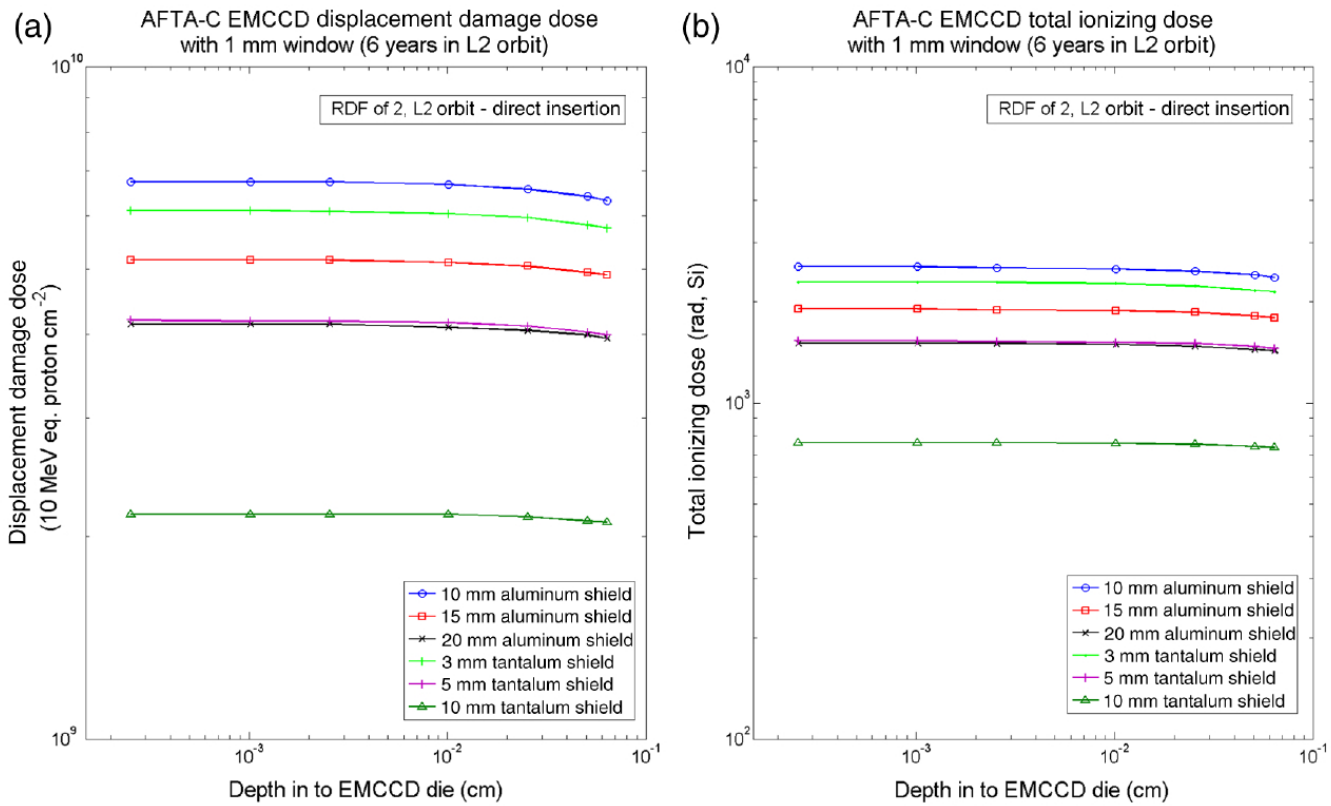
- Frame transfer configuration
- High responsivity (HR) output – conventional CCD operation
- Large Signal (LS) output – EM gain operation
- Standard & Corner elements
  - Bend-around to reduce die size
  - 468 selected to balance the 1056 element row and thus act as buffer (with 604 elements) to increase readout speed



Review of Radiation Analysis

Radiation transport code NOVICE used to predict DDD and TID in L2

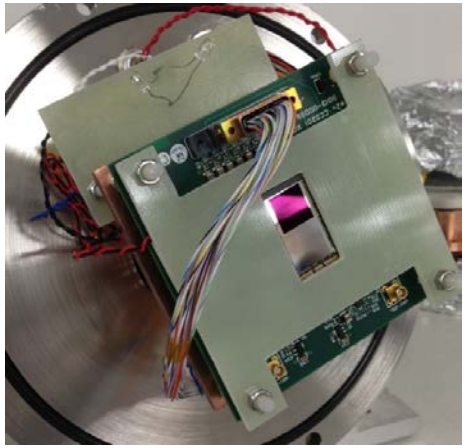
- Direct insertion orbit, i.e. trajectory through Earth's trapped-particle rad belts is inconsequential
- Code was run for GEO and contribution from Earth-trapped protons, electrons was removed
  - This method was validated by comparison with GSFC prediction for L2 orbit using a different tool
  - RDF = 2 was used; model run at 95% confidence level
  - Code was run for a range of camera shielding materials/thicknesses to inform choice of maximum test exposure
  - Performance after mission life exposure will be used to iterate on shielding material/thickness
- Code predicted cumulative TID of only 1 krad with 1 mm glass window
  - => DDD is the major hazard; TID test not needed in this phase

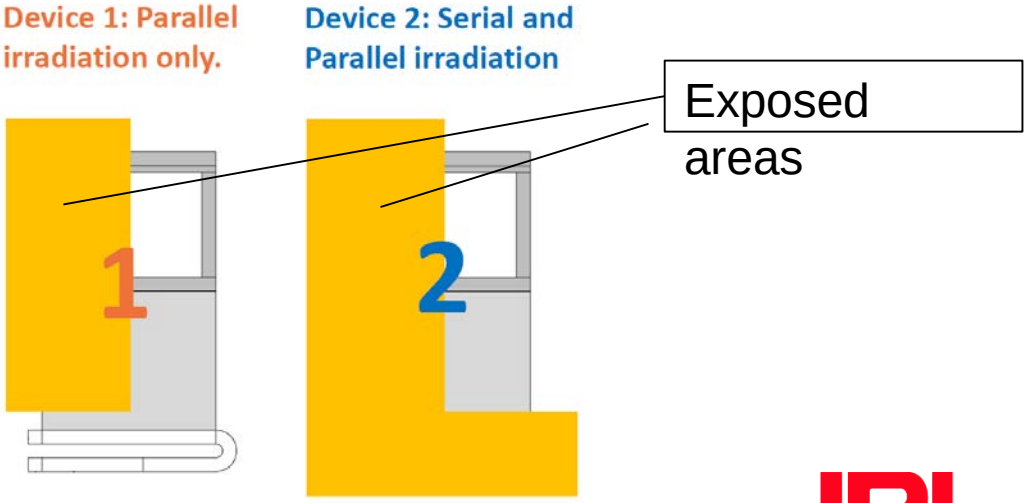


Phase I Operating Conditions

Single exposure of Displacement Damage Dose (DDD) at room temperature

- **Survivability test of detector for 2.5 x 10^9 protons cm^{-2} dose [10 MeV equivalent]**
  ~3 years at L2 orbit with shielding
- Irradiation at Paul Scherrer Institute Beamline facility in Switzerland in April 2015
- Assessed degradation of:
  - Read Noise, EM gain, Clock Induced Charge, Dark current, Charge Transfer Efficiency
- DUT: Engineering-grade EMCCD m/n 201-20
- **T = 293 K during irradiation; 165 ±2 K during post exposure measurement**
- Frame time = 100 sec
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)
- **Unbiased during exposure**





Phase II Operating Conditions

- DUT Science-grade EMCCD m/n 201-20
- Facility: Helios 3 Beamline, Harwell, UK
- T = 165 ±2 K for irradiation; (±5 K during measurements)
- Frame time = 100 sec
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)
- Biased during exposure to monitor flatband voltage shifts
- Applied bias voltages during test same as for Phase I for comparison*
  - * Except for the two voltages driving EM gain
- Four cumulative doses summing to 7.5 x 10^9 pr/cm^2 [10 MeV equivalent]
  - Fourth dose smaller than prescribed due to facility failure
    - Reported but not used in analysis
- Performance fully characterized **before** campaign and **after each** of four doses
  - Dark current, CIC, EM gain, RN, X-ray CTI, EPER, amplifier responsivity

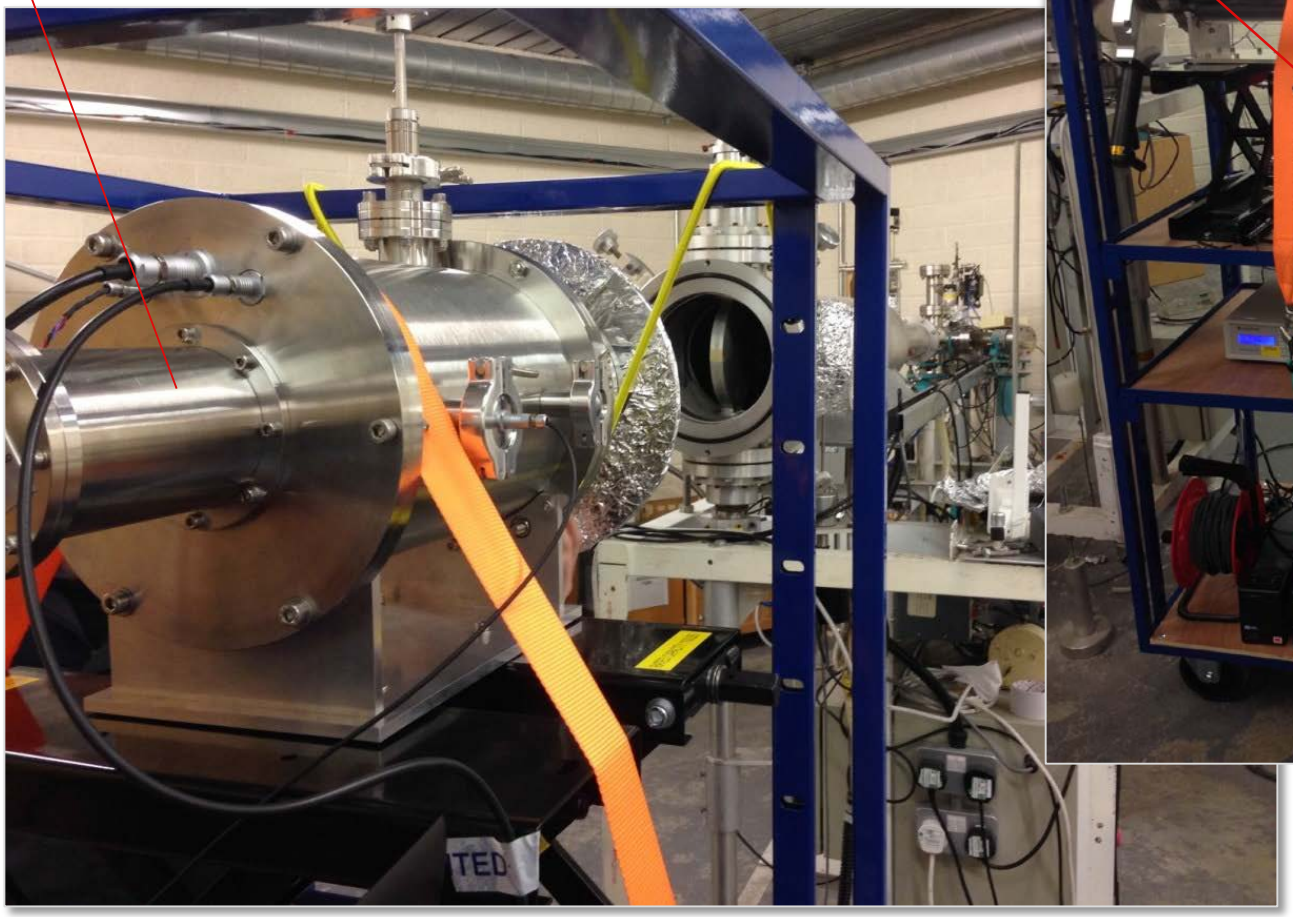
Exposure Dose [10^9 protons/cm^{-2}]	Cumulative Dose [10^9 protons/cm^{-2}]
0	0
1	1
1.5	2.5
2.5	5
2.5	7.5

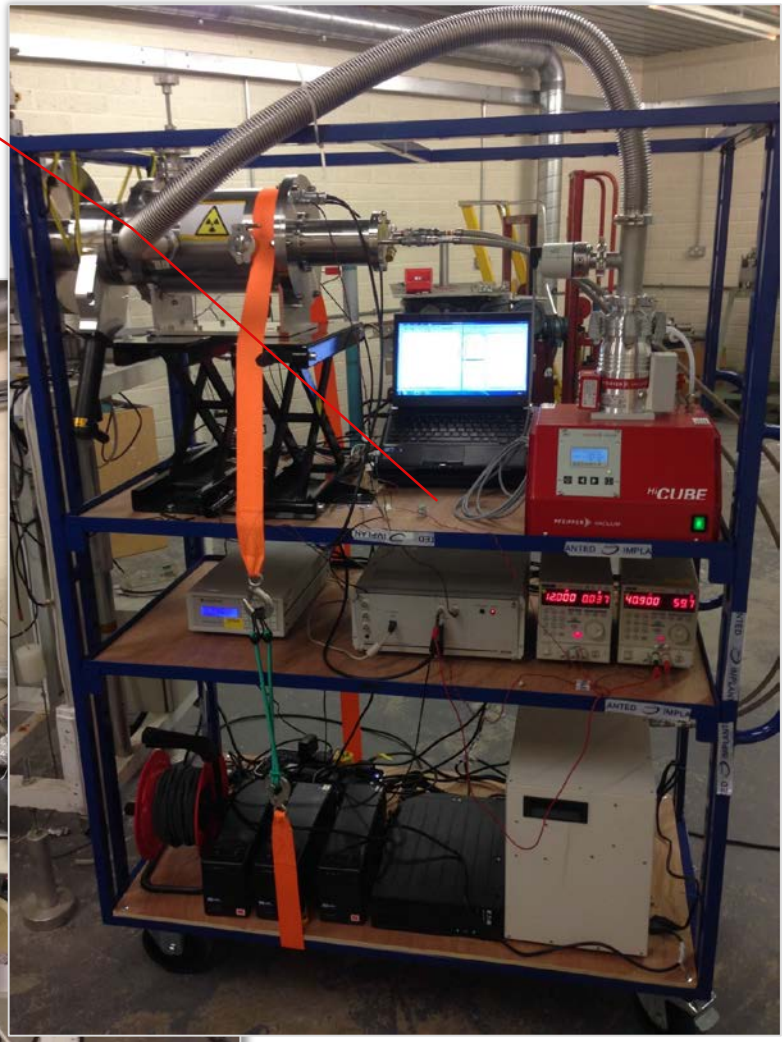
Phase II Facility

Helios 3 Beamline, Harwell, UK – range 0-10 MeV

Alignment of cryostat with beamline

Alignment of cryostat with beamline





Parallel Clock Induced Charge

- Clocking process accelerates minority carriers to high energies and impact ionization results in electron-hole pairs
- Accumulation of holes in insulator results in flat-band voltage shift
- Dependence on clock amplitude
- Inversely related to clock freq.
- Conclusion:
  - CIC increase is small compared to dark current
  - Flat-band shift can be compensated by bias voltages

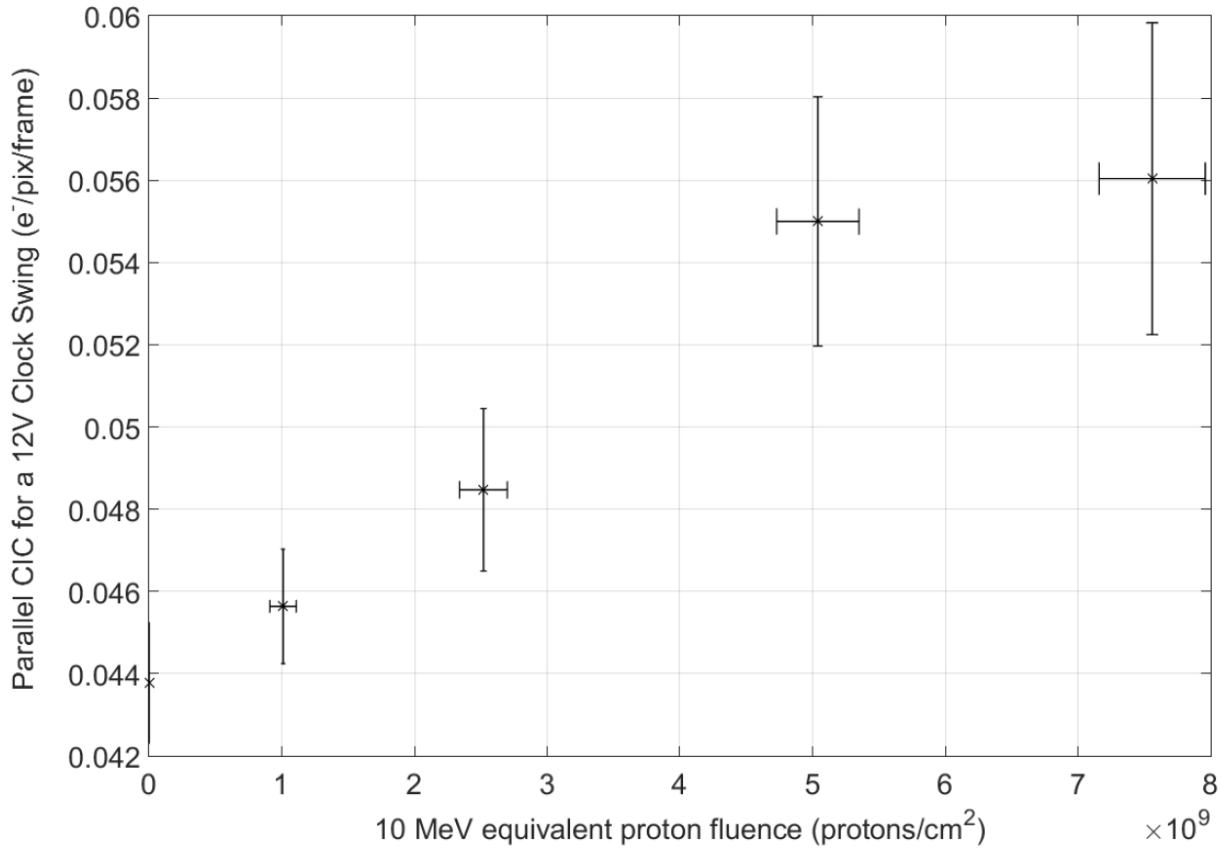


Figure 9.6.4: Illustration of parallel CIC measured for a 12V clock swing as a function of irradiation fluence. The CIC measured for the final fluence (7.5×10^9 protons/cm^2) agrees with the penultimate fluence within the quoted errors.

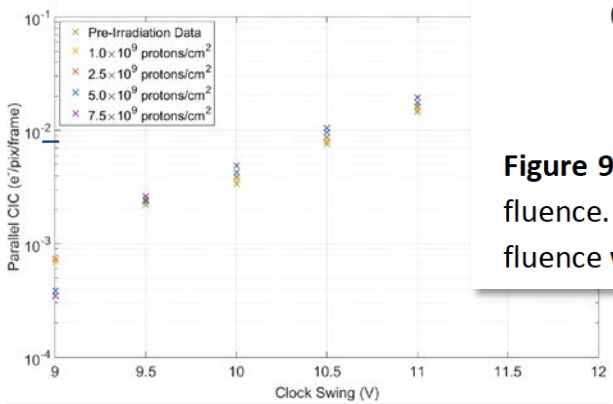


Figure 9.6.3: Illustration of CIC results for each clock swing measurement and irradiation fluence. Error bars are excluded for clarity.

Dark Current

- Linear degradation with proton fluence
- 8x reduction of dark current after 1 week RT anneal
- No further reduction after 2nd week RT anneal
- For same fluence RT irradiation device dark current ~10x lower
- Conclusion:
  - Dark current marginally fails EOL requirement after third dose
  - This is easily mitigated by increasing shield thickness

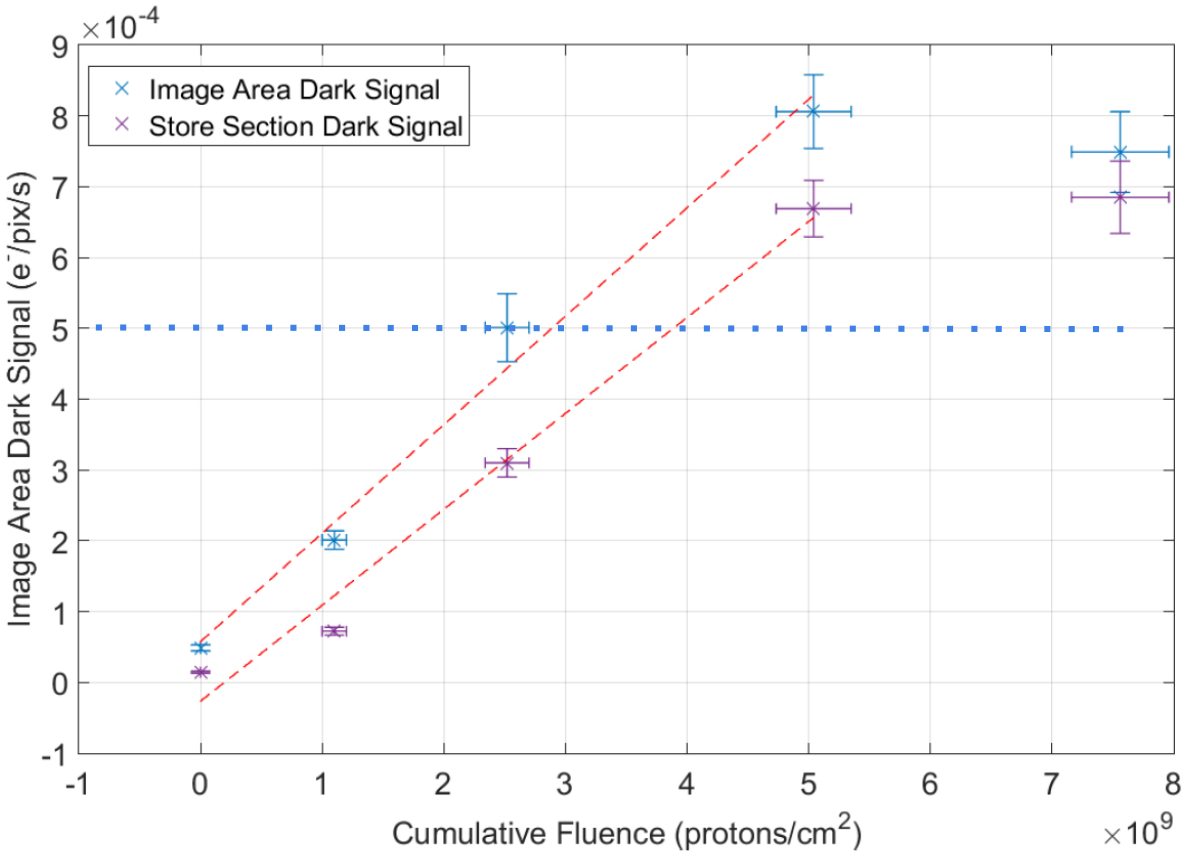


Figure 9.7.2: Dark signal values for each proton fluence. Data is shown for dark current measured in the image area and frame store region. The image area systematically exhibits higher dark current; an observation noted in other studies with back thinned sensors that also have an aluminium frame store section.

Electron Multiplication Gain

- EM gain observed to degrade with fluence

Table 9.4.1: Summary of measured multiplication gain values for each method. No measurement is available using the dark defect method for the pre-irradiation case since no dark defects were present.

Cumulative Fluence (10 MeV equiv. protons/cm^2)	Multiplication Gain (X-ray method) Rϕ2HV = 40.9 V	Multiplication Gain (Dark defect method) Rϕ2HV = 40.9 V
Pre-Irradiation	154±5	N/A
1.0×10^9	137±5	134±3
2.5×10^9	122±16	128±3
5.0×10^9	122±22	128±4
7.5×10^9	111±16	125±6
7.5×10^9 following 1 week 298K anneal	110±16	N/A
7.5×10^9 following 2 week 298K anneal	111±17	N/A

Electron Multiplication Gain

- Phase I RT irradiation showed no change in EM gain
- EM gain is not expected to change from irradiation
- Degradation in EM gain versus cumulative passed signal agrees with pre irradiation aging curve
- Note continued trend even after fourth (failed) dose
- Conclusion:
  - EM gain degradation is attributed to device aging

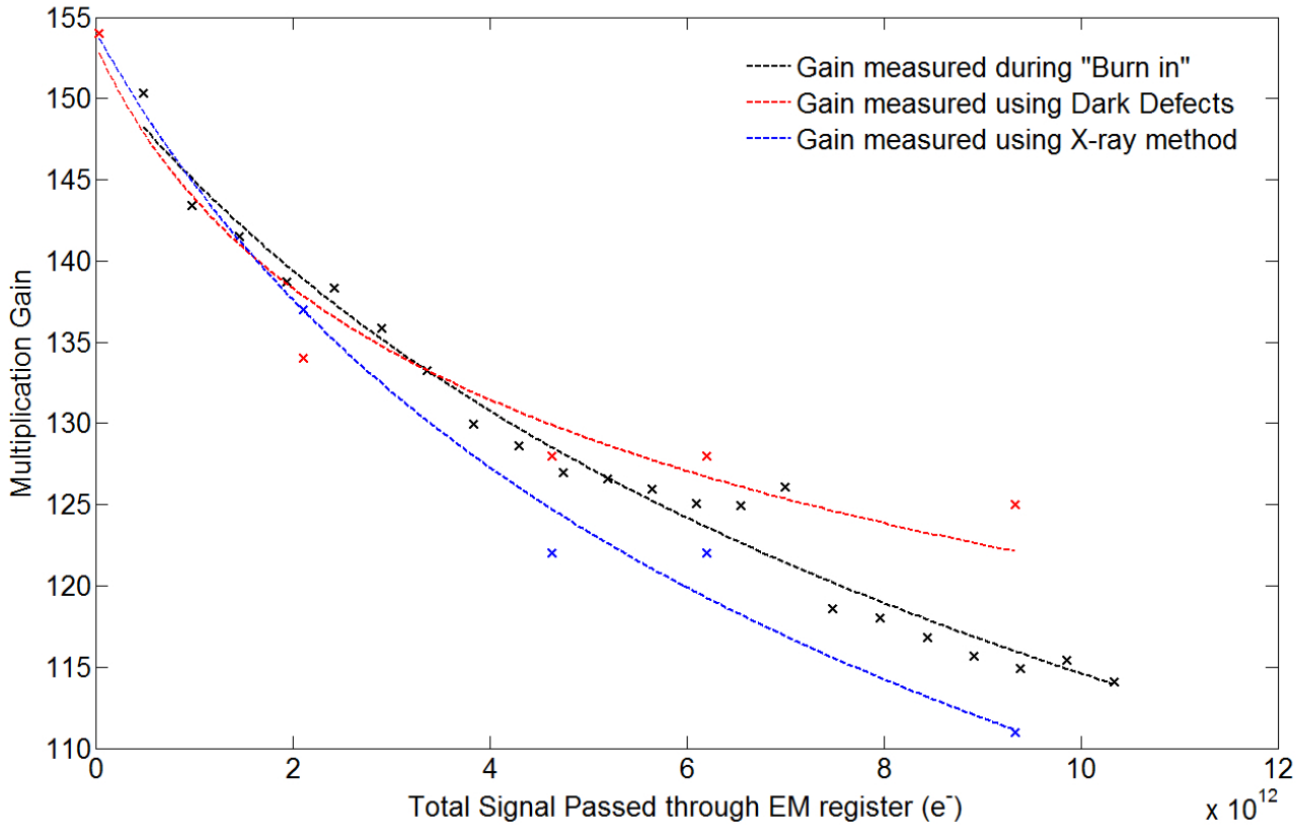


Figure 9.4.1: Multiplication gain measured as a function of total signal passed through the EM register. Both the X-ray method and dark defect method are consistent with the expected drop due to ageing within the quoted errors (Table 9.4.1). The deviation from the trend at the larger signal levels is within expected levels for the uncertainty of the measurements.

Effective Read Noise

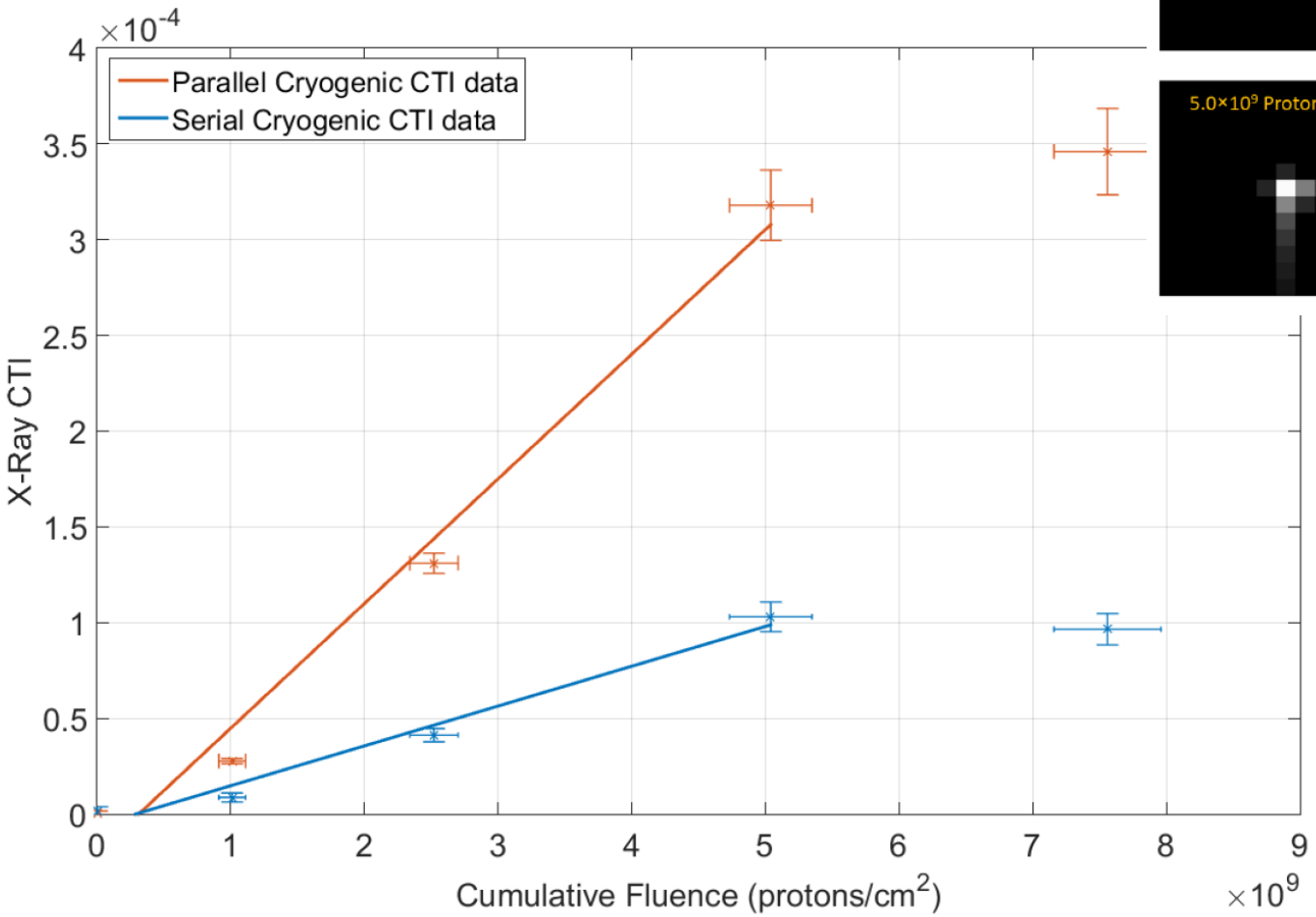
- Effective RN = RN/Emgain;
- Two RN measurement methods used; Back-clocked method seems more accurate
- Conclusion: The increase in effective read noise is attributed to the decrease in multiplication gain associated with device aging effects. Removing this trend, any effective read noise degradation is unresolvable.

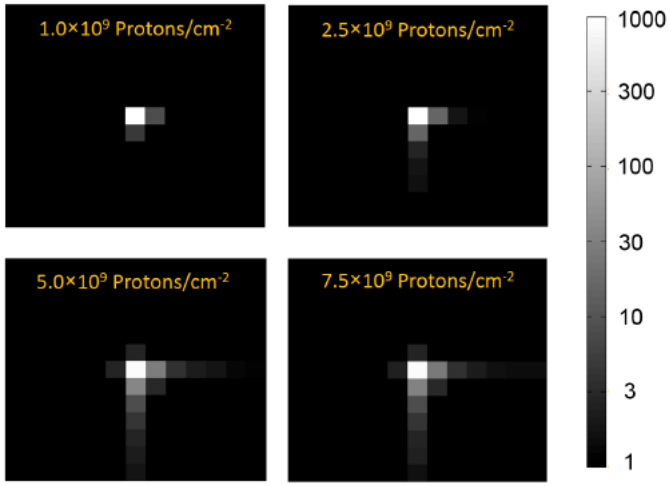
Table 9.5.1: Summary of effective read noise results as a function of irradiation fluence.

	Disabled Rϕ2HV Method		Backclocked method (used in Phase I)	
Cumulative Proton Fluence (protons/cm^2)	**Effective Read Noise (e^-)**	**Expected result based on gain change (e^-)**	**Effective Read Noise (e^-)**	**Expected result based on gain change (e^-)**
Pre-Irradiation	(0.48±0.02)	(0.48±0.02)	(0.83±0.03)	(0.83±0.03)
1.0×10^9	(0.62±0.03)	(0.54±0.02)	(0.94±0.01)	(0.93±0.04)
2.5×10^9	(0.89±0.05)	(0.61±0.10)	(1.07±0.01)	(1.04±0.16)
5.0×10^9	(1.50±0.09)	(0.61±0.13)	(1.49±0.04)	(1.04±0.23)
7.5×10^9	(1.64±0.13)	(0.67±0.11)	(1.38±0.03)	(1.15±0.19)
7.5×10^9 (1-week room temperature anneal)	(0.72±0.04)	(0.68±0.11)	(1.17±0.02)	(1.16±0.19)
7.5×10^9 (2-week room temperature anneal)	N/A	N/A	(1.31±0.02)	(1.16±0.19)

X-Ray CTI

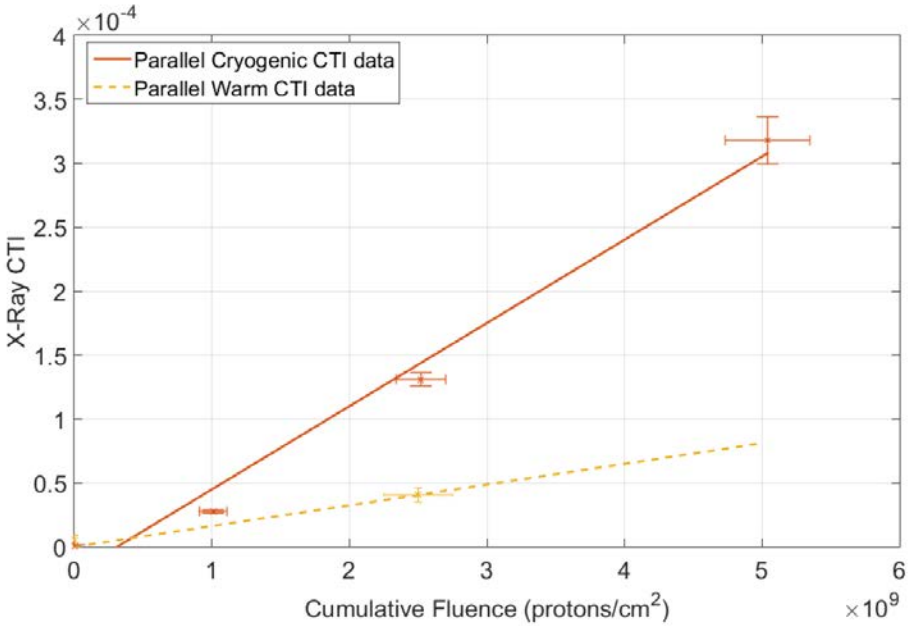
- X-ray events result in a nearly fixed number of photo-electrons (1616 e-)
- CTE is the average charge loss per pixel transfer;
- CTE = (charge lost per transfer) ÷ (signal size)
- CTI = 1 - CTE





X-Ray CTI: cryo-test vs. RT test

- Greater degradation observed for cryogenic irradiation than RT
- This is consistent with previous studies (from CEI)
- May have impact on high flux outer rim of dark hole or target acquisition images



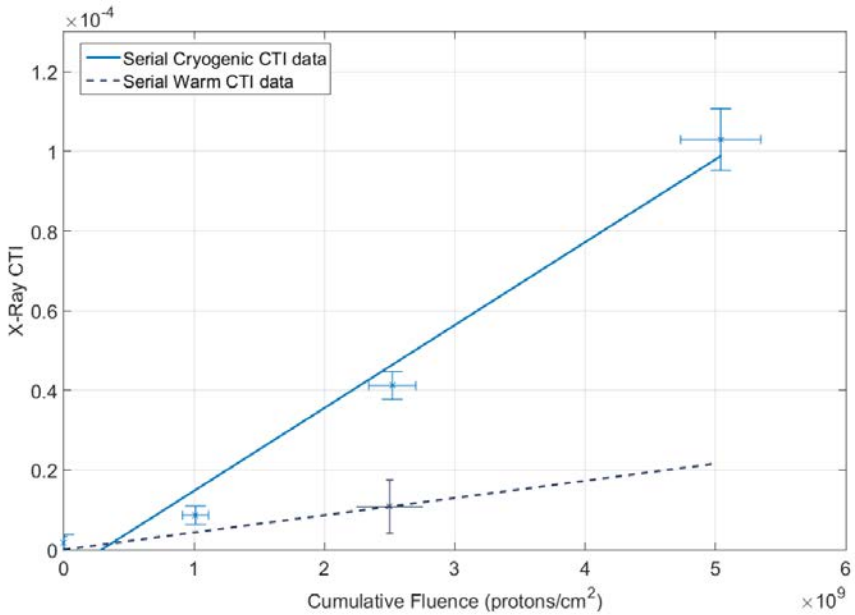
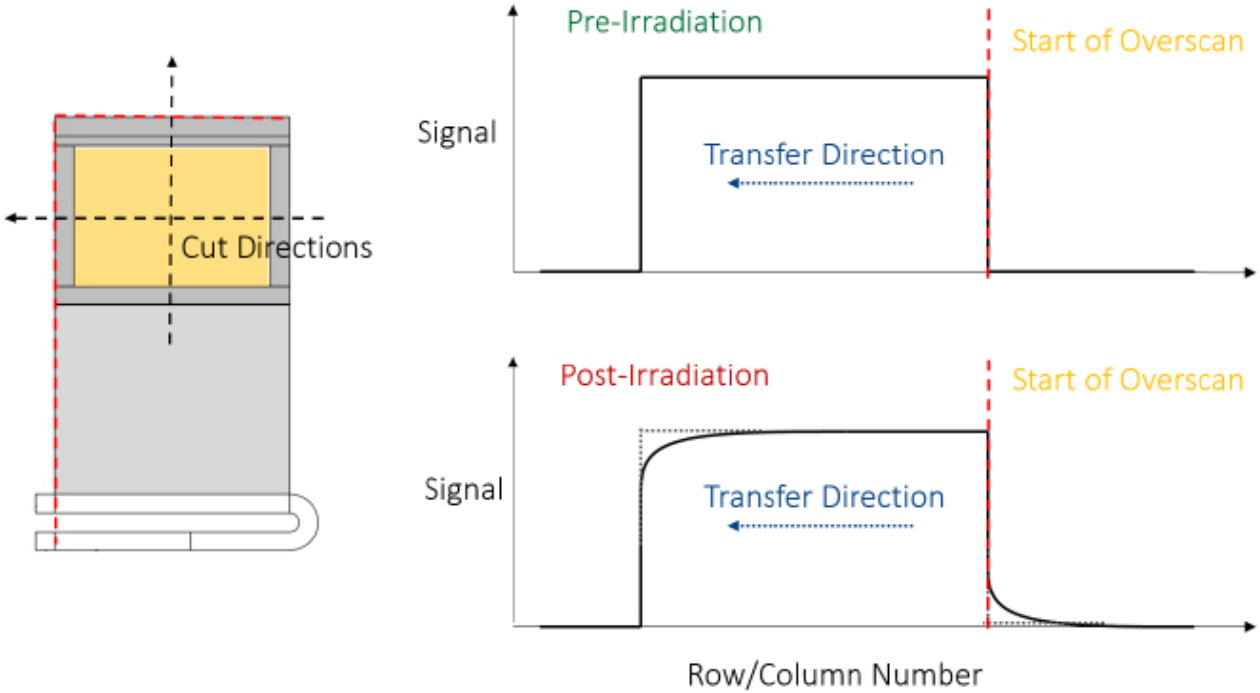


Figure 9.8.3: Graphical comparison of Phase 1 warm irradiation results and Phase 2 cryogenic irradiation parallel X-ray CTI results. The results from the Phase 1 investigation are shown for Device 2 where both the parallel and serial directions were irradiated. Only a single irradiation was delivered during Phase 1 (2.5×10^9 protons/cm^{-2}) which has been used to generate a trend line for comparison.

Low flux CTE

- Extended Pixel Edge Response (EPER)
- Flat field resulting in average of 10 electrons per pixel
- Parallel and serial overscan technique used to produce perfectly sharp edge to flat field
- Parallel and serial tails measured
- CTI_{EPER} = (charge in emission tail) ÷ (signal level × n. transfers)
- Possible that flat field tail is worse than tail from a single psf
- X-ray CTI probes charge capture whereas EPER CTI probes charge emission



Low flux CTE

- Raw measurment of EPER tail

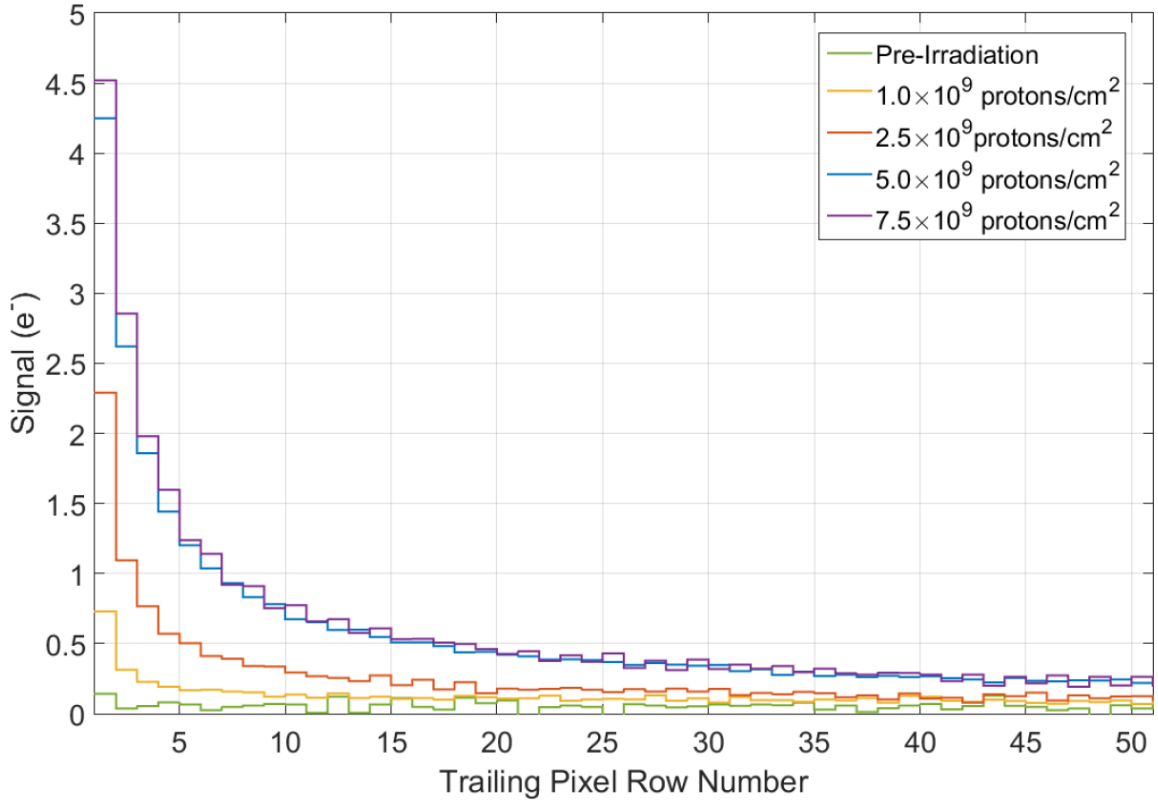


Figure 9.9.4: The first 50 rows of the parallel EPER tail for each fluence level. Pixel 1 is the first pixel after the flat field (approximately 10 electrons).

Low flux CTE

EPER CTI Measurement	Phase 1 room temperature irradiation. (Signal ≈ 8e$^-$)	Phase 2 cryogenic irradiation. (Signal ≈10 e$^-$)	Approximate factor difference between warm and cryogenic irradiation
Parallel CTI	$(3.94\pm0.45) \times 10^{-4}$	$(8.31\pm0.52) \times 10^{-4}$	≈2
Serial CTI	$(2.32\pm0.38) \times 10^{-4}$	$(6.84\pm0.15) \times 10^{-4}$	≈3

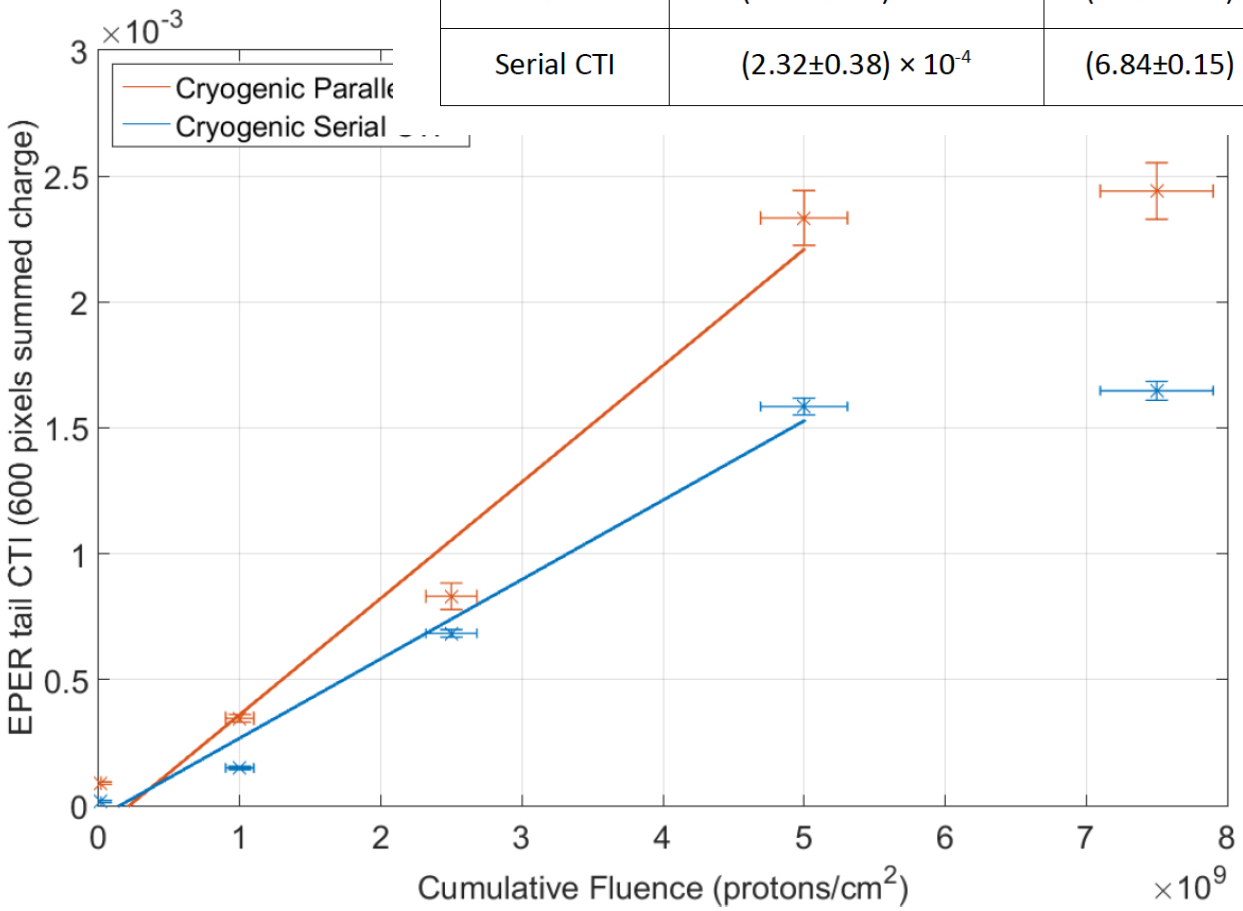


Figure 9.9.6: Integrated EPER parallel and serial tail CTI plotted as a function of cumulative fluence level.

Low flux CTE

Table 9.9.2: EPER tail CTI values for each Fluence level. Annealing results are included however, it should be noted that the illumination level is different which in turn affects the CTI result.

Cumulative Fluence (protons/cm^2)	Illumination (e^-)	Parallel Integrated Charge CTI (600 rows)	Serial Integrated Charge CTI (600 Columns)
Pre-Irradiation	(9.85±0.80)	(8.88±0.49) x 10^{-5}	(1.65±0.47) x 10^{-5}
1.0×10^9	(10.1±0.77)	(3.46±0.16) x 10^{-4}	(1.50±0.10) x 10^{-4}
2.5×10^9	(10.1±0.87)	(8.31±0.52) x 10^{-4}	(6.84±0.15) x 10^{-4}
5.0×10^9	(9.56±0.98)	(2.33±0.11) x 10^{-3}	(1.59±0.03) x 10^{-3}
7.5×10^9	(9.86±1.0)	(2.44±0.11) x 10^{-3}	(1.65±0.04) x 10^{-3}
7.5×10^9 – 1 week 298K anneal	(16.02±1.54)	(2.11±0.37) x 10^{-3}	(1.38±0.04) x 10^{-3}
7.5×10^9 – 2 week 298K anneal	(15.83±1.65)	(1.60±0.36) x 10^{-3}	(1.04±0.04) x 10^{-3}

Phase II Summary

	10 MeV equivalent cumulative Proton Fluence (protons/cm^2)				
Parameter	**Pre-Irradiation**	**1.0×10^9**	**2.5×10^9**	**5.0×10^9**	**7.5×10^9**
Parallel FPR CTI (10 e$^-$ signal)	$(3.79\pm5.45)\times10^{-6}$	$(1.66\pm0.07)\times10^{-4}$	$(4.08\pm0.08)\times10^{-4}$	$(7.06\pm0.29)\times10^{-4}$	$(7.20\pm0.25)\times10^{-4}$
EPER Parallel CTI (10 e$^-$ signal)	$(8.88\pm0.49)\times10^{-5}$	$(3.46\pm0.16)\times10^{-4}$	$(8.31\pm0.52)\times10^{-4}$	$(2.33\pm0.11)\times10^{-3}$	$(2.44\pm0.11)\times10^{-3}$
EPER Serial CTI (10 e$^-$ signal)	$(1.65\pm0.47)\times10^{-5}$	$(1.50\pm0.10)\times10^{-4}$	$(6.84\pm0.15)\times10^{-4}$	$(1.59\pm0.03)\times10^{-3}$	$(1.65\pm0.04)\times10^{-3}$
X-Ray Parallel CTI (X-ray density ≈ 1 event per 2700 pixels)	$(0.569\pm1.0)\times10^{-6}$	$(2.76\pm0.13)\times10^{-5}$	$(1.31\pm0.05)\times10^{-4}$	$(3.18\pm0.18)\times10^{-4}$	$(3.46\pm0.23)\times10^{-4}$
X-Ray Serial CTI (standard register, X-ray density ≈ 1 event per 2700 pixels)	$(1.67\pm2.08)\times10^{-6}$	$(8.63\pm2.32)\times10^{-6}$	$(4.12\pm0.35)\times10^{-5}$	$(1.03\pm0.08)\times10^{-4}$	$(9.65\pm0.82)\times10^{-5}$
Image Area Dark signal (e$^-$/pix/s)	$(4.89\pm0.42)\times10^{-5}$	$(2.01\pm0.13)\times10^{-4}$	$(5.01\pm0.48)\times10^{-4}$	$(8.06\pm0.52)\times10^{-4}$	$(7.49\pm0.57)\times10^{-4}$
Parallel CIC (IMO) (e$^-$/pix/frame)	$(4.38\pm0.15)\times10^{-2}$	$(4.56\pm0.13)\times10^{-2}$	$(4.85\pm0.12)\times10^{-2}$	$(5.50\pm0.30)\times10^{-2}$	$(5.60\pm0.37)\times10^{-2}$
Multiplication Gain[i]	154±5	137±5	122±16	122±22	111±16

[i] The observed decrease in multiplication gain is thought to be due to device aging

Summary of Findings

- Last dose failed; Cumulative dose ends up being 5.0 x 10^9 pr/cm^2
- Dark current degradation easily mitigated by thicker shielding
- CIC degradation by ~20% above BOL is acceptable
- EM gain degradation due to device aging and is manageable.
- Effective Read Noise degradation is attributed to degradation of EM gain register due to aging
- For the specific operating conditions of this campaign, irradiation at cryo temp under bias results in greater performance degradation than for unbiased room-temperature irradiation at an equivalent exposure (10 MeV equivalent protons)
  - Different trap species have different thermal dependence
- Conclusion: Conventional CCD performance parameters nearly pass EOL requirements, easily mitigated by beefier shielding design
- Still evaluating effect of traps on low flux frames with psf and speckle
- Effects of RT anneal are favorable for dark current and low flux CTI

RESERVE SLIDES

CCD201-20 Trap Mitigation Methods

Trap mitigations for the existing standard product CCD201-20

- Custom clock waveform using multi-level clocking
- Fill traps by low level illumination
- Annealing

CCD201-20 Redesign Considerations

- Reduction in number of register elements
- Narrow the charge channel
- Reduction/removal of barrier implants in image area

Calibration

Table 9.2.1: System Calibration results for Rϕ2HV = 40.9 V for each stage of the campaign

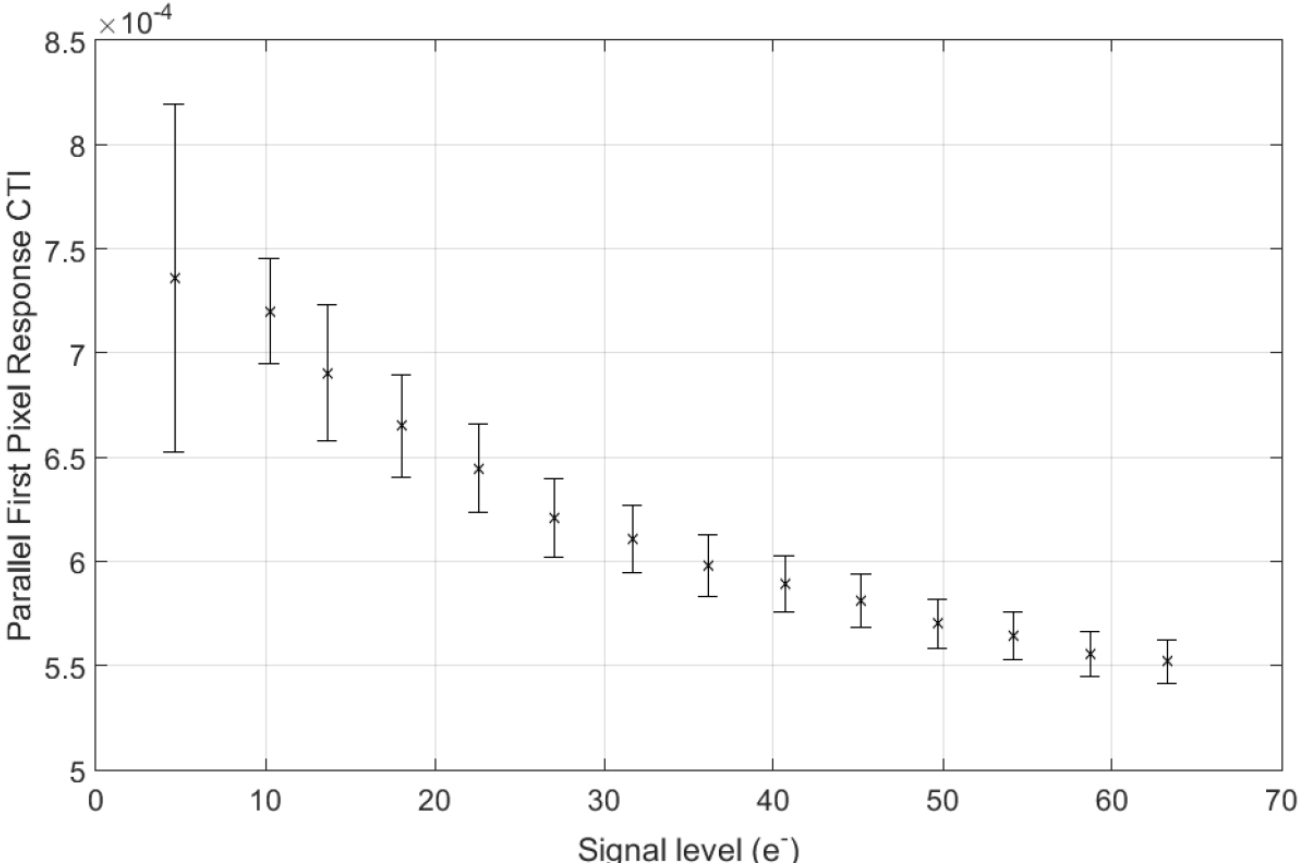
Cumulative Fluence (10MeV equiv. protons·cm^{-2})	**System Calibration (Rϕ2HV = 40.9 V) (e$^-$/DN)**
Pre-Irradiation	0.160 ± 0.005
1.0×10^9	0.178 ± 0.005
2.5×10^9	0.205 ± 0.008
5.0×10^9	0.222 ± 0.012
7.5×10^9	0.240 ± 0.016
7.5×10^9 following 1 week 298K anneal	0.241 ± 0.014
7.5×10^9 following 2 week 298K anneal	0.234 ± 0.013

Output Amplifier Responsivity

Table 9.3: Summary of measured Amplifier Responsivity values

Cumulative Fluence (10MeV equiv. protons/cm^2)	Estimated cumulative Total Ionising Dose (krad)	Amplifier Responsivity (μV/e$^-$)
Pre-Irradiation	0.0	(1.03±0.11)
1.0×10^9	0.52	(1.04±0.14)
2.5×10^9	1.31	(1.01±0.14)
5.0×10^9	2.36	(0.94±0.15)
7.5×10^9	3.93	(0.95±0.11)
7.5×10^9 following 1 week 298K anneal	3.93	(0.98±0.12)
7.5×10^9 following 2 week 298K anneal	3.93	(0.97±0.17)

Low flux CTE


×10^-4
8.5
8
7.5
7
6.5
6
5.5
5
0
10
20
30
40
50
60
70
Parallel First Pixel Response CTI
Signal level (e^-)