Jet Propulsion Laboratory
California Institute of Technology

Milestone-7: Low Noise Detector
WFIRST Coronagraph

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Acknowledgement

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Outline

- Executive Summary
  - Definition and success criteria
- Radiation transport simulations
- Radiation testing overview
- EMCCD characterization
  - Beginning of Life (BOL)
  - End of Life (EOL)
- Summary

Summary

Milestone Verification Work

- EMCCDs were exposed to high energy protons at room temperature and at cryo-operating temperatures
  - Displacement Damage Dose was consistent with 6 year life in an L2 orbit
- EMCCD meets MS-7 low noise requirements at Beginning of Life (BOL) & at End of Life (EOL)
- In addition to dark current and read noise, many other performance parameters were characterized and showed acceptable degradation after radiation exposure

EMCCD (e2V CCD201-20) satisfies MS-7 criteria

MS-7 Objective

2.3.7 Key Milestone 7

Spectrograph detector and read-out electronics is demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.

Significance: A spectrograph sensor with sufficiently low read noise and dark current has been identified as one of the technology gaps for the coronagraph instrument. Passing Milestone 7 will demonstrate that this gap has been successfully closed, and both sensor and read-out electronics that possess performance needed to meet AFTA coronagraph science requirements have been identified and have a clear path to flight.

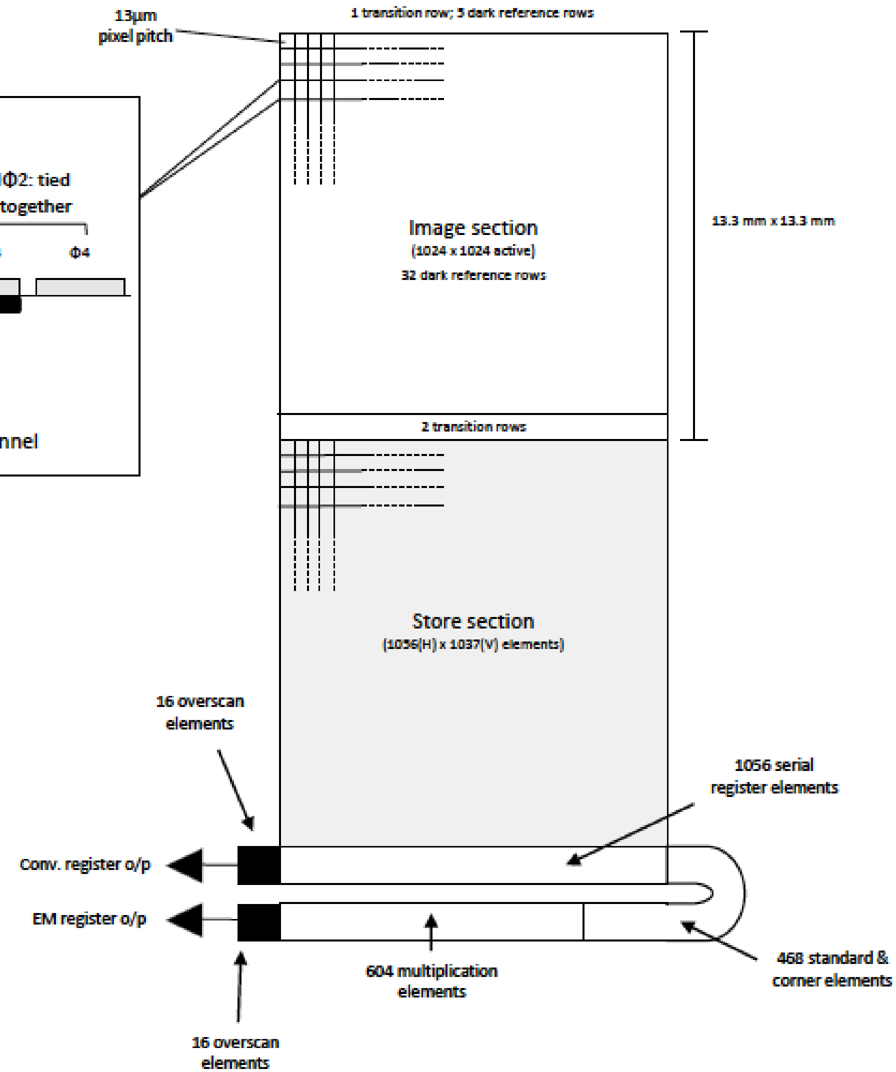
Verification Method: Samples of the sensor selected for the IFS are operated using flight-like electronics and tested under dark and imaging conditions. The dark tests provide all the sensor-specific noise levels. If the sensor is an EMCCD (currently considered the likely choice) the test will include read noise, dark current, and clock induced charge. Charge transfer efficiency will be measured using spot images at various locations on the sensor. The tests will be done before and after irradiation with the appropriate fluence of protons to mimic the on-orbit conditions.

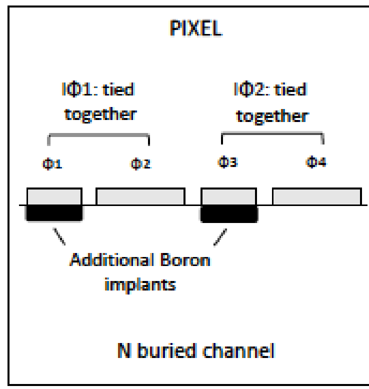
Excerpted from *WFIRST-AFTA CGI Technology Development Plan*

JPL Doc D-81964, 17 March 2014

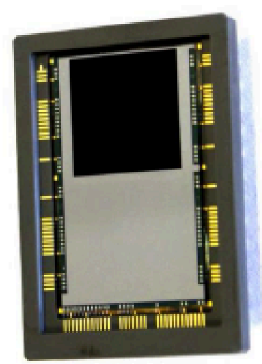
e2V CCD201-20 Architecture

- 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





Picture of CCD201-20



Taken from *Harding & Demers, et al. (2016)*

Radiation Exposure

How is exposure determined?

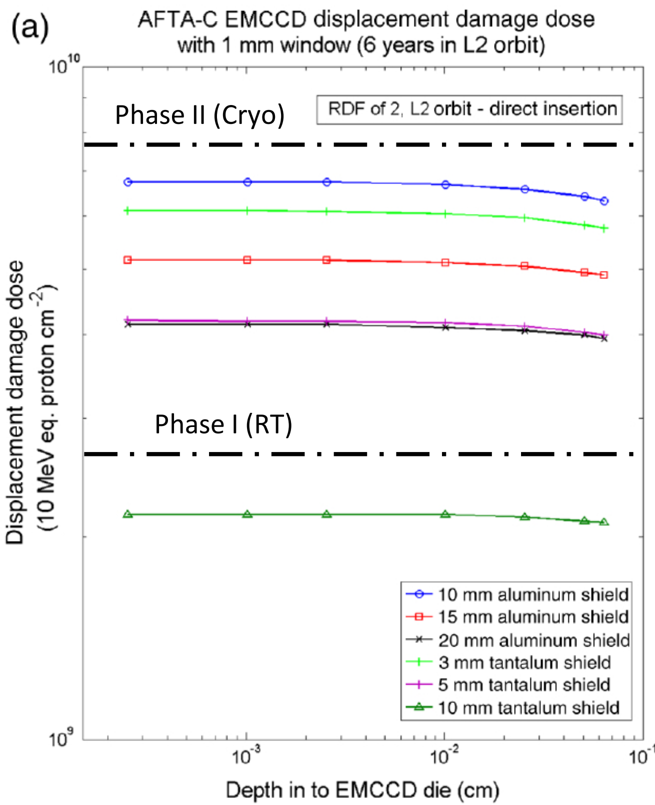
- Radiation testing simulates the *amount of damage* expected over life on orbit
- First simulate the L2 environment using validated code
- Then simulate damage exposure of detector using radiation transport code
- Specify total fluence over lifetime [particles/cm^2]
  - Displacement Damage Dose (DDD)
  - Total Ionizing Dose (TID)
- Convert the predicted lifetime fluence to a fluence at a given reference particle energy, e.g. 10 MeV protons
- Convert the reference fluence for a specific facility to deposit the required energy in the device under test (DUT)
  - Use the standard Non-Ionizing Energy Loss (NIEL) Function
  - Example: for specification in 10 MeV proton energy determine fluence for 5 MeV energy beamline
    - Fluence at 5 MeV = (Fluence at 10 MeV) ÷ (NIEL function)
    - Where 10 MeV NIEL function = $\frac{8}{E_p^{0.9}}$, where E_p is the beamline energy

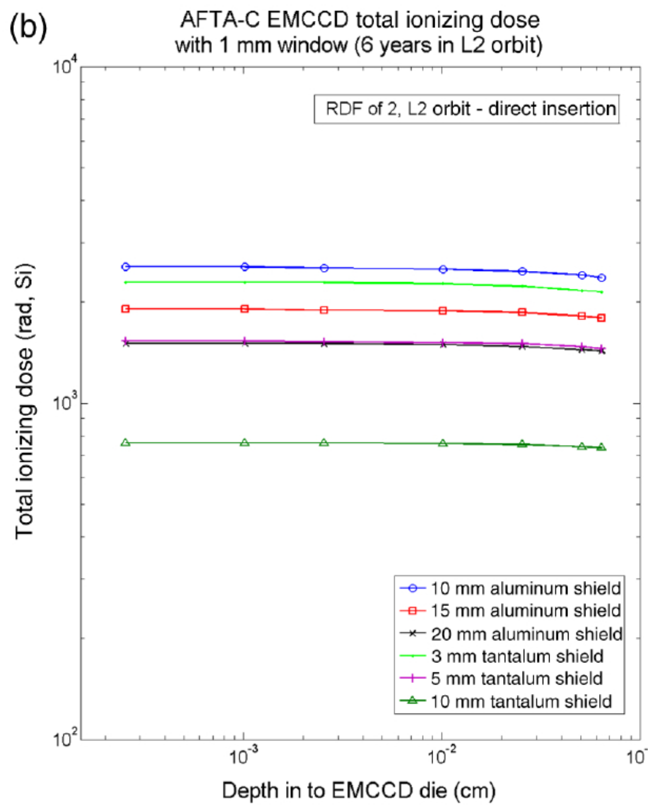
Summary of Radiation Analysis

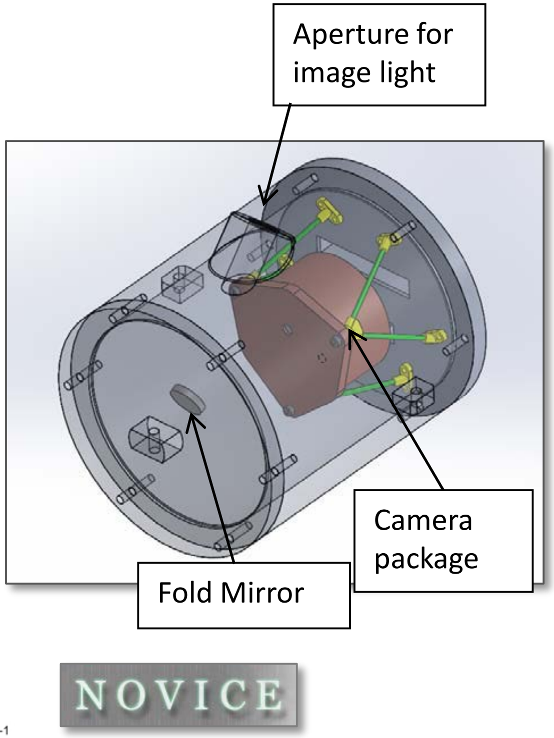
Radiation transport code NOVICE used to predict DDD and TID in L2

- Direct insertion orbit, i.e. trajectory through Earth's trapped-particle rad belts is inconsequential
- To simulate L2, code was run for GEO and contributions from Earth-trapped protons, electrons were removed
  - 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 was used to optimize 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

Harding & Demers, et al. (2016)







Radiation Code Comparison

Solar Proton Code Cross Check

- Predictions of solar protons at L2 for WFIRST and JWST were compared
- WFIRST (JPL model at 6 yrs)
- JWST (GSFC model scaled to 6 yrs)

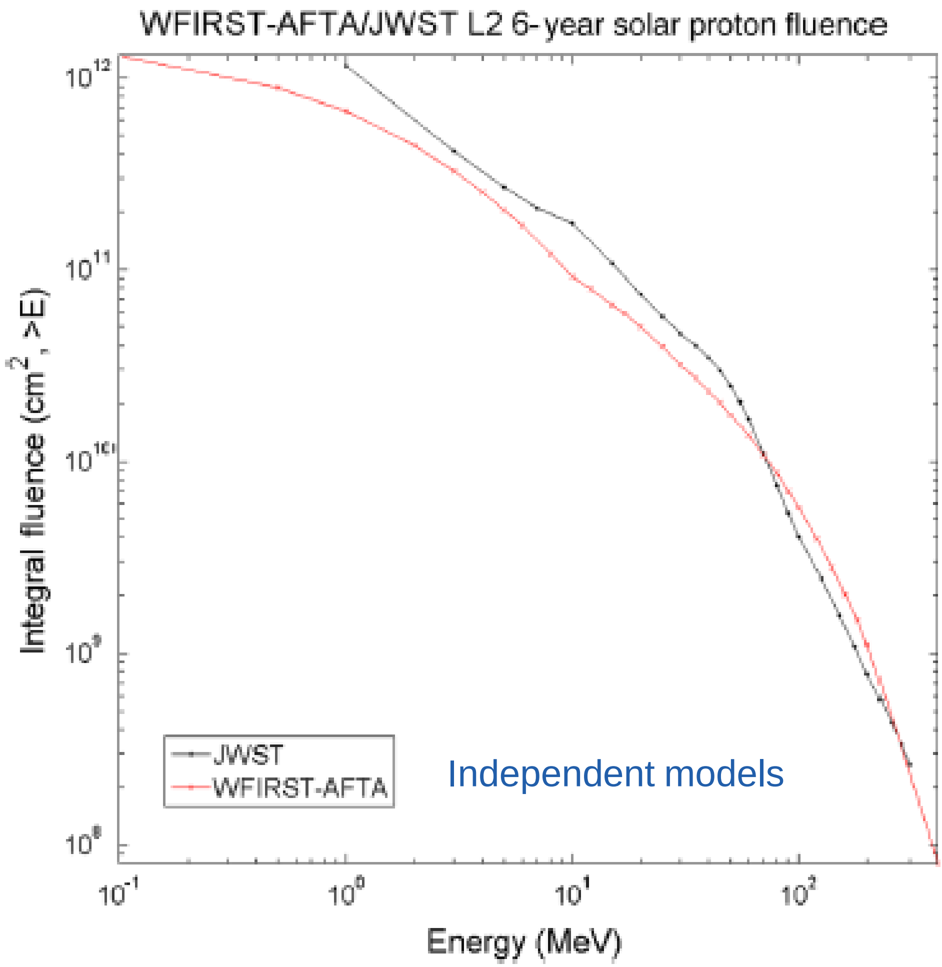
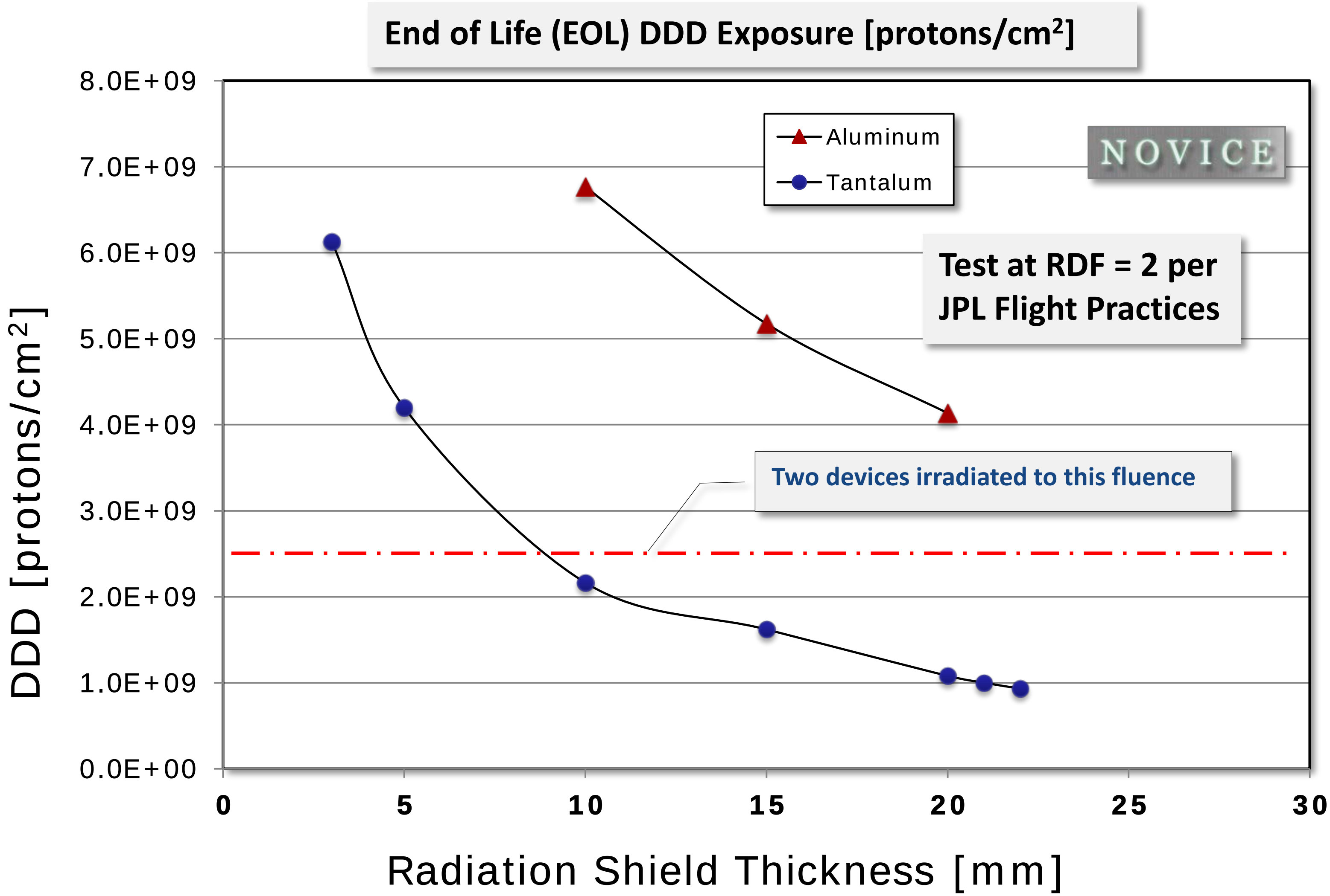


Fig. 4 Comparison of independent predictions for the solar proton fluence in a direct insertion L2 orbit for the WFIRST and JWST missions. WFIRST data were calculated based on the JPL 91 Solar Proton model at a 95% confidence level and with a radiation design factor (RDF) = 2. JWST data were scaled to 6 years based on 5-year data taken from "The Radiation Environment for the JWST" (JWST-RPT-000453).[35]

Limits of Shielding



Data from analysis by Michael Cherng *JPL Internal Memo 5132-15-015*, 18 March 2015 & recent results July 2016

Radiation Testing : Phase I

Single Displacement Damage Dose (DDD)

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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]**
  ~Corresponds to 6 years at L2 orbit with Ta shielding
- DUT engineering-grade EMCCD: e2V m/n CCD201-20
- Paul Scherrer Institute Beamline, Switzerland in April 2015
- Assessed degradation of:
  - Read Noise, EM gain, Clock Induced Charge, Dark current, Charge Transfer Inefficiency
- T = 293 K during irradiation;
- 165 ±2 K during post exposure measurement
- Unbiased during exposure
- Frame time = 100 sec
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)

DUT = device under test

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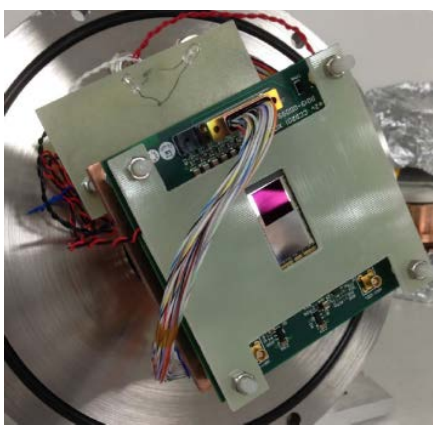
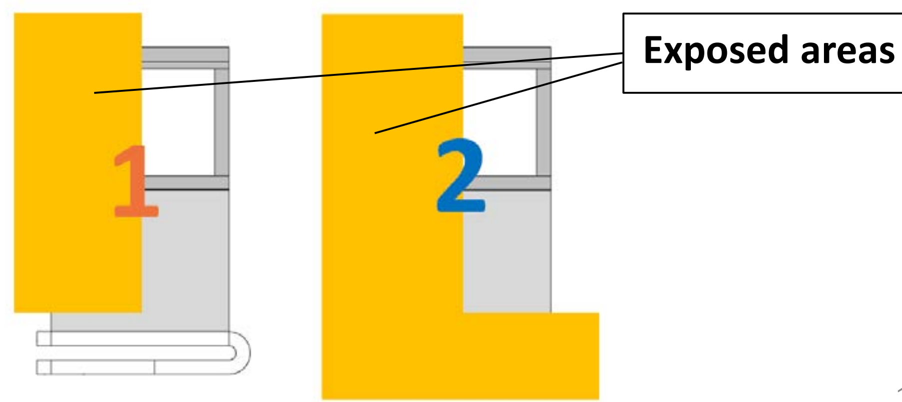


Device 1: Parallel irradiation only.

Device 2: Serial and Parallel irradiation



Radiation Testing: Phase II

Incremental Displacement Damage Dose (DDD) at Cryo

Four separate exposures of Displacement Damage Dose (DDD) at cryo-temp

- **Characterize the performance degradation at intermediate points in 6 year life cycle**
- DUT science-grade EMCCD: e2V m/n CCD201-20
- Performance fully characterized before campaign and after each of four doses
- Facility: Helios 3 Beamline, Harwell, UK
- T = 165 ±2 K for irradiation; (±5 K during measurements)
- Biased during exposure to monitor flatband voltage shift
- Inverted Mode Operation (IMO): suppression of large surface dark current
- Serial readout rate of 700kHz (some exceptions)
- 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

EMCCD Electronics

Electronics used for testing

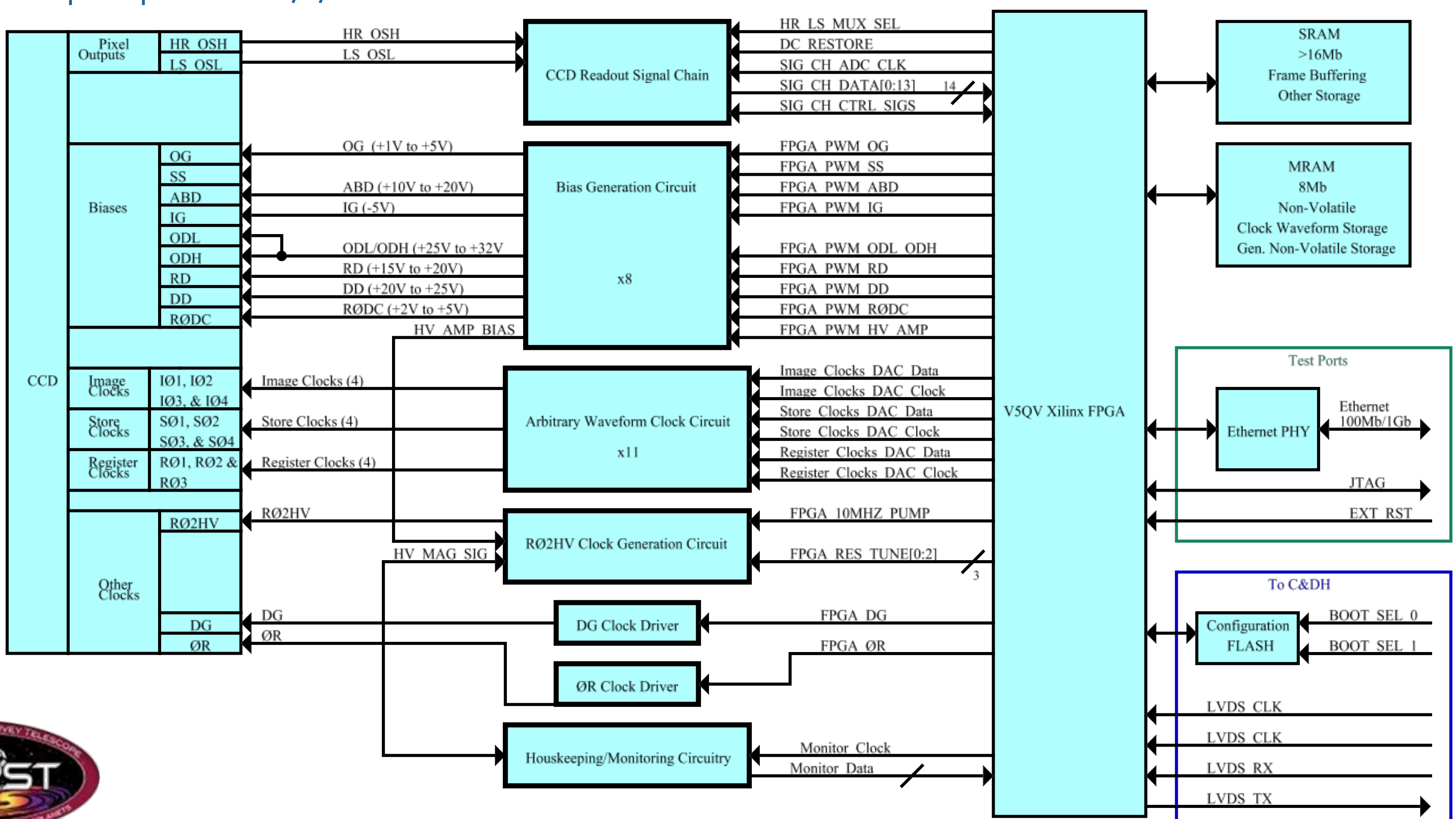
- Using the commercial NüVü EMN-2 electronics (CCCP v.3), JPL has demonstrated the MS-7 required BOL & EOL noise performance
- NüVü has identified flight analog components for its EMN-2 design to establish a path to flight
- In parallel, JPL has designed flight EMCCD electronics using flight-rated components
- For ambient temperature- and cryo-radiation testing, CEI used commercial XCAM electronics

JPL Electronics Design

Flight electronics driver has been designed

- All key components have flight heritage
  - FPGA – Xilinx Virtex-5QV (V5QV)
  - 14-bit ADC – Honeywell HMXADC9246 (now AD9246S)
  - DAC – Analog Devices AD9731
  - Preamp – LMH6702
  - Op Amp – LM7171

CCD Readout Electronics Module Block Diagram



Radiation Testing: Results

- **Characterization was independently carried out by CEI and JPL**
- JPL used the NüVü EMN2 camera system
- CEI used the Xcam camera system
- Phase I
  - CEI and JPL each characterized devices before and after single dose
- Phase II
  - CEI carried out all characterization

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

- In the following pages, measurement results will be labelled with the logo of the institution that did the work

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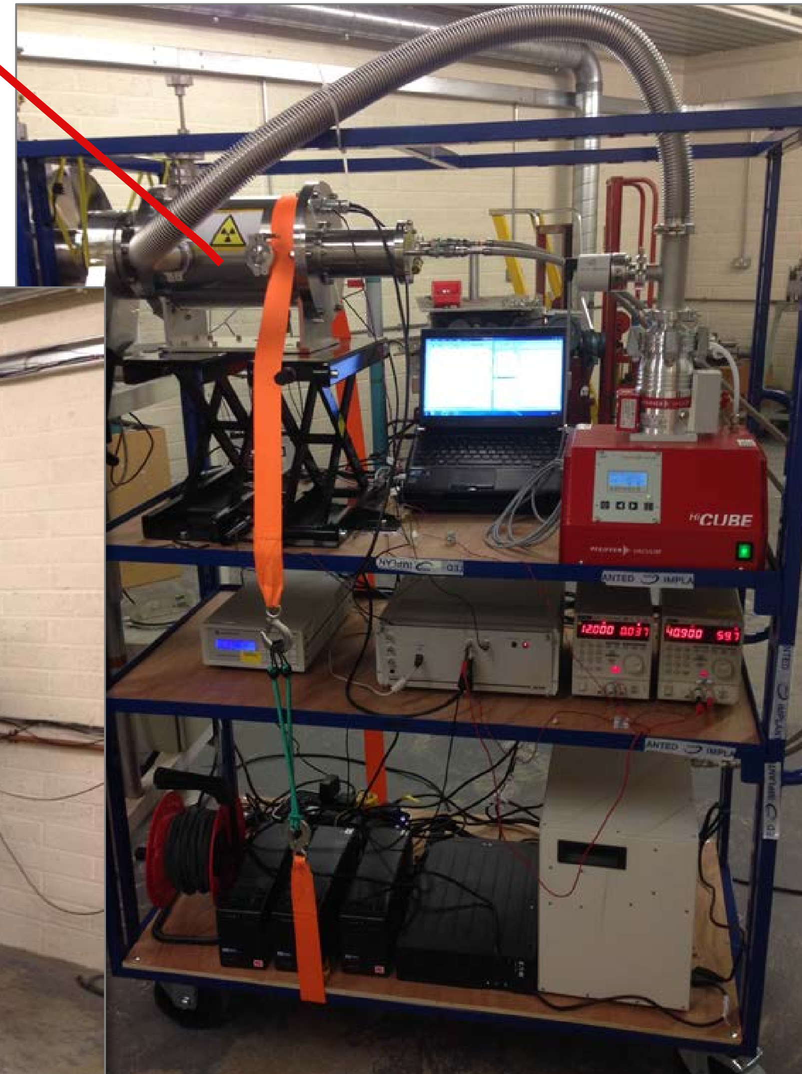
Phase II Facility – cryo radiation

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

Cryostat and EMCCD characterization hardware

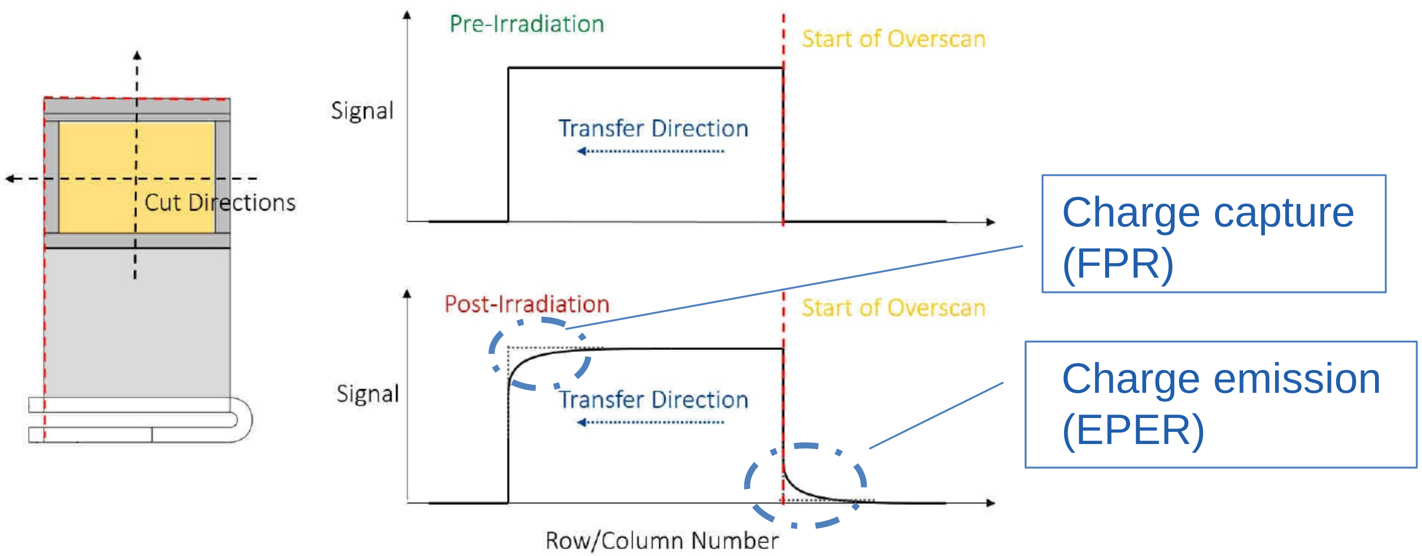
Alignment of cryostat with beamline



Charge Transfer Inefficiency

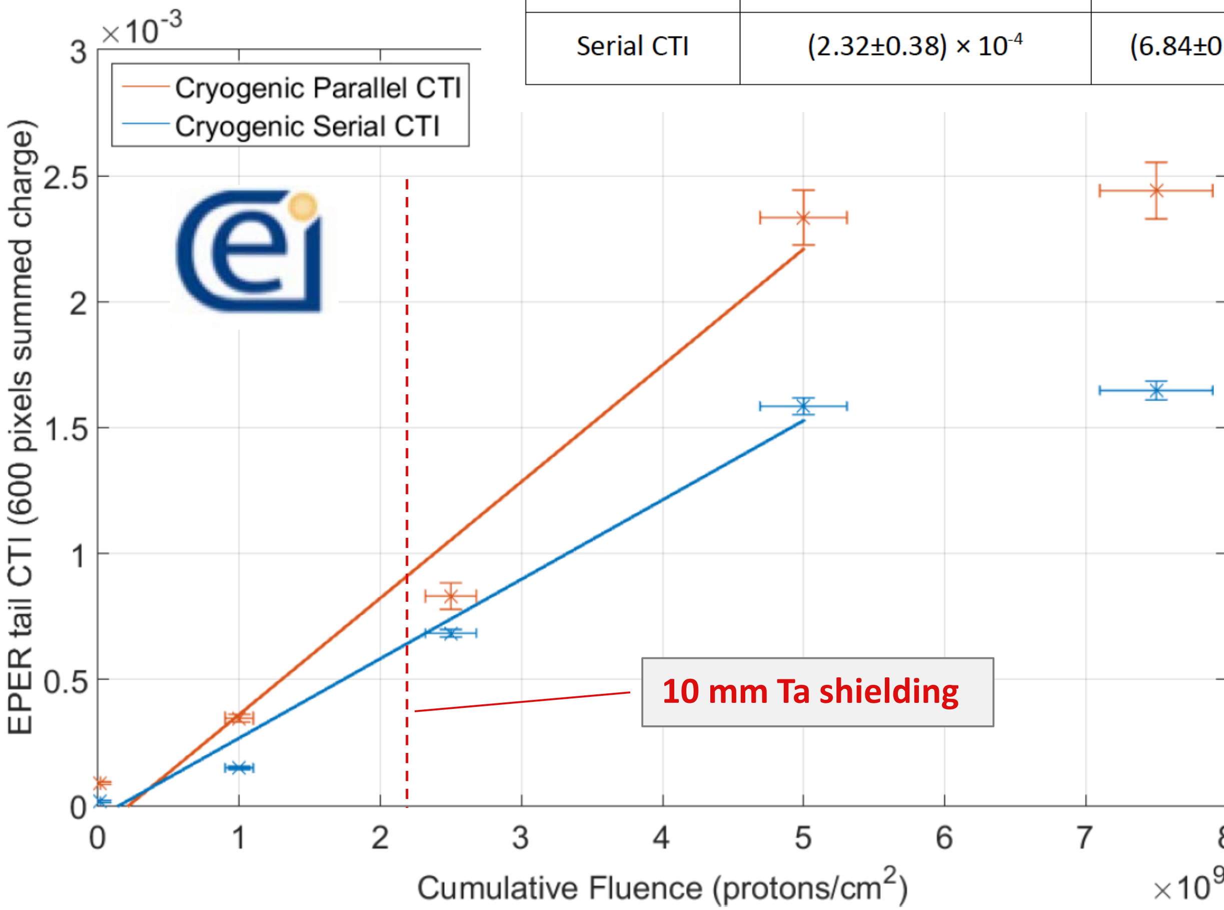
What is Charge Transfer Ineffiency (CTI)?

- Undamaged device: transfer process is highly efficient, between 5 & 6 nines
  - Example: for a 1K×1K array & 5N CTE, 0.2% of charge from farthest removed pixel is lost during transfer process to the readout
- Damaged device: CTI is dominated by defect-induced traps
  - Some signal charge is captured & later released by traps after the original signal packet has been transferred forward
  - Gives rise to a tail of deferred charge
- Measurement of Extended Pixel Edge Response (EPER) & First Pixel Response (FPR)
  - Flat field illumination at average of 10 electrons per pixel
- CTI(EPER) = (Charge in emission tail) ÷ (Signal level x no. transfers)
- CTI(FPR) = (Charge lost in first row/column) ÷ (Signal level x no. transfers)



Charge Transfer Inefficiency - EPER

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	$(3.94 \pm 0.45) \times 10^{-4}$	$(8.31 \pm 0.52) \times 10^{-4}$	≈2
Serial CTI	$(2.32 \pm 0.38) \times 10^{-4}$	$(6.84 \pm 0.15) \times 10^{-4}$	≈3



- No attempt made to optimize CTI via readout modes & clock frequency
- Only characterizing degradation

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

Charge Transfer Inefficiency - FPR

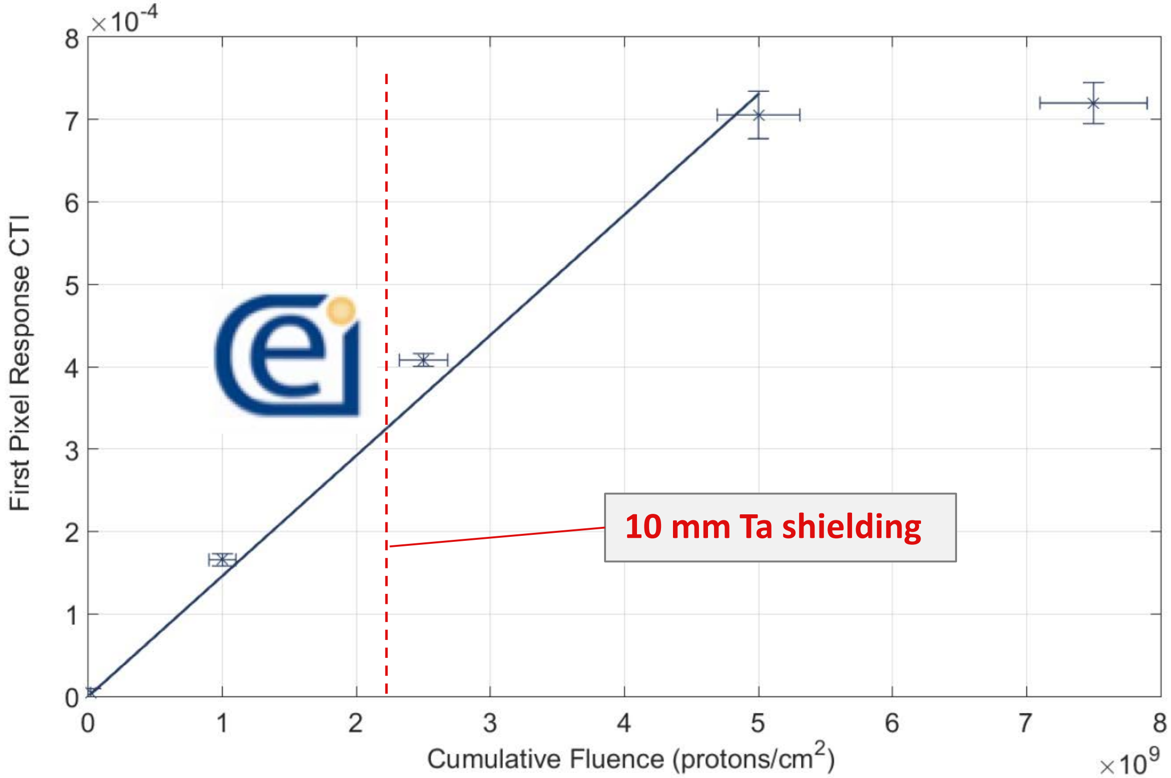


Figure 9.9.7: FPR Parallel CTI as a function of cumulative fluence level.

- No attempt made to optimize CTI via readout modes & clock frequency
- Only characterizing degradation

Readout Noise in EMCCD

What is Readout Noise?

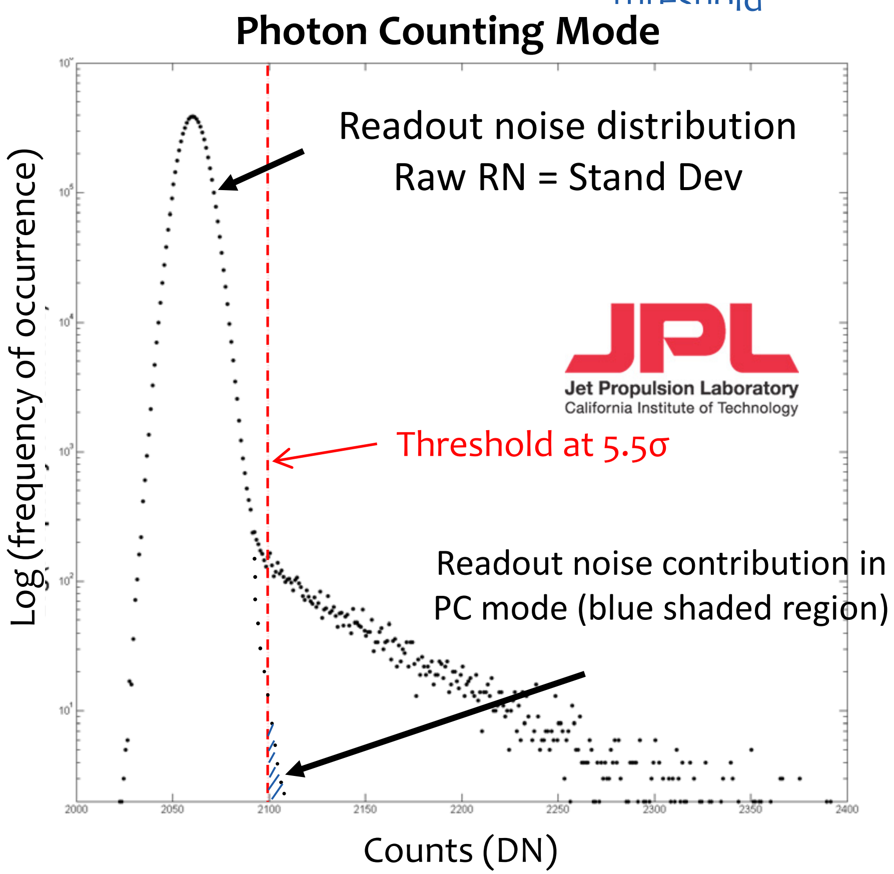
- Read noise is noise generated during the readout process
- It is noise associated with the conversion of charge to an electric impulse at output amplifier

Analog Mode

- Read noise is Gaussian
- Effective RN = RN/EM gain
- Proportionately reduced by EM gain

Photon Counting Mode

- Read noise is Gaussian
- Essentially zero using photon counting threshold



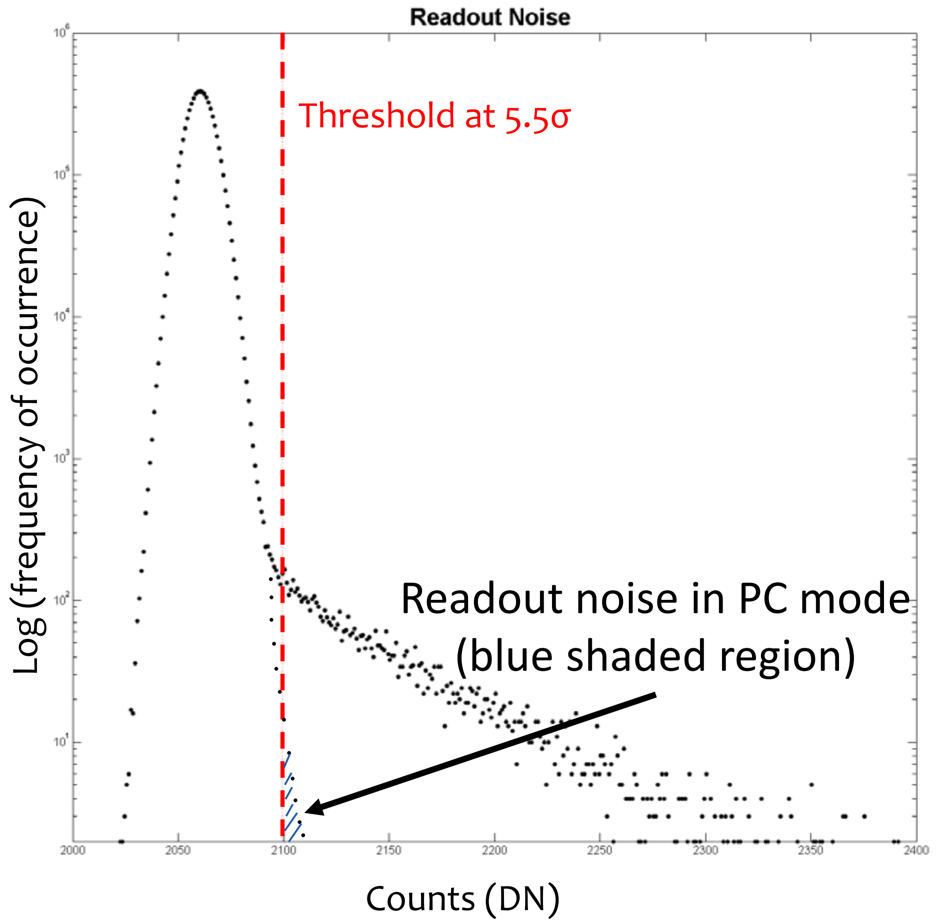
Readout Noise

EOL Readout Noise

MS-7 requirement: 1e$^-$/pix/frame

RN (no EM gain) = 75 e$^-$ @ 10MHz

RN (w/EM gain & PC) = 1.7×10^{-6} e-/pix/frame



Clock Induced Charge

What is Clock Induced Charge (CIC)?

- Noise contribution created during charge transfer ("spurious charge")
  - Clock swing from inverted to non-inverted state accelerates minority carriers (holes) previously trapped at the insulator interface to high energies
  - Collision of accelerated holes with silicon ions (impact ionization) results in electron-hole pairs and spurious electrons
- CIC is present in all CCDs but only detectable in EMCCDs
- Accumulation of holes in insulator results in flat-band voltage shift
- Dependence on
  - # of transfers
  - Clock amplitude
  - Clock freq. (inverse relation)
  - Resolution of clock edge
  - Mode of operation (IMO vs. NIMO)
- Independent of integration time

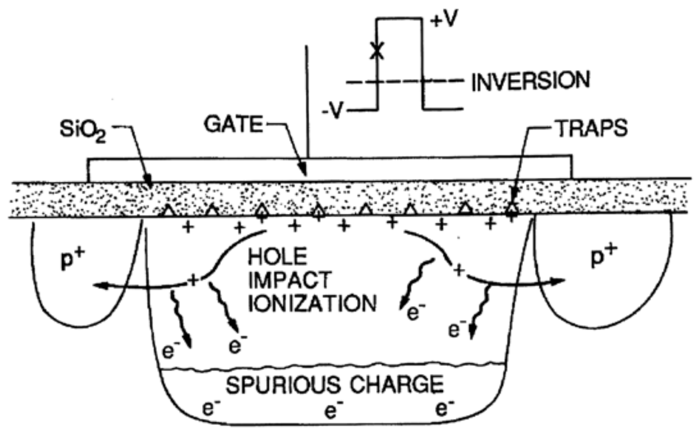


Figure 7.24 Spurious-charge generation.

Figure from
Scientific Charge-Coupled Devices
J.R. Janesick, SPIE Press 2001

Parallel Clock Induced Charge

- CIC is sensitive to clock amplitude
- Inversely related to clock freq. (lower graph)
- 10x lower CIC has been demonstrated by JPL using NüVü electronics (2×10^{-3} e-/pix/fr)
- Conclusion:
  - CIC increase is small compared to dark current
  - Flat-band shift can be compensated by bias voltages

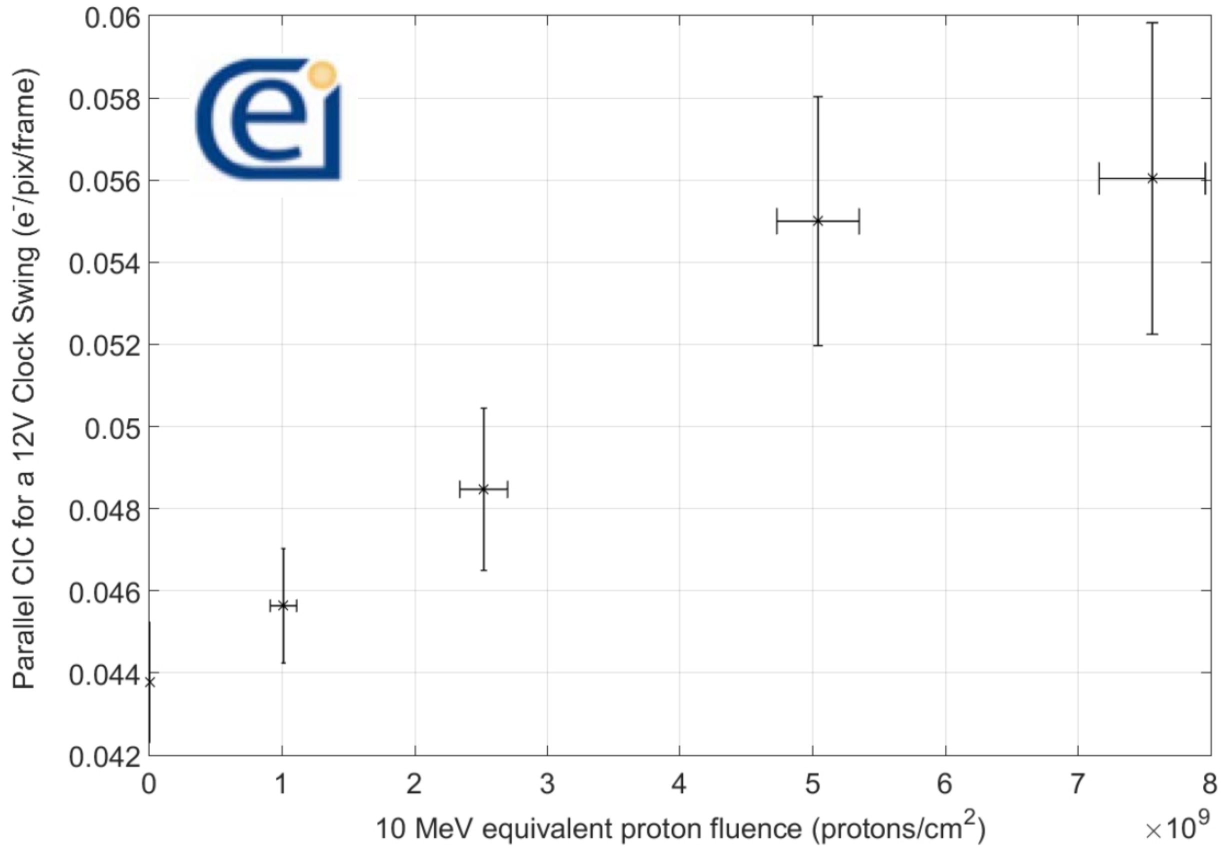


Figure 9.6.4: Illustration of parallel CIC measured for a 12V clock swing as a function of irradiation fluence. The CIC measured for the final fluence (7.5×10^9 protons/cm^2) agrees with the penultimate fluence within the quoted errors.

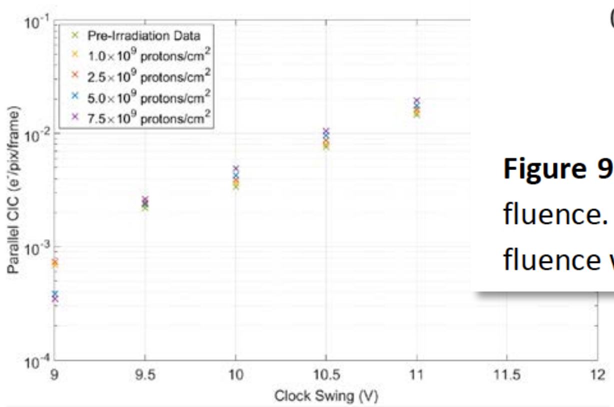


Figure 9.6.3: Illustration of CIC results for each clock swing measurement and irradiation fluence. Error bars are excluded for clarity.

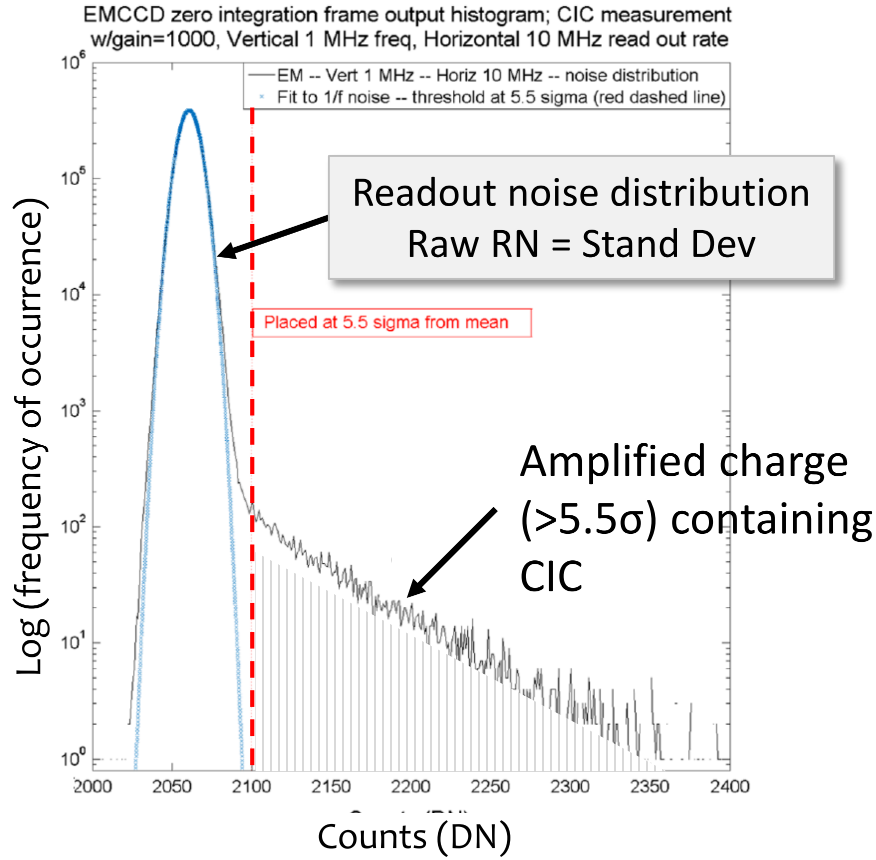
Clock Induced Charge

Can measure CIC by taking zero exposure, zero integration frames with high EM gain and plotting histogram (see right)

CIC (BOL) < 2.1×10^{-3} e-/pix/frame

CIC (EOL) < 2.3×10^{-3} e-/pix/frame

No MS-7 requirement on CIC



EOL clock-induced charge in EMCCD

Amplifier	Horizontal Rate [MHz]	Vertical Freq. [MHz]	EM Gain	V_{ss} [volts]	CIC	Units
High gain electron multiplication	10	1	1000	4.5	1.25×10^{-3}	e-/pix/frame
High gain electron multiplication	10	1	1000	0	2.30×10^{-3}	e-/pix/frame

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

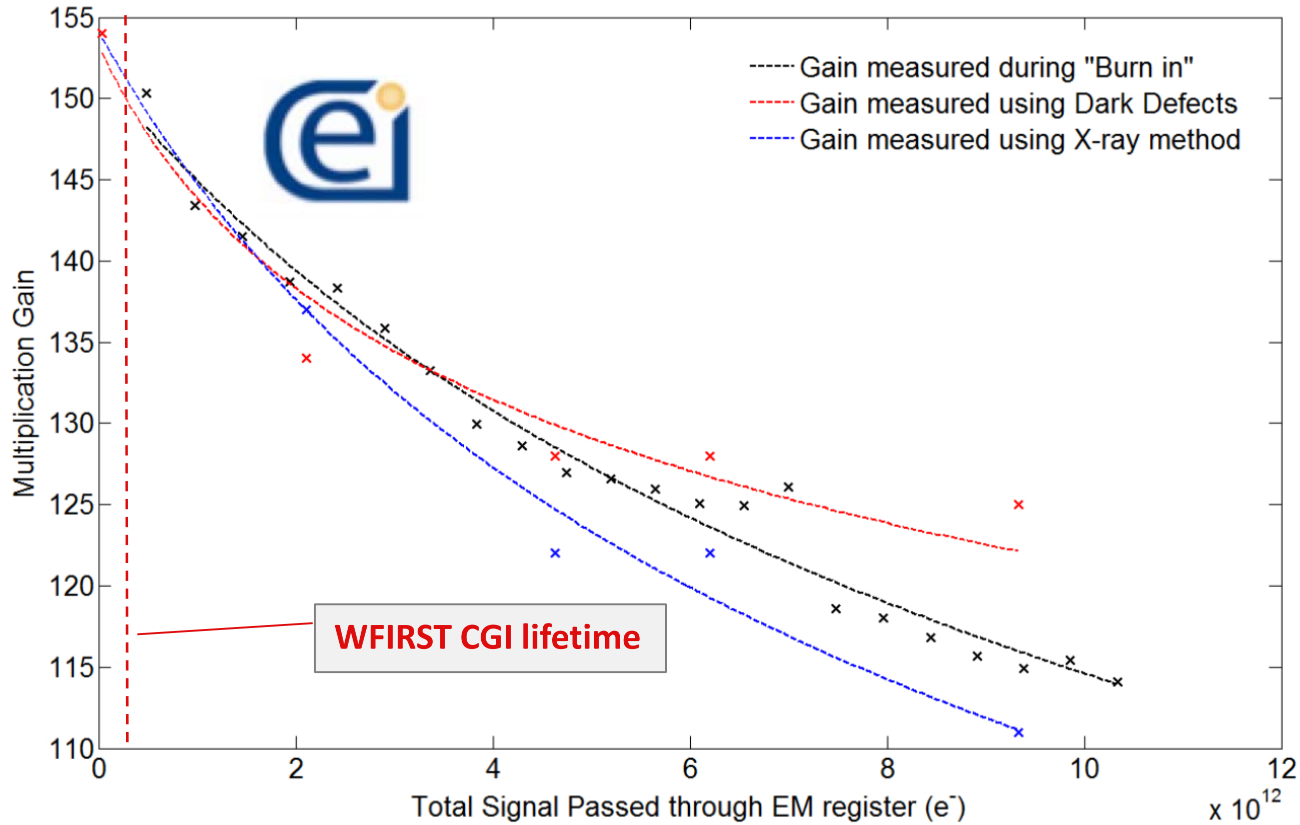
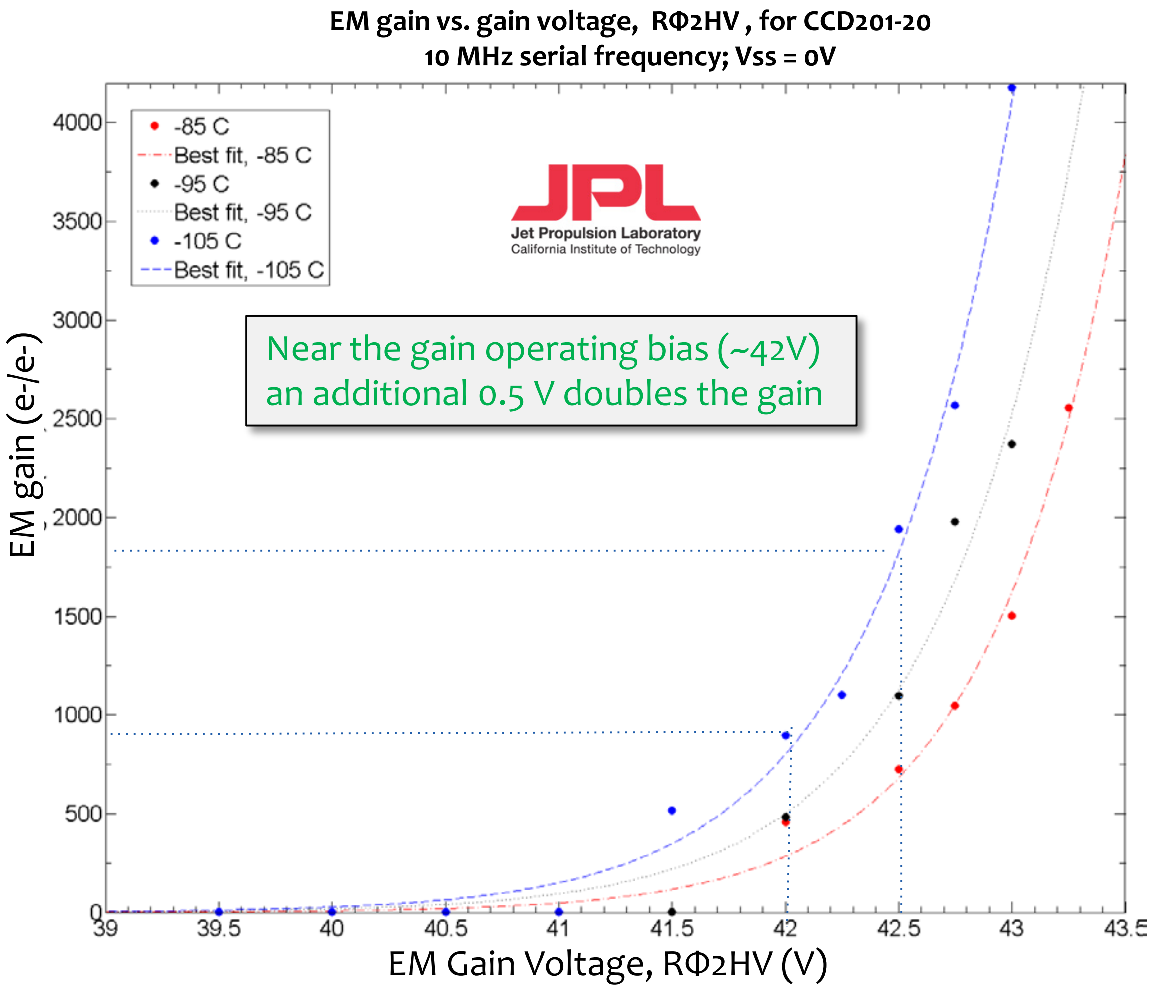


Figure 9.4.1: Multiplication gain measured as a function of total signal passed through the EM register. Both the X-ray method and dark defect method are consistent with the expected drop due to ageing within the quoted errors (Table 9.4.1). The deviation from the trend at the larger signal levels is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

Gain Control Authority

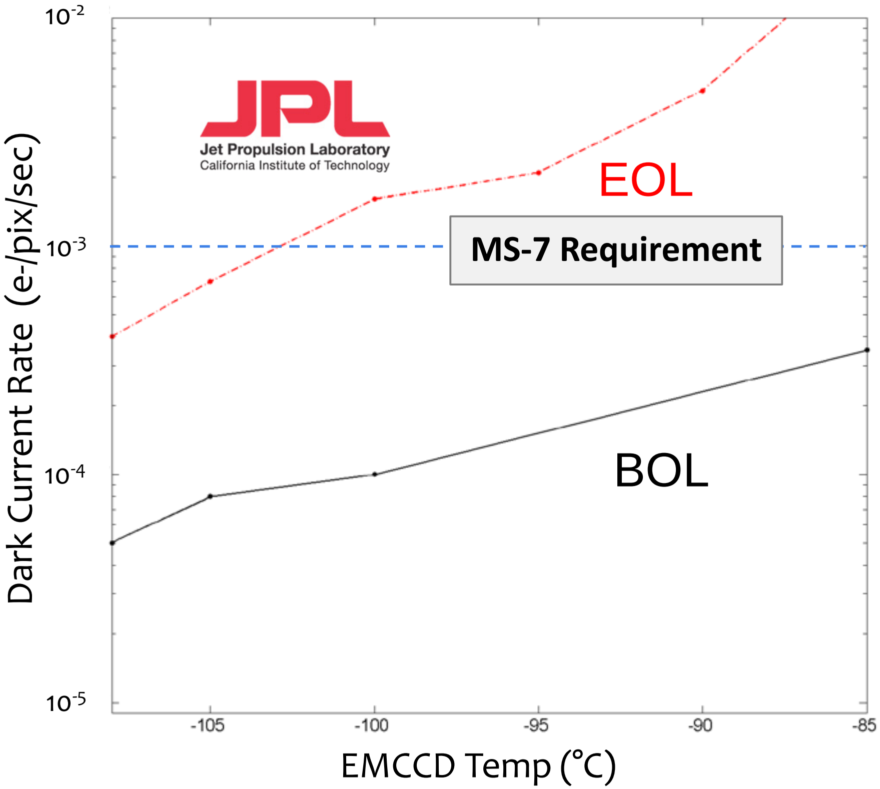
Modest gain degradation over life cycle is easily compensated by gain voltage increase



Dark Current

What is Dark current?

- Thermal generation of minority carriers common in all semiconductor devices
- Lower dark current achieved by cooling a device
- Surface dark current is suppressed in inverted mode operation (IMO)
- Non-inverted mode operation (NIMO) can also provide low dark current at a lower temperature than IMO



Dark current:

MS-7 requirement: 0.001 e^-/pix/sec

BOL (IMO) = 0.00003 e^-/pix/sec; T = 168K

EOL (NIMO) = 0.0007 e^-/pix/sec; T = 168K

Dark Current

- Linear degradation with proton fluence
- 8x reduction of dark current after 1 week RT anneal (not shown)
- For same fluence, RT irradiation device dark current ~10x lower
- Conclusion:
  - Dark current passes MS7 requirement after full campaign (5×10^{-5} pr/cm^2)
  - 10 mm thick Ta shield results in EOL dark current < 10^{-4} e-/pix/s

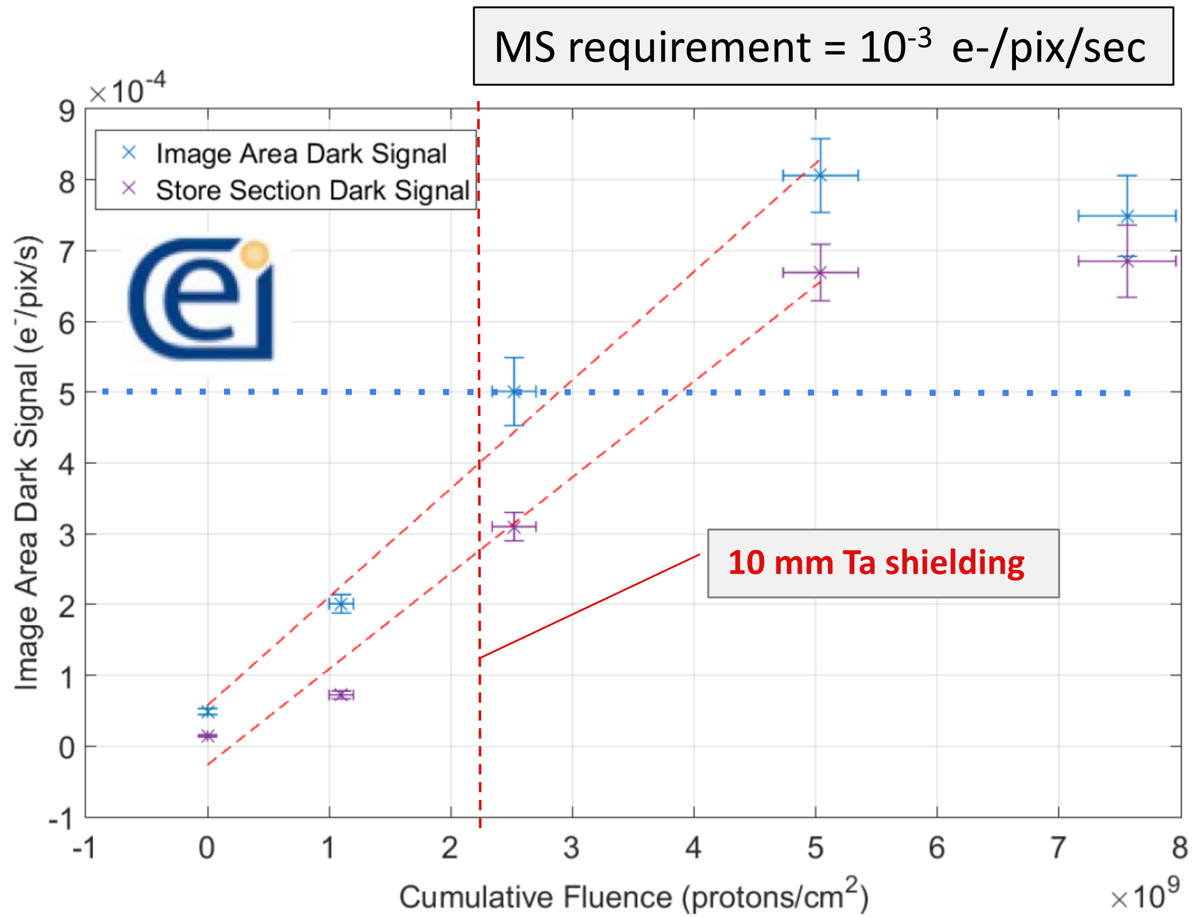
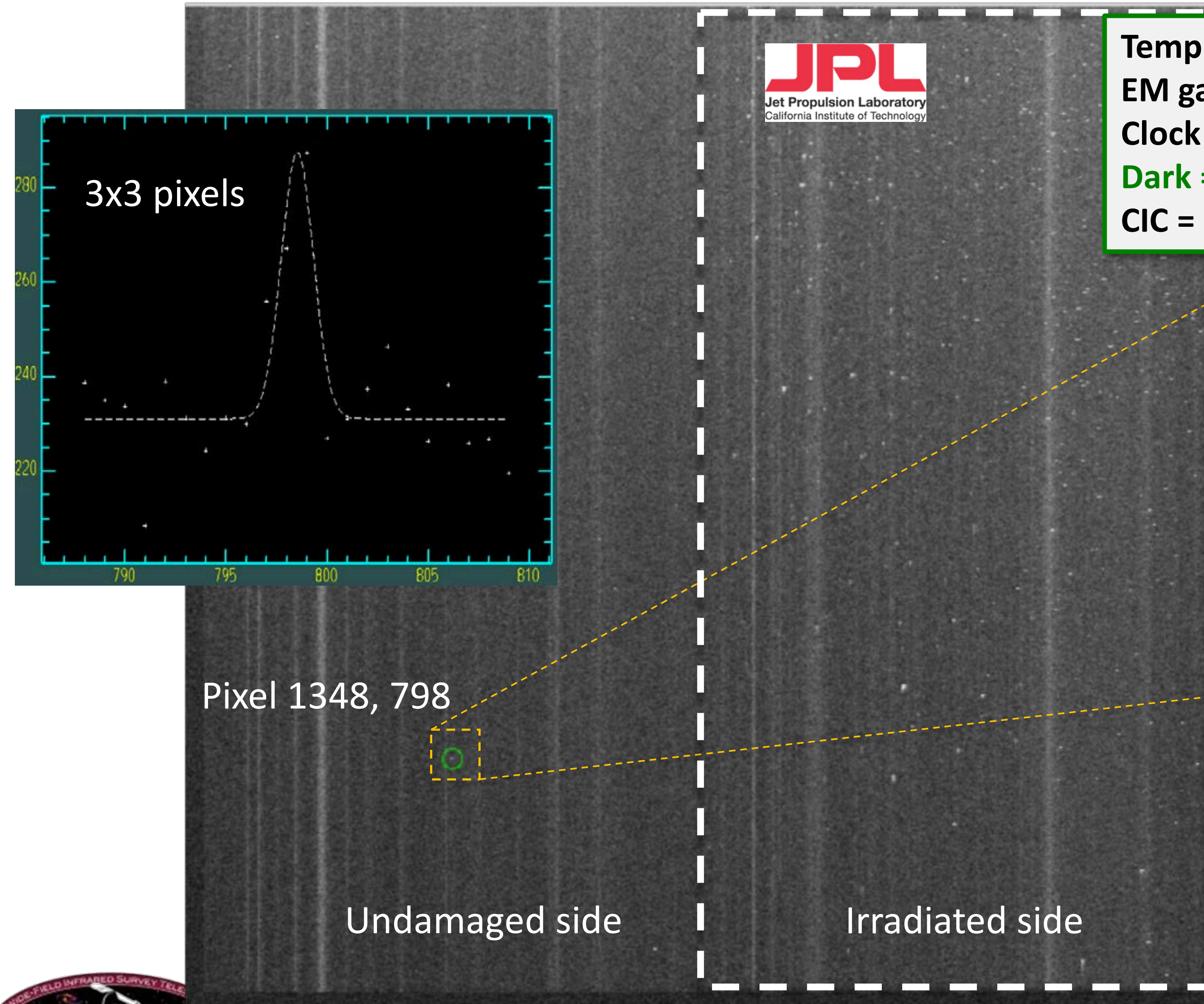
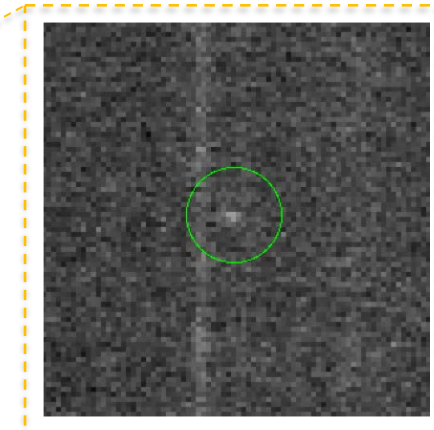


Figure 9.7.2: Dark signal values for each proton fluence. Data is shown for dark current measured in the image area and frame store region. The image area systematically exhibits higher dark current; an observation noted in other studies with back thinned sensors that also have an aluminium frame store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

Low Flux PSF Measurement – BOL



Temp = -105 C (168 K)
EM gain = 1100
Clock swing (serial = +10 V)
Dark = 0.0004 e-/px/sec
CIC = 0.002 e-/px/fr



Low flux detection:
PSF = 0.02 e-/PSF/fr
3×3 pixels

Serial ← Parallel

Low Flux PSF Measurement – 2.5×10^9 pr/cm²

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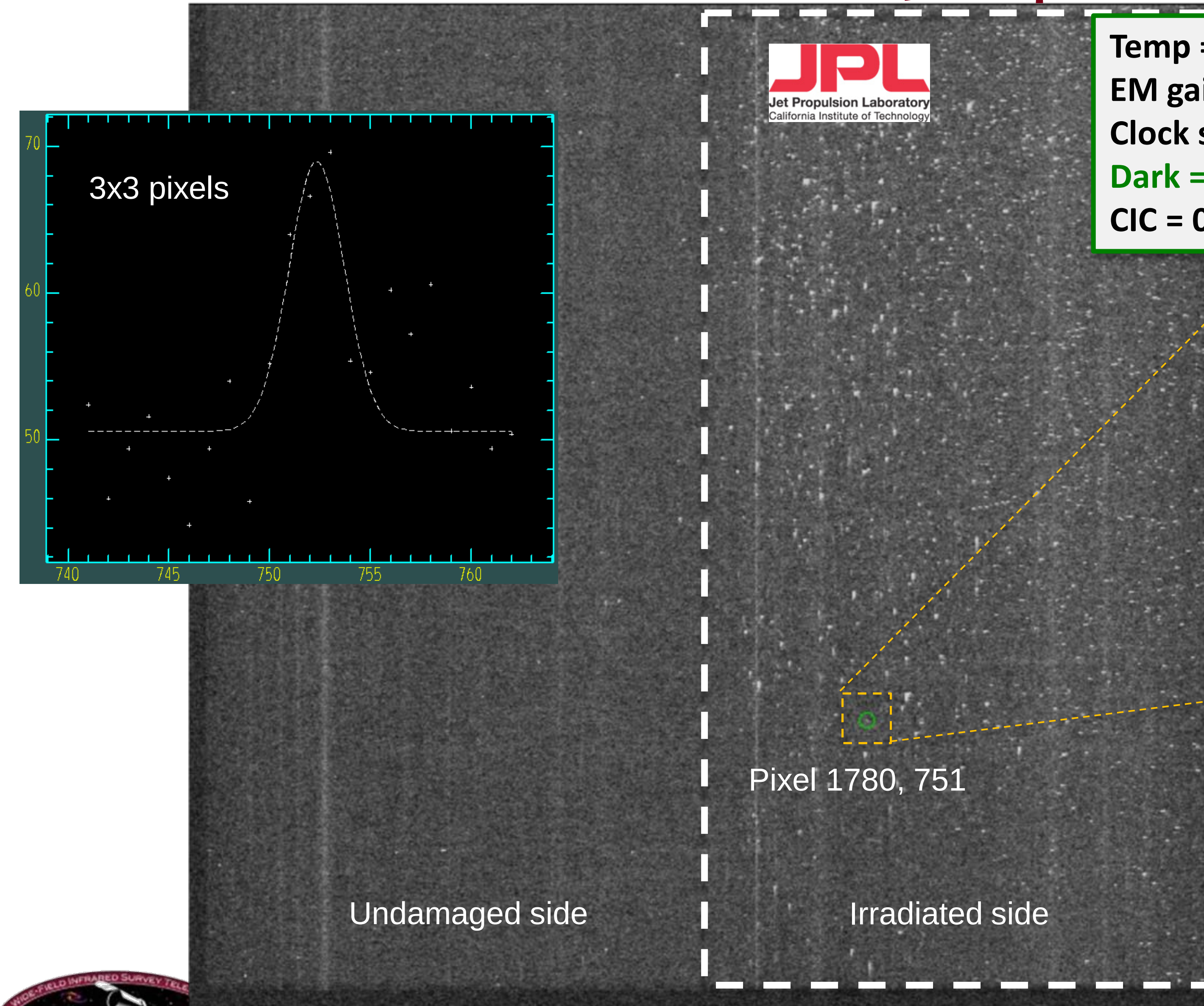
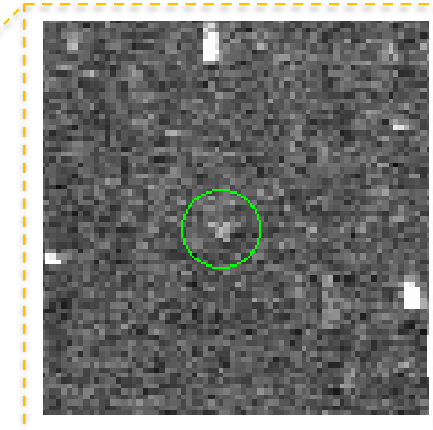


Temp = -105 C (168 K)
EM gain = 1100
Clock swing (serial = +10 V)
Dark = 0.0007 e-/px/sec
CIC = 0.002 e-/px/fr



Low flux detection:
PSF = 0.06 e-/PSF/fr
3×3 pixels

Serial
Parallel

Cryo Radiation Test Summary

Parameter	Units	Org.	Pre-Irradiation	Post-Irradiation 2.5×10^9 pr/cm²	MS-7 Requirement
Image area Dark Current	e-/pix/sec	JPL	$(3.00 \pm 0.40) \times 10^{-5}$	$(7.00 \pm 0.0) \times 10^{-4}$	1.0×10^{-3}
Effective Read Noise	e-/pix/frame	JPL	$(1.70 \pm 0.0) \times 10^{-6}$	$(1.70 \pm 0.0) \times 10^{-6}$	1.0
Total CIC	e-/pix/frame	JPL	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.3 \pm 0.2) \times 10^{-3}$	—
EPER Parallel CTI (10e- signal)	-	CEI	$(8.88 \pm 0.49) \times 10^{-6}$	$(8.32 \pm 0.52) \times 10^{-4}$	—
EPER Serial CTI (10e- signal)	-	CEI	$(1.65 \pm 0.47) \times 10^{-5}$	$(6.84 \pm 0.15) \times 10^{-4}$	—
X-Ray Parallel CTI (1 event/2700 pix)	-	CEI	$(0.569 \pm 1.0) \times 10^{-6}$	$(1.31 \pm 0.05) \times 10^{-4}$	—
X-Ray Serial CTI (1 event/2700 pix)	-	CEI	$(1.65 \pm 2.08) \times 10^{-6}$	$(4.12 \pm 0.35) \times 10^{-5}$	—

NOTES

1. CEI measurements made at 165K using XCAM commercial electronics, not performance optimized
2. JPL measurements made at 168K using NüVü flight-like commercial electronics, performance optimized
3. CEI read noise measurement (not shown) made in analog mode with low gain
4. JPL read noise measurement made in photon counting mode with high gain
5. JPL EOL measurements are optimized for extremely low flux detection and result in slightly higher dark current.

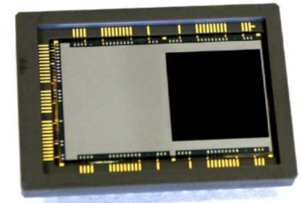
Summary of Findings

- Cryo-radiation testing (DDD) was carried out up to a cumulative dose of 5.0 x 10^9 pr/cm^2
  - In L2 expect < 2.5 x 10^9 pr/cm^2 (10 MeV equivalent)
- Dark current degradation is minimal and passes MS-7 criterion
  - Can reduce degradation of dark current and CTI by warming the detector at zero bias for long periods (while CGI is not observing)
- Effective Read Noise is not degraded by the radiation
- CIC degradation by ~10% is acceptable
- EM gain degradation ~25% due to device aging (not radiation)
  - Handily compensated by drive voltage
- Required radiation shield design is understood

Conclusion: CCD201-20 with flight-like electronics meets Milestone-7 requirements

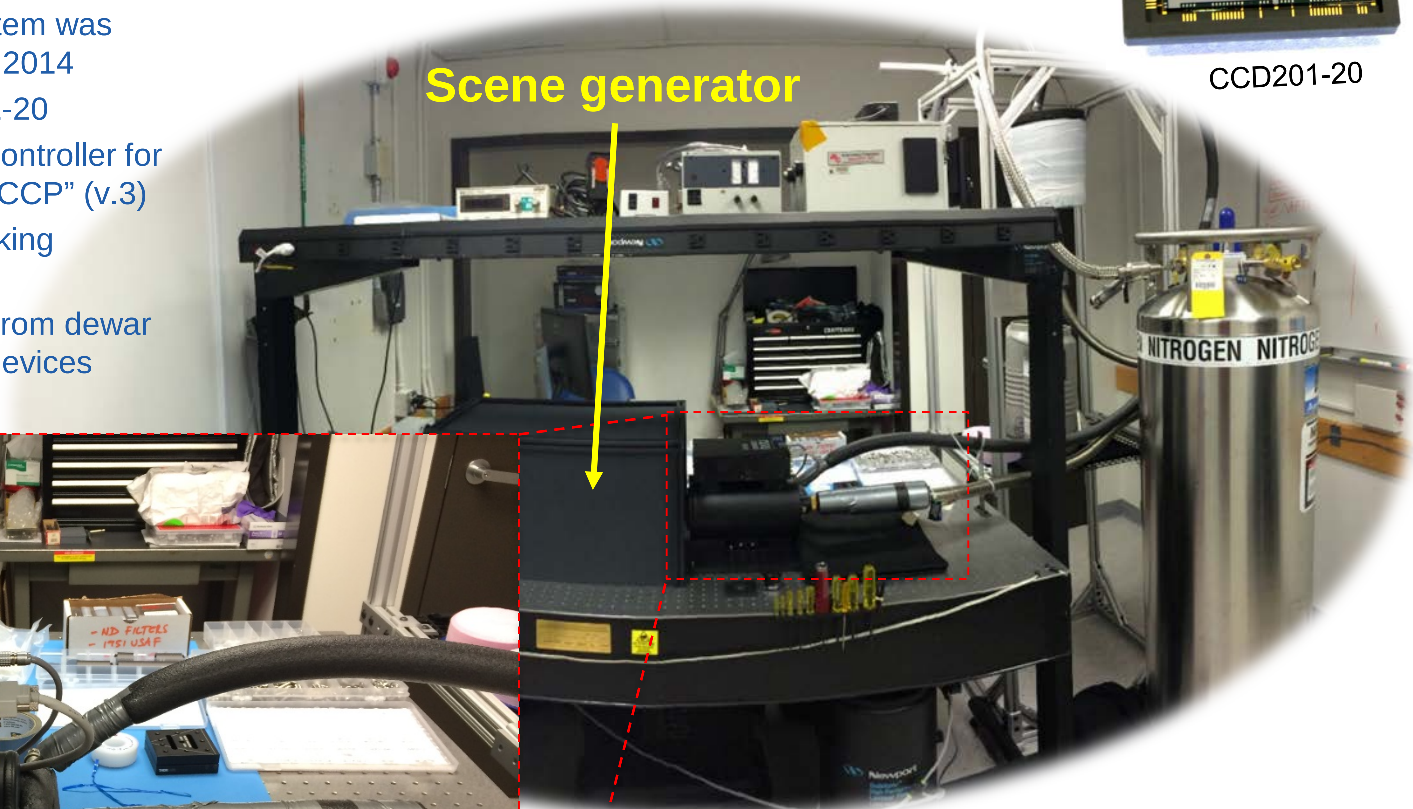
RESERVE SLIDES

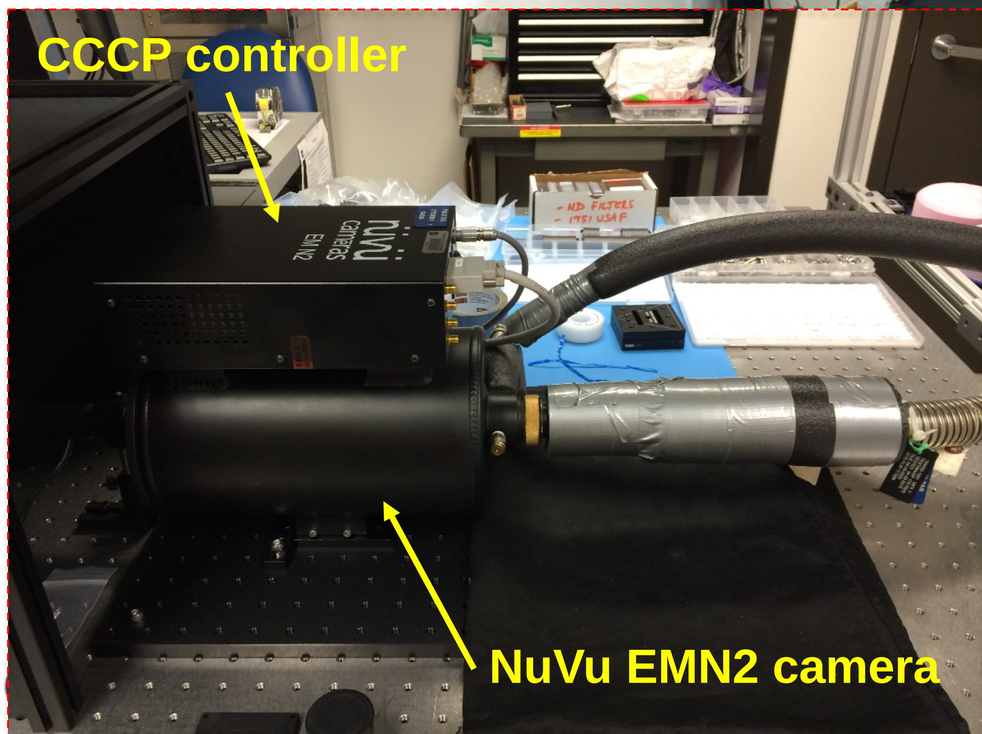
EMCCD test laboratory



CCD201-20

- NuVu EMN2 camera system was delivered to JPL, Oct 15, 2014
- EMN2 houses a CCD201-20
- System uses the “CCD Controller for Counting Photons”, or “CCCP” (v.3)
- Allows full access to clocking waveforms
- Sensor can be removed from dewar and replaced with other devices





- The NuVu EMN2 was used to characterize:
  - BOL performance
  - EOL performance
  - Radiation damage
  - Clocking optimization in CCD controller for improved performance
- CGI-relevant low flux testing

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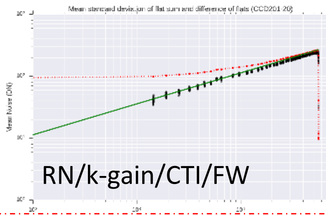
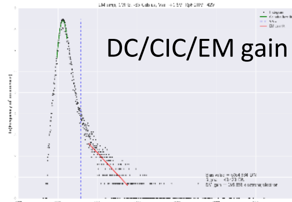
The road to sub electron detection

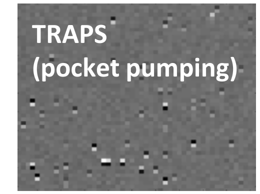
Detector characterization

- *Beginning of life*
- *Scientific CCD201-20*
- *NuVu EMN2 camera*

- Read noise (RN)
- Conversion gain (k-gain)
- Dark current (DC)
- Clock Induced Charge (CIC)
- Charge transfer inefficiency (CTI)
- Linearity/full well (FW)/DSNU
- EM gain
- ***Development of POCKET PUMPING***



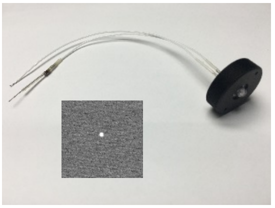


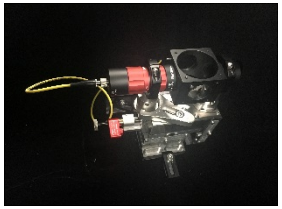


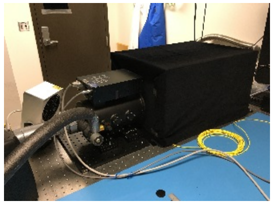
Scene generator implementation

- *Produces PSF ~3x3 px*
- *ZERO background*

- LED
- ND filters
    - OD=0.1/0.5/1/2/3/4
- Collimator/camera
- Arbitrary signal generator
- Complete light-tight enclosure



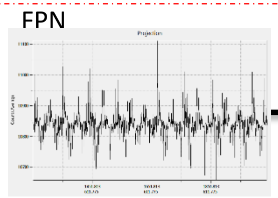


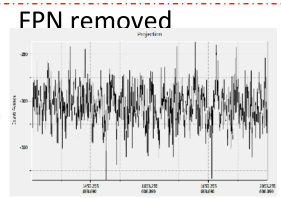


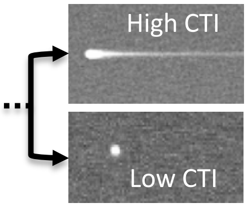
Fixed Pattern Noise /clock optimization

- *Characterization and removal of FPN*
- *Optimize CTI*

- Remove FPN
- **Modify clocking voltages**:
- *RφDC & φR (high)*
- *Rφ2HV*
- *Rφ1,2,3 (high/low)*
- *Iφ/Sφ1,2,3,4 (high/low)*
- *Vss*



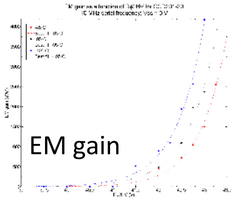


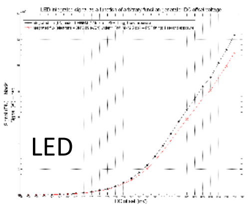


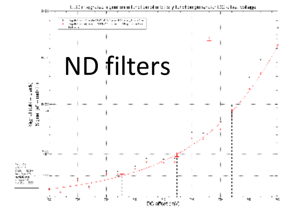
Sys. calib. & photon counting software

- *Characterizing performance of scene generator*

- EM gain vs. RΦ2HV
- LED/ND filter calibration
- Dark current & CIC trade-off (& CTI)
- Python routine development for photon counting
- Python routine development for photometry



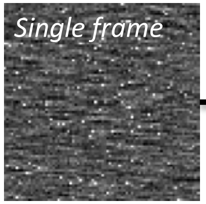


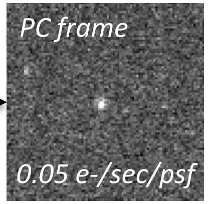


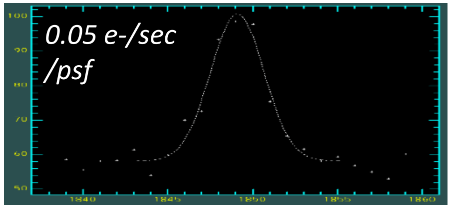
Low flux detection

- *Obtain calibrated low flux data*
- *Produce photon counted image*

- **Total signal in 3x3 PSF core**:
- *100 e-/sec/psf*
- *50 e-/sec/psf*
- *25 e-/sec/psf*
- *10 e-/sec/psf*
- *1 e-/sec/psf*
- *0.05 e-/sec/psf*



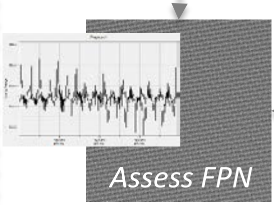




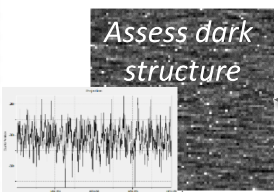
Photon counting with an EMCCD

CALIBRATION

Bias raw data



Create masterbias frame

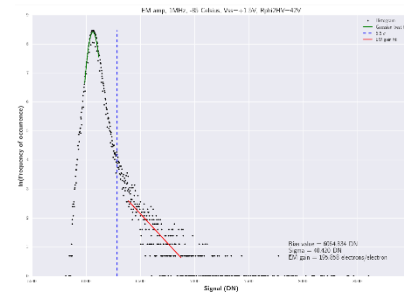


Create masterdark frame

Dark raw data

PHOTON COUNTING

Science raw data



Science data now de-biased, FPN removed and dark subtracted

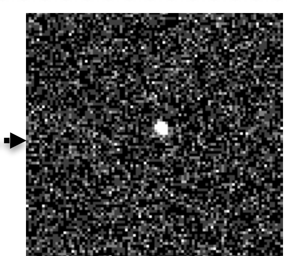
Create histogram of calibrated science data (per frame)

Threshold each histogram at 5.5σ

Create photon map of thresholded frames (<5.5σ=0; >5.5σ=1)

Construct FITS PC image

PSF fitting
Photometry
3x3 pixel FWHM



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Low flux measurement results

✖ = PSF pixel position

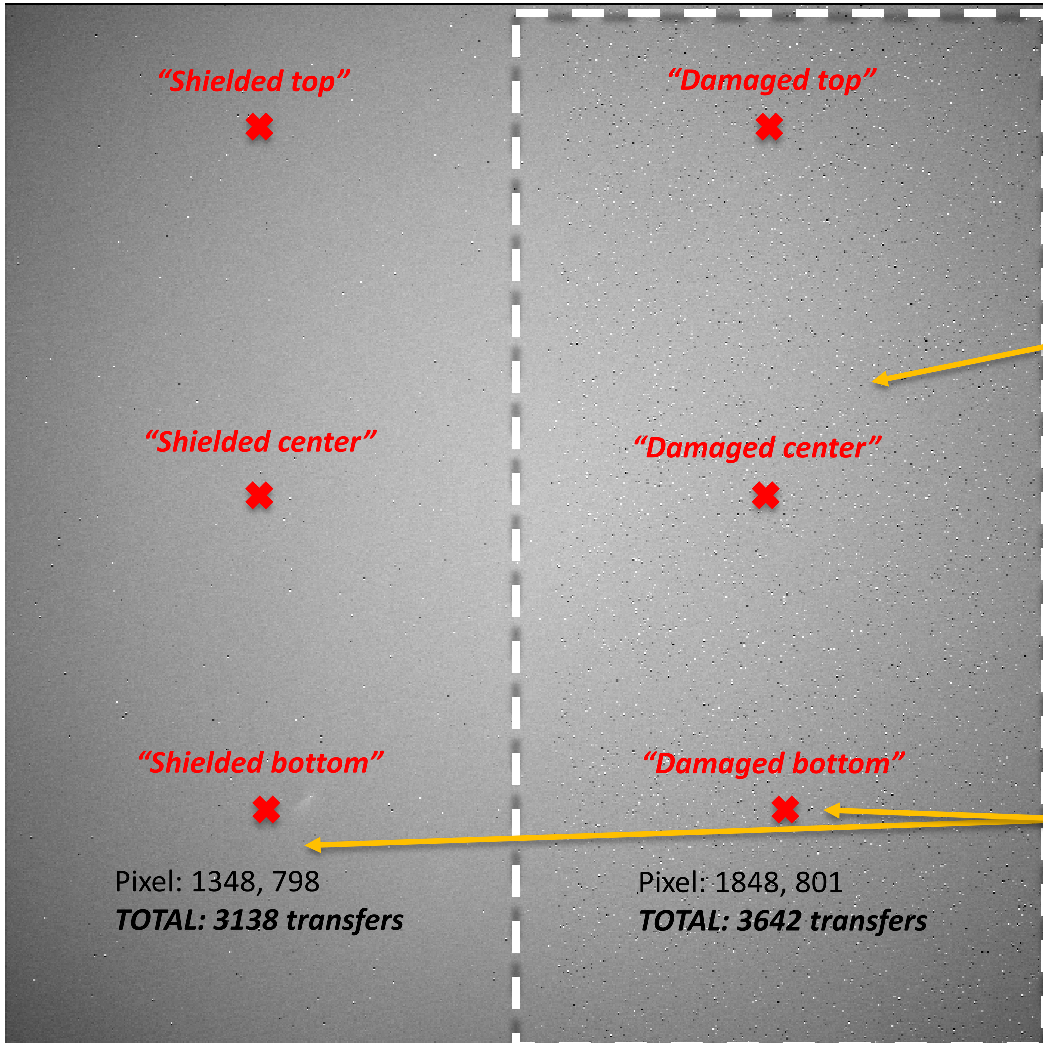
Direction of charge transfer

Serial

Parallel

Pixel: 1104, 1

Pixel: 2144, 1



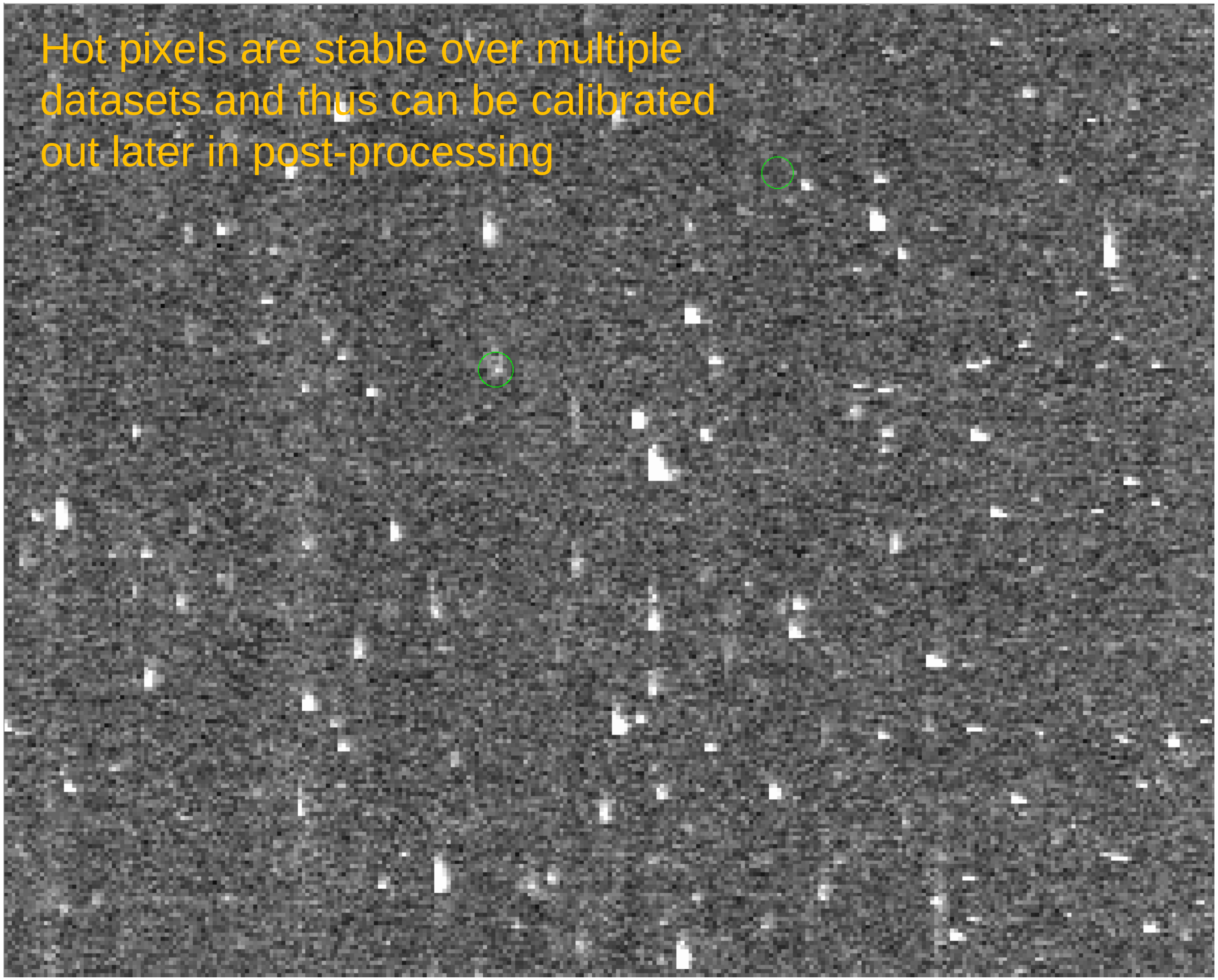
Pixel: 1104, 1024

Pixel: 2144, 1024

Irradiated section ("speckles" are trapping sites identified by Pocket Pumping technique)

Data was taken at All points shown. The following results only show the two "worst case" in terms of max. #transfers

Hot pixel stability



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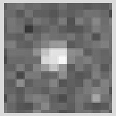
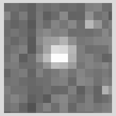
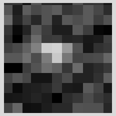
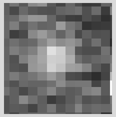
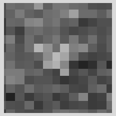
Detections thus far <1 e-/PSF/fr

Target regime [e- per 3x3 px PSF]	Region of device	ND filter stack [OD]	Calibrated transm. [%]	#frames [T_int]	Pixel location	#transfer [pixels]	Expected fluence [e-/PSF/fr]*	Meas. Fluence [e-/pix/fr]	Meas. Fluence [e-/PSF/fr]	PSF image
~1.0	Shielded	ND1xND3 [OD 4]	0.027	7200 [1 sec]	1338, 95	2426	1.08	0.03	0.3	
~1.0	Irradiated	ND1xND3 [OD 4]	0.027	7200 [1 sec]	1850, 97	2940	1.08	0.04	0.4	
0.1	Shielded	ND1xND3x ND1 [OD 5]	0.0029	41400 [1 sec]	1348, 798	3139	0.12	0.002	0.02	
0.1	Irradiated	ND1xND3x ND1 [OD 5]	0.0029	3780 [10 sec]	1853, 803	3649	1.2	0.015	0.15	
0.05	Irradiated	ND1xND3x ND1 [OD 5] {LED x 0.5 intensity}	0.0029	4680 [10 sec]	1780, 751	3524	0.6	0.01	0.1	

Note 1: *"PSF" above refers to a 3x3 pixel region.*

Note 2: *PSF testing also performed at 100 e-, 50 e-, 25 e- and 10 e-, on six regions of the device as proof concept for the scene generator: 3 on shielded side and 3 on irradiated side.*

Note 3: **The "Expected fluence" column prediction is based on the OD-filter %-transmission calibration in column 4, where a stack of filters (column 3) is placed in the path of a calibrated raw LED raw spot, in units of e-/PSF/fr*

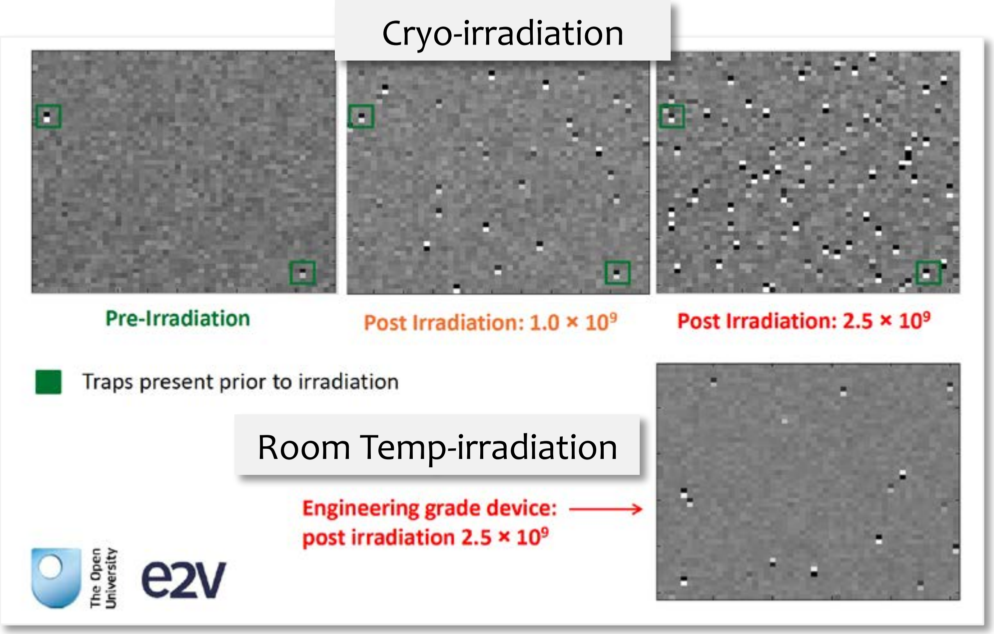
Pre-Phase A IFS Detector Requirements

Pre-Phase A IFS detector requirements – *largely based on current performance*
Developed 1st QTR 2015

CGI IFS/Imaging Camera with e2v CCD201-20				
Parameter	**Actual Value**	**Requirement**	**Unit**	**Notes**
Active pixels	1024×1024	1024×1024	---	---
Pixel pitch	13×13	13×13	microns	Effective area: 177.2mm^2
Effective read noise @ 10MHz w/gain	0.107	0.2	e^-	EM amp w/EM gain ×1000 (77.167e^- at unity gain)
Reciprocal gain performance @ 10MHz	17.632	N/A	e^-/ADU*	Read noise with unity gain = 77.167 e^-
Saturation signal per pixel	50863	N/A	e^-	EM amp full well @ 1MHz vertical frequency
Dark current	9.0×10^{-5}	1×10^{-4}	e^-/pix/sec	Temp -105 deg C, IMO
Clock induced charge @ 5σ threshold	0.0013	0.0018	e^-/pix/frame	10MHz horizontal frequency; 1MHz vertical frequency; EM gain=1000
Quantum Efficiency	88	88	%	Value at 660nm, 165K
	68	68	%	Value at 770nm, 165K
	28	28	%	Value at 890nm, 165K

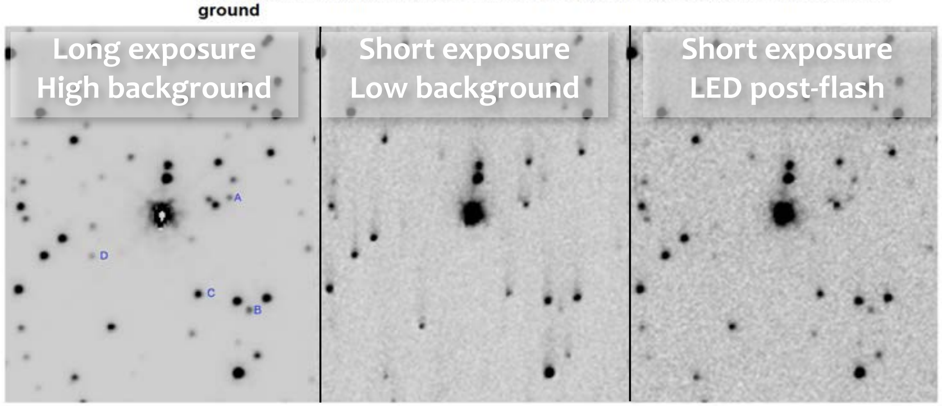
Image Degradation & Fat Zero

- Radiation campaign revealed significant increase in silicon lattice defects in the regime of DDD ~10^9 protons/cm^2
- Defects are manifested as charge traps that reduce CTE
- Traps can be “imaged” using the pocket pumping technique



- HST WFC3 showed that Fat Zero (via LED pre-flash) fills the traps and mitigates the deferred charge tails

Figure 6.16: Mitigation of CTE Losses Using a Modest Increase in Image Background



WFC3

A portion of the Omega Cen central field far from the readout amplifier. The left panel shows the result of a stack of eight 700s images, with minimal CTE losses. The middle panel shows a stack of nine 10s exposures with only ~2e⁻ natural background each; note the charge trails due to CTE loss extending upwards from each source in the field. The right panel is a stack of nine 10s exposures with ~16e⁻ background total (sky + post-flash) in each image.

Outstanding Tasks

- Use image degradation trap model to derive a requirement on maximum allowed trap density at EOL
- Continue to explore low flux detection of EMCCD at BOL and EOL
- Investigate the effects of secondary emission from 10 mm thick Ta shield

CCD201-20 Trap Mitigation Methods

Trap mitigations for the existing standard product CCD201-20

- Robust camera shielding
- Custom clock waveform using multi-level clocking
- Warm EMCCD to CGI temperature (282K) & apply zero bias while not in use
- Fill traps by low level illumination
- Annealing at higher temperatures (TBD)
- Early Mission observations of key science targets

Detector Trap Density Requirement

- Compute a requirement on the maximum trap density in the IFS detector at end of life (EOL).
- Approach
  - Use the detector trap model to determine the trap density that increases integration time to perform spectral characterization of a representative planetary system (TBR) at SNR of 5 (TBR) by a factor of 3x (TBR) at nominal placement on IFS detector (TBR).
- Assumptions
  - Nominal placement for planet signal is at the center of IFS detector (1512 frame pixels)
  - The relative densities of trap species is fixed; as determined by pocket pumping
  - The density of the trap ensemble is varied to derive the requirement