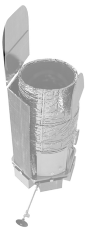


EMCCD Update

Leon Harding, Bijan Nemati, Rick Demers

10/6/2016

FSWG Meeting

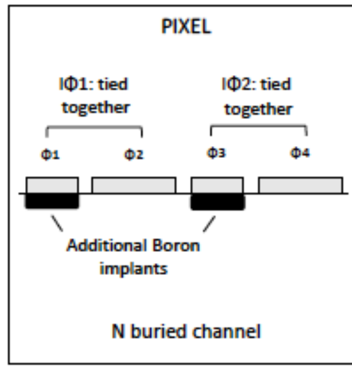
Linthicum Heights, MD

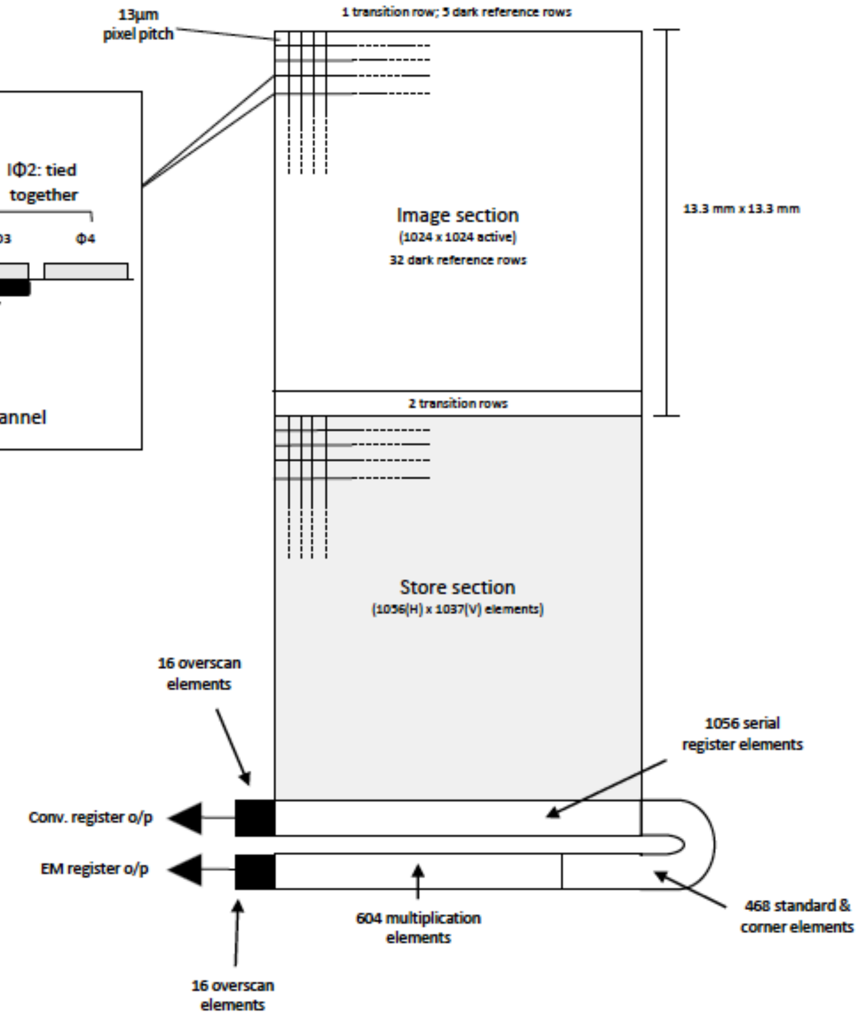
Overview

- Detector Milestone 7 is passed
- In this talk we will present highlights of the latest EMCCD performance results:
  - 2 Phase radiation study: characterize detector before/after
  - EMCCD scene generator: Low flux measurements achievements
- Path forward for detector modeling and laboratory work

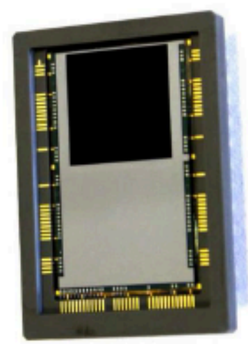
e2V CCD201-20 Architecture

- 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



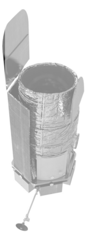


Picture of CCD201-20



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

Cryo Radiation Test Summary



Parameter	Units	Org.	Pre-Irradiation	Post-Irradiation 2.5×10^{9} pr/cm^{2}
Image area Dark Current	e-/pix/sec	JPL	$(3.00\pm0.40)\times10^{-5}$	$(7.00\pm0.50)\times10^{-4}$
Effective Read Noise	e-/pix/frame	JPL	1.70×10^{-6}	1.70×10^{-6}
Total CIC	e-/pix/frame	JPL	$(2.1\pm0.2)\times10^{-3}$	$(2.3\pm0.2)\times10^{-3}$
EPER Parallel CTI (10e- signal)	-	CEI	$(8.88\pm0.49)\times10^{-6}$	$(8.32\pm0.52)\times10^{-4}$
EPER Serial CTI (10e- signal)	-	CEI	$(1.65\pm0.47)\times10^{-5}$	$(6.84\pm0.15)\times10^{-4}$
X-Ray Parallel CTI (1 event/2700 pix)	-	CEI	$(0.569\pm1.0)\times10^{-6}$	$(1.31\pm0.05)\times10^{-4}$
X-Ray Serial CTI (1 event/2700 pix)	-	CEI	$(1.65\pm2.08)\times10^{-6}$	$(4.12\pm0.35)\times10^{-5}$

NOTES

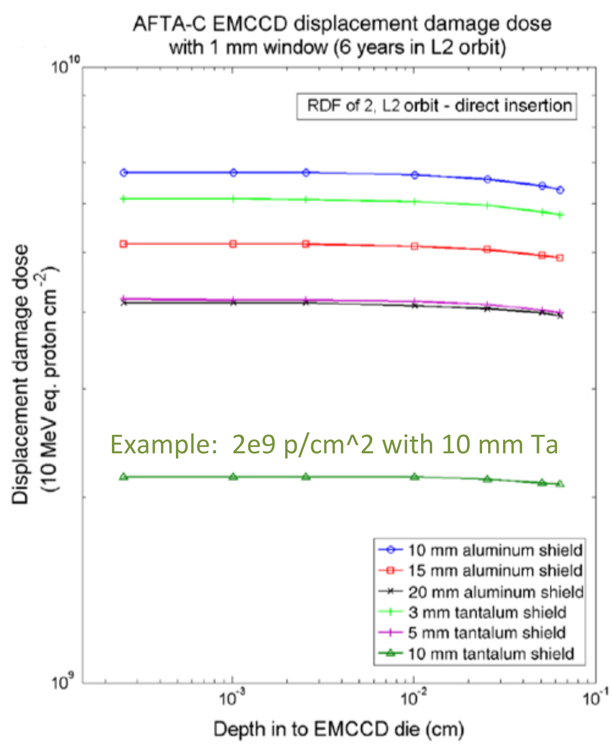
1. CEI measurements made at 165K using XCAM commercial electronics, not performance optimized
2. JPL measurements made at 168K using NüVü flight-like commercial electronics, performance optimized
3. CEI read noise measurement (not shown) made in analog mode with low gain
4. JPL read noise measurement 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.

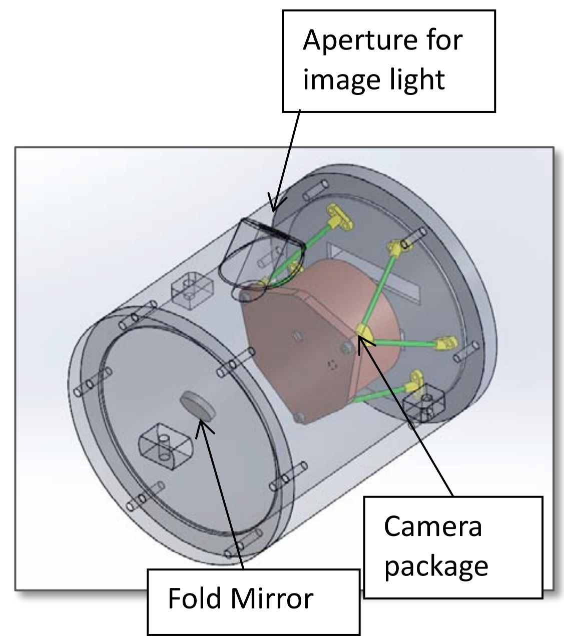
Radiation Exposure

- Detector performance depends on exposure to radiation
- Exposure is expressed in terms of *fluence* over the irradiation period, in units of equivalent 10-MeV protons incident per cm^2
- We exposed our devices to various levels of radiation and characterized the device at intervals
- We used NOVICE model to estimate EOM fluence for various shielding alternatives

Harding & Demers, et al. (2016)

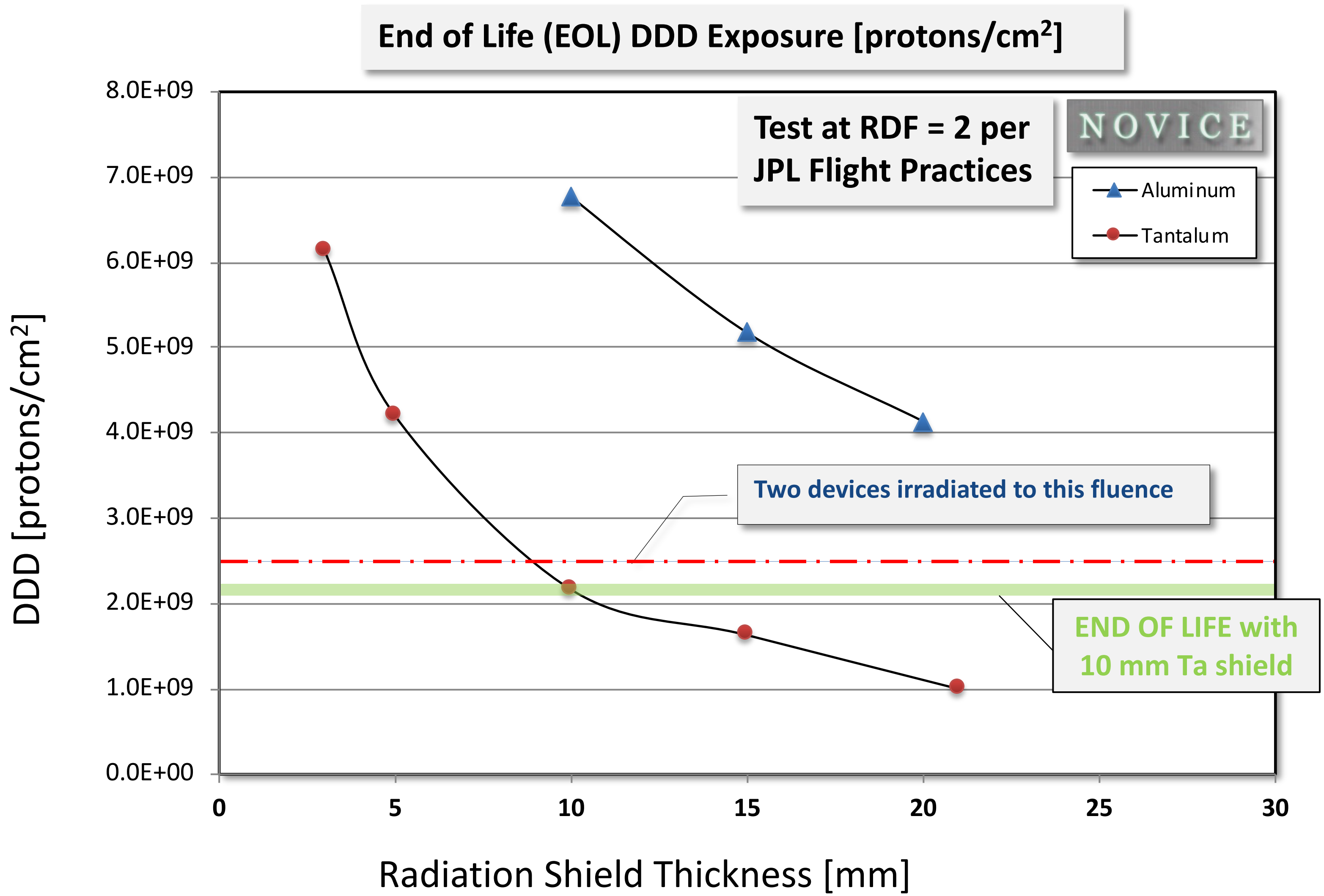
Displacement damage dose (DDD) can cause charge traps, and transfer inefficiency





NOVICE

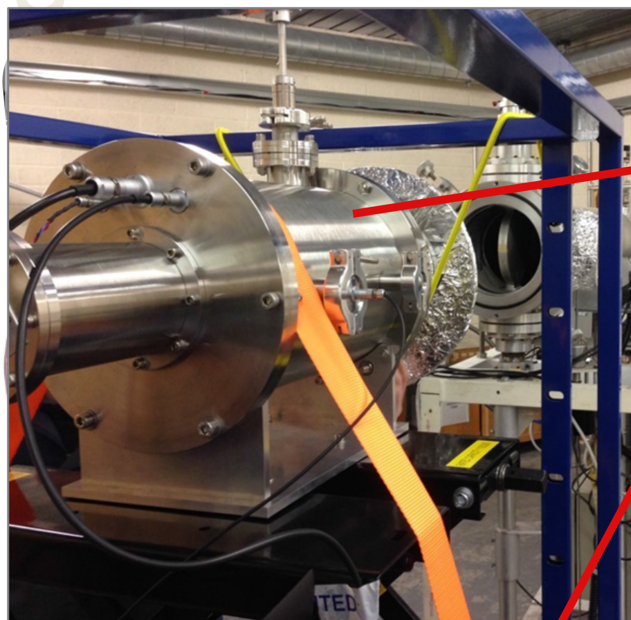
How Much Can Shielding Help?

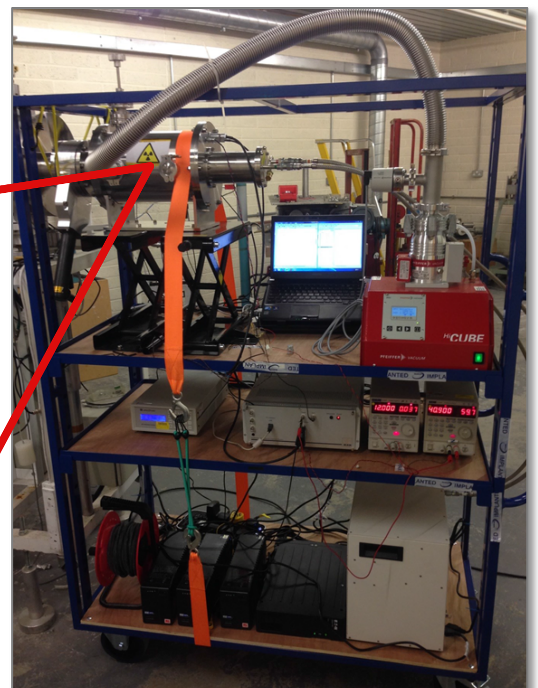


Data from analysis by Michael Cherng JPL Internal Memo 5132-15-015, 18 March 2015 & recent results July 2016

Radiation Testing

- **<u>Testing was done in two phases:</u>**
- **<u>Phase 1</u>**: single exposure of DDD at room temp for 2.5 x 10^9 p/cm^2
  - Corresponds to >6 years in L2 orbit with 10 mm Ta shielding
- **<u>Phase 2</u>**: four separate exposures of DDD at cryo temp to characterize intermediate points in mission life time
  - Performance fully characterized after each of the four doses: 1, 2.5, 5.0 and 7.5 x 10^9 p/cm^2

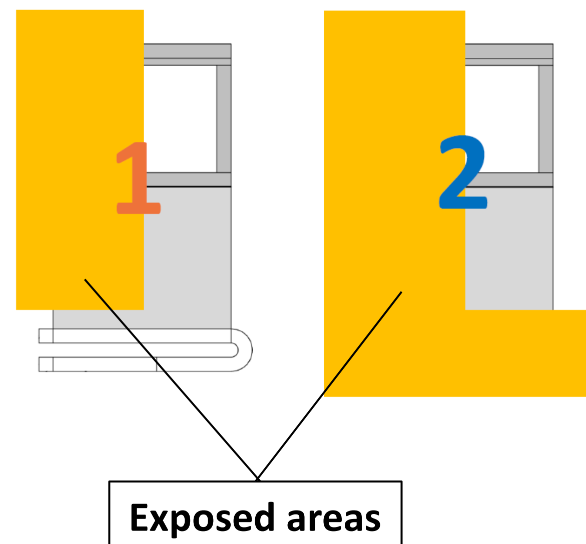




Cryostat and EMCCD characterization hardware

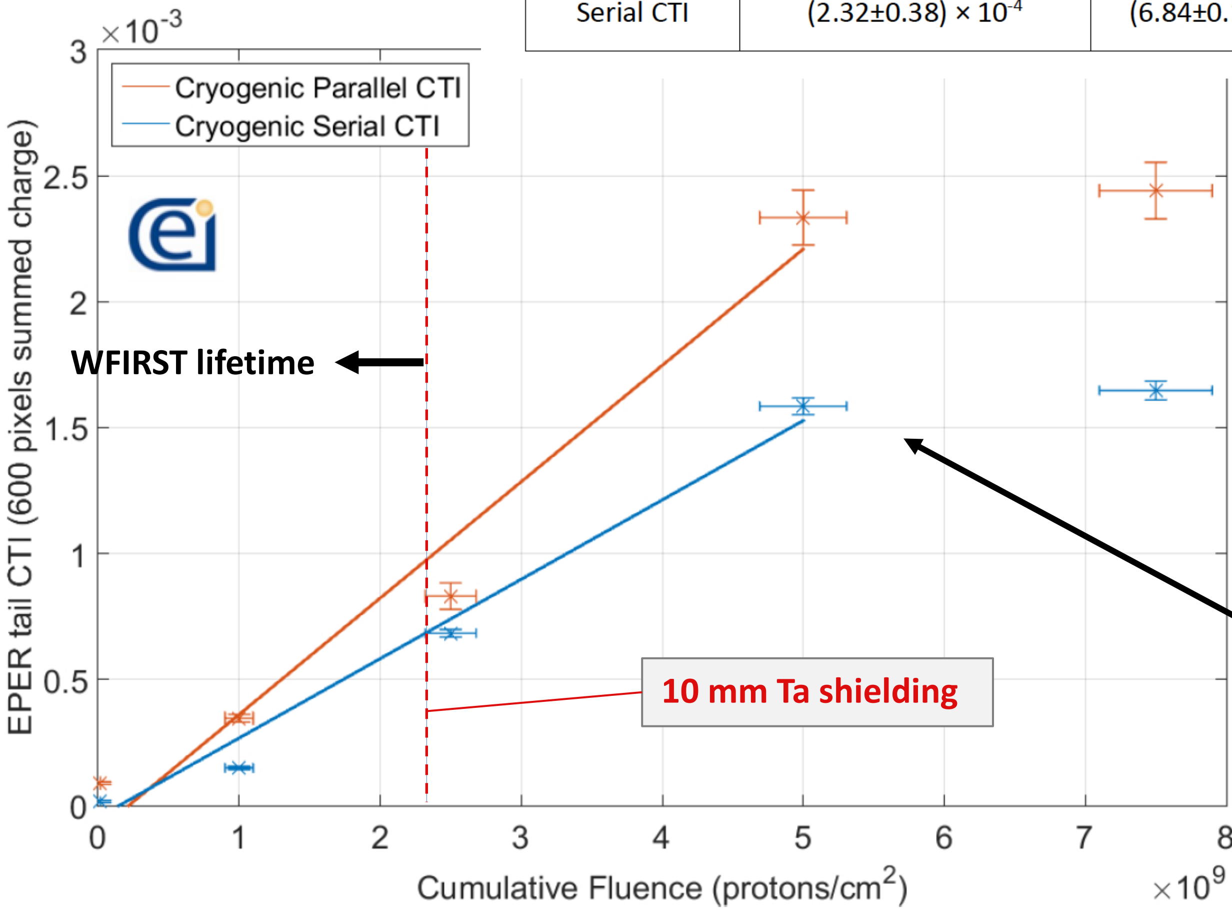
Device 1: Parallel irradiation only.

Device 2: Serial and Parallel irradiation



Charge Transfer Inefficiency

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

Devices tested to damage far beyond total WFIRST mission lifetime

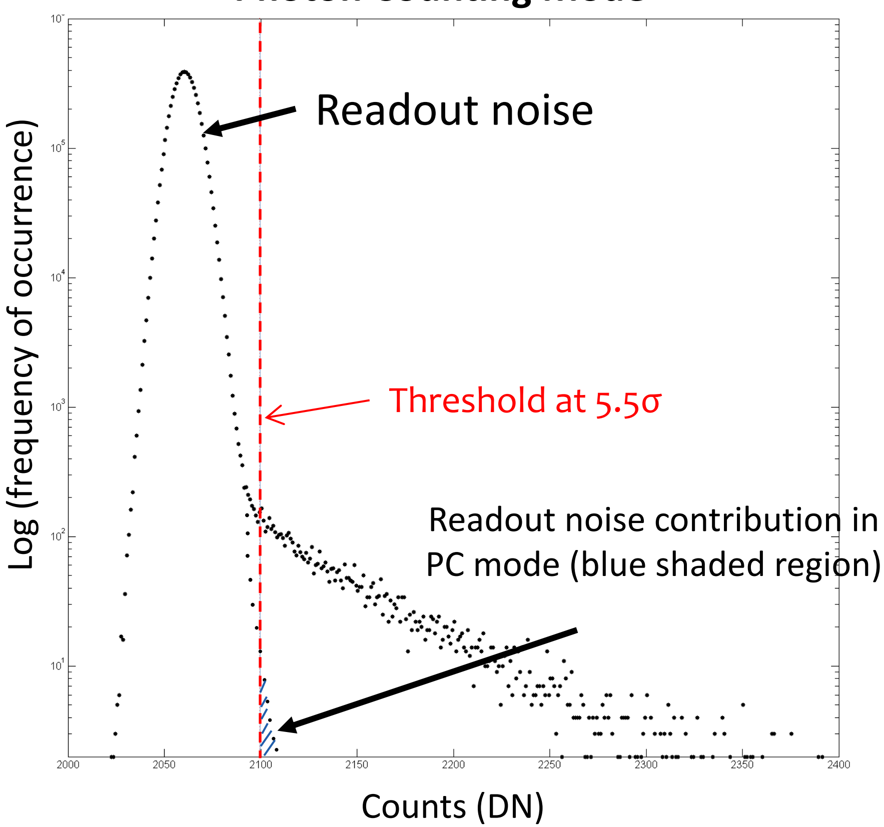
Figure 9.9.6: Integrated EPER parallel and serial tail CTI plotted as a function of cumulative fluence level.

Readout Noise in EMCCDs

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

Photon Counting Mode



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

EOL Readout Noise

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

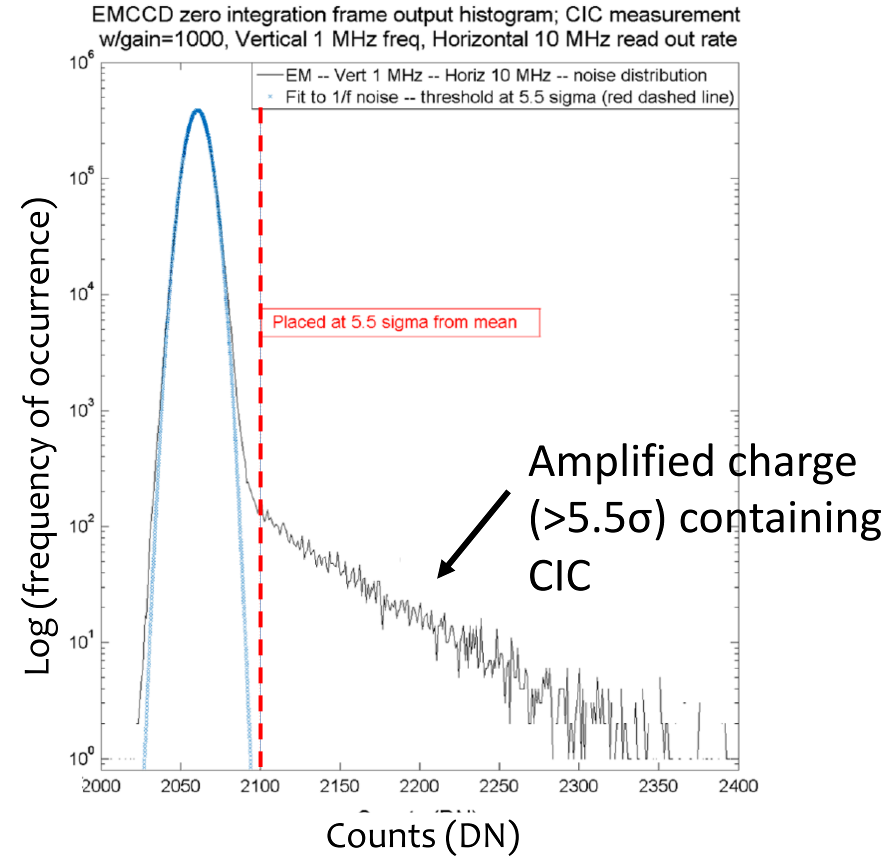
RN (w/EM gain & PC) = 1.7×10^{-6} e-

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



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

Parallel Clock Induced Charge

Coronagraph

- 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

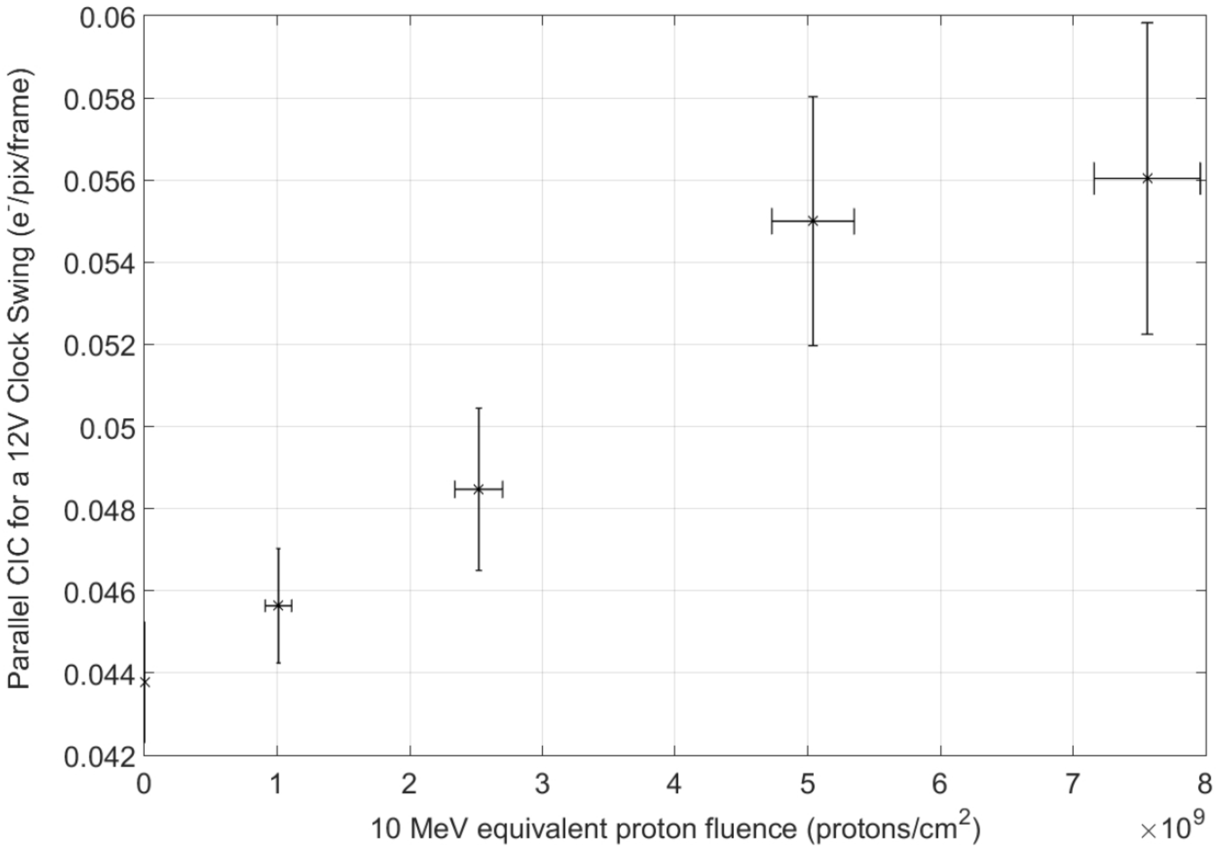


Figure 9.6.4: Illustration of parallel CIC measured for a 12V clock swing as a function of irradiation fluence. The CIC measured for the final fluence (7.5×10^9 protons/cm^2) agrees with the penultimate fluence within the quoted errors.

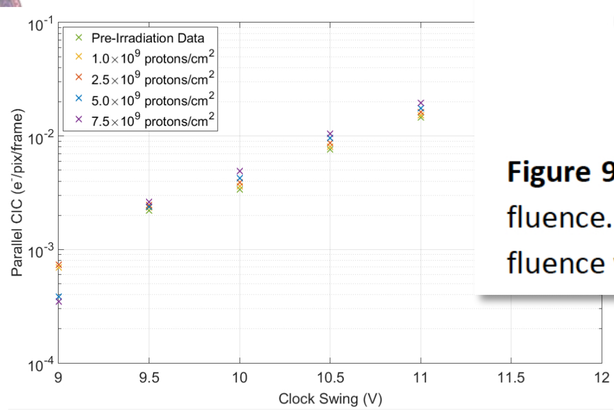
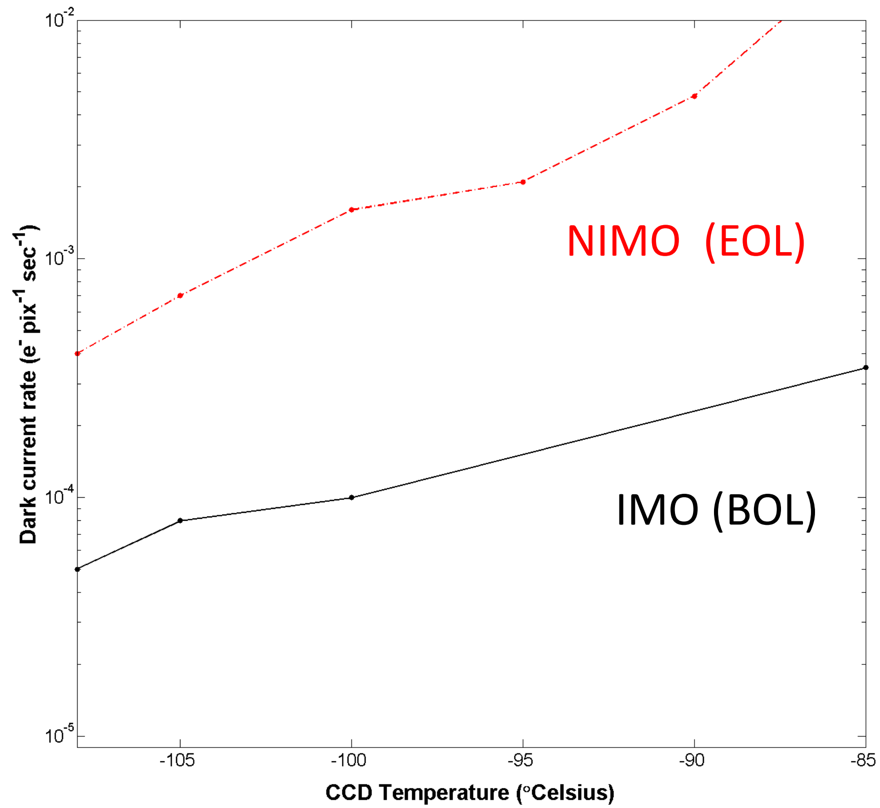


Figure 9.6.3: Illustration of CIC results for each clock swing measurement and irradiation fluence. Error bars are excluded for clarity.

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 at 168 K:

MS requirement = 0.001 e-/pix/sec
BOL (IMO) = 0.00003 e-/pix/sec
EOL (NIMO) = 0.0007 e-/pix/sec

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 passes EOL requirement after third dose
  - Using 10 mm Ta shield thickness

MS requirement = 10^{-3} e-/pix/sec

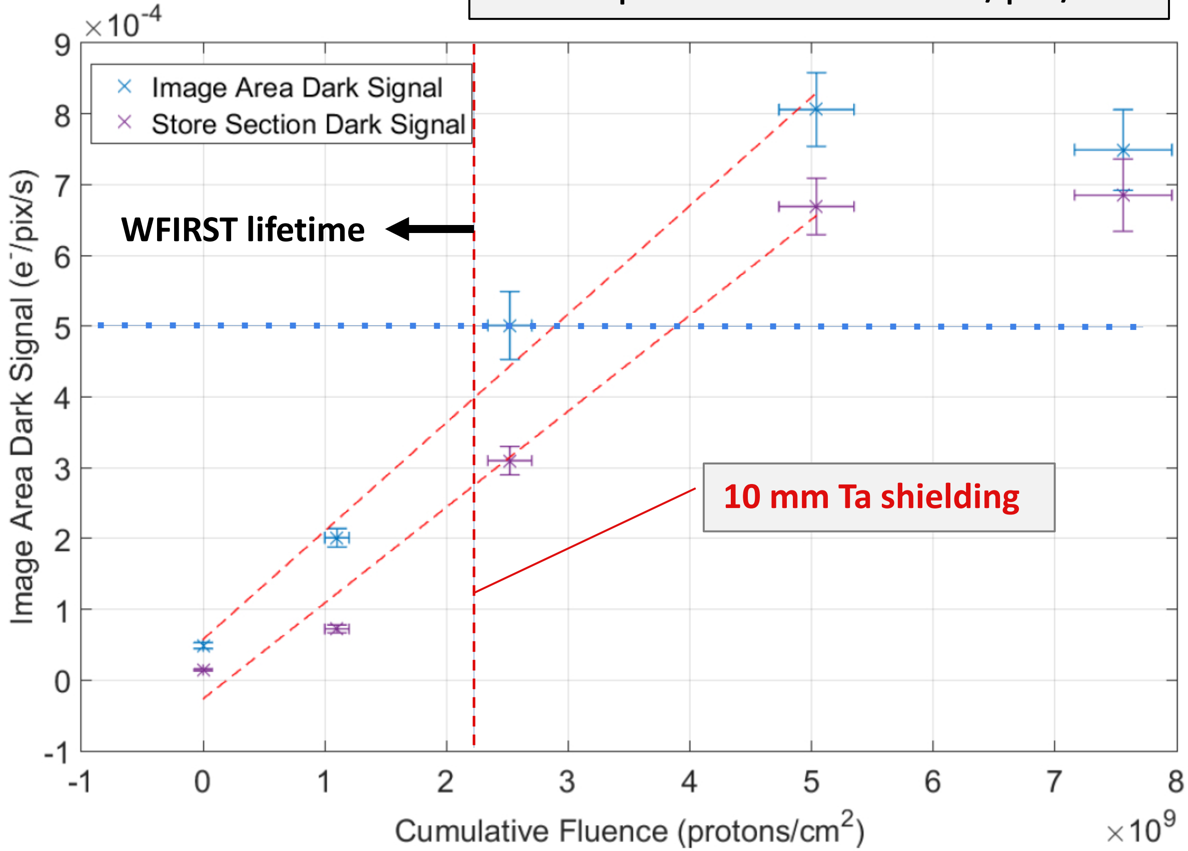
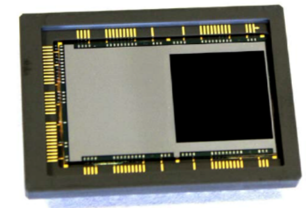


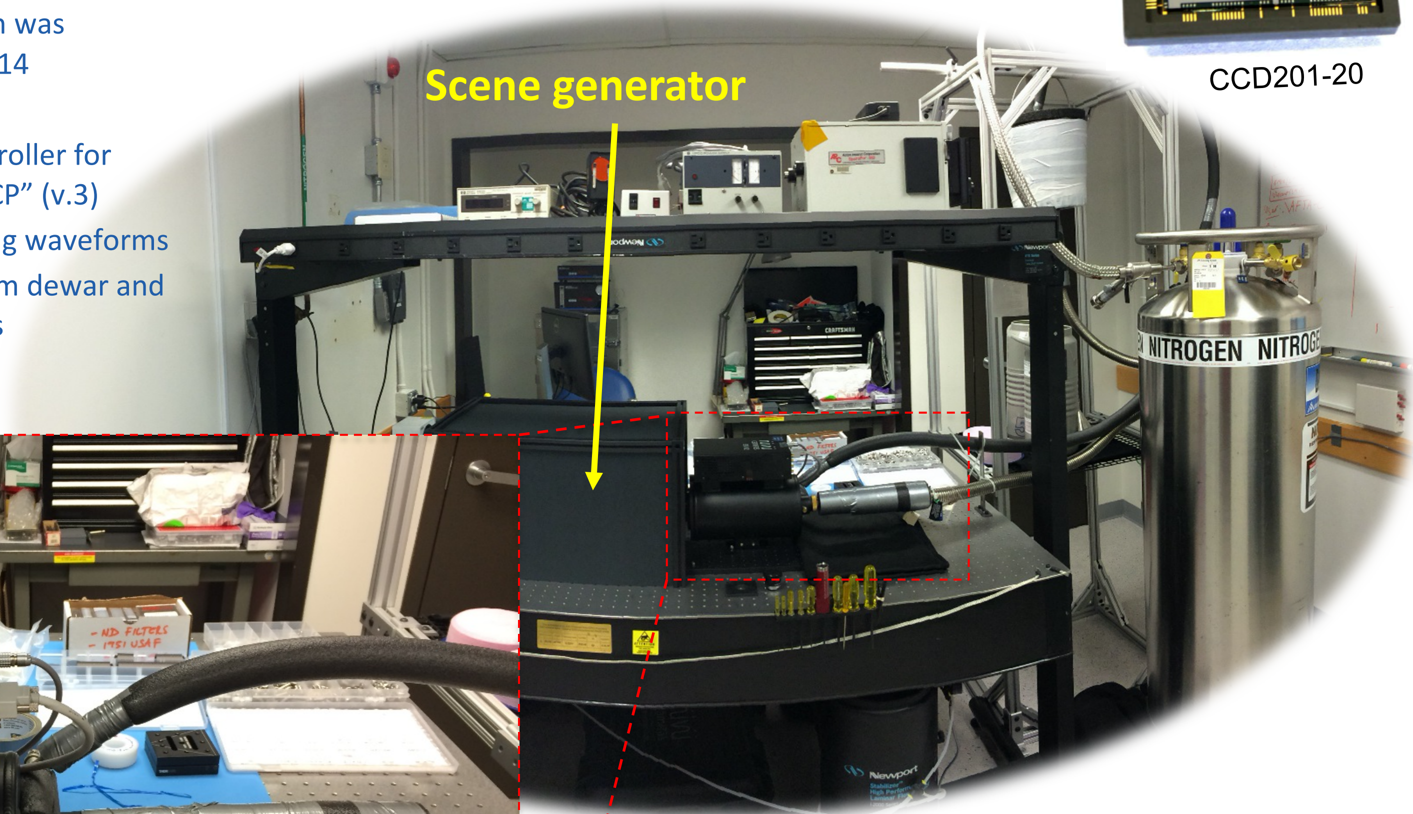
Figure 9.7.2: Dark signal values for each proton fluence. Data is shown for dark current measured in the image area and frame store region. The image area systematically exhibits higher dark current; an observation noted in other studies with back thinned sensors that also have an aluminium frame store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

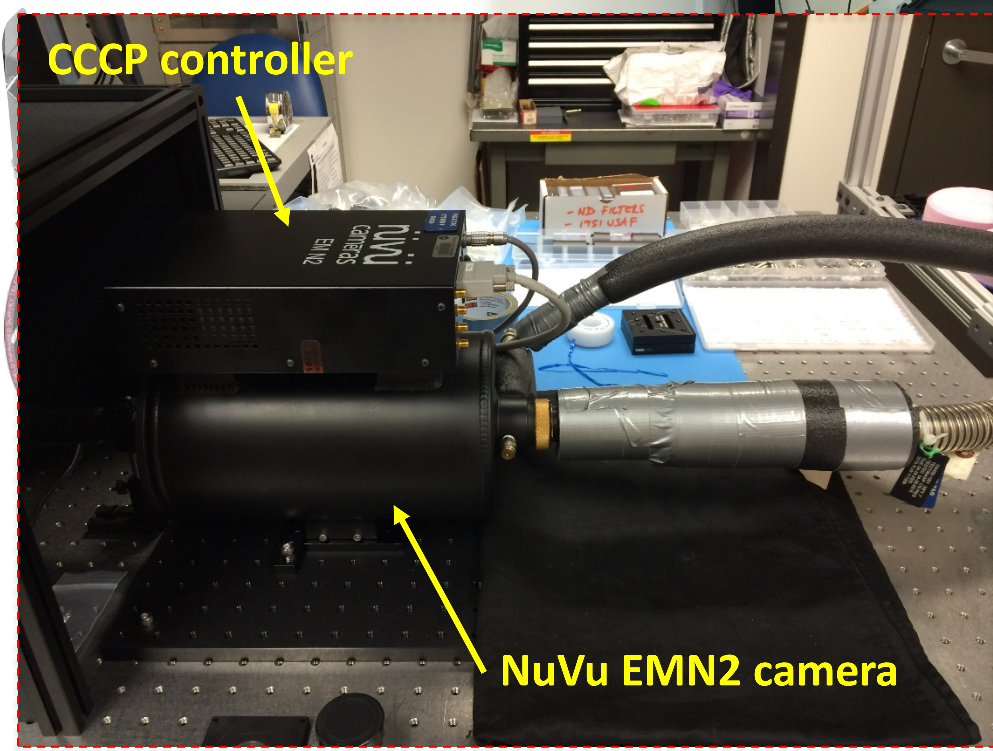
EMCCD test laboratory

- 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



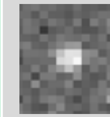
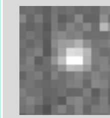
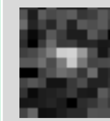
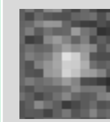
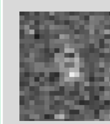
CCD201-20





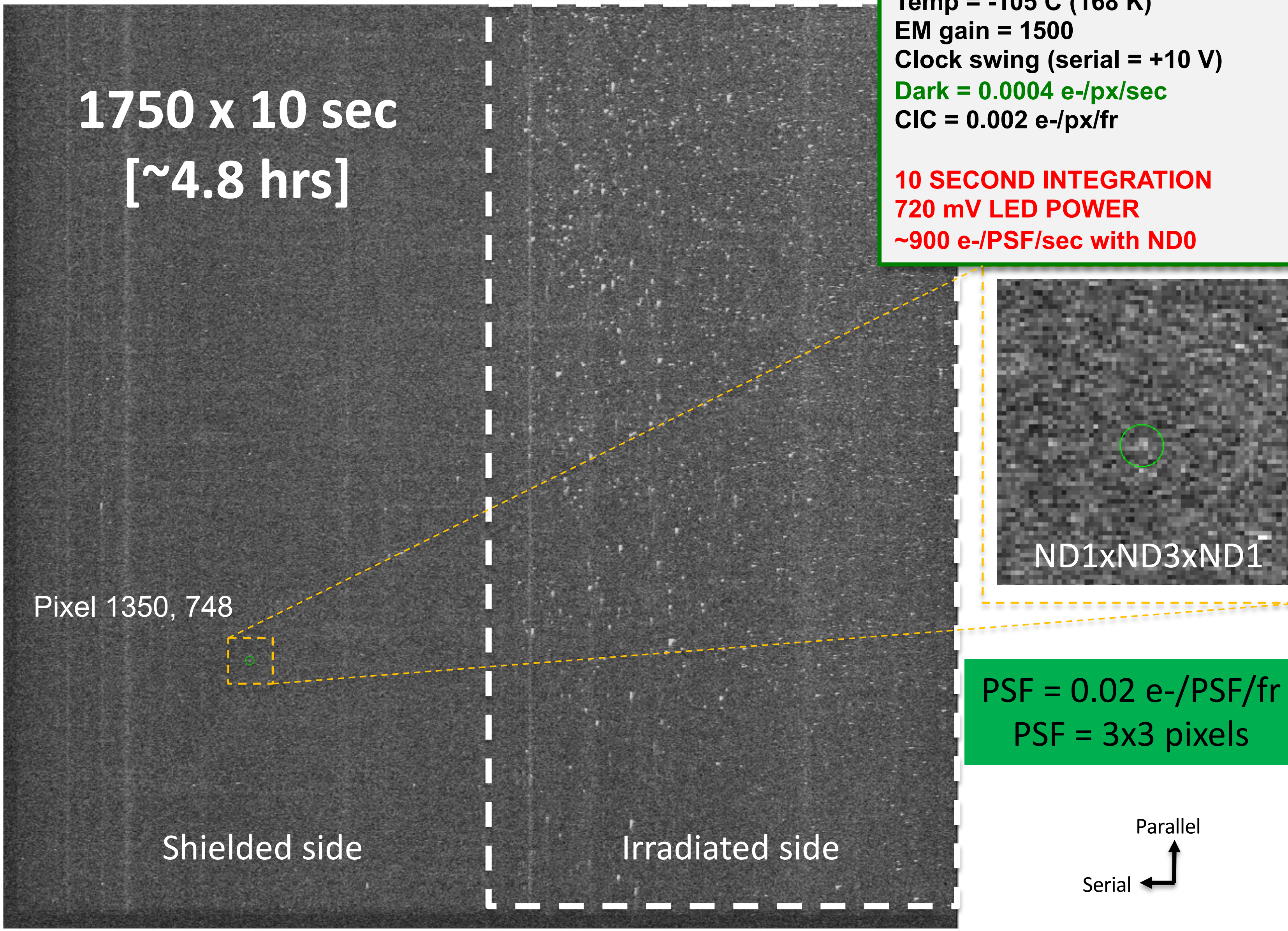
- The NuVu EMN2 was used to characterize:
  - BOL performance
  - EOL performance
  - Radiation damage
  - Clocking optimization in CCD controller for improved performance
- CGI-relevant low flux testing

Summary of Detections <1 e-/PSF/fr

Region of device	ND filter stack [OD]	Calibrated transm. [%]	#frames [T_int]	Pixel location	#transfer [pixels]	Expected fluence [e-/PSF/fr]*	Measured Fluence [e-/PSF/fr]	Measured Fluence [e-/pix/fr]	PSF image
Shielded	OD 4	0.027	7200 [1 sec]	1338, 95	2426	1.08	0.3	0.03	
Irradiated	OD 4	0.027	7200 [1 sec]	1850, 97	2940	1.08	0.4	0.04	
Shielded	OD 5	0.0029	41400 [1 sec]	1348, 798	3139	0.12	0.02	0.002	
Irradiated	OD 5	0.0029	3780 [10 sec]	1853, 803	3649	1.2	0.15	0.015	
Irradiated	OD 5 {LED x 0.5 intensity}	0.0029	4680 [10 sec]	1780, 751	3524	0.6	0.1	0.01	
Irradiated	OD 5 {LED x 0.25 intensity}	0.0029	4680 [10 sec]	1780, 751	3524	0.02	0.06	0.006	

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*
Note 3: **The "Expected fluence" column prediction is based on OD-filter attenuation of raw LED signal*

Latest PSF Measurement – BOL



Temp = -105 C (168 K)
EM gain = 1500
Clock swing (serial = +10 V)
Dark = 0.0004 e-/px/sec
CIC = 0.002 e-/px/fr

10 SECOND INTEGRATION
720 mV LED POWER
~900 e-/PSF/sec with ND0

PSF = 0.02 e-/PSF/fr
PSF = 3x3 pixels

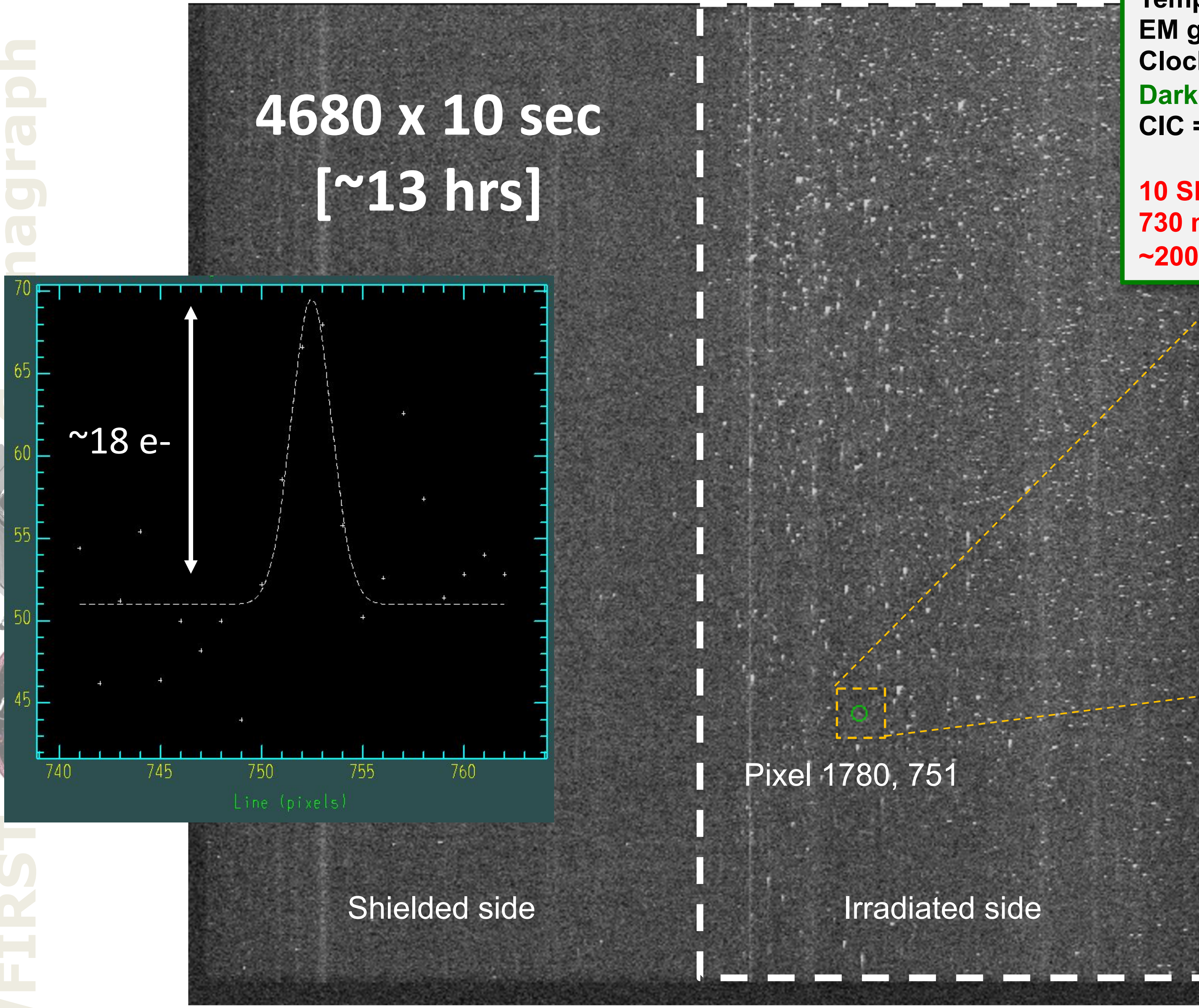
Parallel
Serial

Jet Propulsion Laboratory
California Institute of Technology

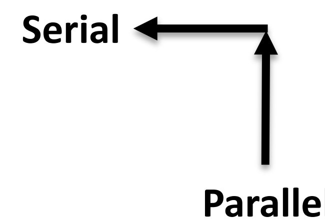
Latest PSF Measurement – EOL

Temp = -105 C (168 K)
EM gain = 1500
Clock swing (serial = +10 V)
Dark = 0.0007 e-/px/sec
CIC = 0.002 e-/px/fr

10 SECOND INTEGRATION
730 mV LED POWER
~2000 e-/PSF/sec with ND0



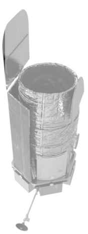
PSF = 0.06 e-/PSF/fr
PSF = 3x3 pixels



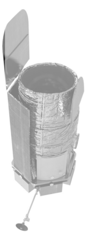
Summary

- **RADIATION STUDY:**
  - Dark current degradation is minimal
  - 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

- **LOW FLUX MEASUREMENTS STUDY:**
  - Lowest flux ever detected from a CCD
  - ***Example***: if one were to remove Coronagraph front-end and operate only with WFIRST telescope and detector (like HST), detection equivalent to a 35th magnitude star! This is deeper than HST deep field
  - Most sensitive detection on a radiation damaged device ever



Path forward

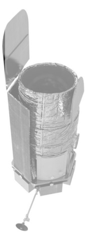


- **<u>On-going and upcoming</u>**:
  1. Understanding low flux capability of EMCCD in the JPL lab (signal floor?)
  2. Trap defect model of image IFS image degradation in same regime as lab measurement
     - *Assess what trap density/volume is tolerable for WFIRST mission*
     - *TCAD produced 3D charge packet density profile for transfer in image/serial pixels*
     - *Incorporation of final inputs from Silcavo TCAD model are in progress*
  3. Compare lab measurement for verification of model
  4. Incorporate detector model into science yield models
  5. Incorporate lab measurement with “planet” spot embedded in a speckle-like background
  6. Investigate other sources of photon noise that might effect signal:
     - *Effects of secondary emission from shielding, e.g. Cherenkov radiation*
     - *Effects of cosmic rays*
     - *Effects of materials in the instrument, optics etc.*

- Instrument team is working to provide a flow-down to give to detector team
- Detector performance can be further improved by modifications

BACKUP

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.

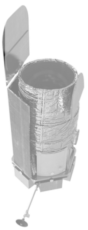
Verification Method: Samples of the sensor selected for the IFS are operated using flight-like electronics and tested under dark and imaging conditions. The dark tests provide all the sensor-specific noise levels. If the sensor is an EMCCD (currently considered the likely choice) the test will include 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

Low Flux Take Away

- We are in good shape for the imager
- For the IFS, we are limited in the lowest flux we can see
- BUT
  - Constraints in our tests are conservative
    - Test detector was irradiated 5X best-estimate EOM flux (2.5X if RDF 2 applied)
    - Tests were done at farthest pixels from SR (4X average no. of frame traps))
    - None of the improvements to the flight design were in place
      - Overspill
      - High sensitivity amplifier
      - Barrier implant changes (deomstrated successfully 282)
      - Narrow channels
    - These changes combined should significantly improve the low flux performance of the EMCCD
- We expect further improvements in the EMCCD EOL performance
- Stay tuned!

Radiation Exposure



How is exposure determined?

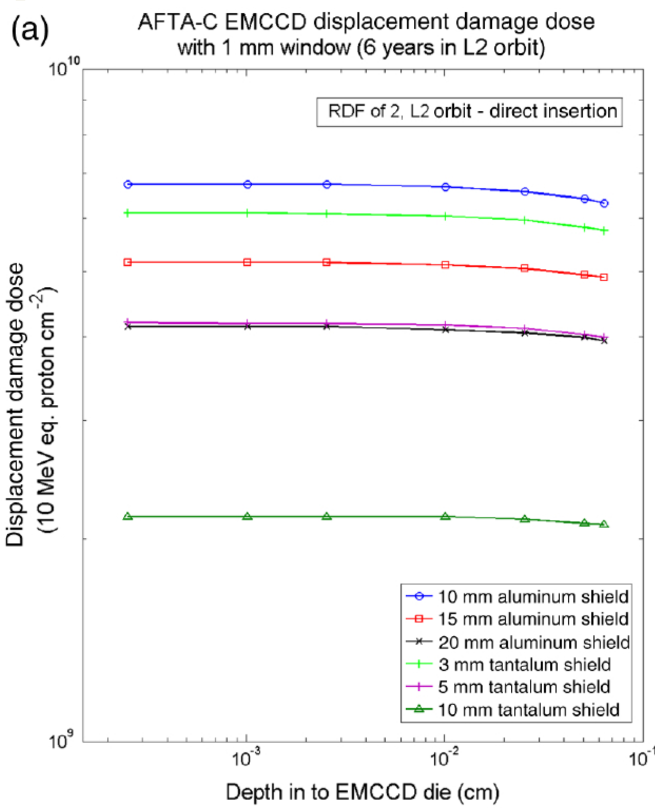
- Radiation testing simulates the *amount of damage* expected over life on orbit
  - First simulate the L2 environment using validated solar proton code
- Then simulate damage exposure of detector using radiation transport code
  - Specify total fluence over lifetime [particles/cm^2]
  - Displacement Damage Dose (DDD)
  - Total Ionizing Dose (TID)
- Convert the predicted lifetime fluence to a reference fluence at a given particle energy, e.g. 10 MeV protons
- Convert the reference fluence for a specific facility to deposit the same energy in the 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

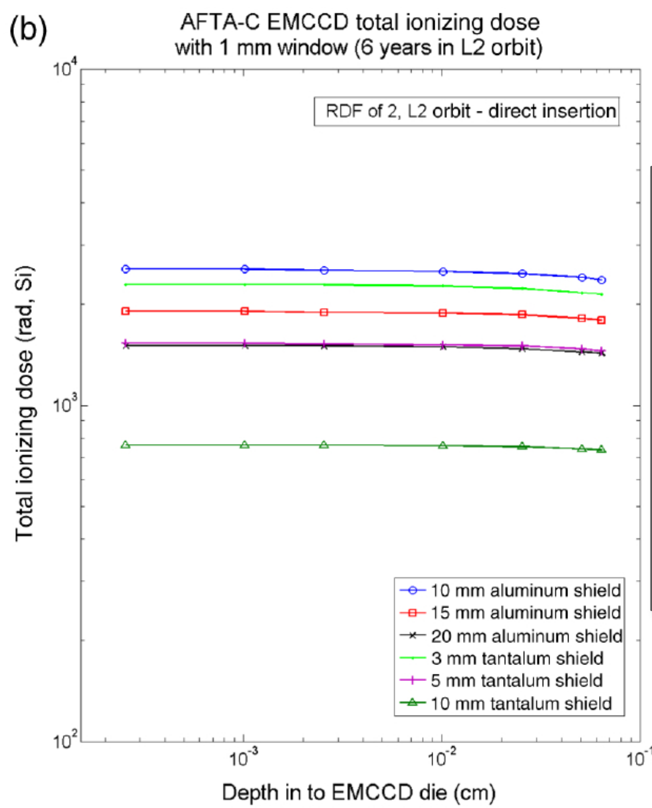
Summary of Radiation Analysis

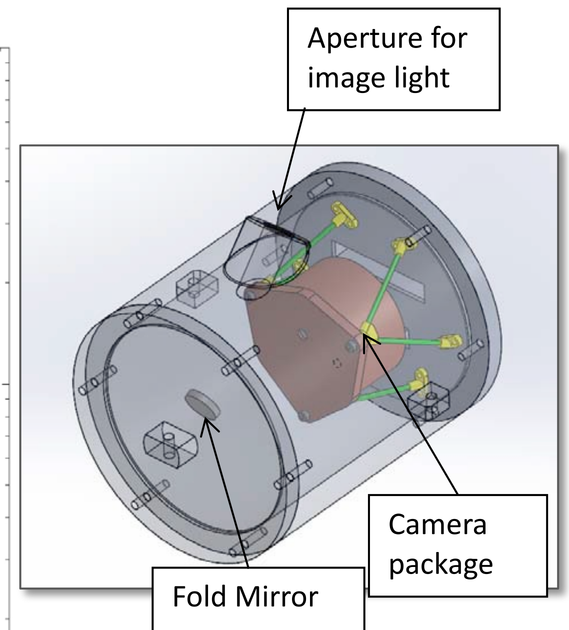
Radiation transport code NOVICE used to predict DDD and TID in L2

- Direct insertion orbit, i.e. trajectory through Earth's trapped-particle rad belts is inconsequential
  - Code was run for GEO and contribution 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 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

Harding & Demers, et al. (2016)

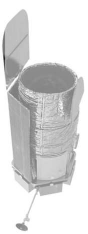






NOVICE

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)

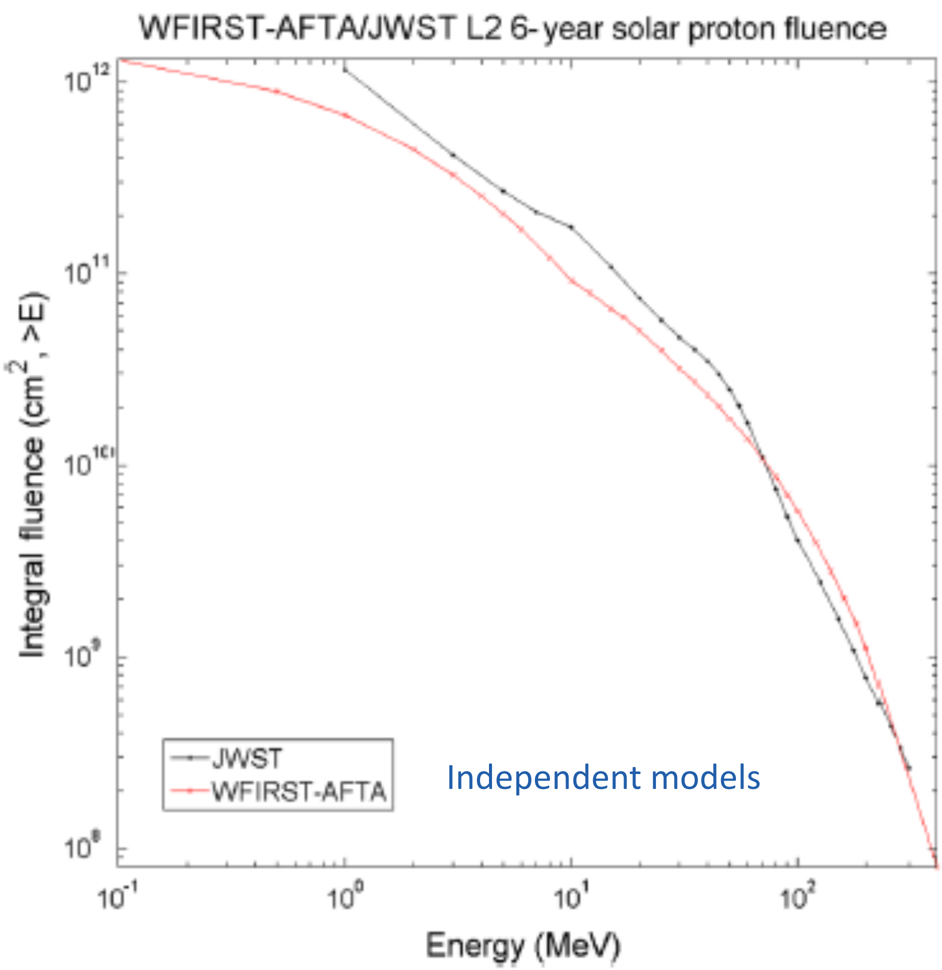
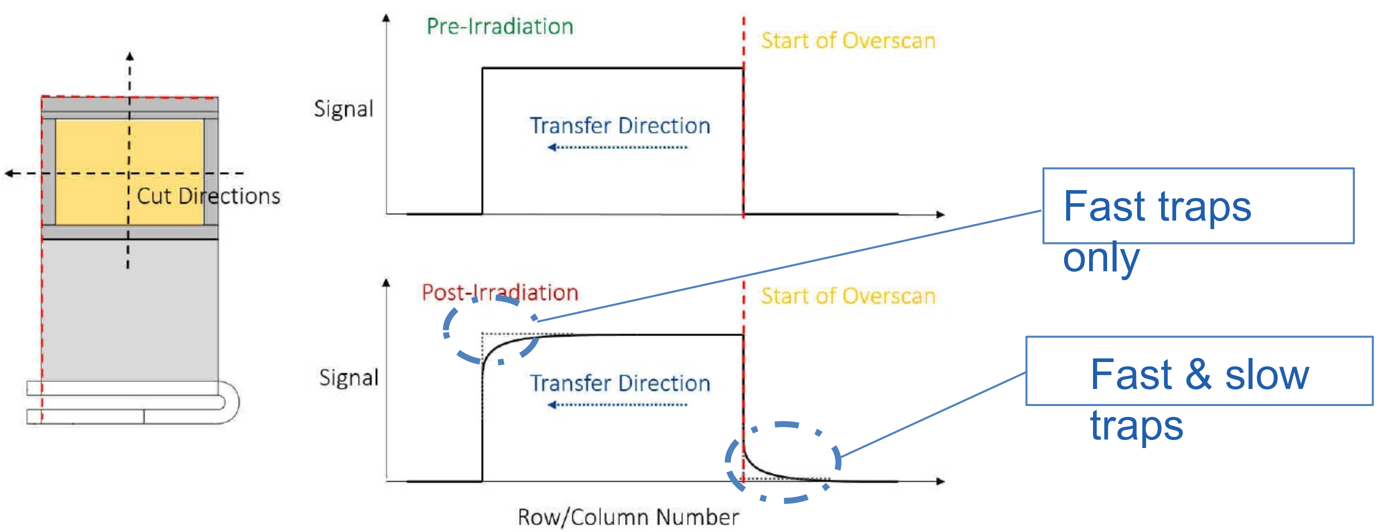


Fig. 4 Comparison of independent predictions for the solar proton fluence in a direct insertion L2 orbit for the WFIRST and JWST missions. WFIRST data were calculated based on the JPL 91 Solar Proton model at a 95% confidence level and with a radiation design factor (RDF) = 2. JWST data were scaled to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

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)
  - Flat field illumination at average of 10 electrons per pixel
- CTI = (Charge in emission tail) ÷ (Signal level x no. transfers)



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

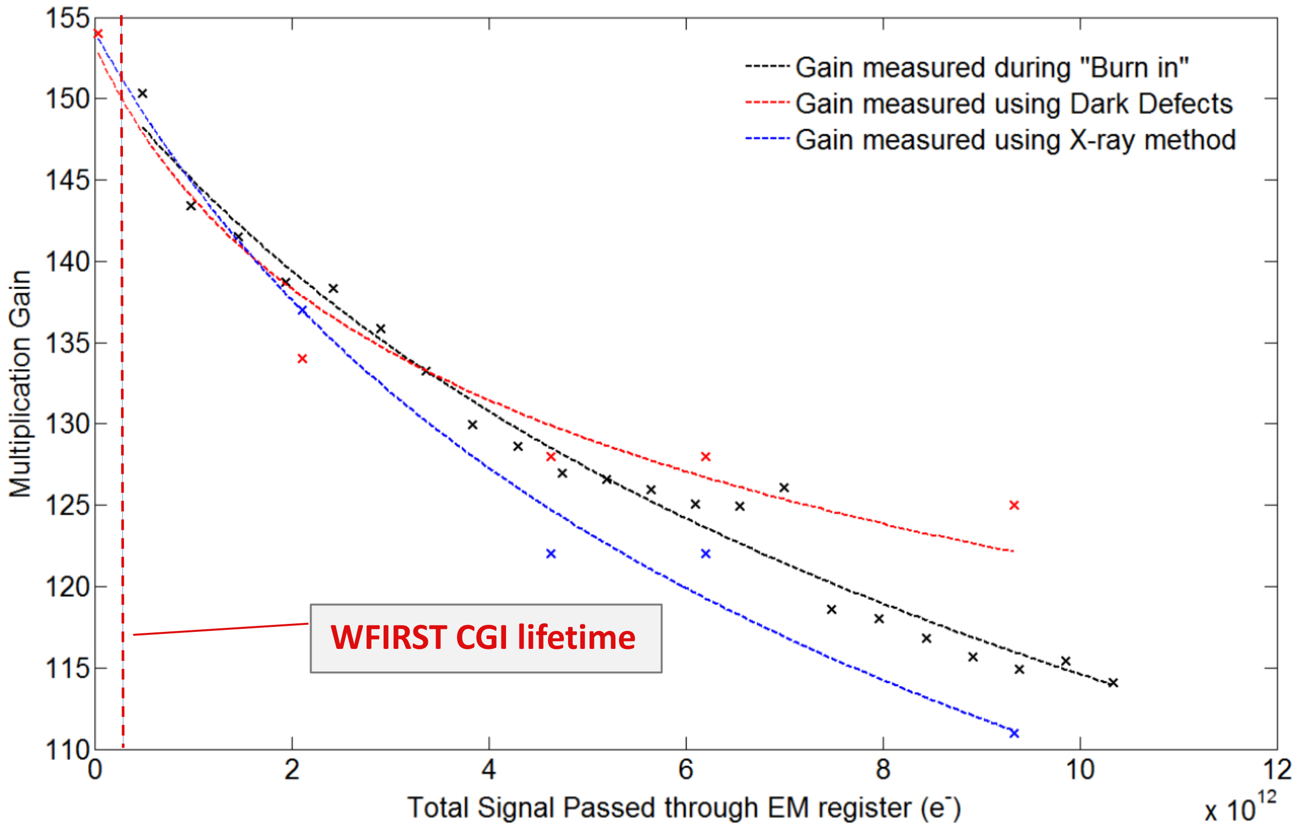
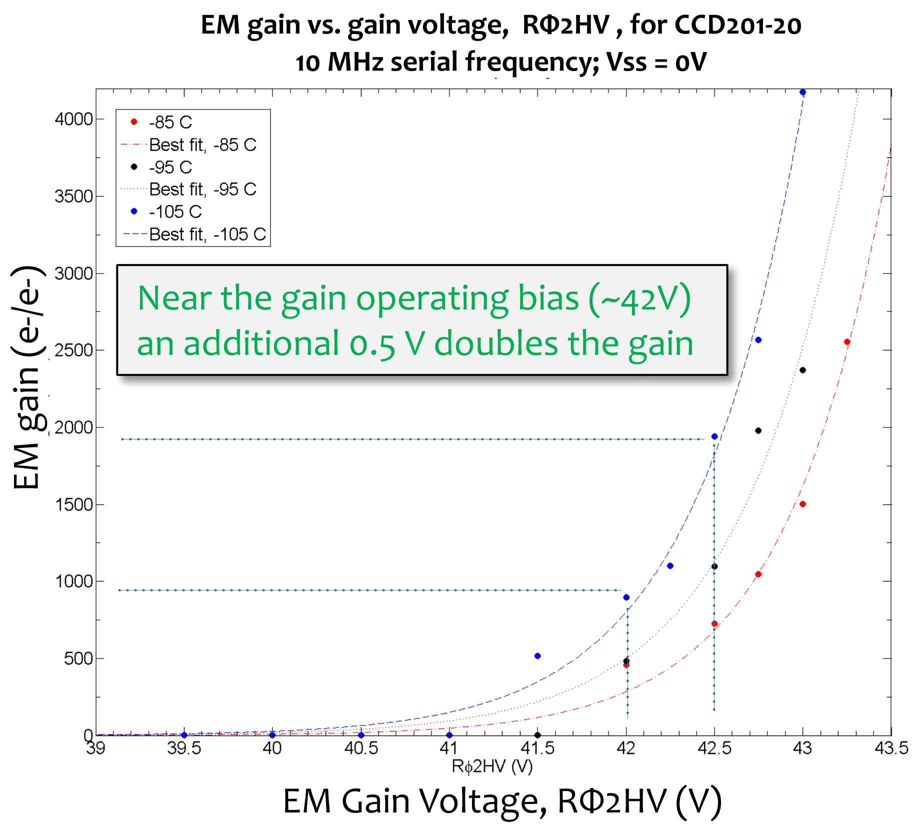


Figure 9.4.1: Multiplication gain measured as a function of total signal passed through the EM register. Both the X-ray method and dark defect method are consistent with the expected drop due to ageing within the quoted errors (Table 9.4.1). The deviation from the trend at the larger signal levels is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

Gain Control Authority (JPL)

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



Photon counting is enabled with the use of EM gain