Radiation Testing of 2-D Imaging Detectors and ADCs

Gordon Hopkinson

Sira Electro-Optics Ltd

South Hill, Chislehurst, Kent, UK,
gordon_hopkinson@siraeo.co.uk

Theme: Star Tracker Applications

- **12-bit ADCs: Analog Devices AD9223**
  Linear Technology LTC1415
  - **Co-60 and heavy ion evaluation tested**
- **ASCoSS Active Pixel Sensor (from IMEC)**
  - **Co-60, 10 MeV proton and heavy ion evaluation tested**
- **EEV CCDs: CCD02 (288 x 385 22 μm x 22 μm pixels)**
  CCD47-20 (1024 x 1024 13 μm x 13 μm pixels)
  - **Investigation of displacement damage effects on charge transfer efficiency and star position measurements (also applicable to *laser communications* and *space science* missions)**

Irradiations

- **Co-60: at ESTEC 21-24 September 1999 .**
  - **Dose rate 0.26 to 2.6 krad(Si)/hr.**
  - **6 x ASCoSS (2 UB) , 8 x each ADC type (2 UB)**

Devices irradiated	Dose step krad(Si)	Exposure time hours	Dose rate krad(Si)/hour	Total accumulated dose on ASCoSS devices	Total accumulated dose on ADCs
All ASCoSS	2.0	0.77	2.6	2.0	-
All	4.0	15.1	0.26	6.0	4.0
All, except ASCoSS #s 43, 54, 75	15.2	15.8	0.96	21.2	19.2
ADCs, except #s 6 and 7 (both types)	47.0	18.1	2.6	-	66.2

Irradiations

- **10 MeV protons : ASCoSS and CCD chips, unbiased, AEA Technology, Harwell. 7 December 1998**
- **Heavy ion:** at the Heavy Ion Facility (HIF) at Louvain-La-Neuve (Belgium) on 11 June 1999

$^{40}Ar^{8+}$ ions, (energy 150 MeV),	60° incidence	**LET 28.2 MeV/mg/cm^2**
$^{40}Ar^{8+}$ ions, (energy 150 MeV),	45° incidence	**LET 19.9 MeV/mg/cm^2**
$^{40}Ar^{8+}$ ions, (energy 150 MeV),	normal incidence	**LET 14.1 MeV/mg/cm^2**
$^{20}Ne^{4+}$ ions,(energy 78 MeV),	60° incidence	**LET 11.7 MeV/mg/cm^2**

AD9223 and LTC1415 12-bit ADCs

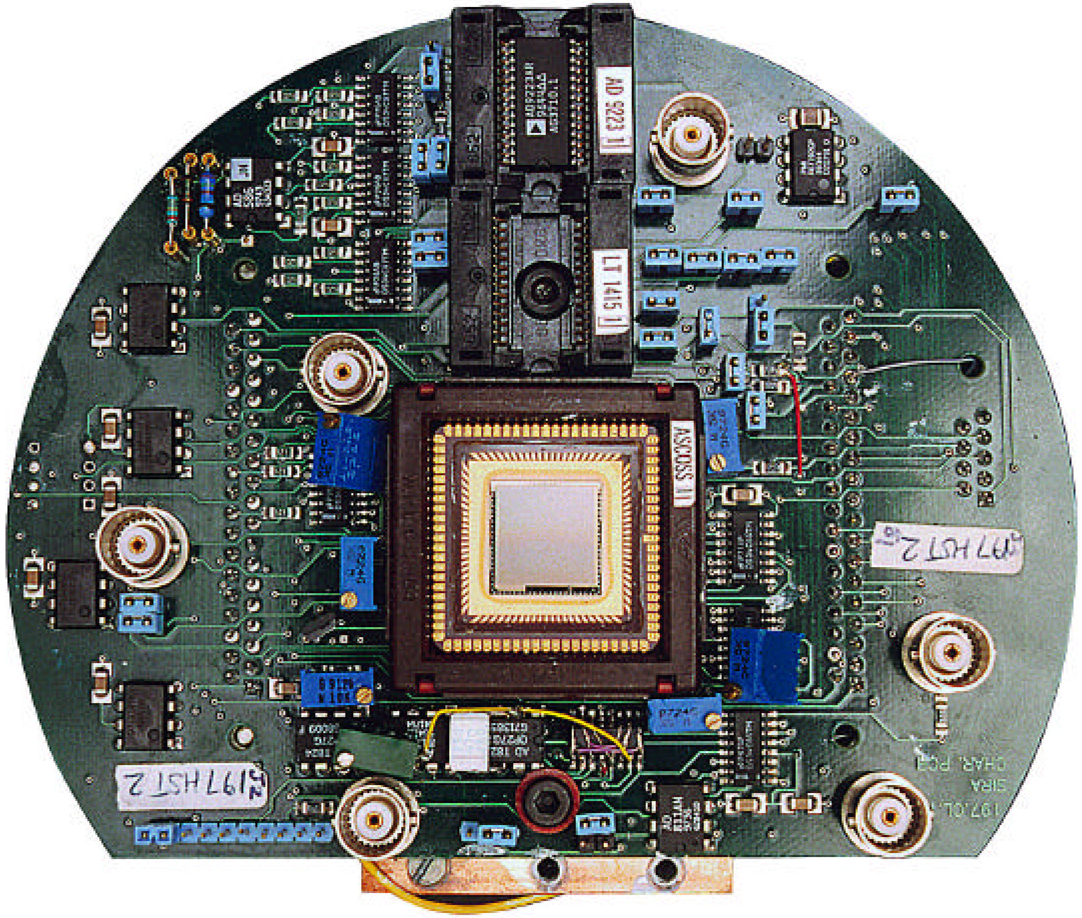
- **AD9223:**
  - **3 MSPS, programmable on-chip (or external) reference**
  - **pipelined architecture with output error correctionlogic**
  - **low power: Vdd(an) 26 mA (max) Vdd(dig) 0.5 mA (max)**
  - **used by Sira on the CHRIS instrument on ESA's PROBA mission**
  - **10 MSPS version (9220) previously tested by Turflinger et al* at high dose rate (71 rad(Si) / s)**
    - dependence on bias condition
    - failed at 35 krad due to DNL and voltage reference but recovered on annealing

*** 1996 IEEE Radiation Effects Data Workshop, pp 6-12**

AD9223 and LTC1415 12-bit ADCs

- **LTC1415**
  - **1.25 MSPS, programmable on-chip (or external) reference**
  - **Low power: 20 mA (max) with ‘nap’ and ‘sleep’ modes**
- **Devices were in plastic surface mount packages and were not burned in**
- **Devices were de-lidded by ESTEC for SEL tests**
- **Two PCBs were designed and manufactured**
  - **bias board for TID and SEL irradiations (all devices)**
  - **characterisation board (single devices)**

ADC & APS Characterisation Board



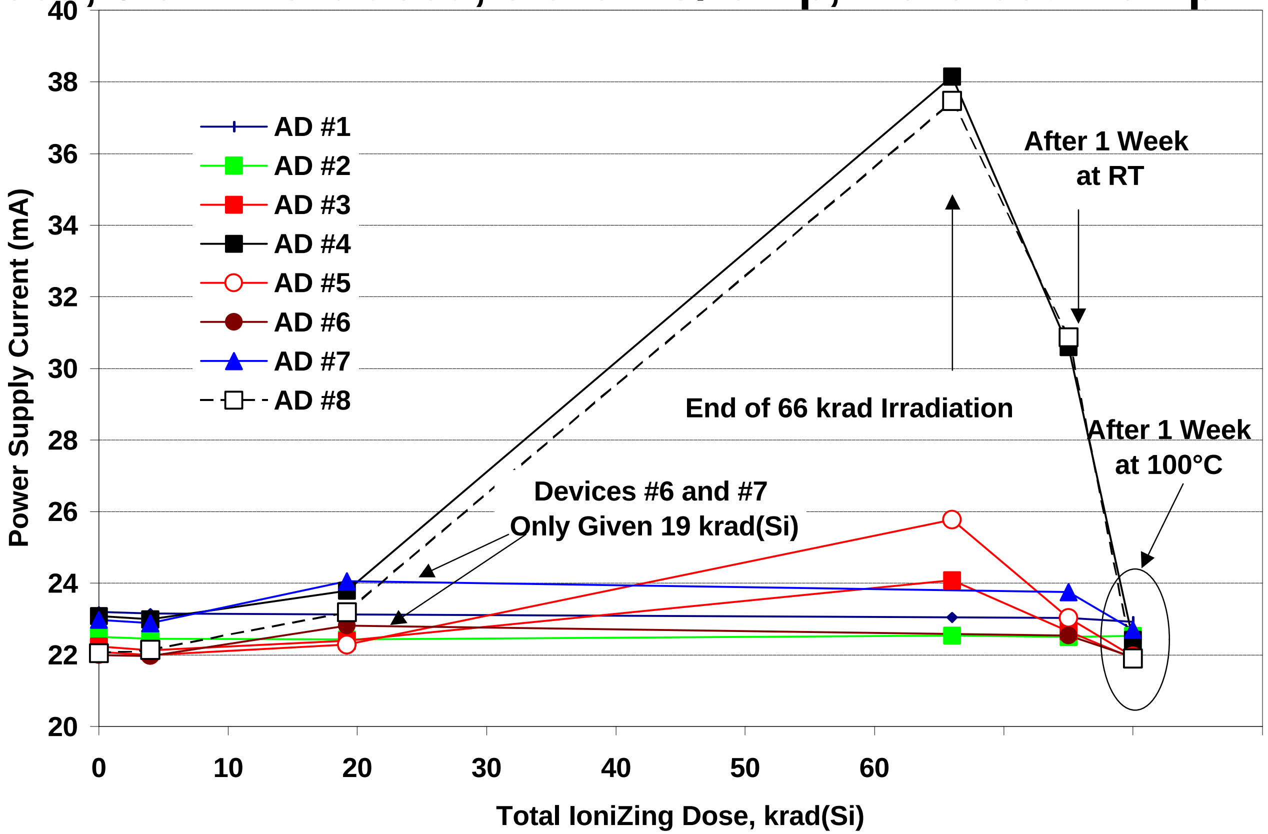
QCA Final Presentation Day
26 January 2000

siraelectro-optics

Co-60 Tests, Power Supply Currents

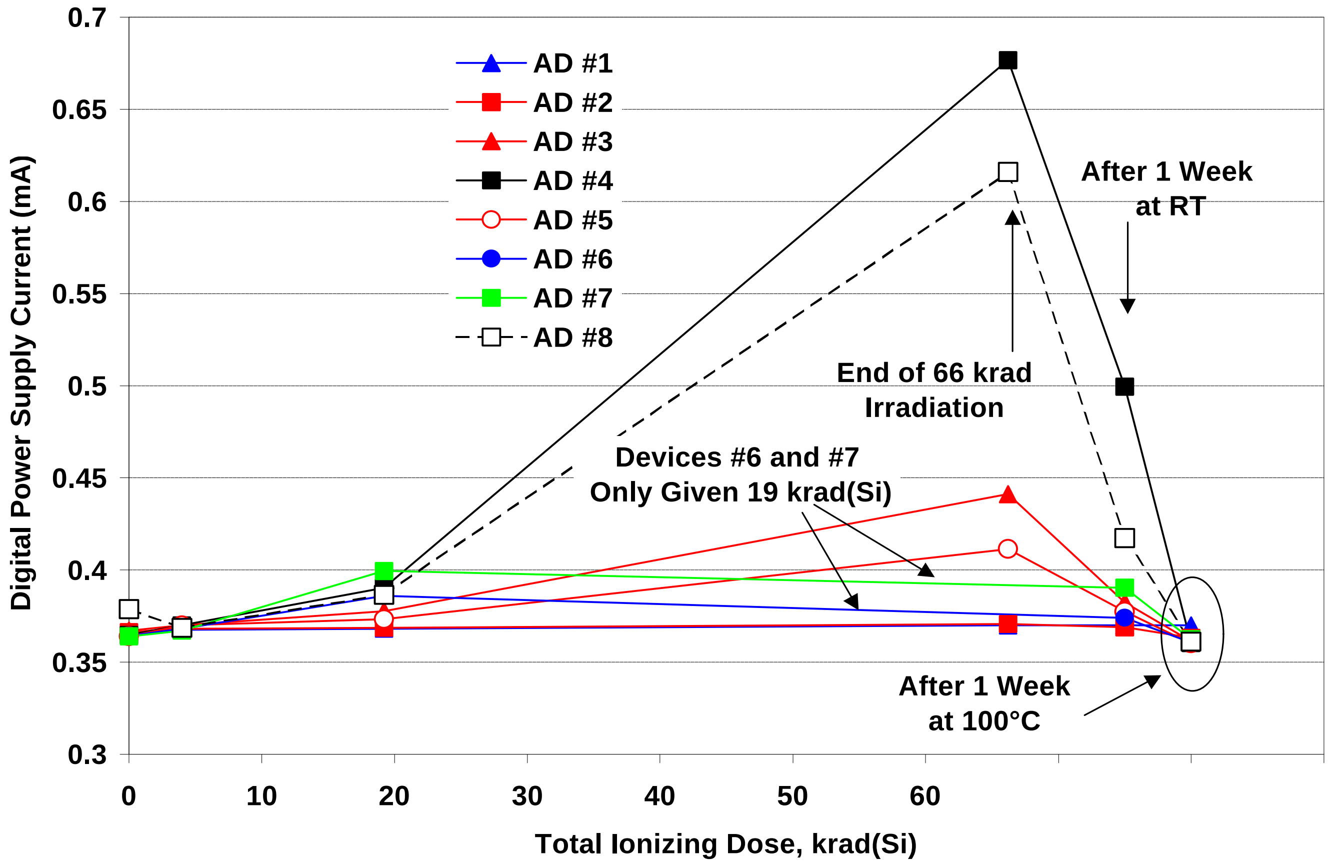
Analogue power supply current for the AD9223 (characterisation board)

1 & 2 unbiased, 3 & 4 DC biased, 5 & 6 DC/ramp, 7 & 8 both ramp input



Co-60 Tests, Power Supply Currents

Digital power supply current for the AD9223 (characterisation board)

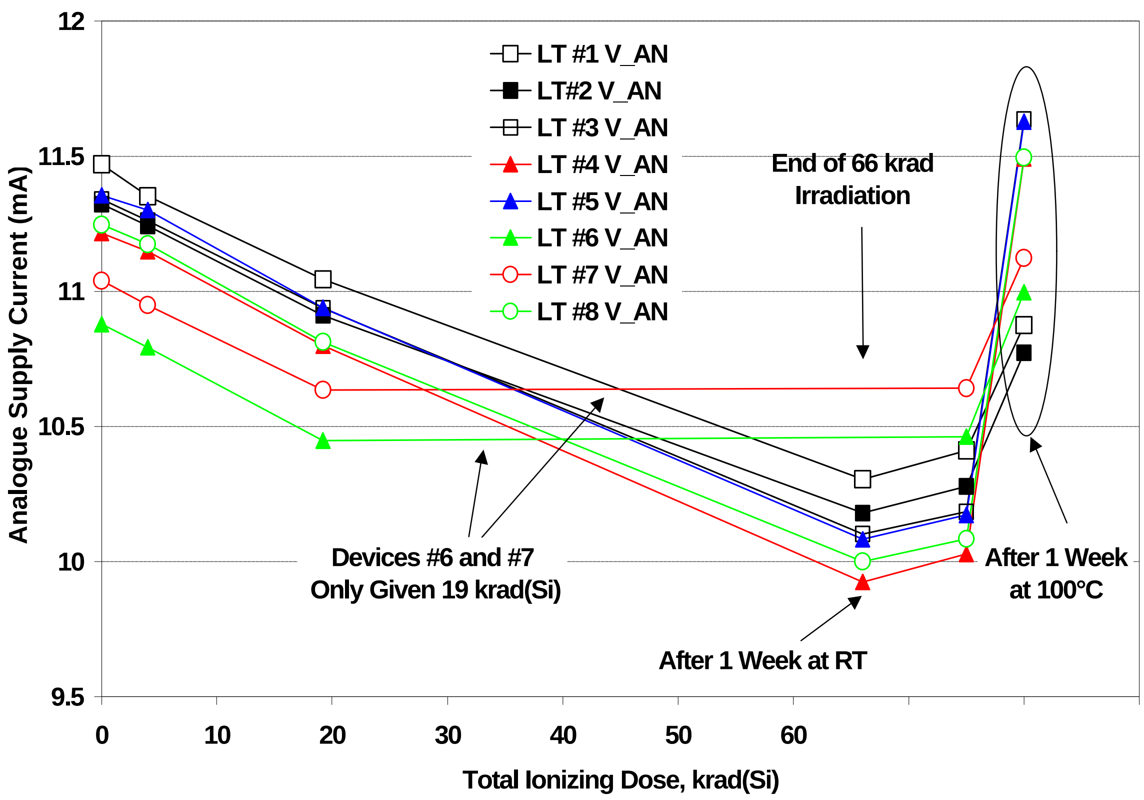


QCA Final Presentation Day
26 January 2000

siraelectro-optics

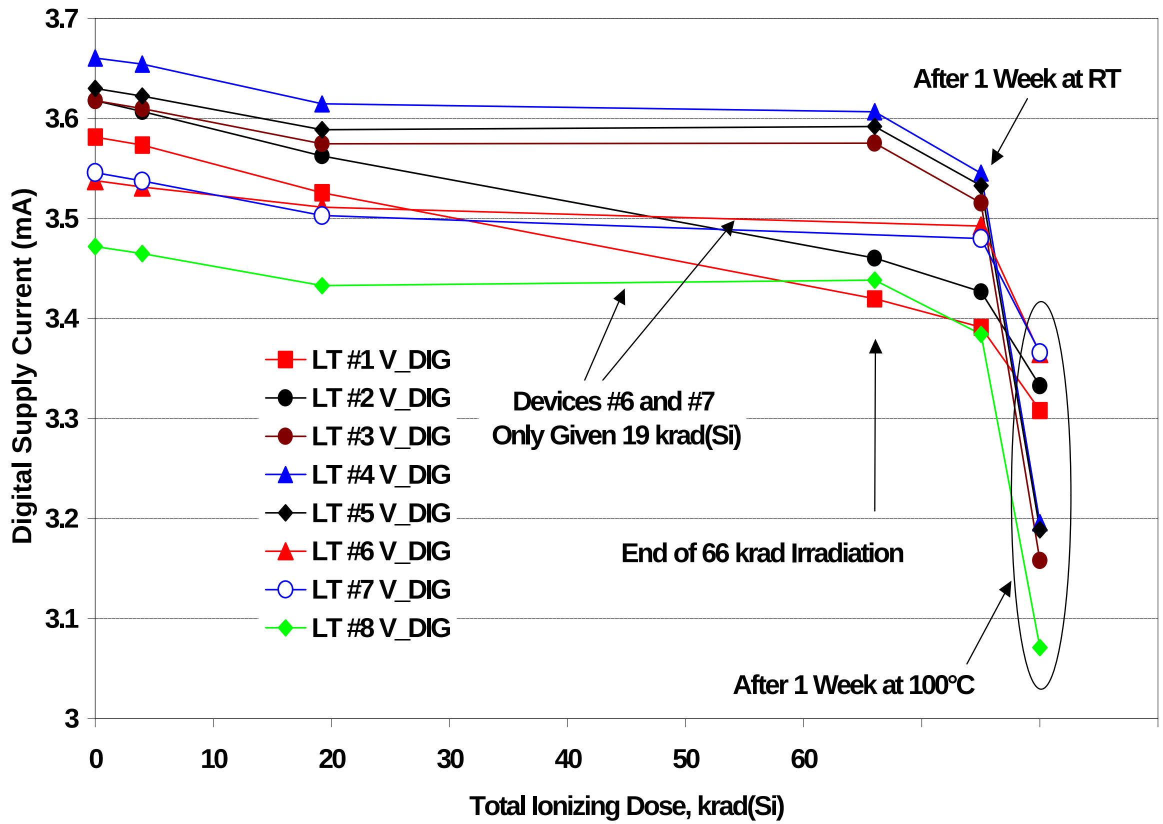
Co-60 Tests, Power Supply Currents

Analogue power supply current for the LTC1415 (characterisation board)



Co-60 Tests, Power Supply Currents

Digital power supply current for the LTC1415 (characterisation board)

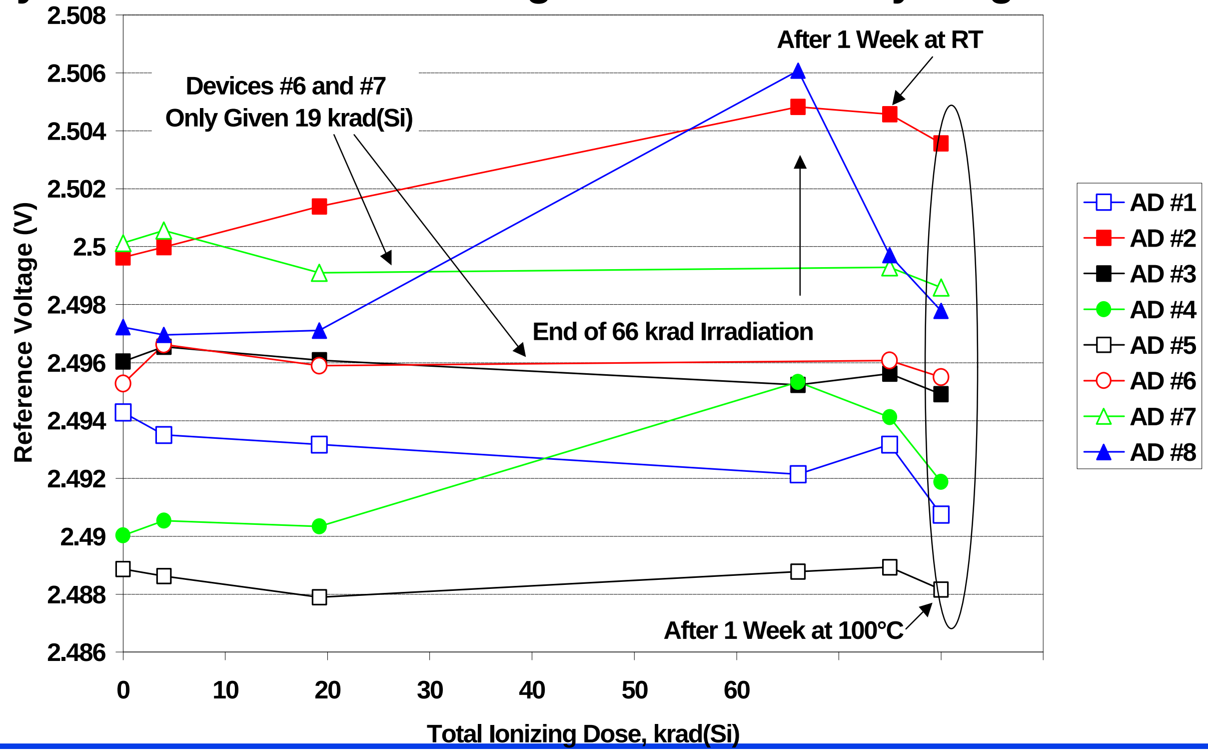


Power Supply Currents: Conclusions

- AD9223 #4 and #8 show large increases in current above ~10 krad (go out of specification), but these anneal out after a 100°C bake.
- Increase coincided with significant degradation in differential non-linearity. Both failed after 19 krad irradiation because of 'stuck bits'.
  - stuck bits were some of the most significant, so output data significantly corrupted.
  - Recovery of the supply current after the bake also coincided with return to normal DNL performance. Devices #4 and 8 also showed larger than average changes in VREF voltage.
- Little change in LTC1415 currents. DNL for unbiased devices (#1 and #2) degraded after 100°C bake - 'rebound' effects ?– but degradation not as severe as for the AD9223 (only least significant bits affected). #1 and #2 also showed largest increase in digital supply current.
- The low power modes for the LTC1415 ('sleep' and 'nap') remained functional for all the tests.

Co-60 Tests: Voltage Reference

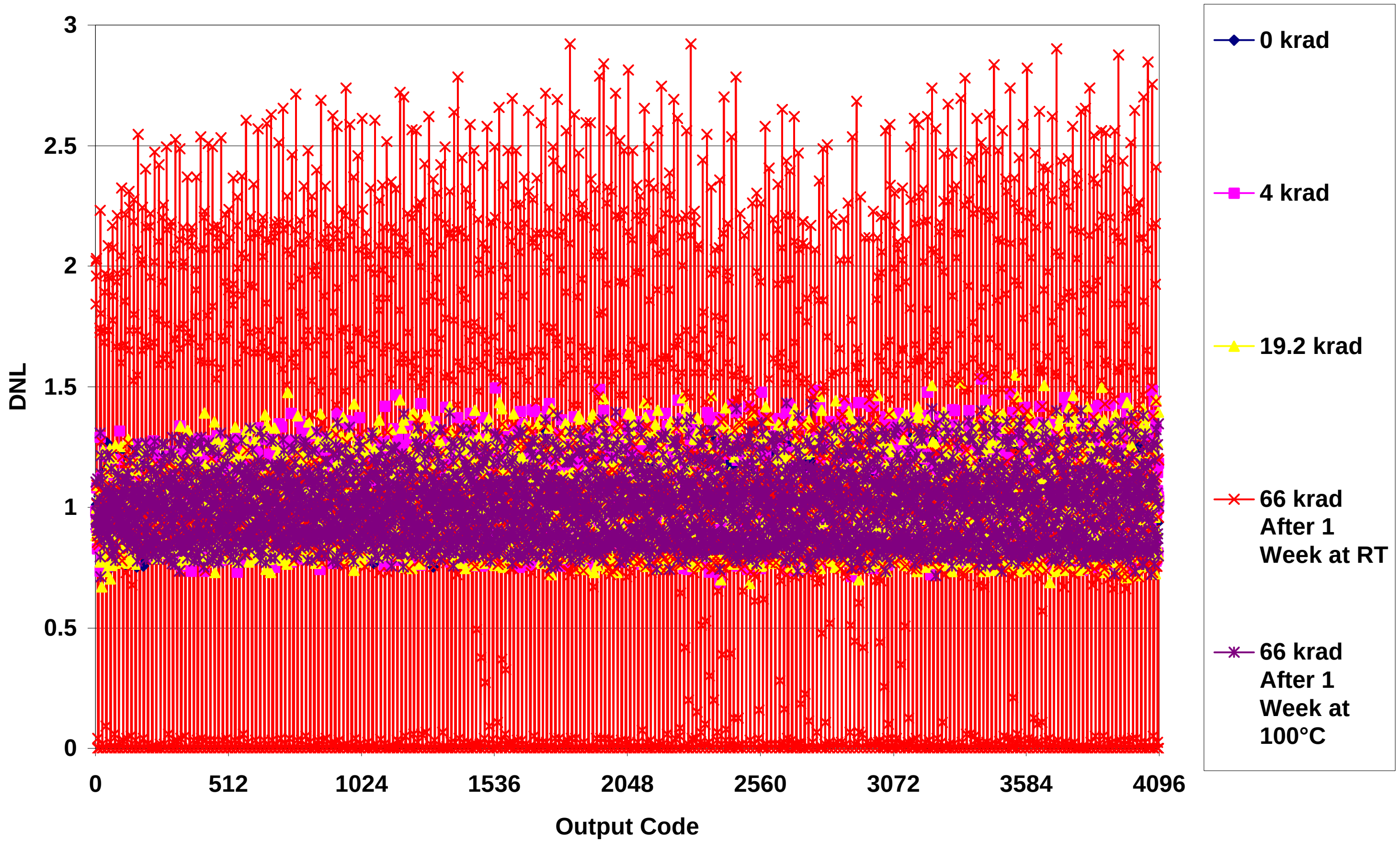
- critical for offset and gain accuracy
- changes were small and within specification (2.5 ± 0.035 V for AD9223 and 2.5 ± 0.020 V for LTC1415)
- not necessary to use an external voltage reference at any stage



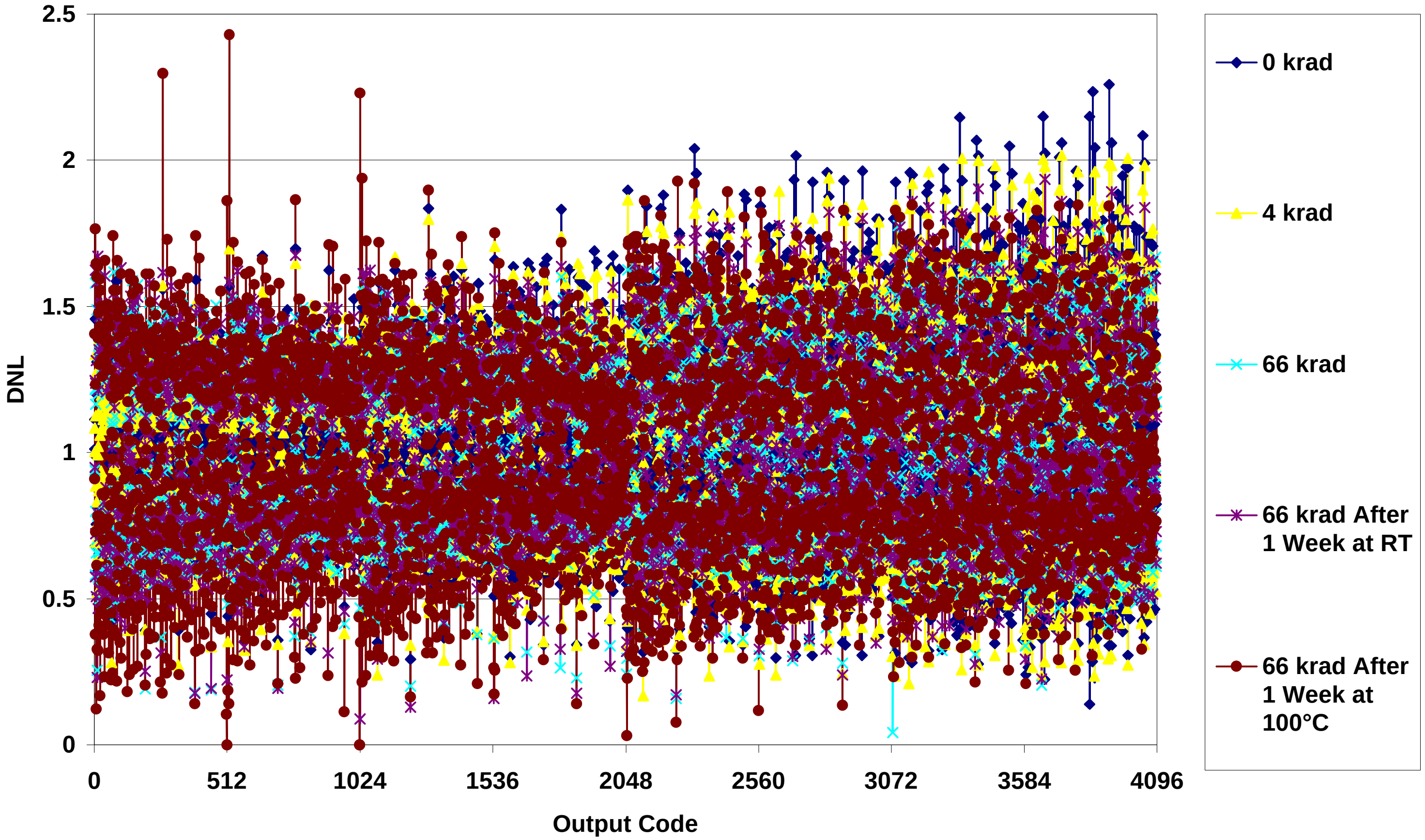
ADCs, Co-60: DNL and INL

- **AD9223:**
  - **Apart from ‘stuck’ bits for devices #4 and #8 immediately after 66 krad(Si), no significant changes in DNL.**
- **LTC1415:**
  - **no significant changes in DNL until after the 100 °C bake when #1 and #2 (un-biased during irradiation) showed increases in DNL – though the DNL for the LTC1415 was in general higher than for AD9223 and the changes in DNL were not dramatic.**
  - **DNL varied with operating conditions and was better at some times than at others, nevertheless changes for devices #1 & #2 are probably significant.**
- **No significant changes in INL for either device**

AD9223 DNL for #4 (Temporarily Failed)

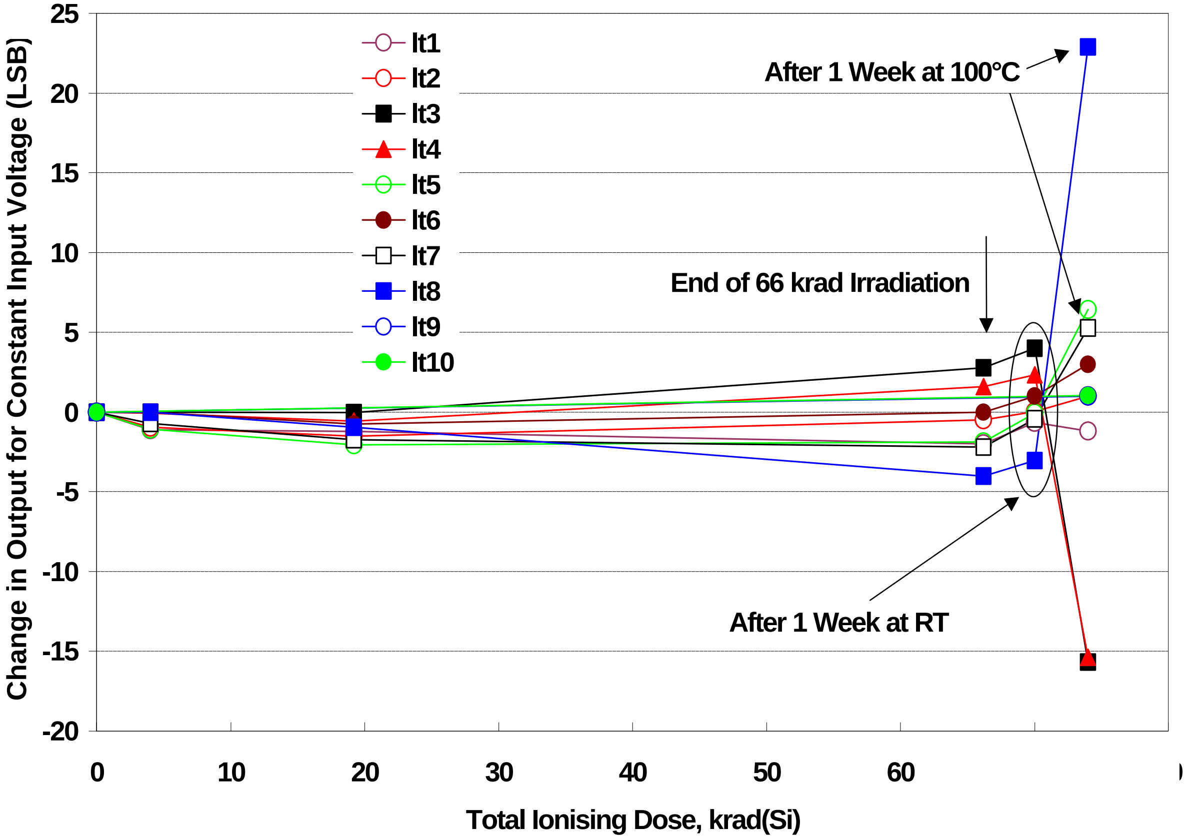


LTC1415 DNL for #2



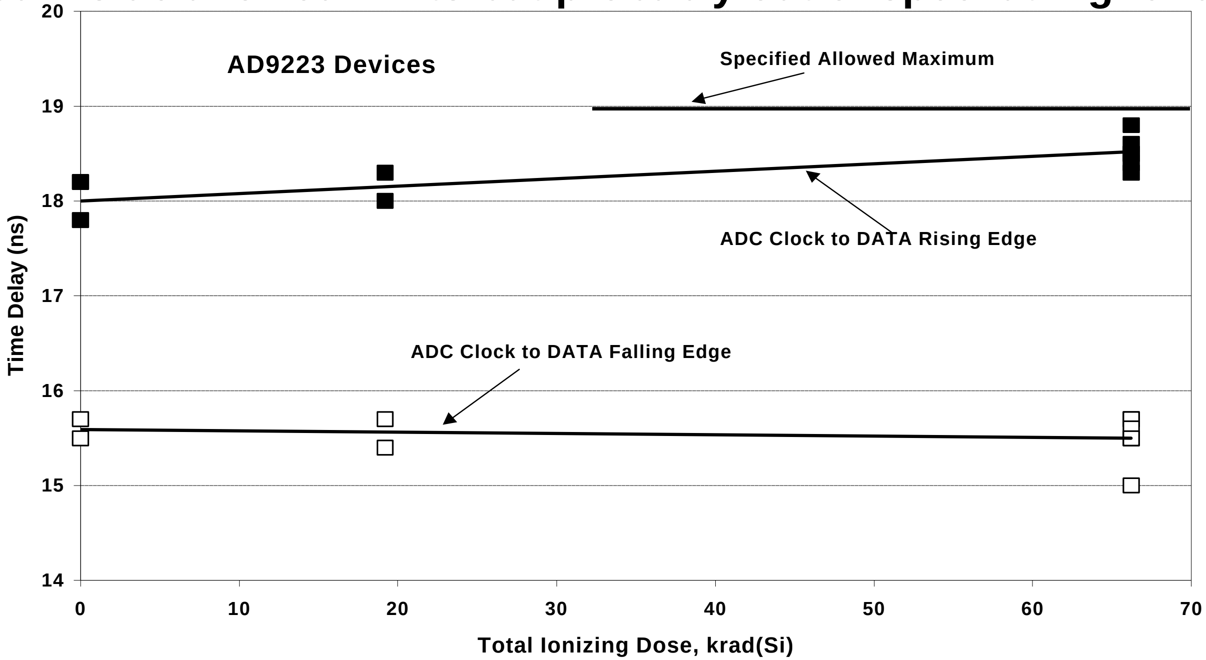
Co-60 ADC Results, Offset

- LTC1415 #s 3, 4 and 8 showed shifts in offset after the 100C bake



Co-60 ADC Results, Timings

- **Delay time between clock and rising/falling edge of data is important.**
  - **remained inside allowed limits but probably out of spec. at higher doses.**



- **The LTC1415 BUSY clock can be used to latch data into an instrument. Data set up time (‘data ready before busy’) is important.**
  - **should be > 20 ns for correct operation, easily satisfied all devices**

Co-60 ADC/SEL Results

- Noise: no significant change
- Threshold voltages: no significant change

- **Latch-up: LTC1415**
  - No latch-up after maximum LET of 28 $MeV/mg/cm^2$ and fluence 5.3 $x10^6/cm^2$.

ADC Latch-up Tests

- **Three de-lidded devices were tested, one from the current CHRIS flight batch A63155.1, date code 9702 (device #2) and two (devices # 1 and 3) from another batch (AG3710.1, date code 9644).**

$^{40}Ar^{8+}$ ions, (energy 150 MeV), normal incidence **LET 14.1 MeV/mg/cm²**

device #1

average cross section = 4.5 10^{-7} cm^2

device #2

average cross section = 2.2 10^{-6} cm^2

device #3

average cross section = 3.5 10^{-7} cm^2

$^{20}Ne^{4+}$ ions, (energy 78 MeV), 60° incidence **LET 5.85 x 2= 11.7 MeV/mg/cm²**

no latch-up seen after 4.1 10^{6} ions/cm^2

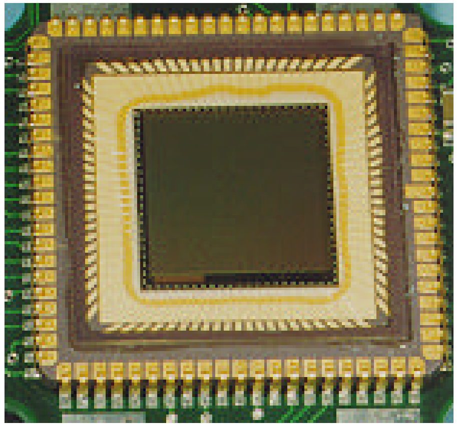
- **threshold for latch-up is ~ 12 MeV/mg/cm²**
- **Expect the saturation cross section is in the range 2 10^{-2} to 2 10^{-4} cm^2**
- **SEL protection circuit implemented on CHRIS**

ADCs: Conclusions

- **AD9223**
  - **Likely to fail at high dose rates after ~ 10 krad(Si): power supply current and ‘stuck’ bits**
  - **Expected to be OK at low dose rates to > 66 krad(Si)**
  - **Vulnerable to SEL**
- **LTC1415**
  - **Performance >66 krad(Si) marginal: some changes in DNL and offset after 100°C bake (rebound ?)**
  - **No SEL after 28 MeV/mg/cm^2**

ASCoSS APS

- Designed by IMEC for demonstrator star tracker for the ESTEC project 'Attitude Sensor Concepts for Small Satellites'.
- 512 x 512 25 μm x 25 μm pixels, 17 μm epi thickness
- Photodiode detectors, CMOS readout High fill factor (~85%) but low MTF (in current version)
- Windowing and short integration time allowed (but reset fault)
- good noise and fixed pattern behaviour (~ 50 electrons) : rivals CCDs in star tracker applications
- On-chip '8-bit' ADC
- CVF ~ 8.5 μV/electron
- Full-well ~ 140,000 electrons



ASCoSS APS: CVF Determination

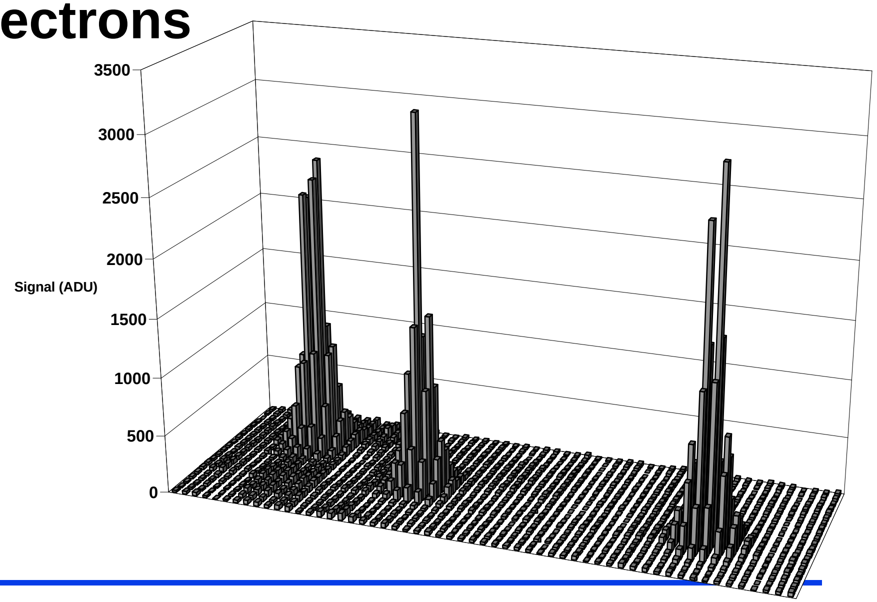
- **Could not use X-ray method: diode volume too small**
- **Could not use mean-variance method: some pick-up present**
- **IMEC design and off-chip gain leads to**

<u>45 electrons/ADU</u>

- **5.5 MeV alpha particle check gives 40 el/ADU assuming an average event size of 1 x 10^6 electrons**

(events have to be in

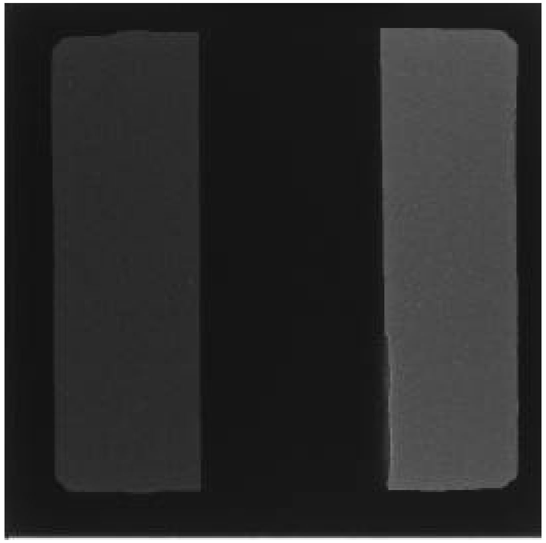
the range 7 x 10^5 to 1.5 x 10^6 el)

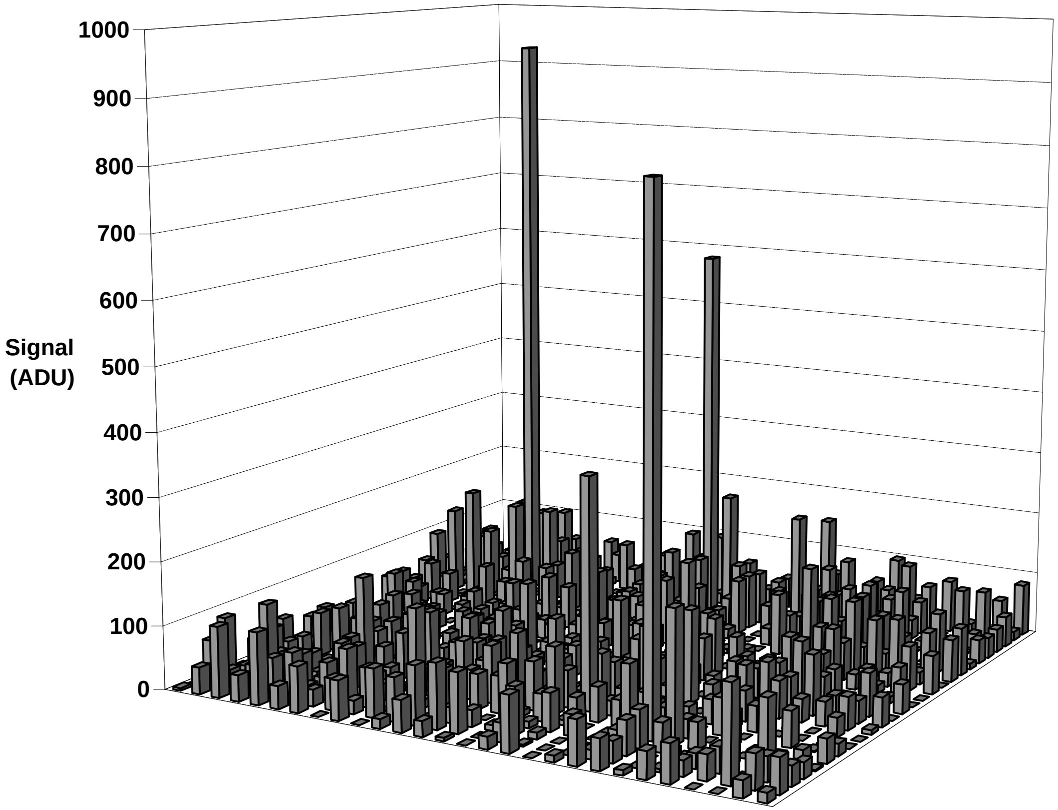


ASCoSS APS: Dark Signal

- **Need to distinguish between thermal dark signal and fixed pattern noise (FPN)**
- **FPN approximately independent of temperature and integration time and ~ 5 ADU (230 es)**
  - need to subtract for accurate work
- **Proton irradiation gives dark current spikes**
  - localised to a pixel
  - tend to be smaller than for CCDs
  - vary as expected with temperature
  - random telegraph signal behaviour
- **Co-60 gives uniform dark signal increase**
  - varies as expected with temperature
  - large increase but anneals

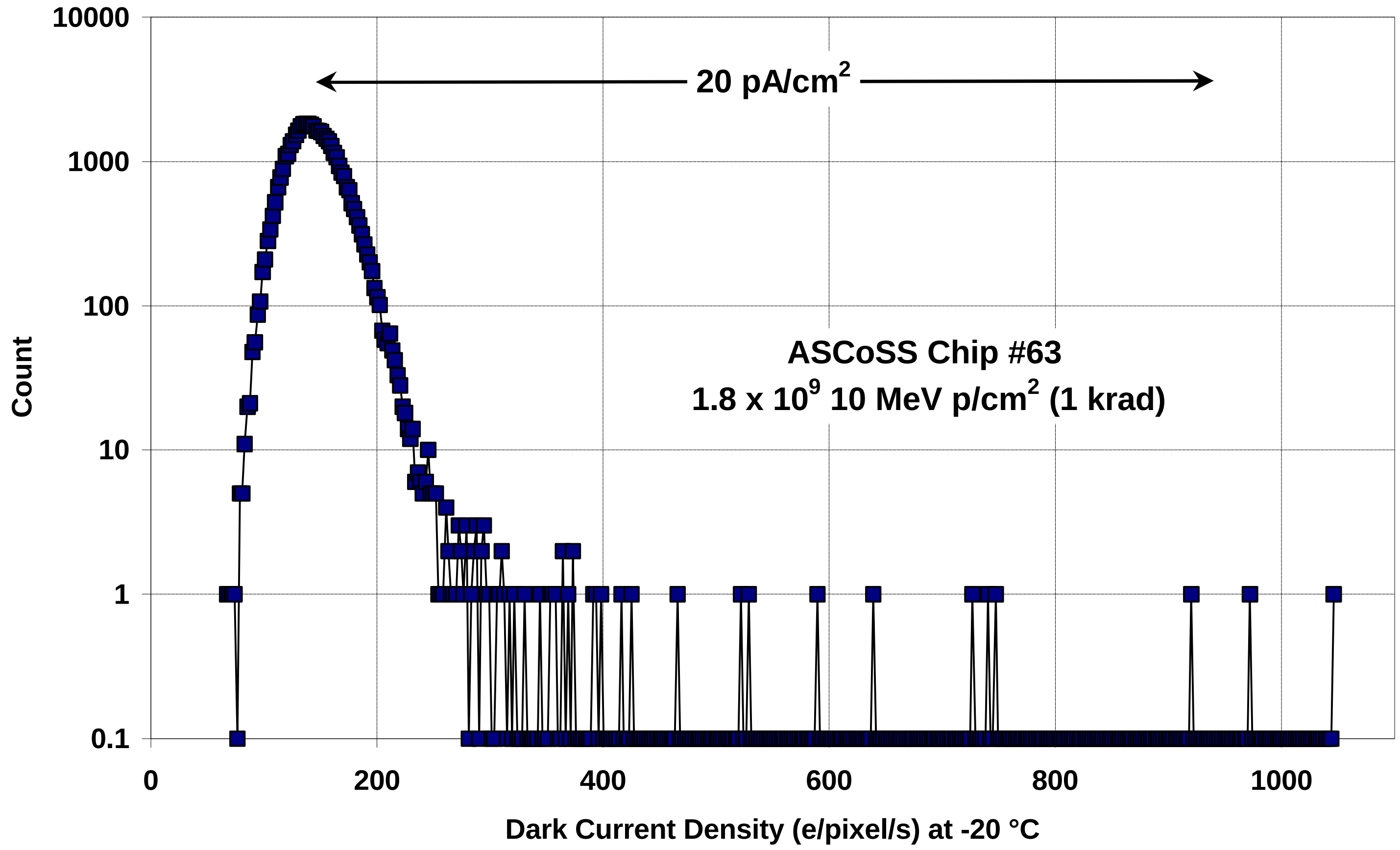
ASCoSS APS: Dark Signal



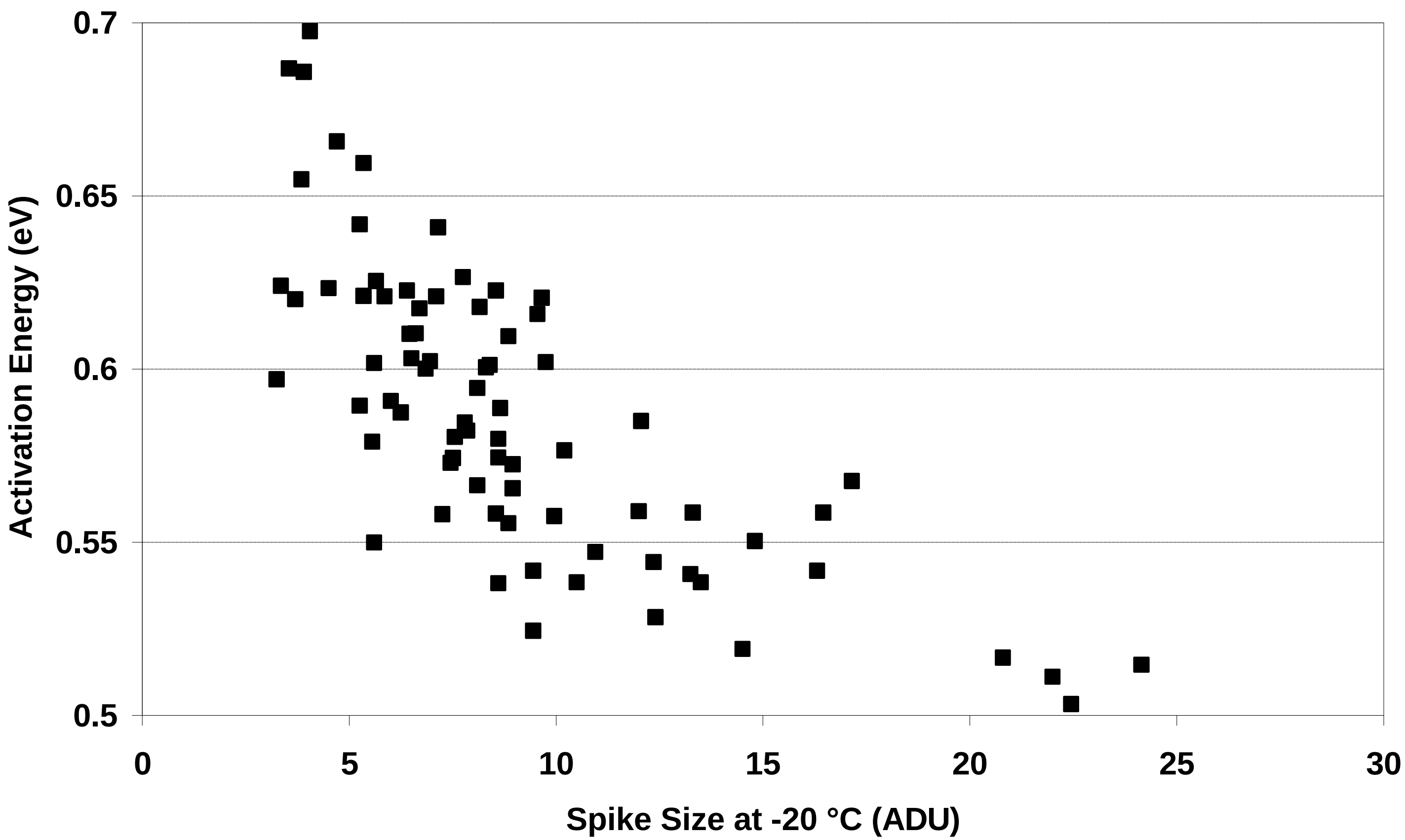


10 MeV Proton Irradiation

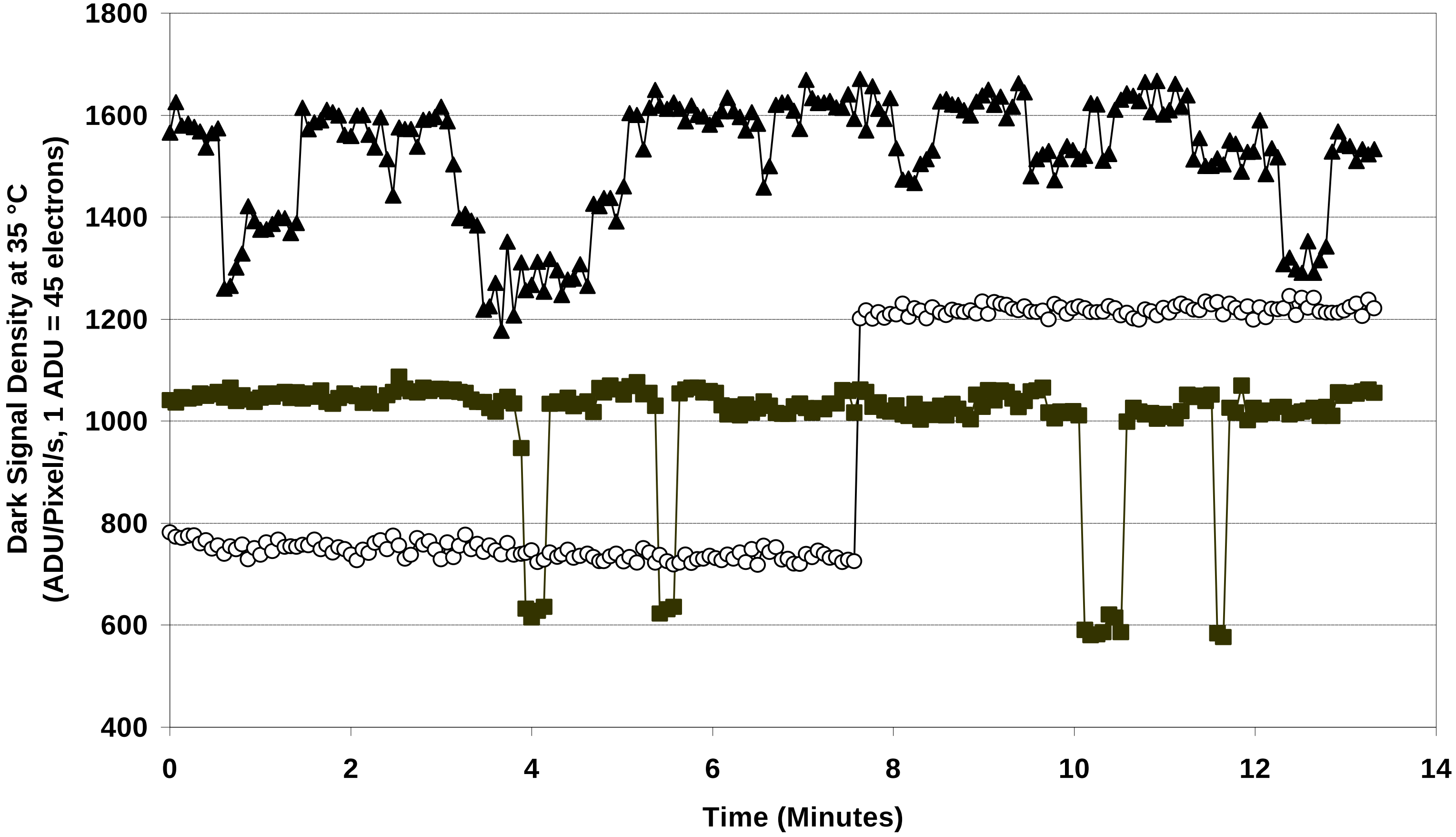
ASCoSS APS: Dark Signal



ASCoSS APS: Dark Signal



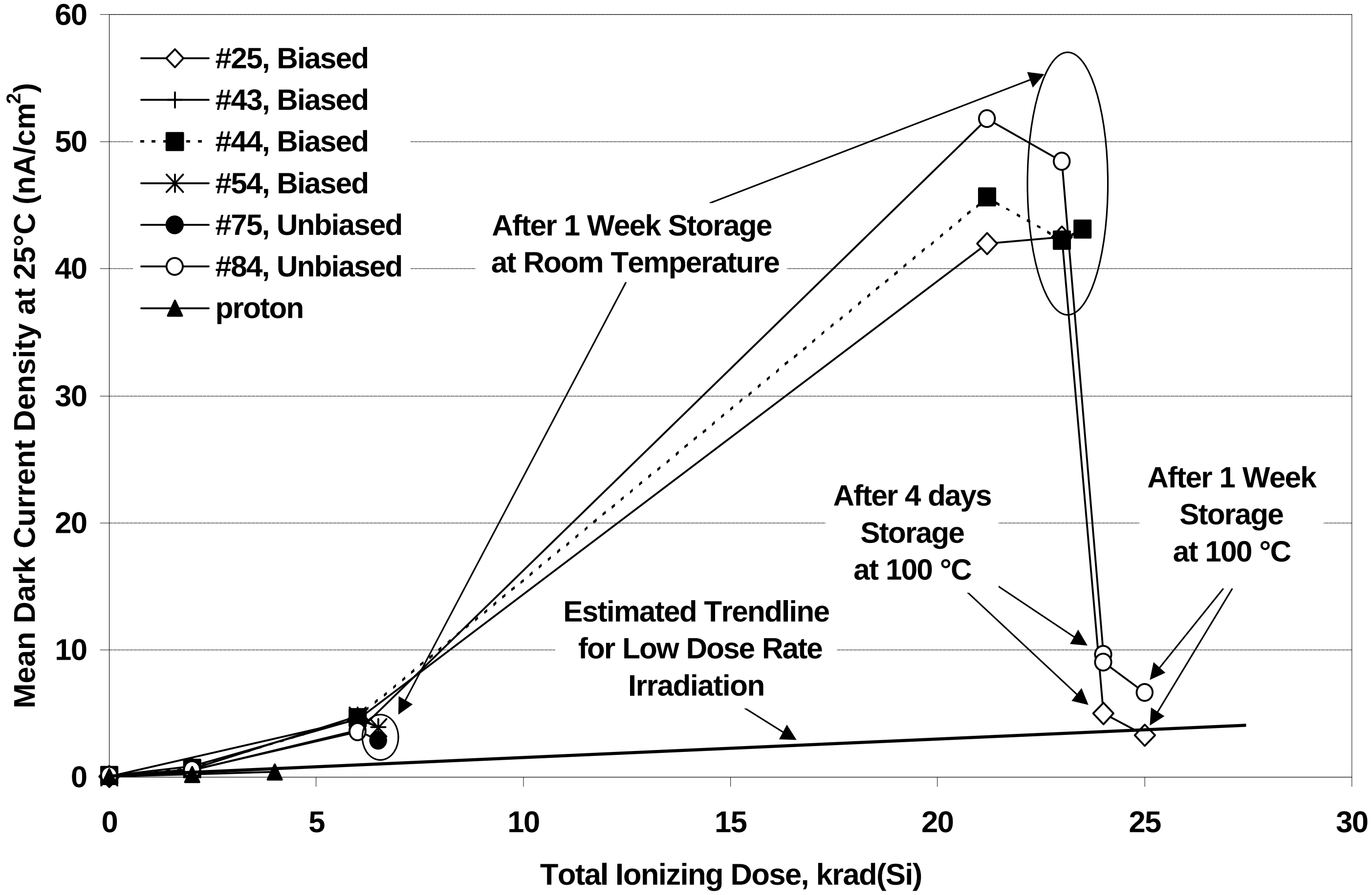
ASCoSS APS: Dark Signal



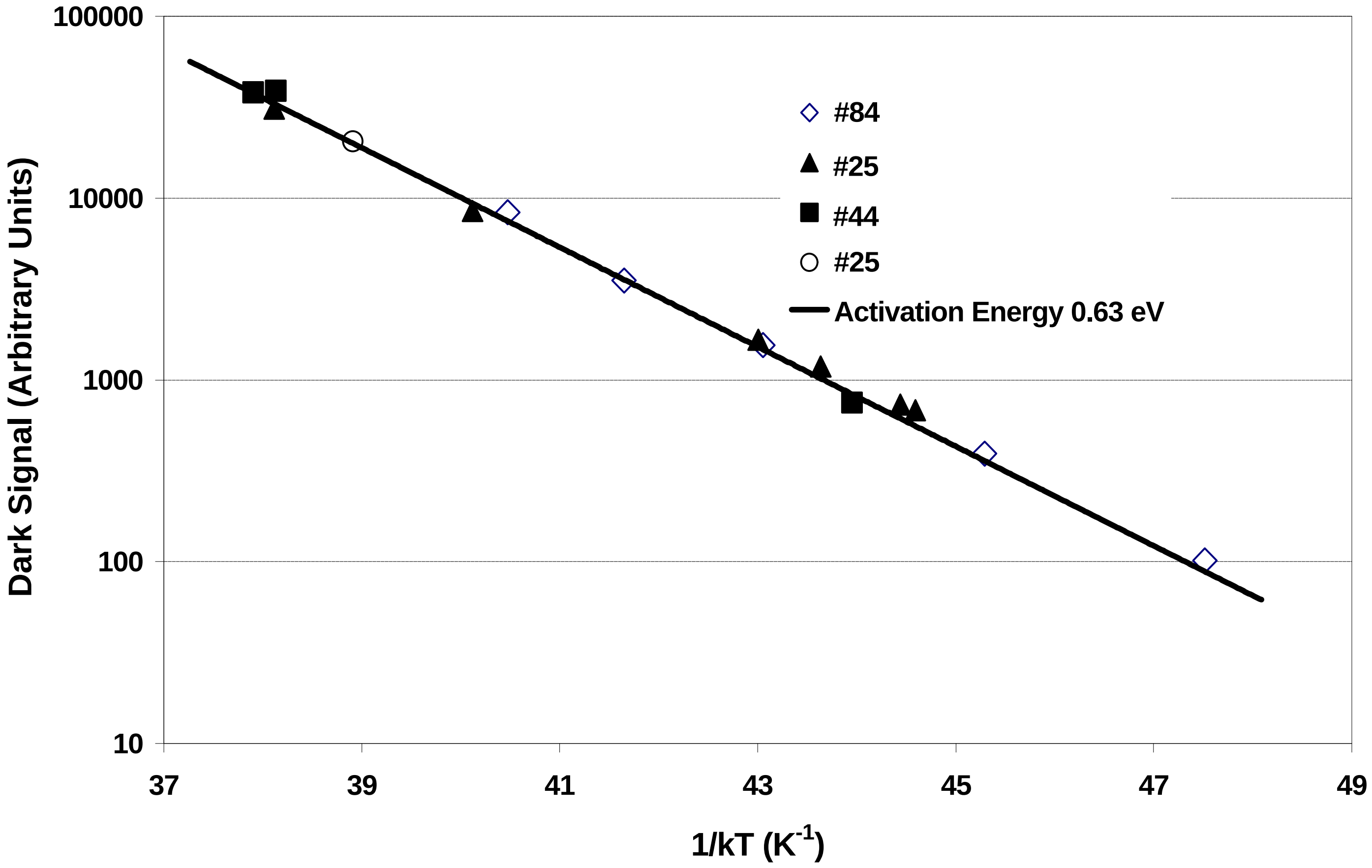
QCA Final Presentation Day
26 January 2000

siraelectro-optics

ASCoSS APS: Dark Signal



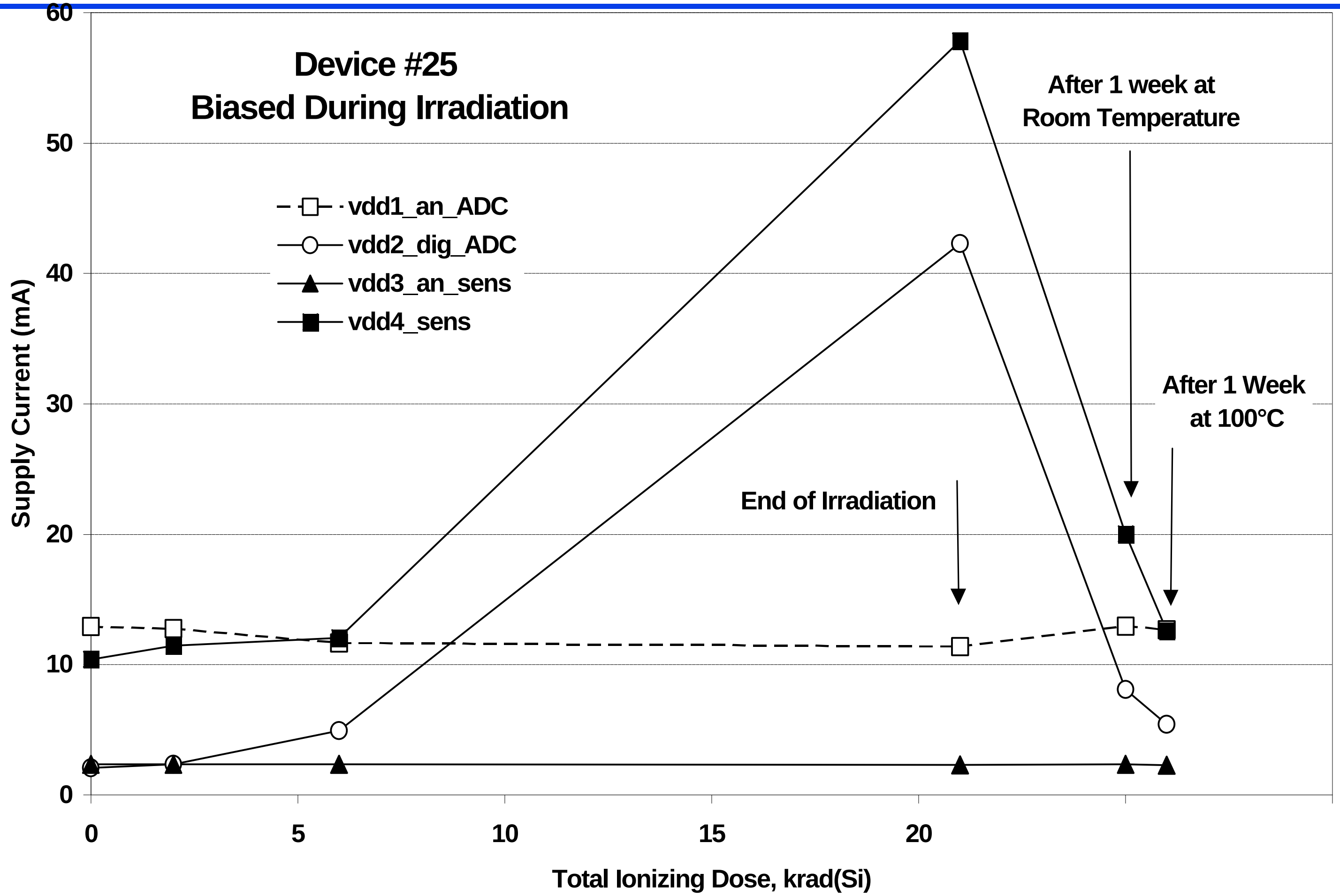
ASCoSS APS: Dark Signal



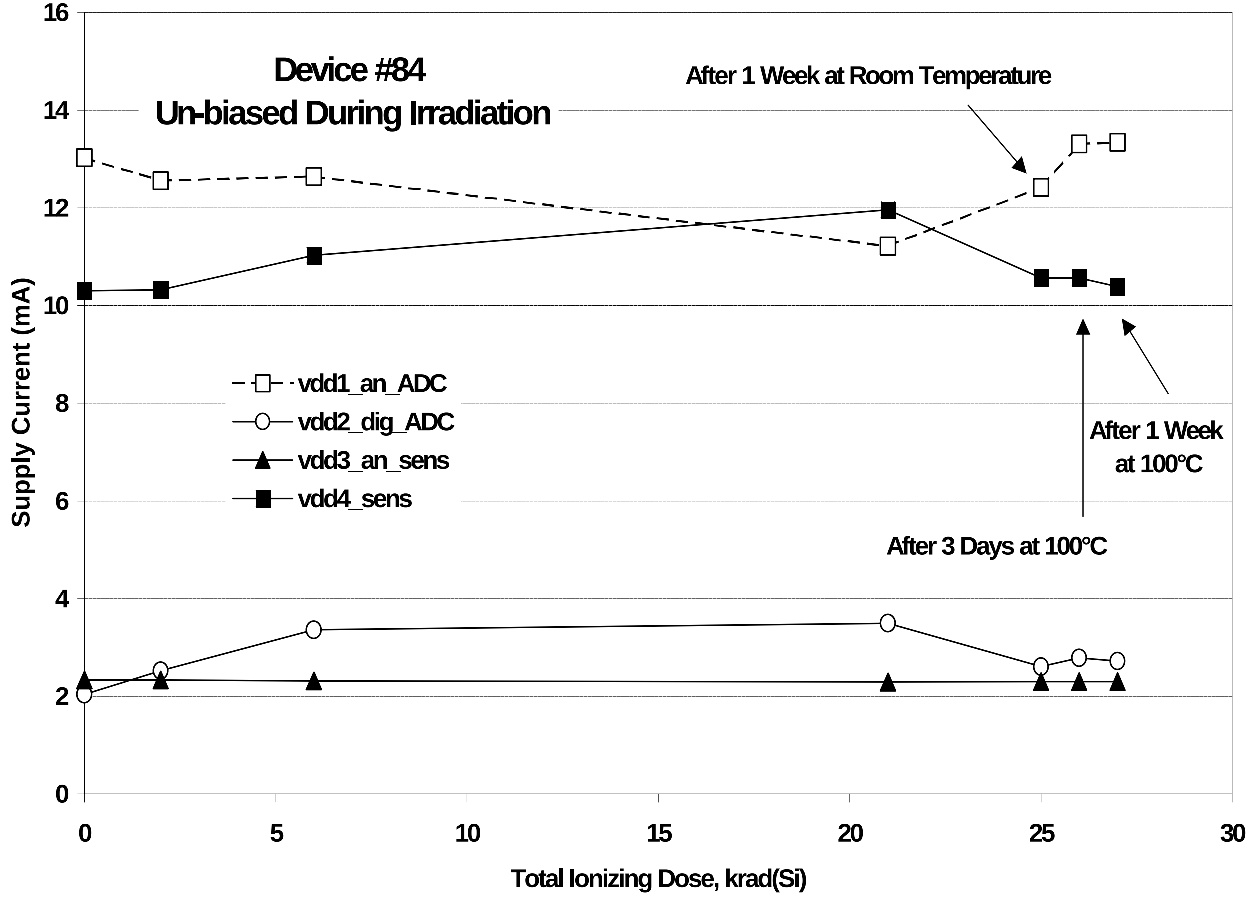
ASCoSS APS: Power Supply Currents

- **Sharp increase in the Vdd1 (digital ADC) and Vdd4 (sensor) supplies after 6 krad(Si) for biased devices (but not the un-biased).**
- **After 21 krad the current limit to the board was nearly exceeded and significant heating of the devices occurred. Higher radiation doses without a current limit could potentially cause device damage: this may have happened with the earlier IMEC tests on IBIS 1 devices.**
- **There is significant post-irradiation annealing. However the annealing occurs at a somewhat variable rate: device #44 annealed with room temperature storage, whereas #25 needed a bake at 100°C.**
- **The other bias supplies were not greatly affected by the irradiation. There were some small changes in particular supplies but these annealed out. The ADC reference voltage remained unchanged.**
- **It is possible that parasitic leakage paths (e.g. in a field oxide) are being turned on just above 6 krad(Si). Annealing of flatband shift would result in a sharp return to normal current levels.**

ASCoSS APS: Power Supply Currents



ASCoSS APS: Power Supply Currents



ASCoSS APS: Other Co-60 data

Threshold Voltage Shift

- Thresholds for ADC CLOCK, ADC CLOCK_XRD and ADC SYNC_XRD were monitored. These supply the three different types of input gate structure used on the device. changes were small (of the order of 0.1 V or less after 21 krad(Si)).

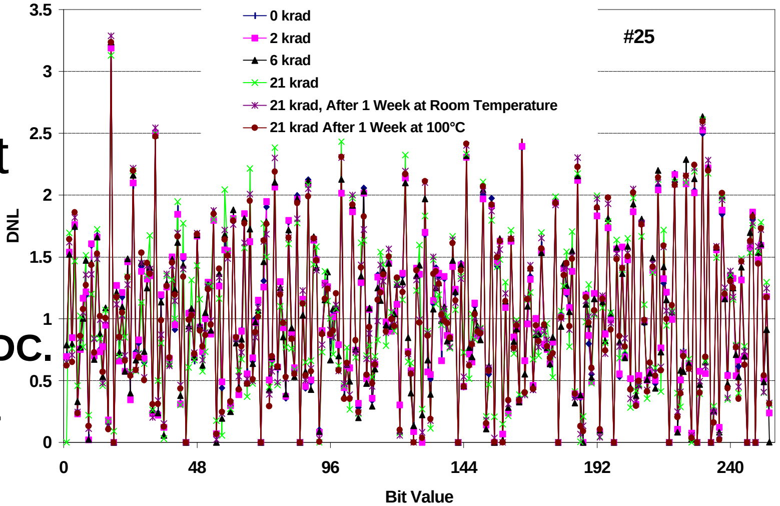
On-chip ADC Performance

- No change in DNL
  - **(7-bit performance at start)**
- small (few LSB) changes in offset
- shows SEL:

threshold ~ 19.9 **MeV/mg/cm²**

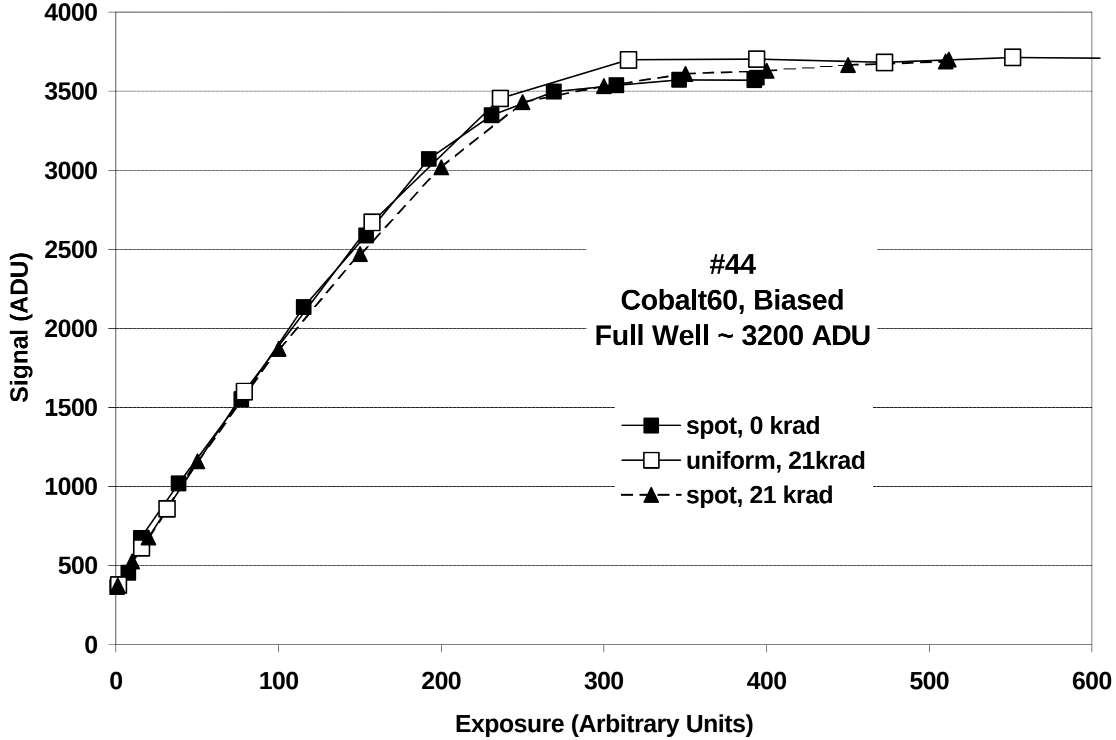
saturation cross section i> 2.2 10^{-6} cm² for on-chip ADC.

Threshold > LET 28.2 MeV/mg/cm² rest of the sensor.

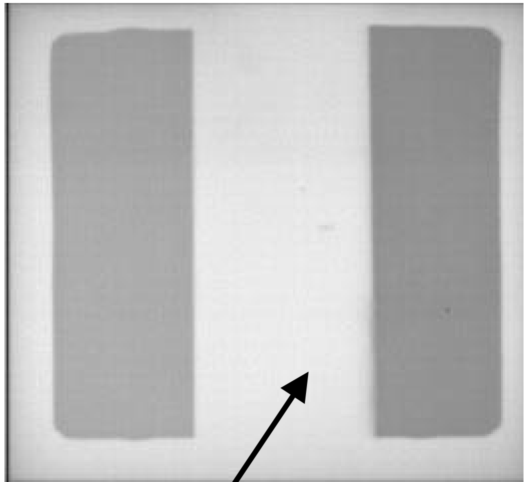


Linearity and Full-well

- Slight ‘roll-off’ in linearity at high signal levels, particularly for spot illumination, but no significant change with radiation, full well capacity remaining at ~ 3200 ADU (14400 electrons)



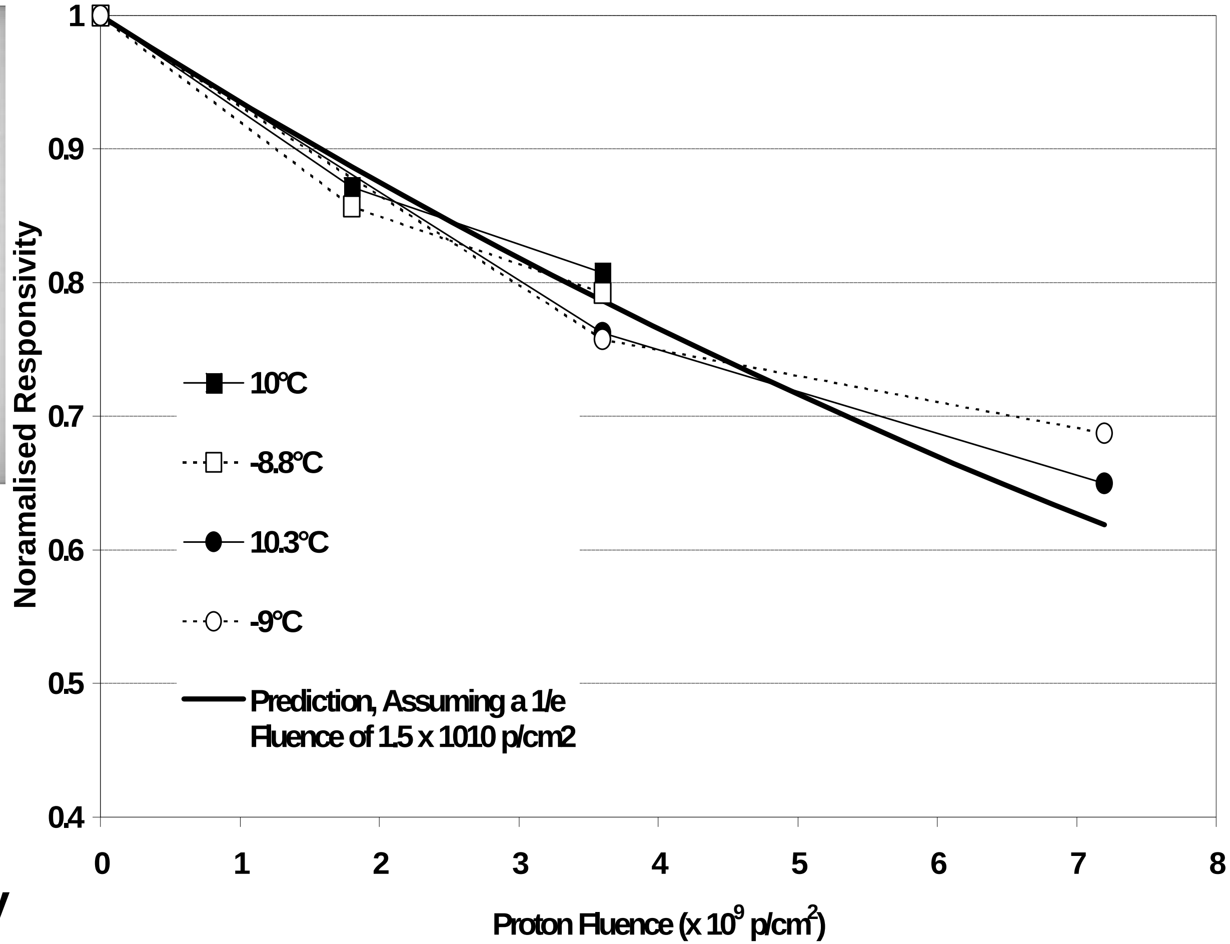
ASCoSS APS: Responsivity



After Proton (also alpha) Irradiation.

No change in PRNU (~2%)

Co-60 showed no change in responsivity



CCD Tests: Test Objects

- **Two EEV CCD47-20 devices:**

CCD47-20-2-231A (grade 2)

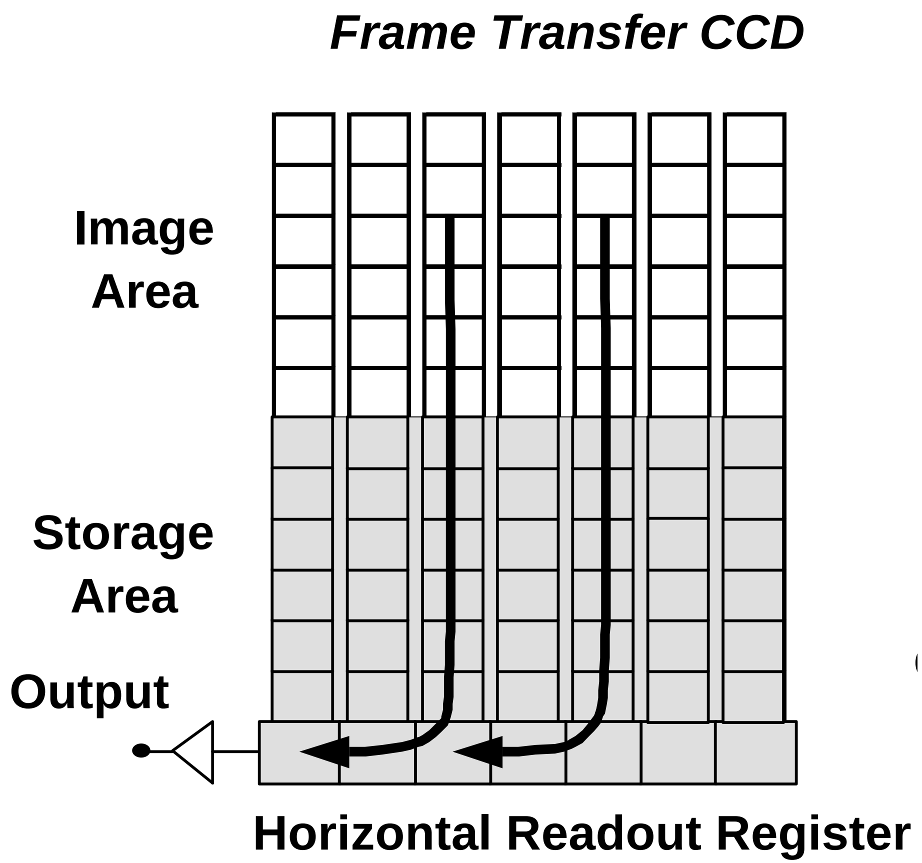
CCD47-20-5-231A (grade 5), both irradiated but only the grade 2 used

  - **frame transfer mode**
  - **1024 x 1024 image area pixels**
  - **13 μm x 13μm pixels, no supplementary buried channel**
  - **Advanced IMO (can only clock image and store registers forwards)**
  - **no store shield**
  - **non-antibloomed**
  - **dump gate**
  - **split readout register**

CCD Tests: Test Objects

- **Two EEV CCD02 devices:**
  - **One IMO device, One AIMO device**
  - **frame transfer mode**
  - **288 x 385 image area pixels**
  - **22 μm x 22 μm pixels, no supplementary buried channel**
  - **With advanced IMO (can only clock image and store registers forwards)**
  - **no store shield**
  - **non-antibloomed**
  - **no dump gate**

CCD Architecture

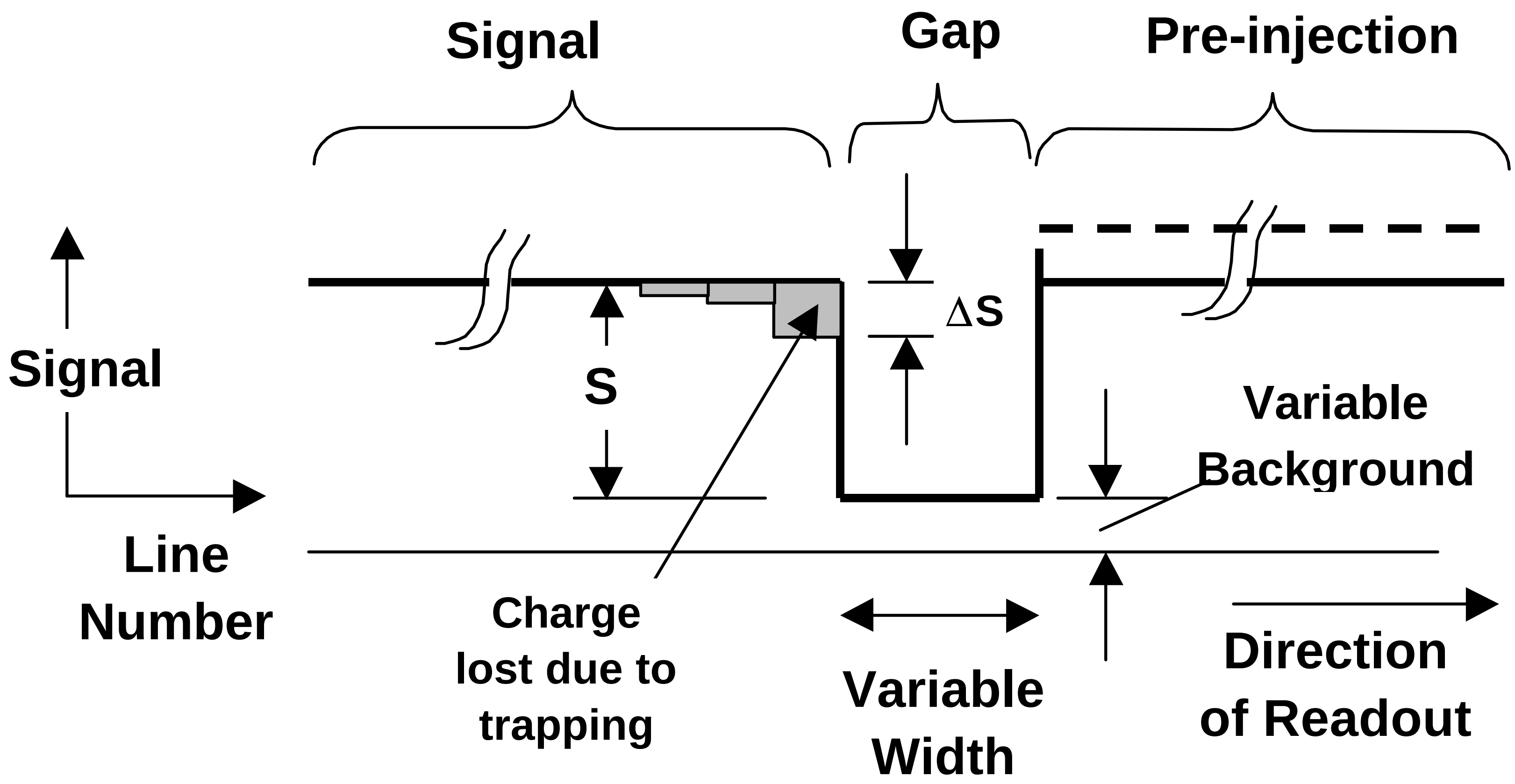


Vertical CTI

- **Charge Transfer Efficiency = CTE =**

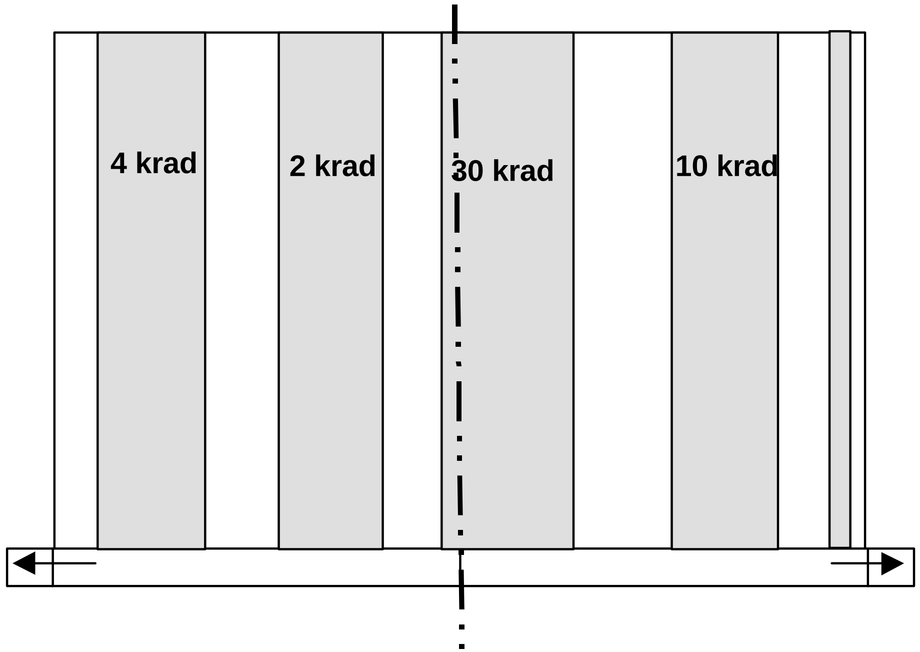
  Fraction charge lost / No. of pixel transfers
- **CTI = 1 - CTE**
- **Will measure ‘worst case CTI’ : all traps empty**
- **Worst case CTI depends on:**
  - **Signal Size**
  - **Background charge**
  - **dwell time in a pixel (I.e. line move time - so dependence of position in the image)**
- **Does *NOT* depend on temperature**

CCD: CTI Measurements Using FPR

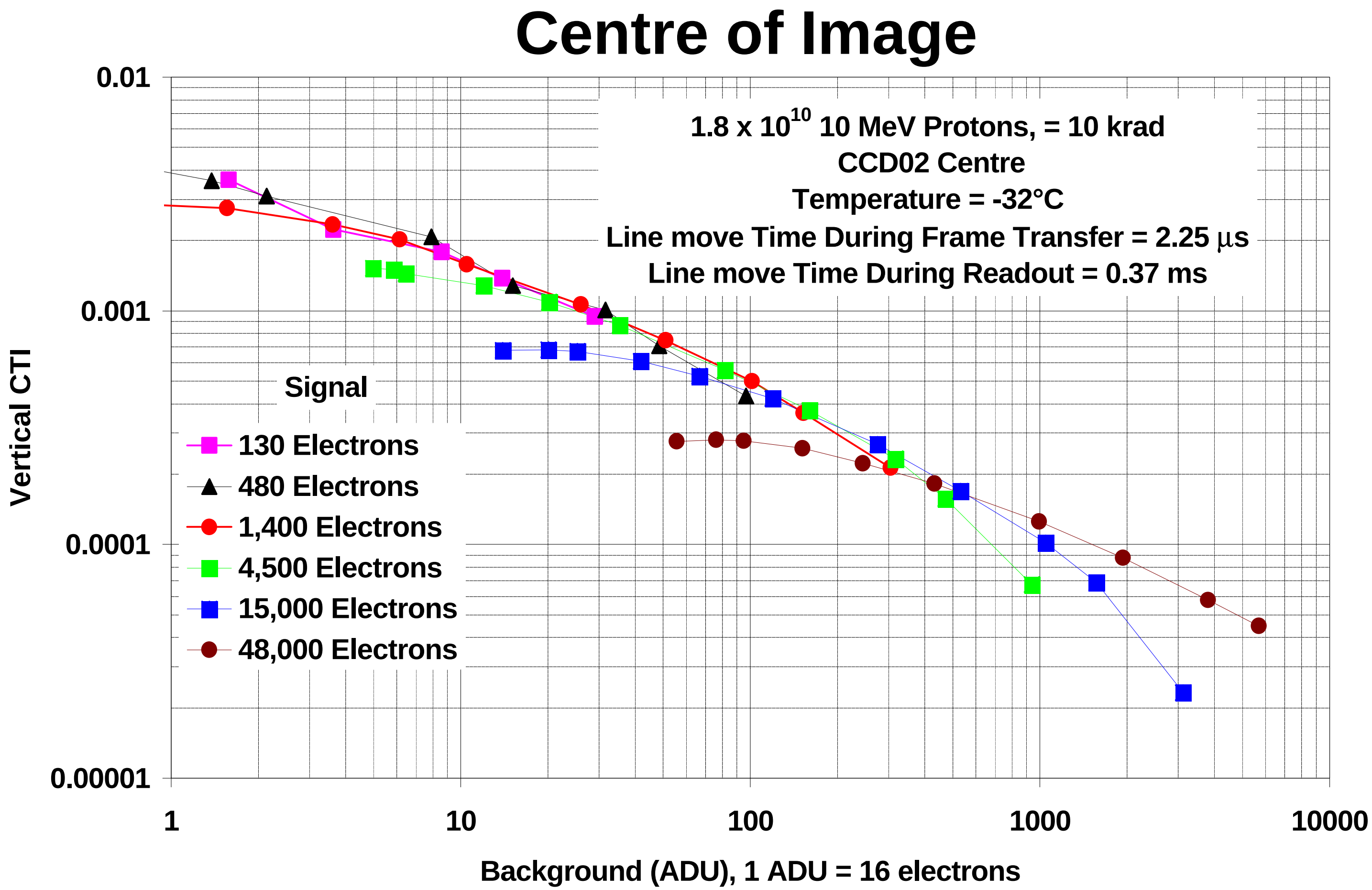


Irradiations

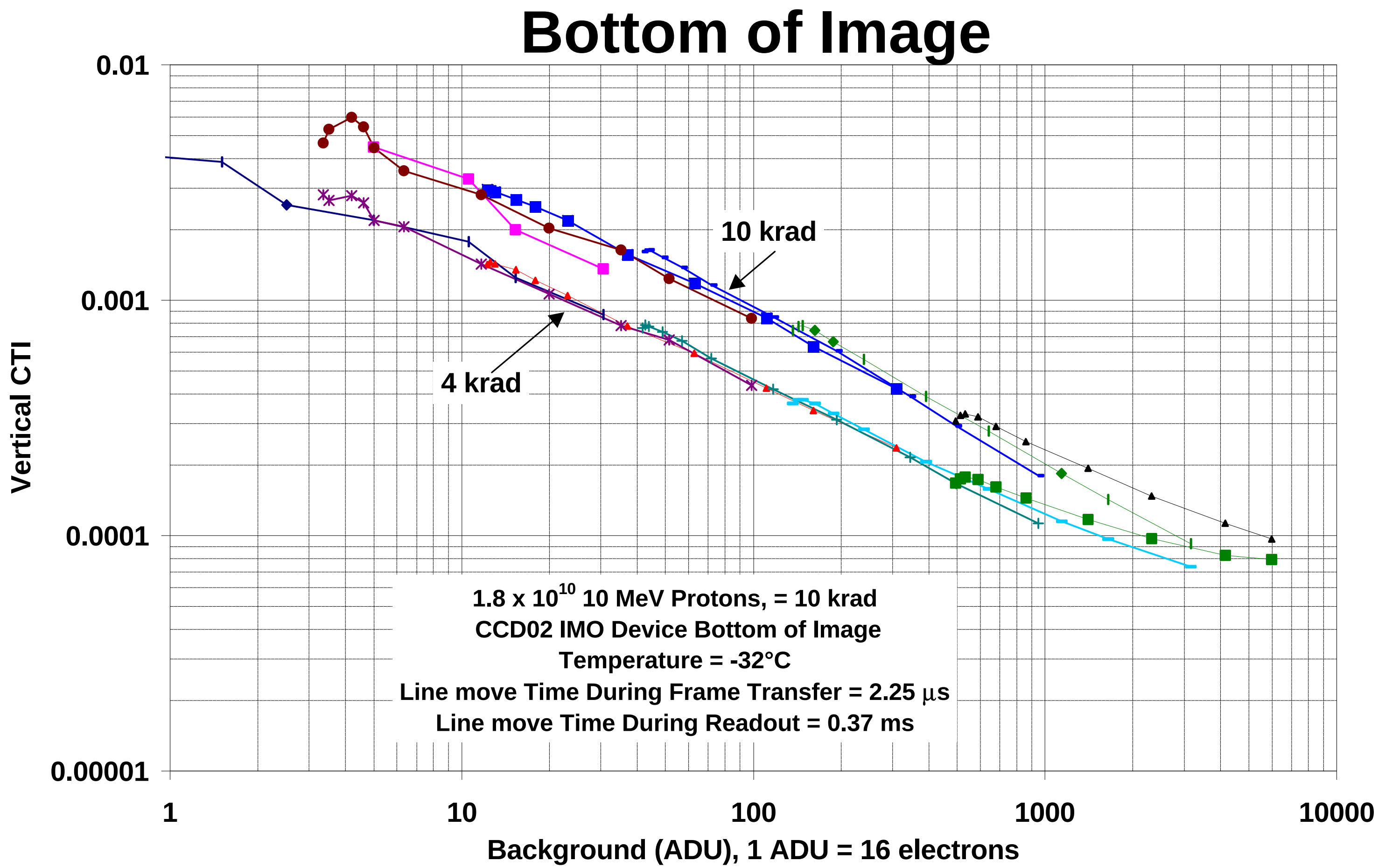
- carried out on 7 December 1998
- Harwell Tandem Van de Graaff accelerator
- 10 MeV protons, normal incidence, unbiased, room temperature
- fluence regions:
- 1.5 mm Al masks



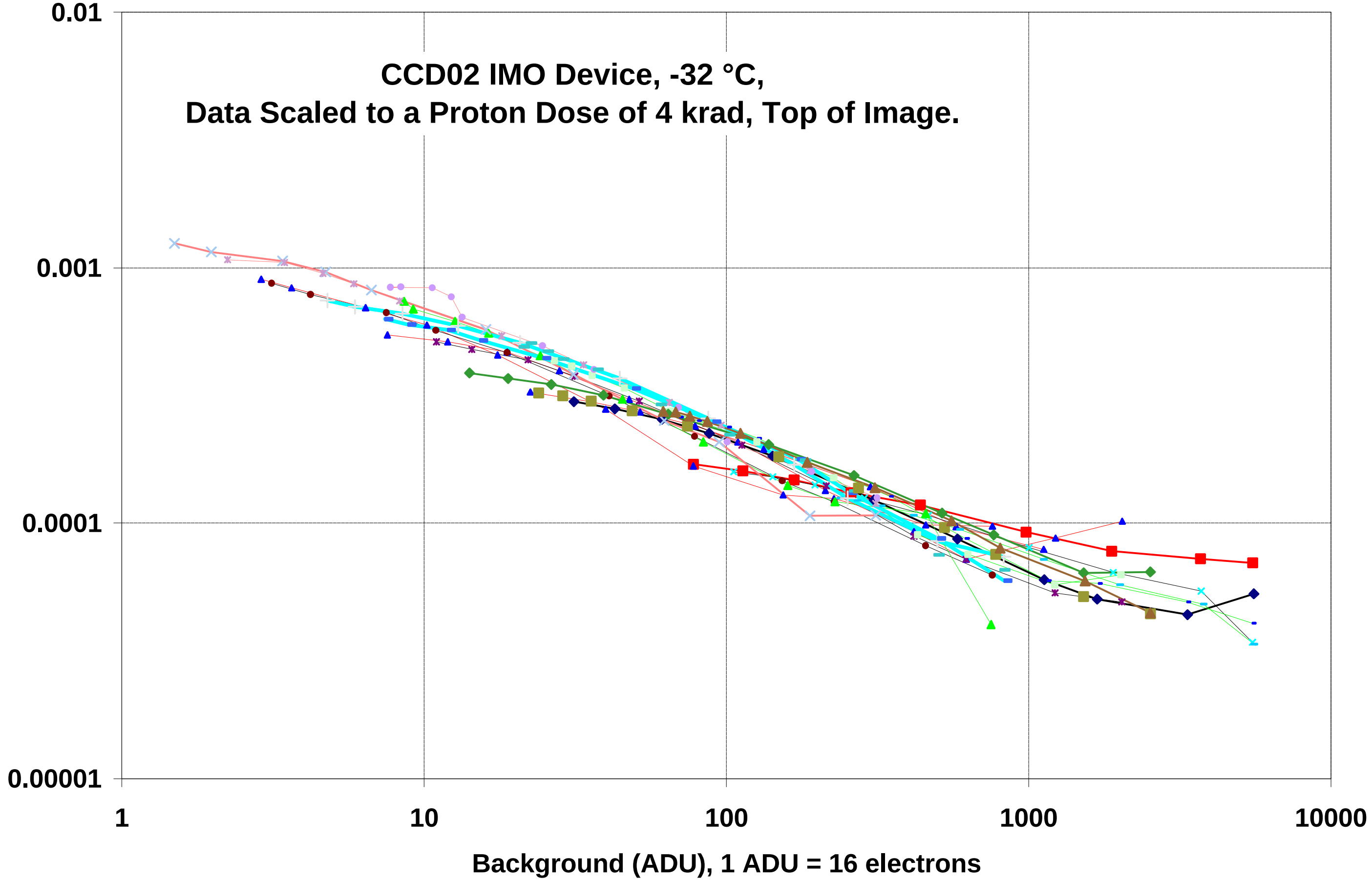
FPR Results, CCD02



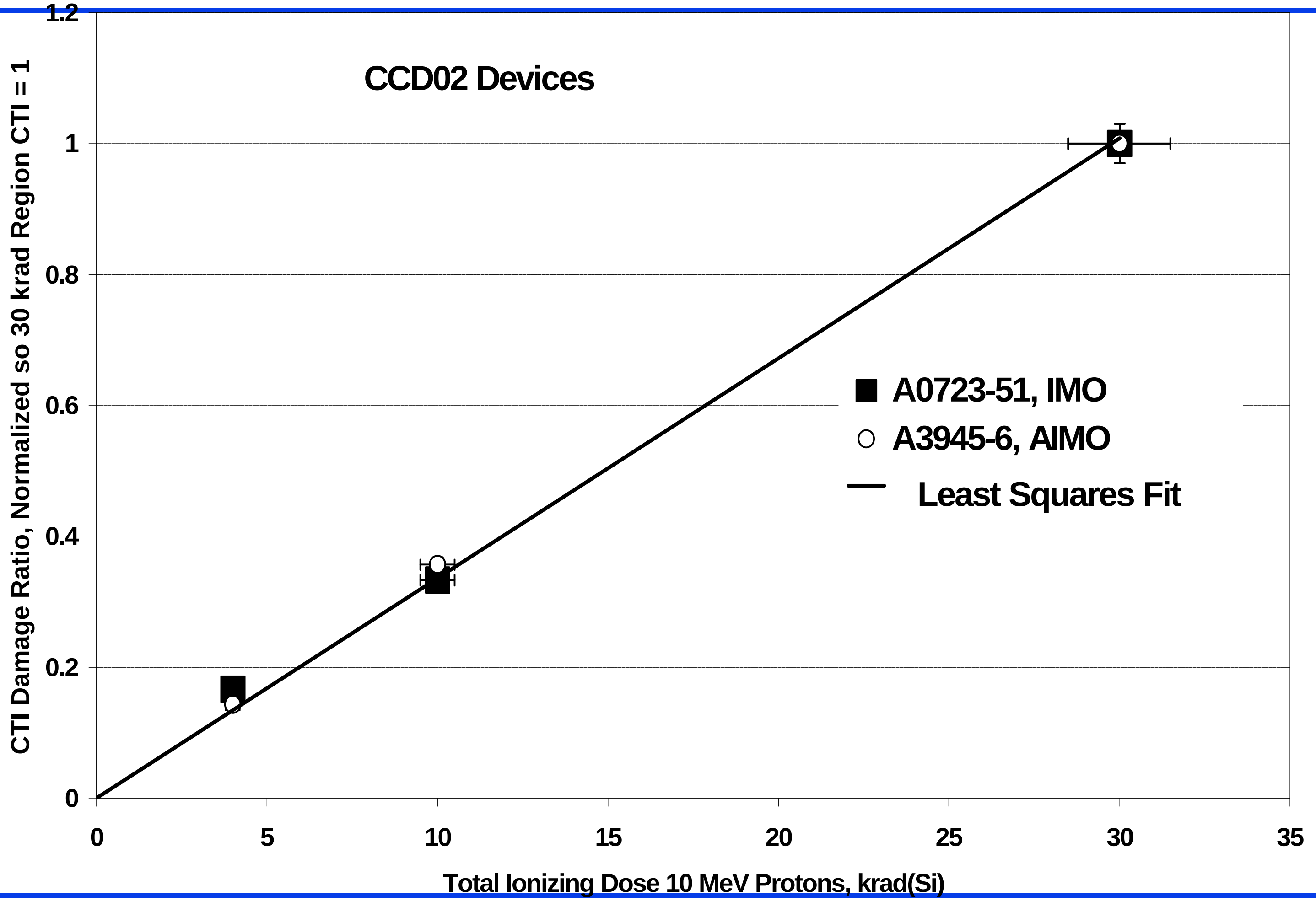
FPR Results, CCD02



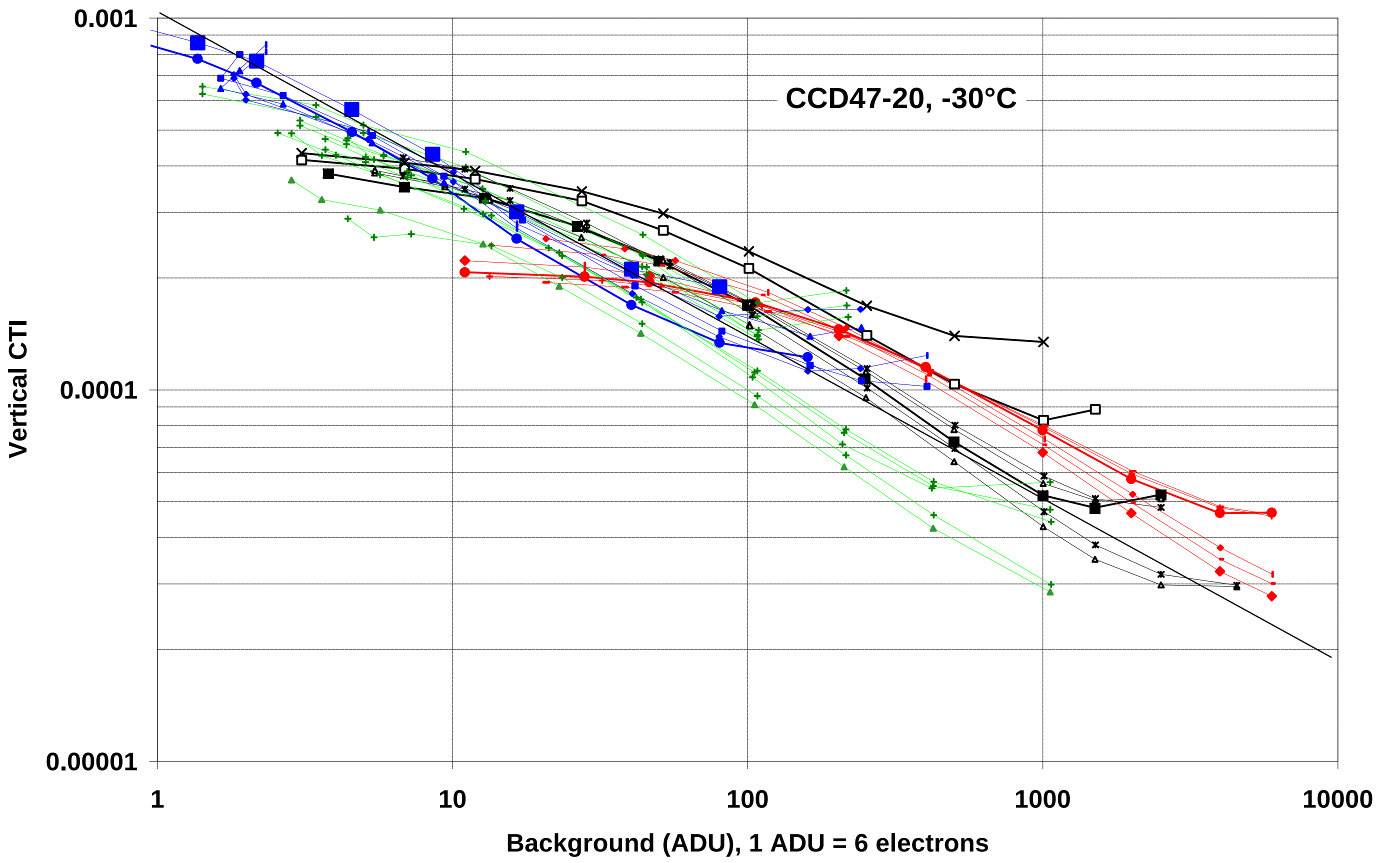
FPR Results, CCD02



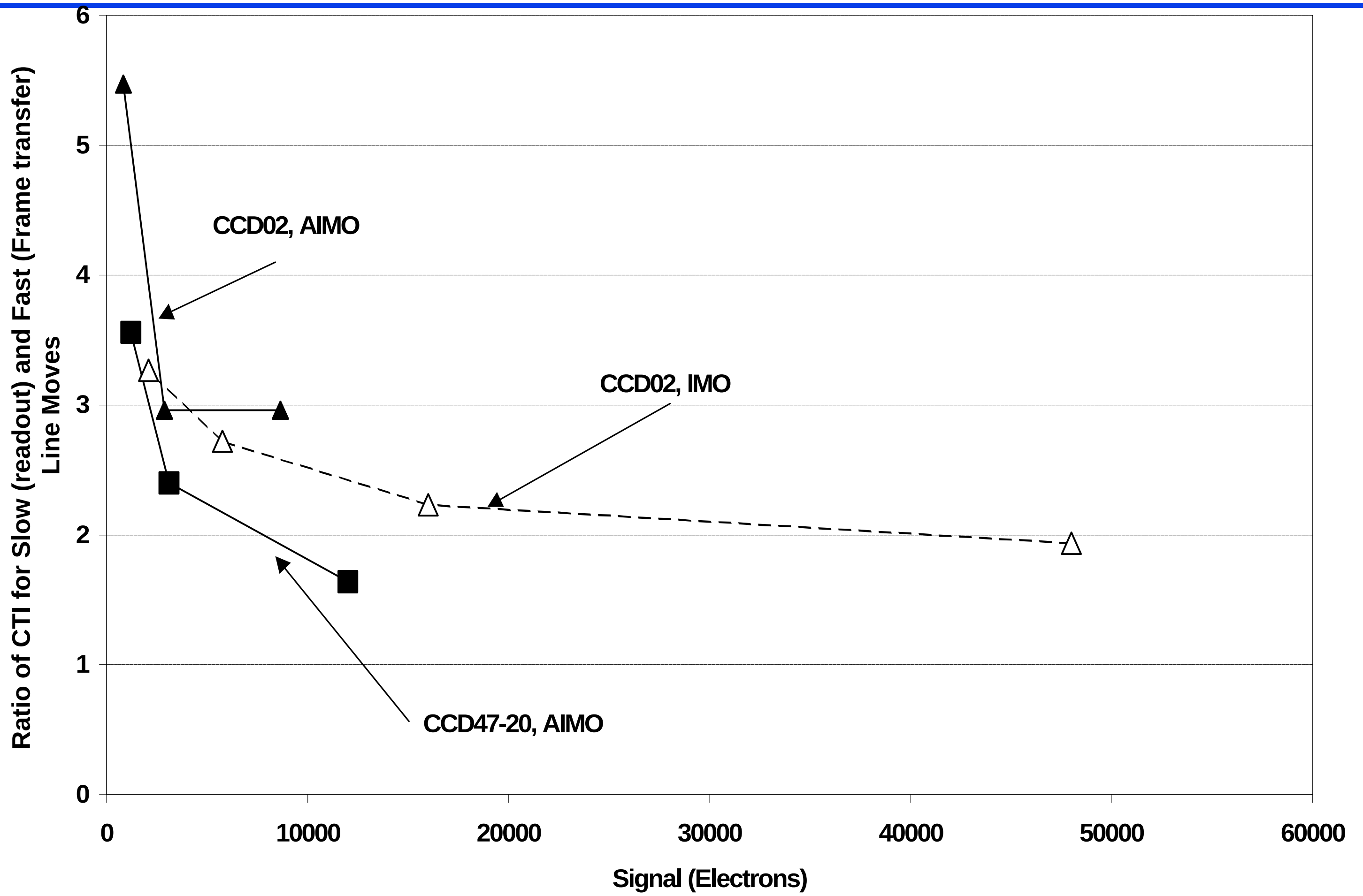
FPR Results, CCD02



FPR Results, CCD47-20



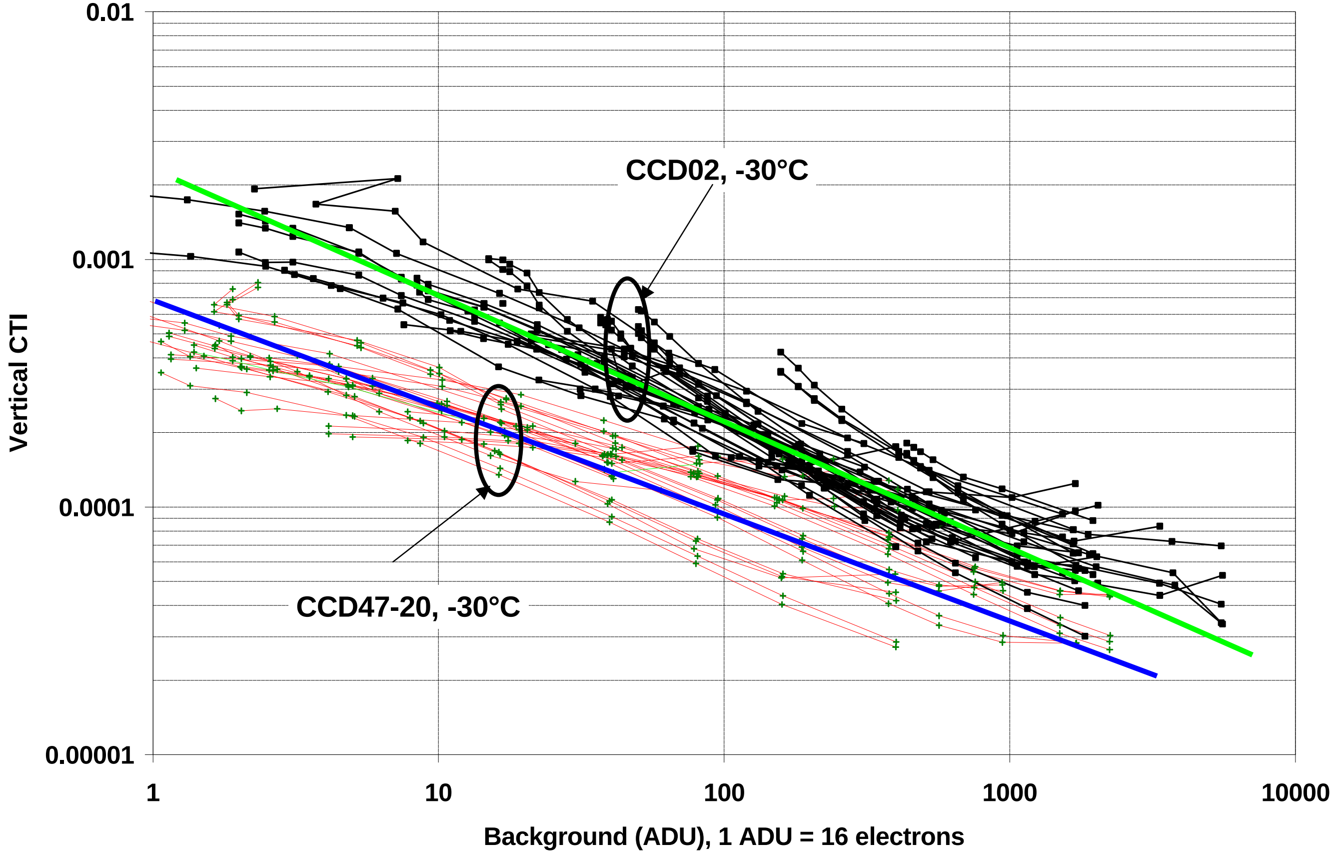
FPR Results, CTI v. Dwell Time



QCA Final Presentation Day
26 January 2000

siraelectro-optics

FPR Results: CCDo2 & CCD47-20



QCA Final Presentation Day
26 January 2000

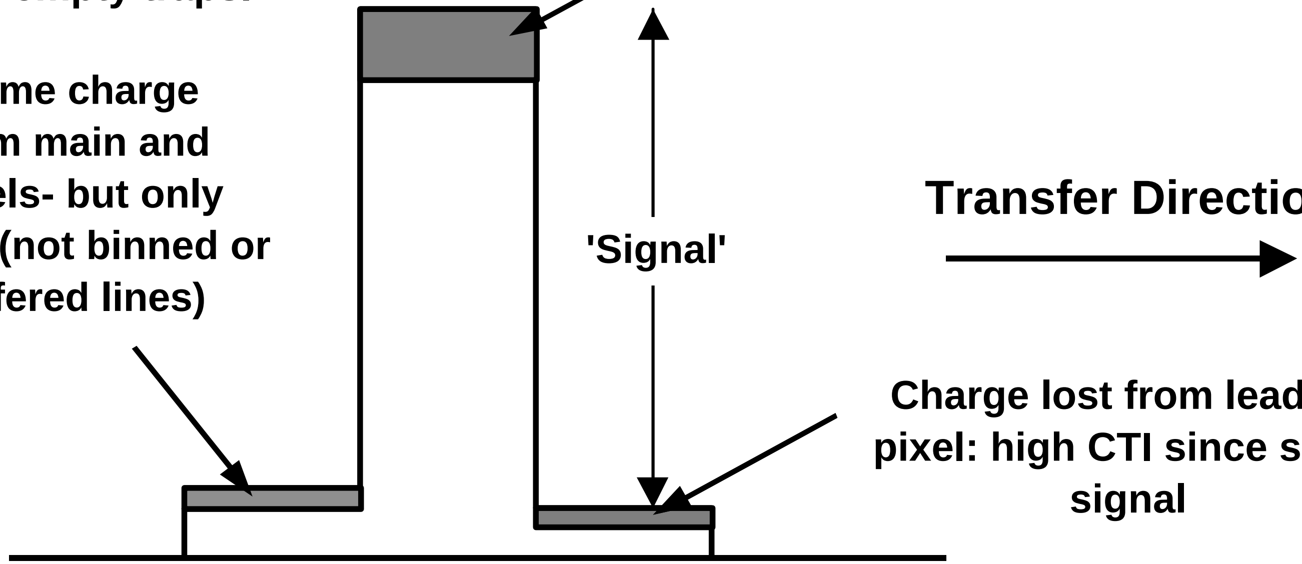
siraelectro-optics

Effect of CTI on Star Images

Charge lost from trailing pixel is very small since it sees no few empty traps.

However some charge differed from main and leading pixels- but only for readout (not binned or frame transfered lines)

Charge lost from main pixel: low CTI since high signal



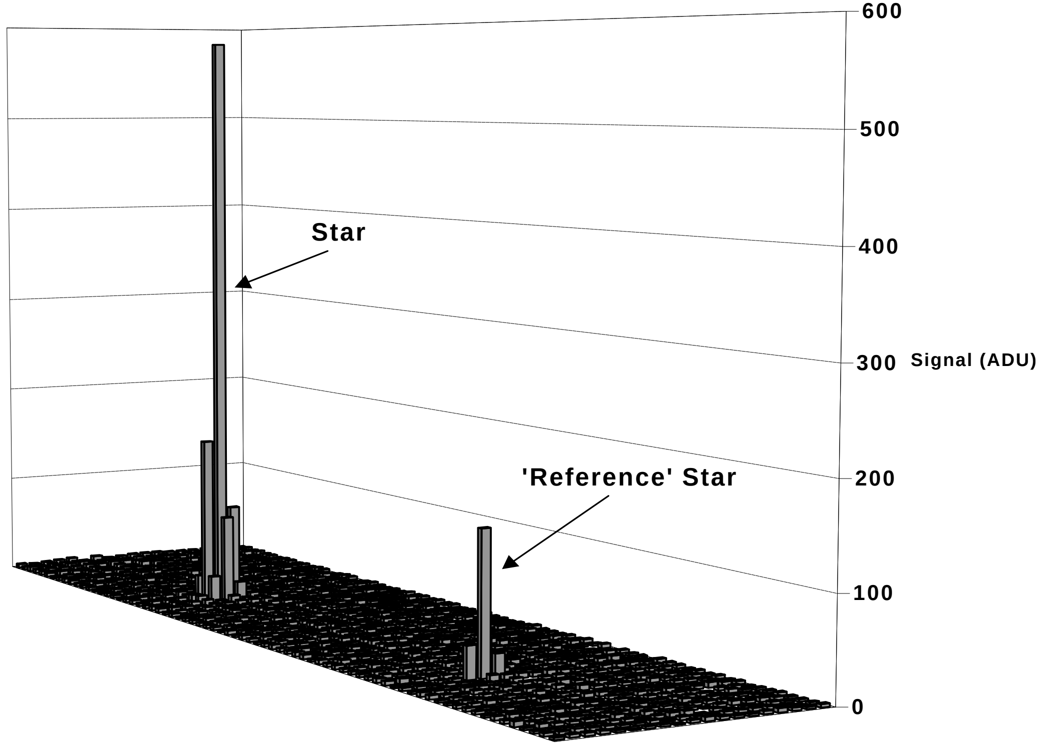
Charge lost from leading pixel: high CTI since small signal

Effects on Image: Prediction / Simulation

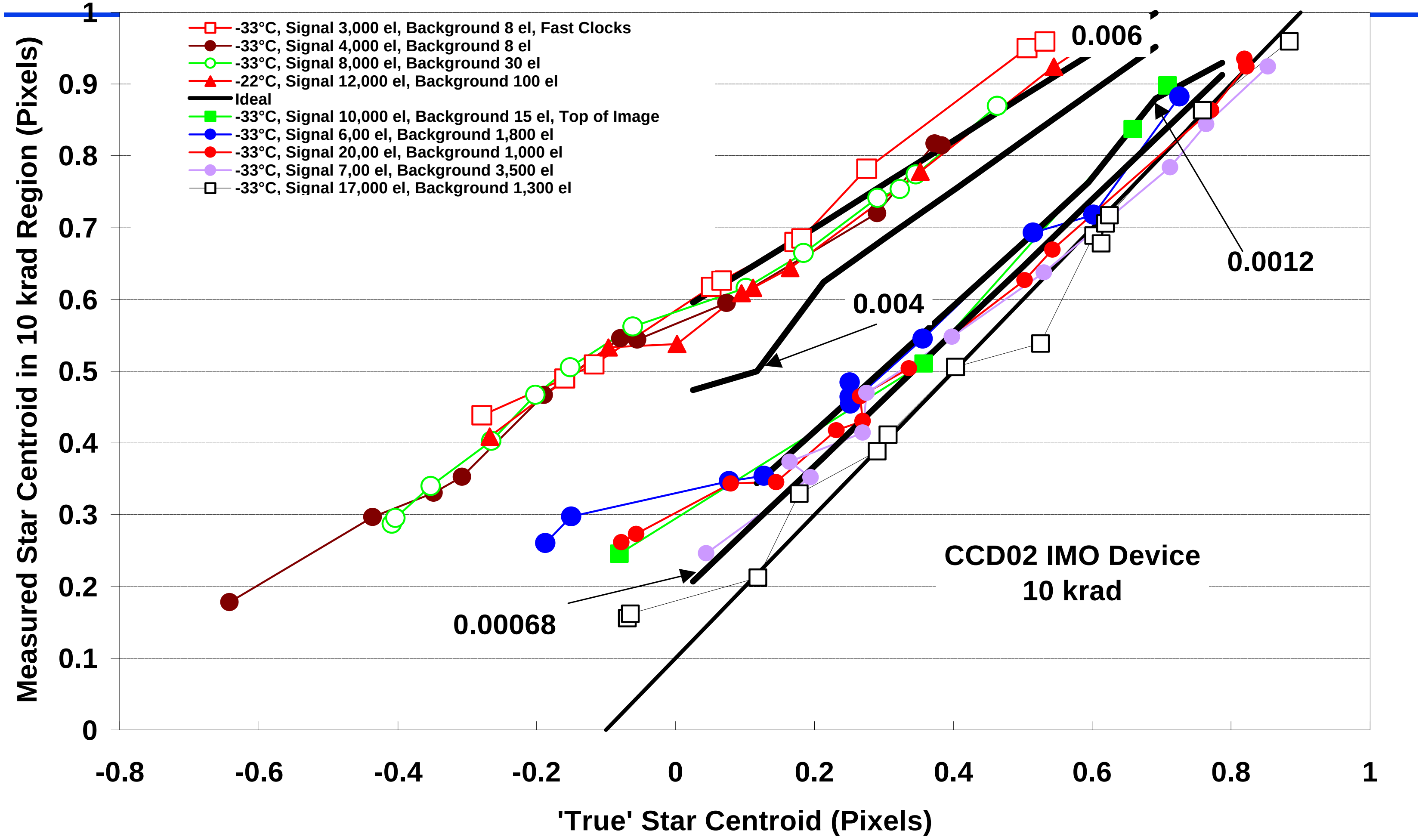
- **Can go from first principles (trap concentration and charge density model)**
  - good but time consuming
- **Sira C code model**
  - signal & background CTI dependence (empirical)
  - tracks emission & capture but effect of trap filling by preceding packets may not be entirely correct
  - can input real star and pixel profiles
- **Sira Excel™ model**
  - only slow line moves are important
  - constant (background dependent) CTI - no signal size dependence
  - Gaussian star profile (at present)
- **But why not measure errors directly ?**

Artificial Star Data

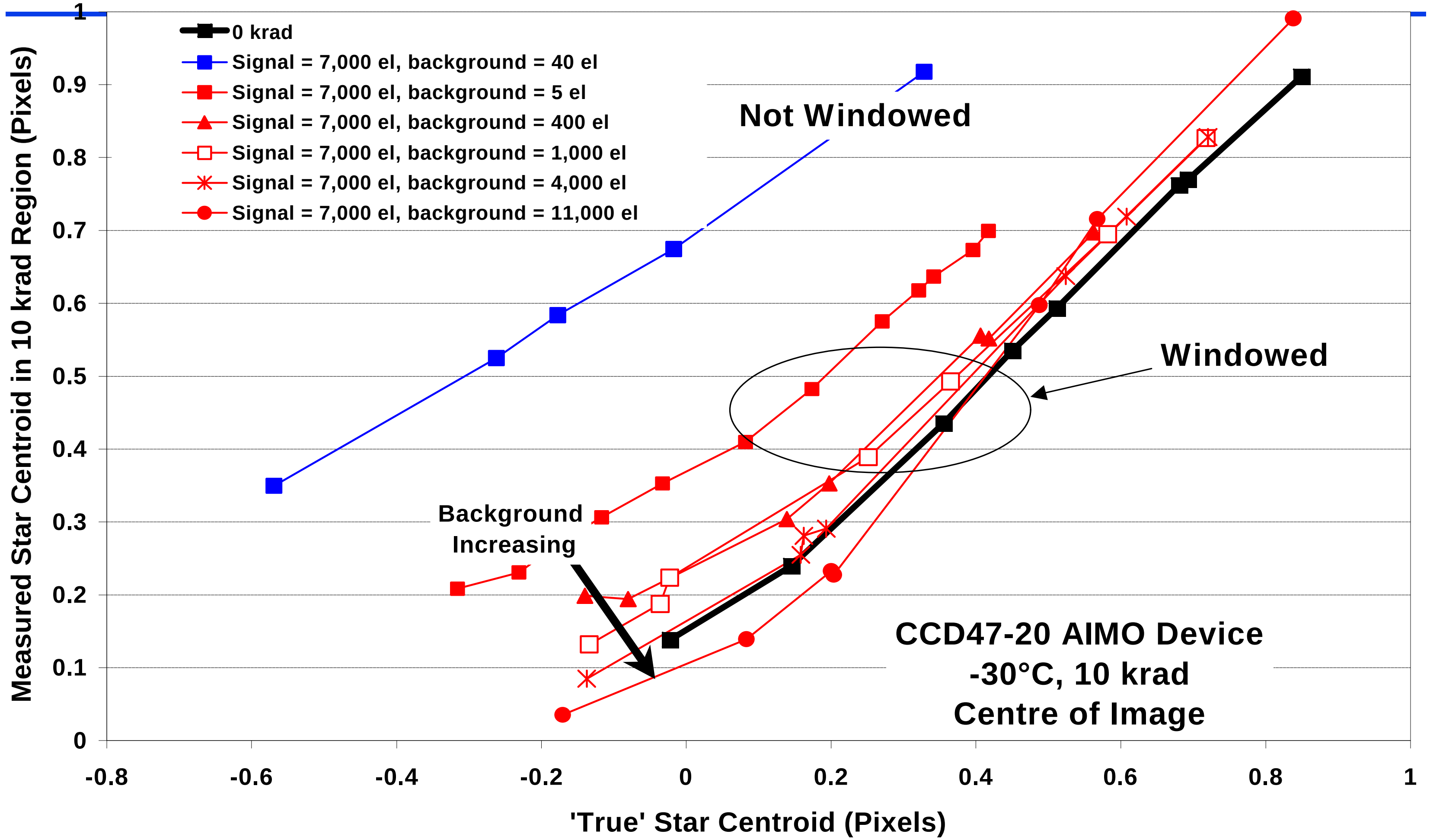
Double Pinhole Illumination System



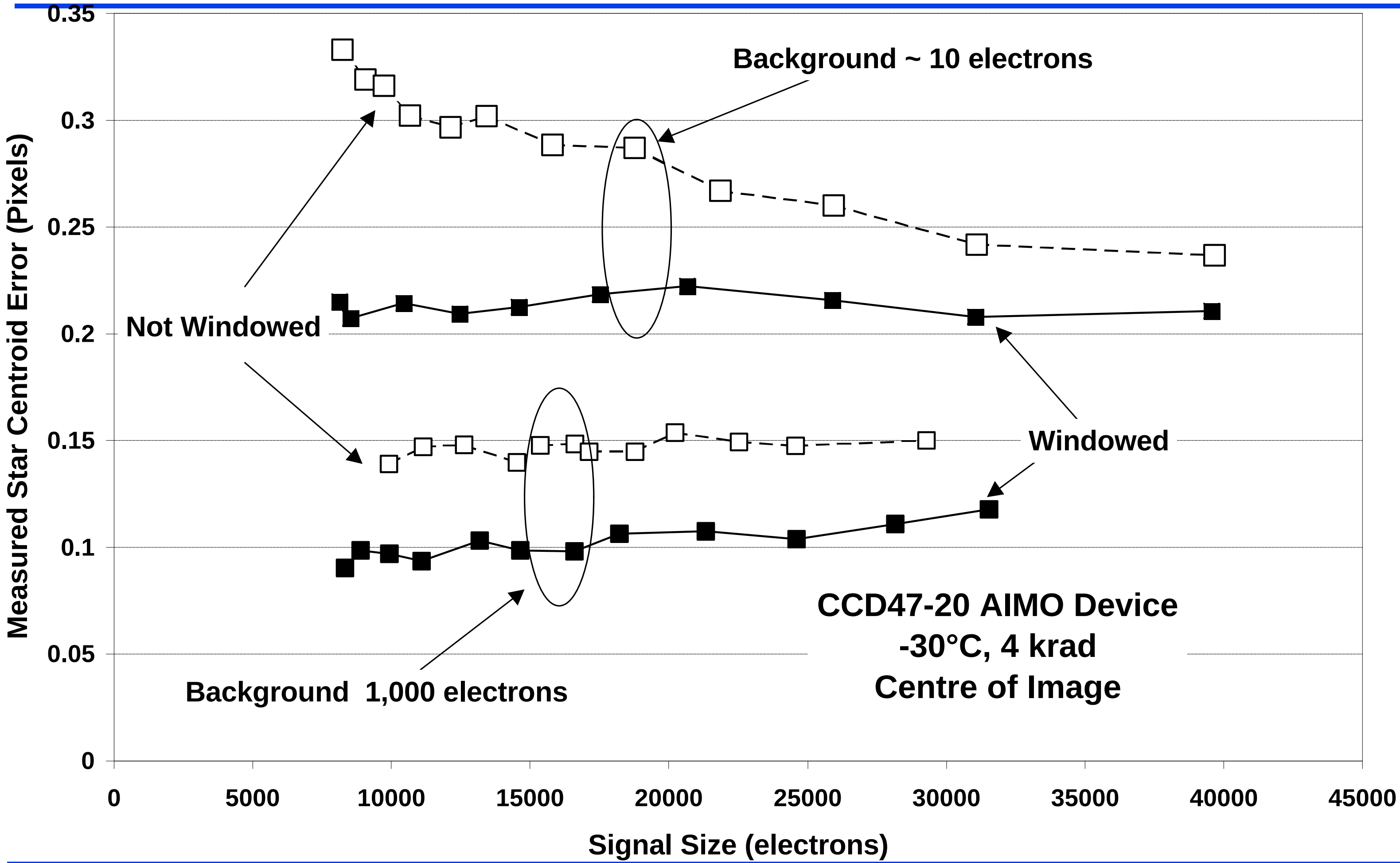
Star Centroid Data: CCD02



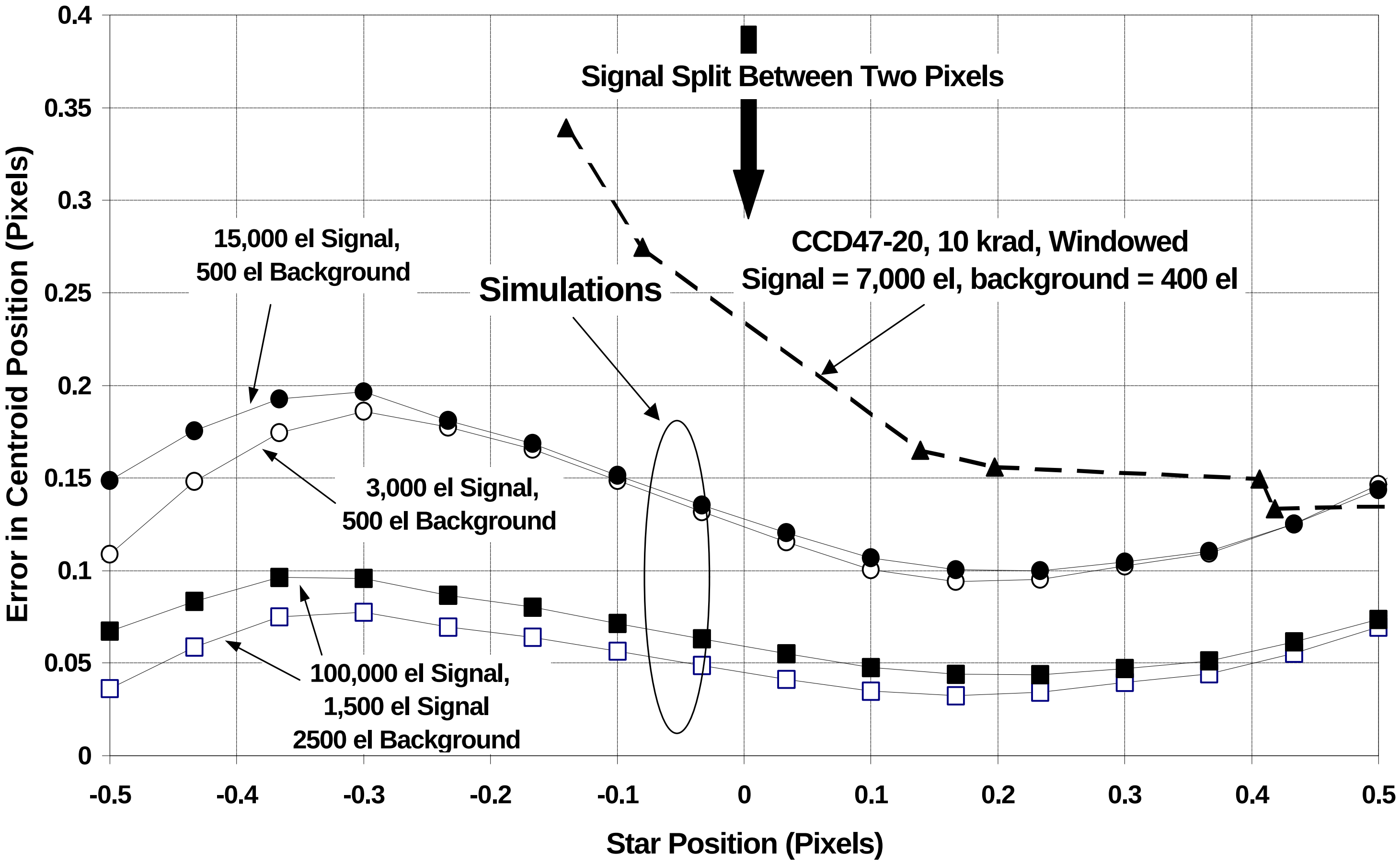
Star Centroid Data: CCD47-20



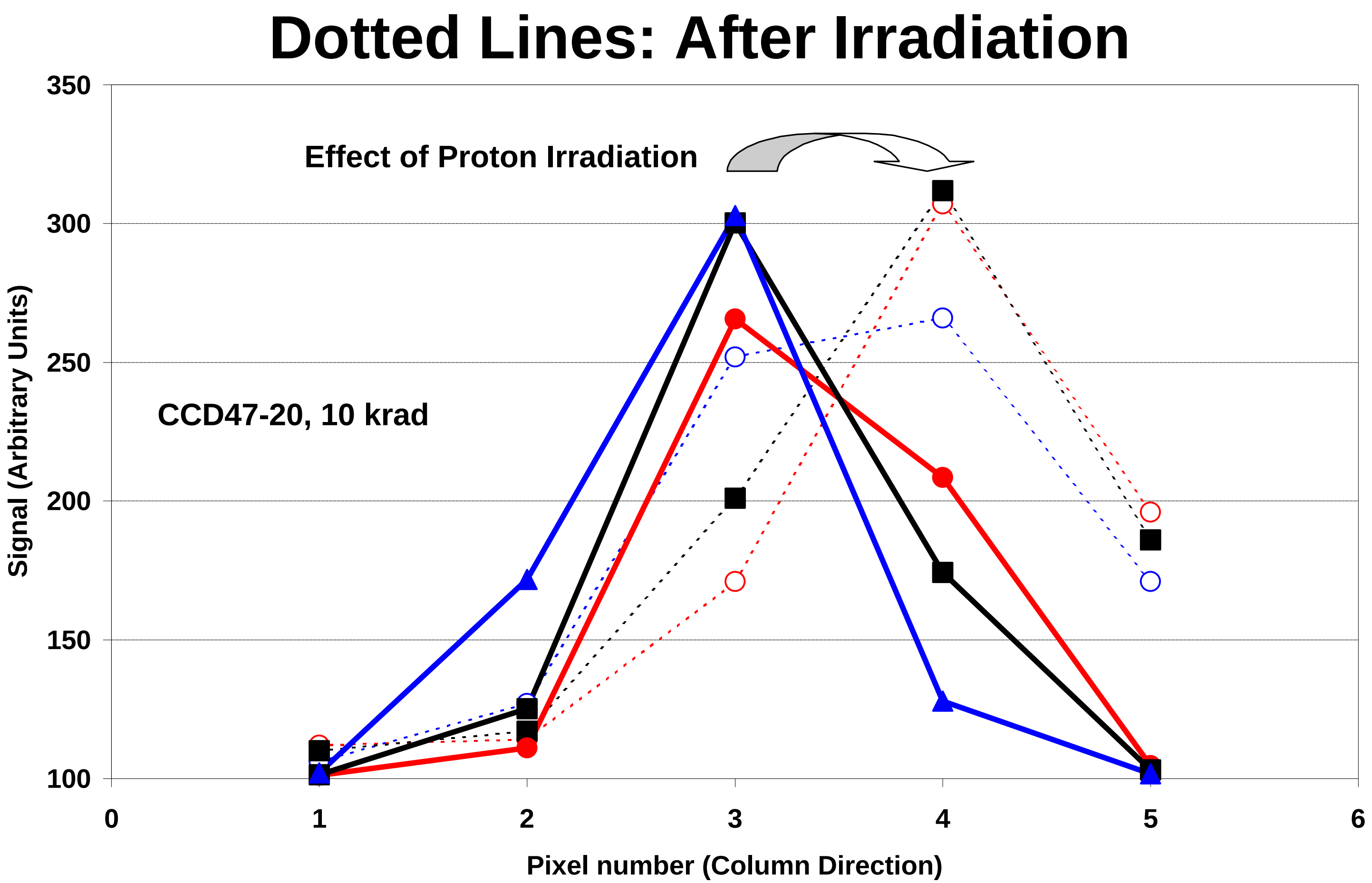
Star Centroid Data: CCD47-20



C code Simulation



Typical ‘Star’ Profiles



Star Centroid Data: Conclusions

- **Large errors for low backgrounds, even for low irradiation levels.**
- **Background ('fat zero') has a large effect. To improve accuracy (better than changing star brightnesses or temperature) increase background level (to > 1000 electrons/pixel for > 4 krad(Si) environments).**
- **The centroid shifts do not change much with location within a pixel but worst when star on the boundary between pixels.**
- **For the same signal and background, the error tends to be worse as the temperature is increased (from –32°C to –22°C). This is because the differed charge is spread over fewer pixels at the higher temperature and tends to distort the star profile more.**
- **Increasing line move times did not have a large effect**
- **Centroid error at top of image (& for windowed readout) is significant (~ 0.1 pixels at low backgrounds: likely due to signal dependence of CTI for fast line moves, also contribution from emission from any fast traps.**

Overall Conclusions

- **AD9223 and LTC1415 should be OK for most low dose mission if AD9223 SEL can be accepted**
- **ASCoSS radiation tolerance better than previously thought (dark current anneals, dark spikes not large) but unexplained responsivity change, ADC shows SEL**
  - new version will have a different pixel structure and new ADC
- **Displacement damage induced CTI in n-channel CCDs studied in detail using FPR method for first time**
- **Double aperture method for star centroid measurement has proved to be simple and reliable**
- **centroid errors can be large for individual stars - but overall error will be reduced by application of star tracker algorithms (‘real-sky’ testing is in progress)**

Further Issues

- **Continue tests on state-of-the art ADCs**
  - perfmance degradation for imaging systems most important
- **Test new version(s) of ASCoSS chip and test structures**
- **Test CTI for new CCDs (to understand dependences)**
- **Use double aperture for routine testing (establish a new figure of merit for imaging systems ?)**