Radiation Testing of CCD and APS Imaging Devices

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Introduction

- **Two types of imaging devices have been tested:**
  - **CCDs from e2v (Chelmsford, UK) and Atmel (Grenoble, France)**
    - **Results presented at NSREC 2004**
  - **Active pixel sensors from Fillfactory (Mechelen, Belgium)**
    - **Results presented at RADECS2004**
- **Contract Report (CCN #2 to 14028/99/NL/MM) submitted June 2003 and available on escies website:**

https://escies.org/public/radiation/esa/database/239DO53FinalReport_iss2.pdf

- **Talk is split in two parts:**
  - **CCD**
  - **APS**

Irradiations

- **9.5 MeV protons (CCD & APS)** - unbiased, RT
  - 9 Oct 2002
  - Ebis Iotron, Harwell, old 'SET' beam line with scatter foil
- **60 MeV protons (CCD)** - unbiased, RT
  - August 2002
  - PSI, Zurich
- **Cobalt60 (CCD & APS)** - biased & unbiased, RT
  - May 2002
  - ESA, ESTEC
- **Heavy Ion (APS)**
  - 21 Nov 2002
  - LLN, Belgium

In all cases dosimetry to ~ ±5%

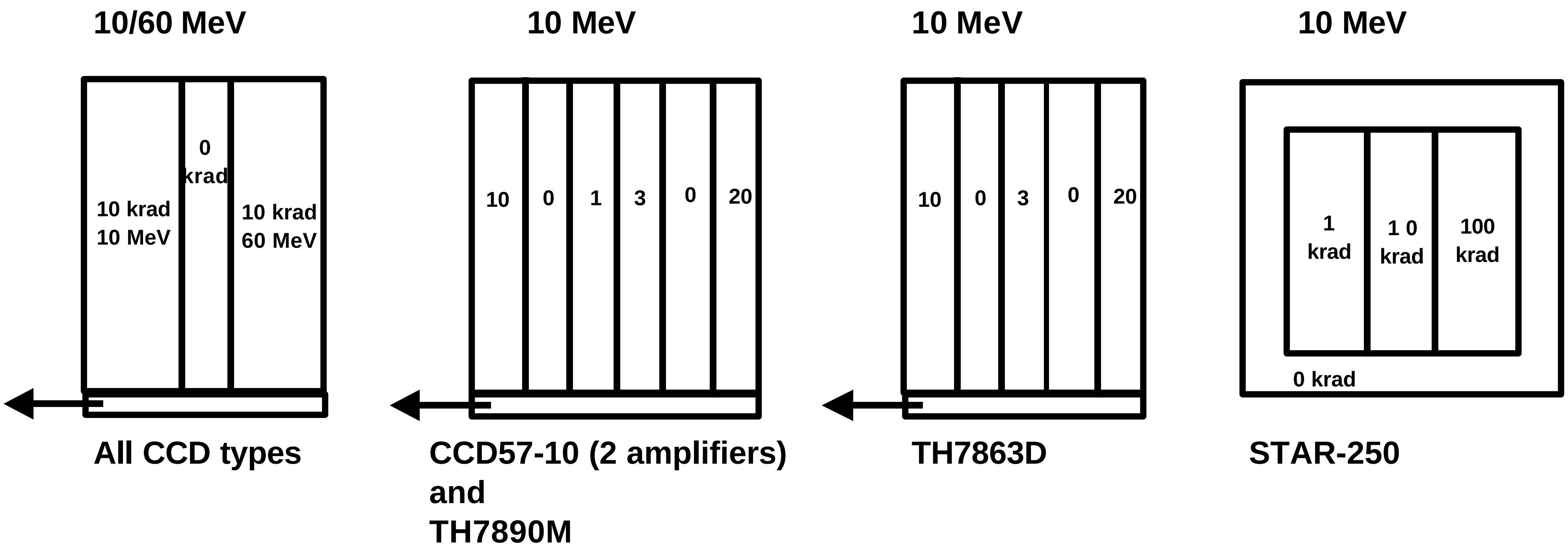
Irradiations

	CCD55-20	CCD57-10	TH7863D	TH7890M	STAR-250 APS	IRIS2 APS
Number available	**2 (1 was damaged and not used)**	**5**	**3**	**6**	**9**	**3**
Cobalt60, biased	1	1	1	1	3	
Cobalt60, un-biased		1	1	1	1	
10 MeV proton		1	1	2	2	
10/60 MeV proton	1	2		2		
Heavy ion					2	2
Control (in-irradiated)	0	0	0	0	1	1

Dose/fluence levels

	CCD55-20	CCD57-10	TH7863D	TH7890M	STAR-250 APS
Cobalt60, biased	17.9 krad(Si) one step	18.1 krad(Si) one step	17.9 krad(Si) one step	11.6 krad(Si) one step	79.2 krad(Si) one step
Cobalt60, un-biased		18.1 krad(Si) plus 17.9 krad(Si) biased	17.9 krad(Si) one step	17.9 krad(Si) one step	79.2 krad(Si)
9.5 MeV proton		0, 1, 3, 10, 20 krad(Si)	0, 3, 10, 20 krad(Si)	0, 1, 3, 10, 20 krad(Si)	0, 1, 10, 100 krad(Si)
9.5/60 MeV proton	0, 10 krad(Si) 10 MeV protons ($1.7\ 10^{10}$ p/cm^2) 60 MeV protons: ($5.9\ 10^{10}$ p/cm^2)	0, 10 krad(Si) 10 MeV protons 60 MeV protons: ($5.9\ 10^{10}$ p/cm^2) =8.1 krad(Si)		0, 10 krad(Si) 10 MeV protons 60 MeV protons: ($5.9\ 10^{10}$ p/cm^2)	

Masking for Proton Irradiations



CCD

Background

- **ESA radiation study in support of Capability Approval for CCDs**
- **Devices studied (all frame transfer):**

e2v (Chelmsford, UK)

CCD57-10 (512 x 512, 13 µm x 13 µm pixel, antibloomed)

CCD55-20 (770 x 576, 22.5 µm x 22.5 µm pixel)

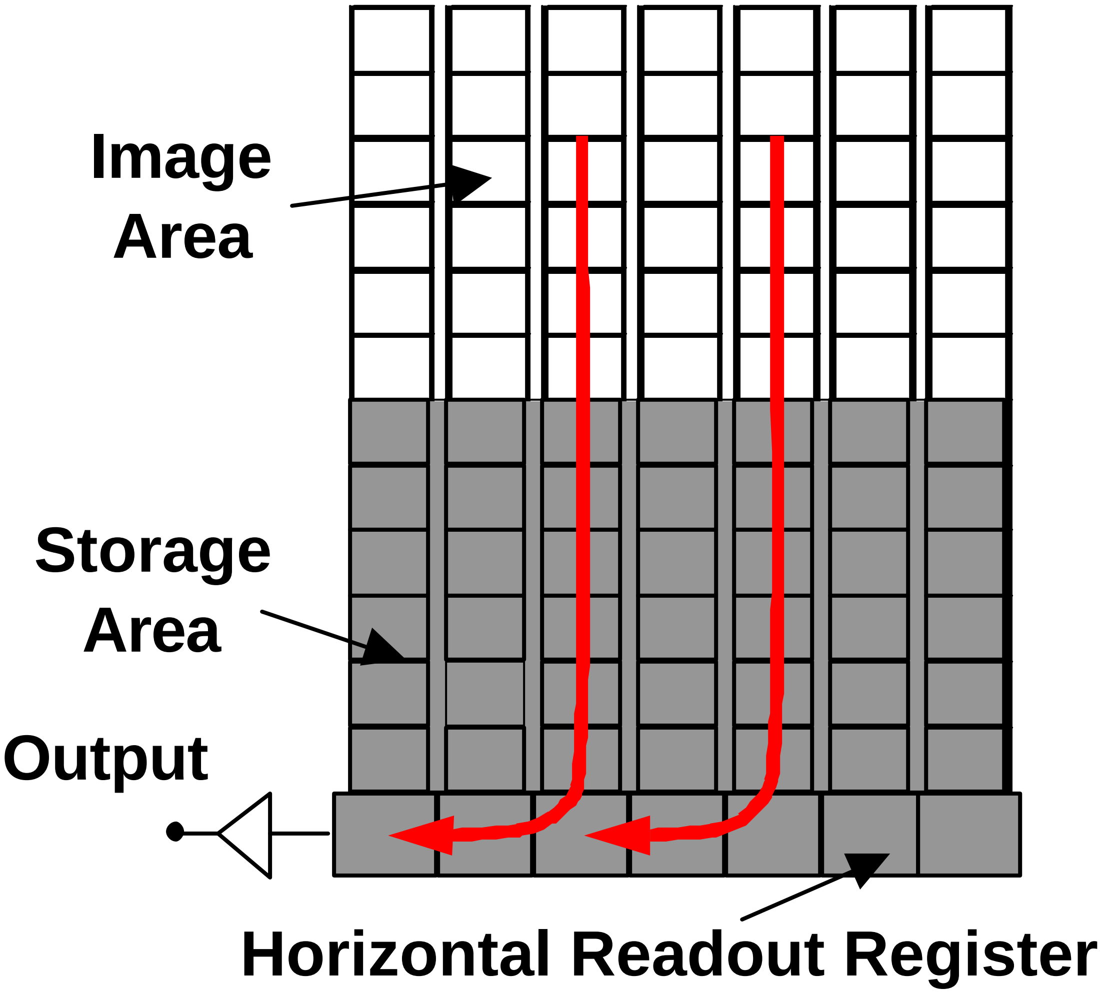
Atmel (France)

TH7890M (512 x 512, 17 µm x 17 µm pixel)

TH7863D (288 x 384, 23 µm x 23 µm pixel)

- **Could compare damage at 60 and 9.5 MeV - on same chip**

CCD Architecture



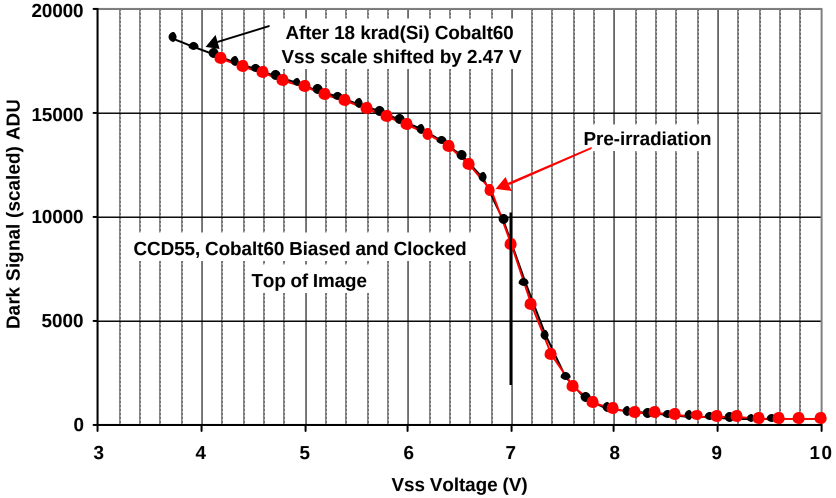
Total Ionizing Dose (Cobalt60)

Flatband voltage Shift (1)

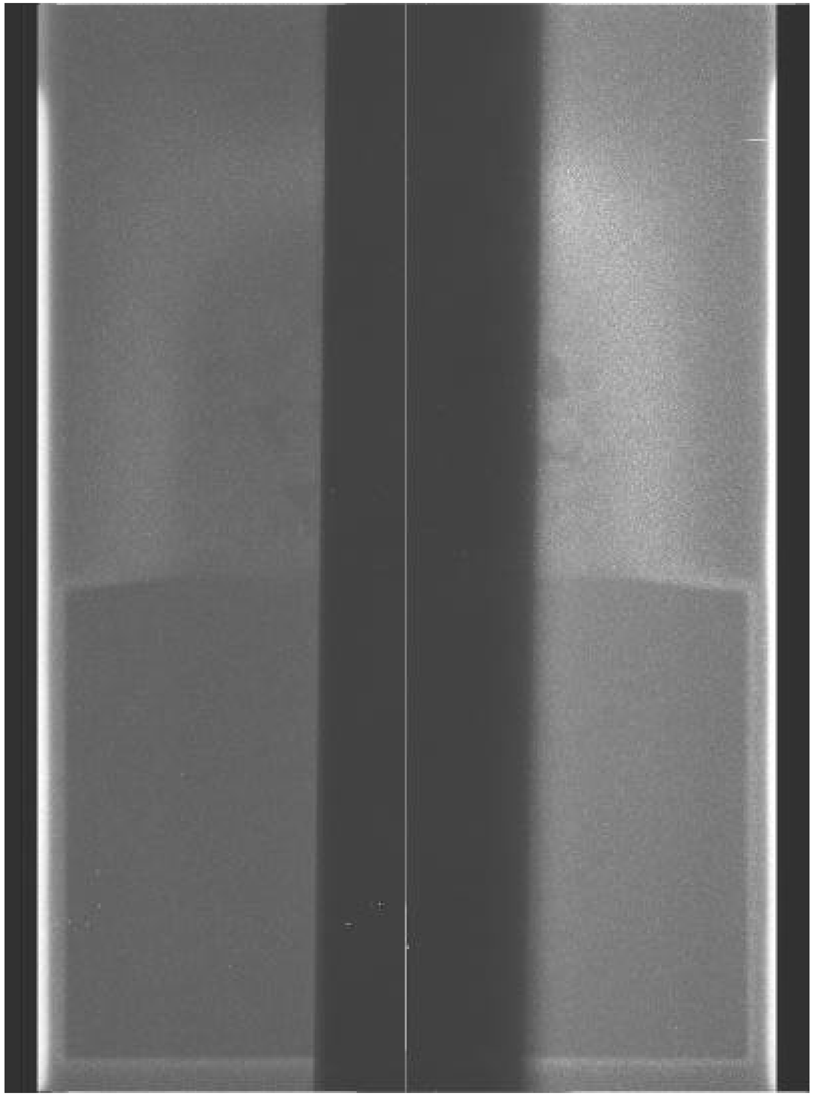
CCD Type	CCD No.	Comment	Total Dose krad(Si)	Voltage shift	V /krad(Si)
CCD57	1	9.5/60 MeV protons	8.1 (60 MeV) 10 (10 MeV)	0.35 (60MeV) 0.25 (10MeV)	0.04 0.025
	2	9.5/60 MeV protons	10	-	-
	3	Cobalt60 biased	18.1	2.75	0.152
	4	Cobalt60 unbiased/biased	18.1 (unbiased) + 17.9 (biased)	3.2	0.027 unbiased
	5	9.5 MeV protons (unbiased)	10 20	0.22 0.46	0.022 0.023
CCD55	1	Cobalt60, biased	17.9	2.47 V	0.138
	3	9.5/60 MeV protons	8.1 (60 MeV) 10 (10 MeV)	0.3 V (60 MeV) 0.1 V (10 meV)	0.037 0.01
TH7890M	1	9.5/60 MeV protons	10	Not measured	-
	2	9.5/60 MeV protons	10	Not measured	-
	4	Cobalt60 biased	11.6	1.7	0.147
	5	Cobalt60 unbiased	17.9	0.60	0.033
	3	9.5 MeV protons	10	Not measured	-
	6	9.5 MeV protons	10/20 krad	0.2/0.42	0.021

Flatband voltage Shift (2)

- CCD57 after cobalt60 irradiation
  - o Clock low voltages (I,S and R) changed from 0 V to –2.0 V
  - o VOG changed from 3V to 1V
- CCD55 after cobalt60 irradiation (17.9 krad, biased)
  - o Clock low voltages (I,S and R) changed from 0 V to –2.5 V
  - o VOG changed from 3V to 1V
  - o VRD chnged from 17 V to 18 V
- CCD55 after 10 krad 60 MeV protons
  - o Clock low voltages (I,S and R) changed from 0 V to –1.0 V



Surface Dark Current

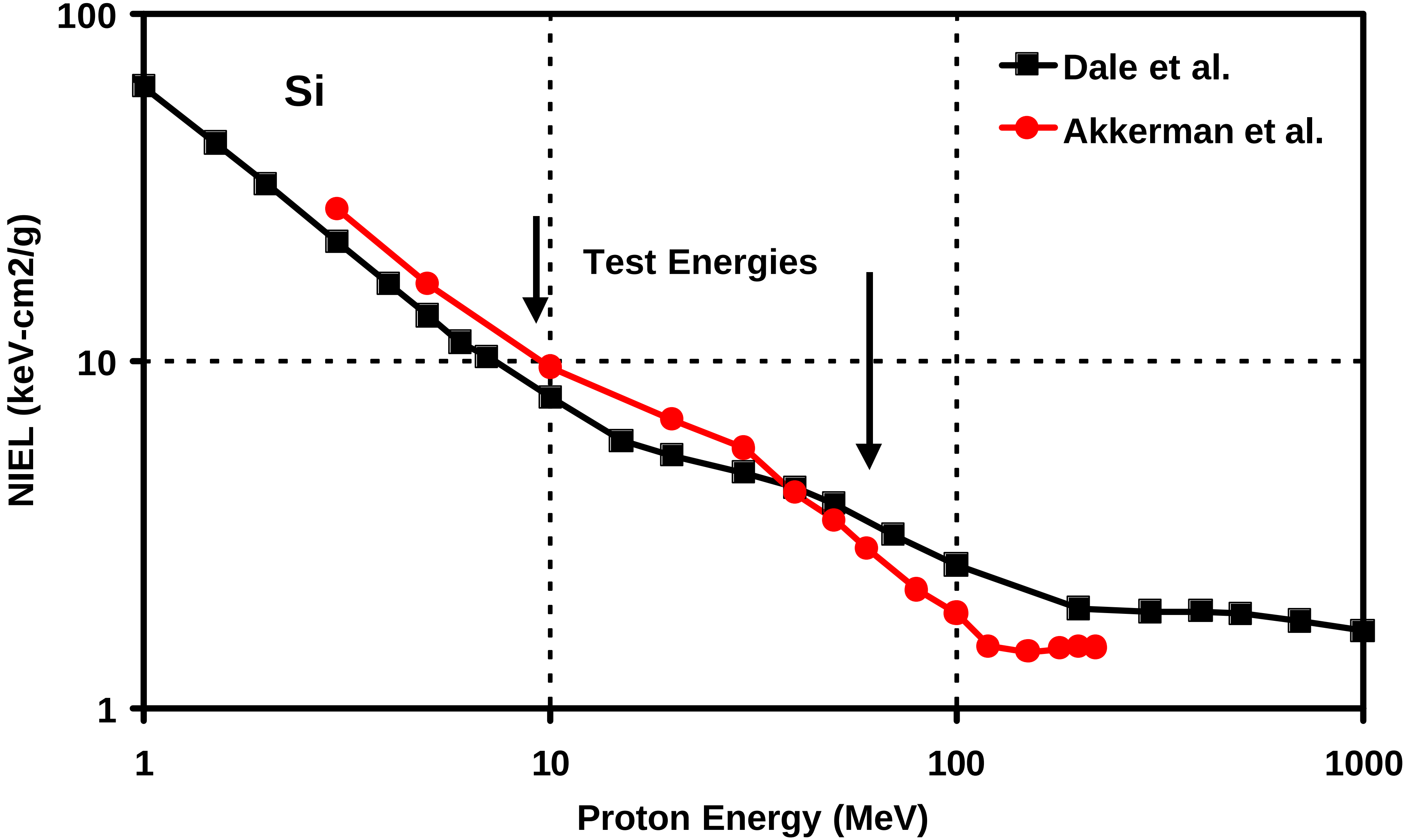


Displacement Damage

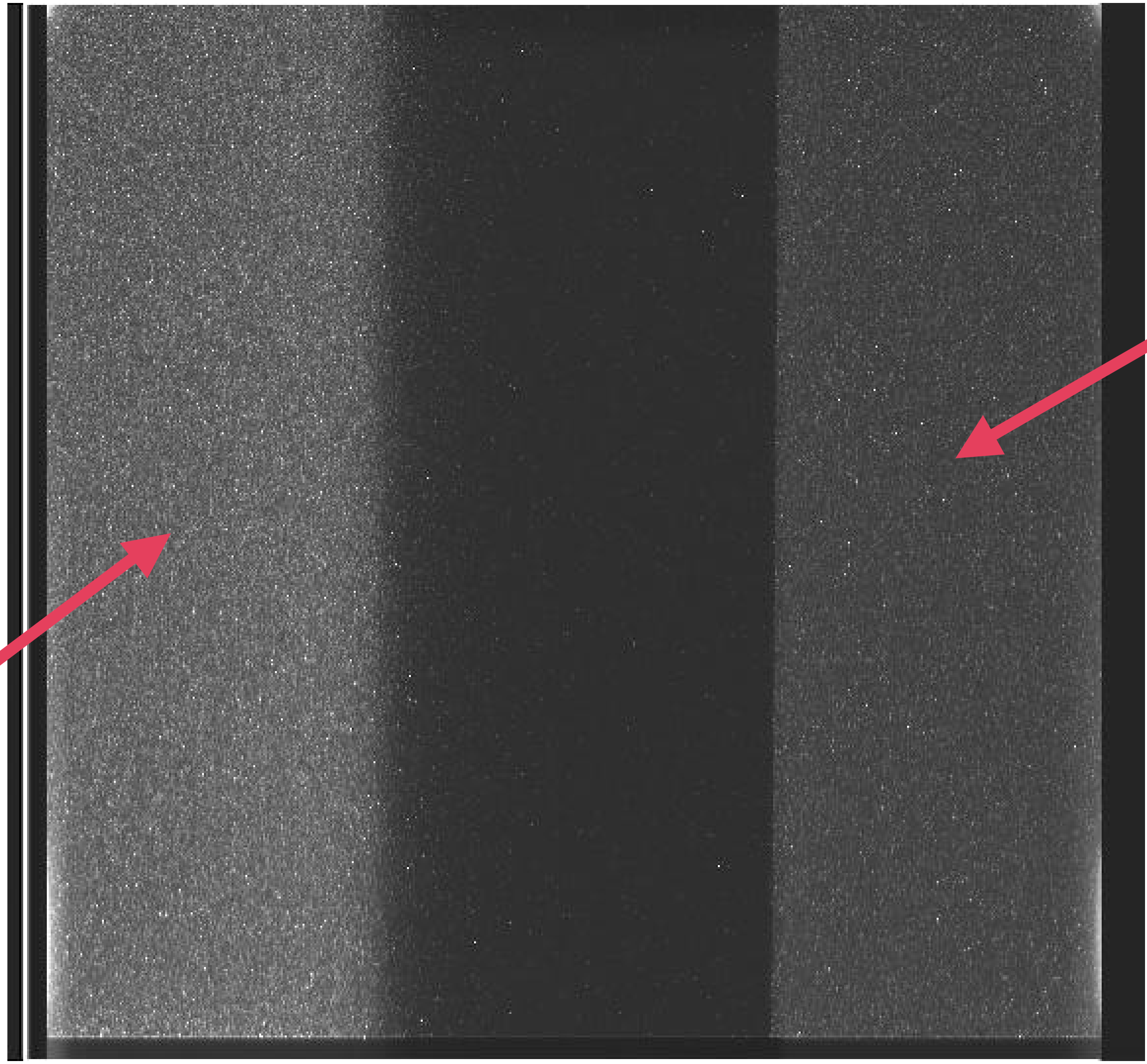
Non-ionizing Energy Loss (NIEL)

- Assume initial damage (vacancies and interstitials) proportional to NIEL (Kinchin-Pease)
- Assume final damage (concentration of electrically active defects) proportional to NIEL, for example:
  - $\frac{\text{concentration of defect A}}{\text{concentration of defect B}}$ independent of proton energy
- Assume electrical effect proportional to NIEL
  - defects are independent, Shockley Read Hall theory
- As proton energy increases, energy of recoils also increases. Above ~ 1 keV (recoil energy) can get cluster damage.
  - Low energy protons - isolated (point) defects
  - High energy protons - increasing proportion of clusters

NIEL for Protons



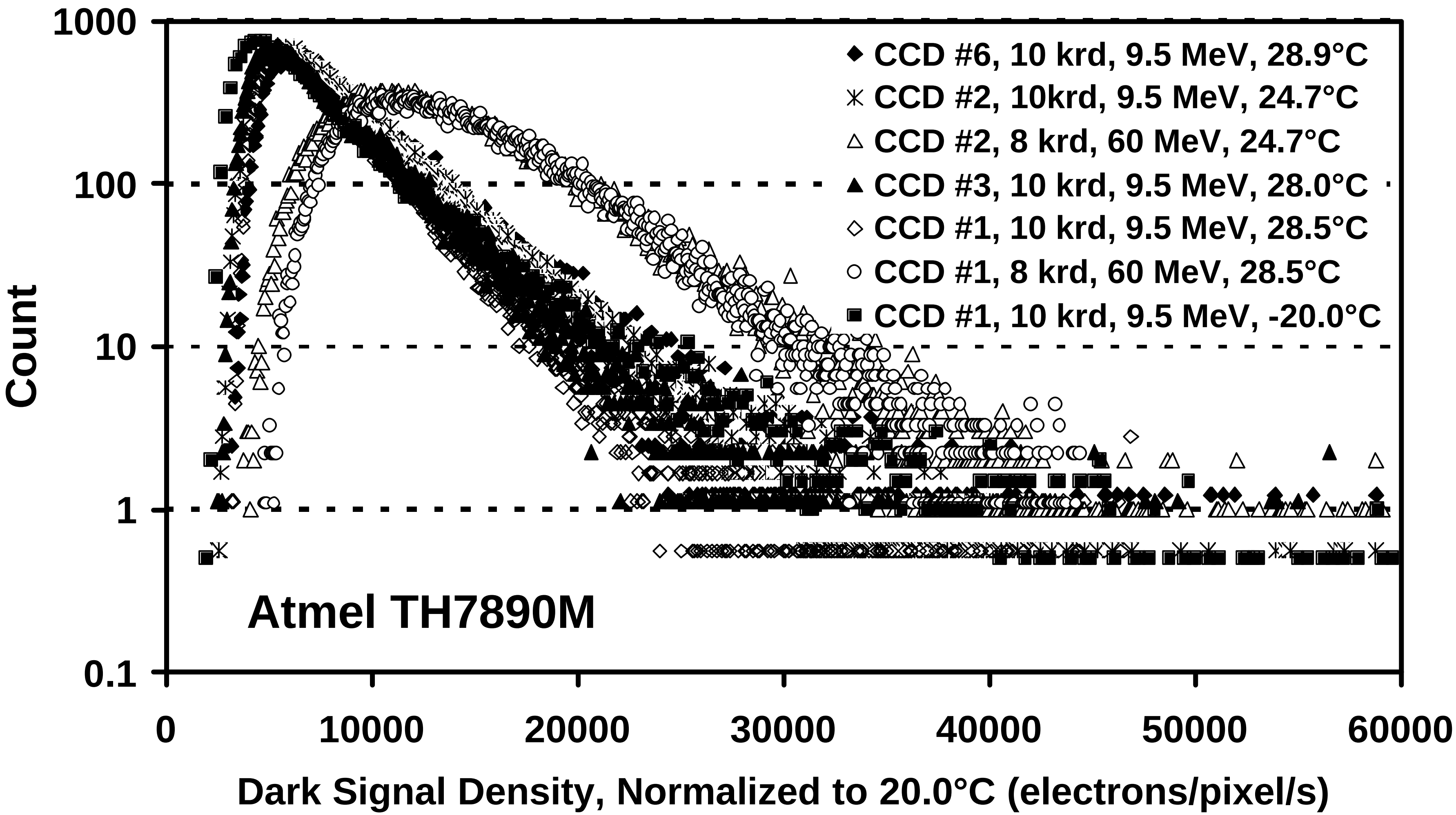
Proton-induced Dark Current



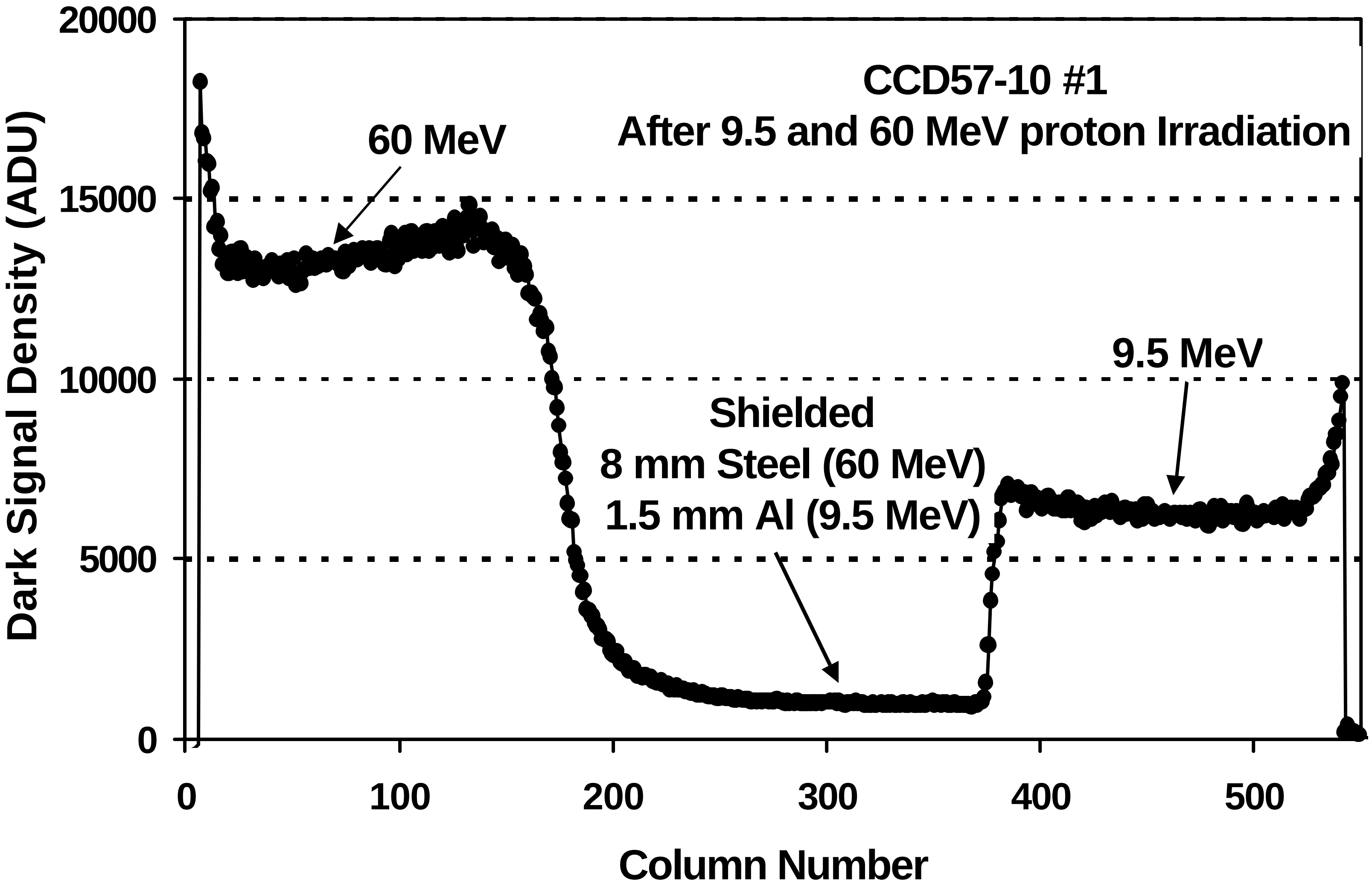
9.5 MeV
1.7 10^{10} p/cm^2

60 MeV
5.9 10^{10} p/cm^2

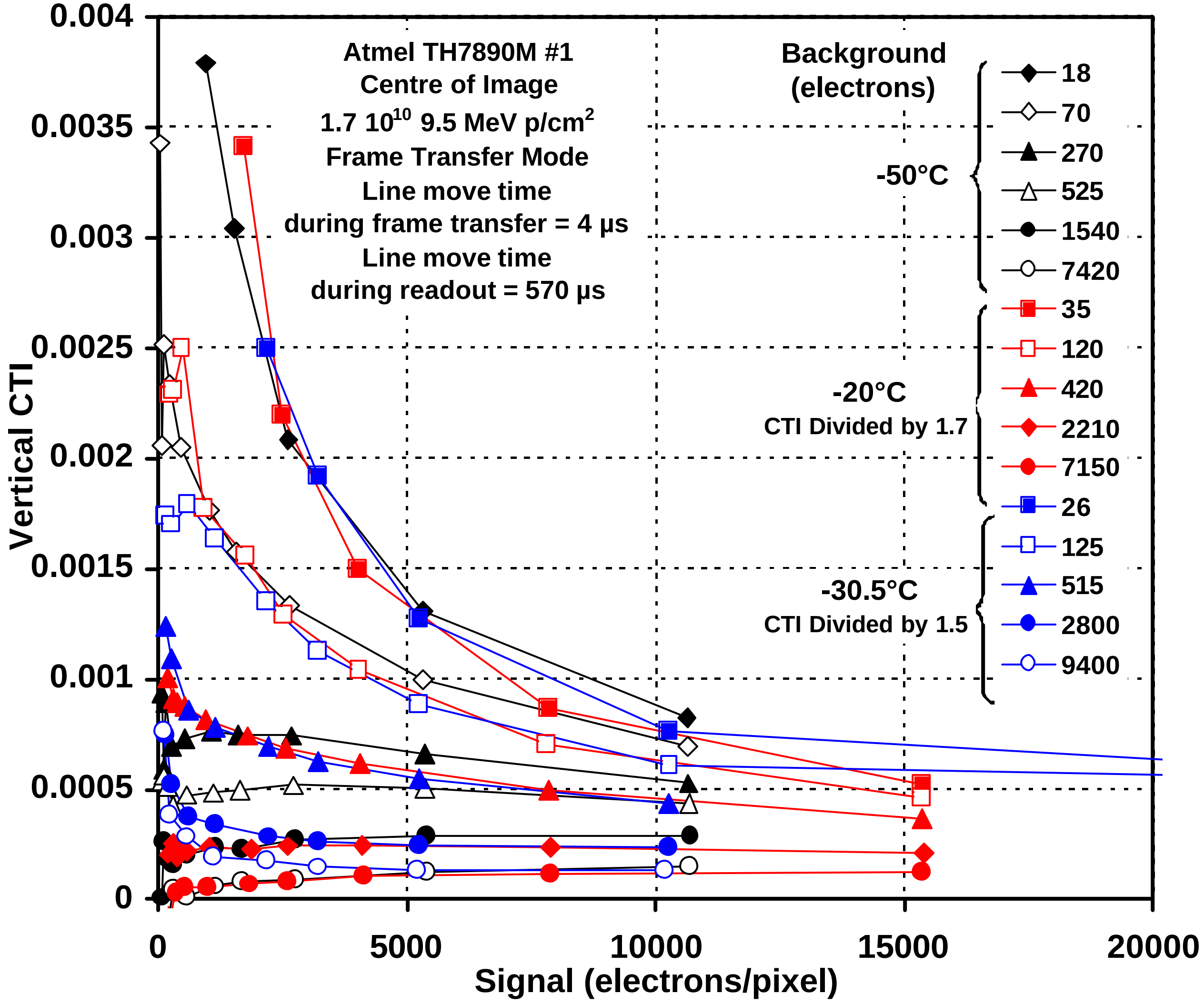
Proton-induced Dark Current



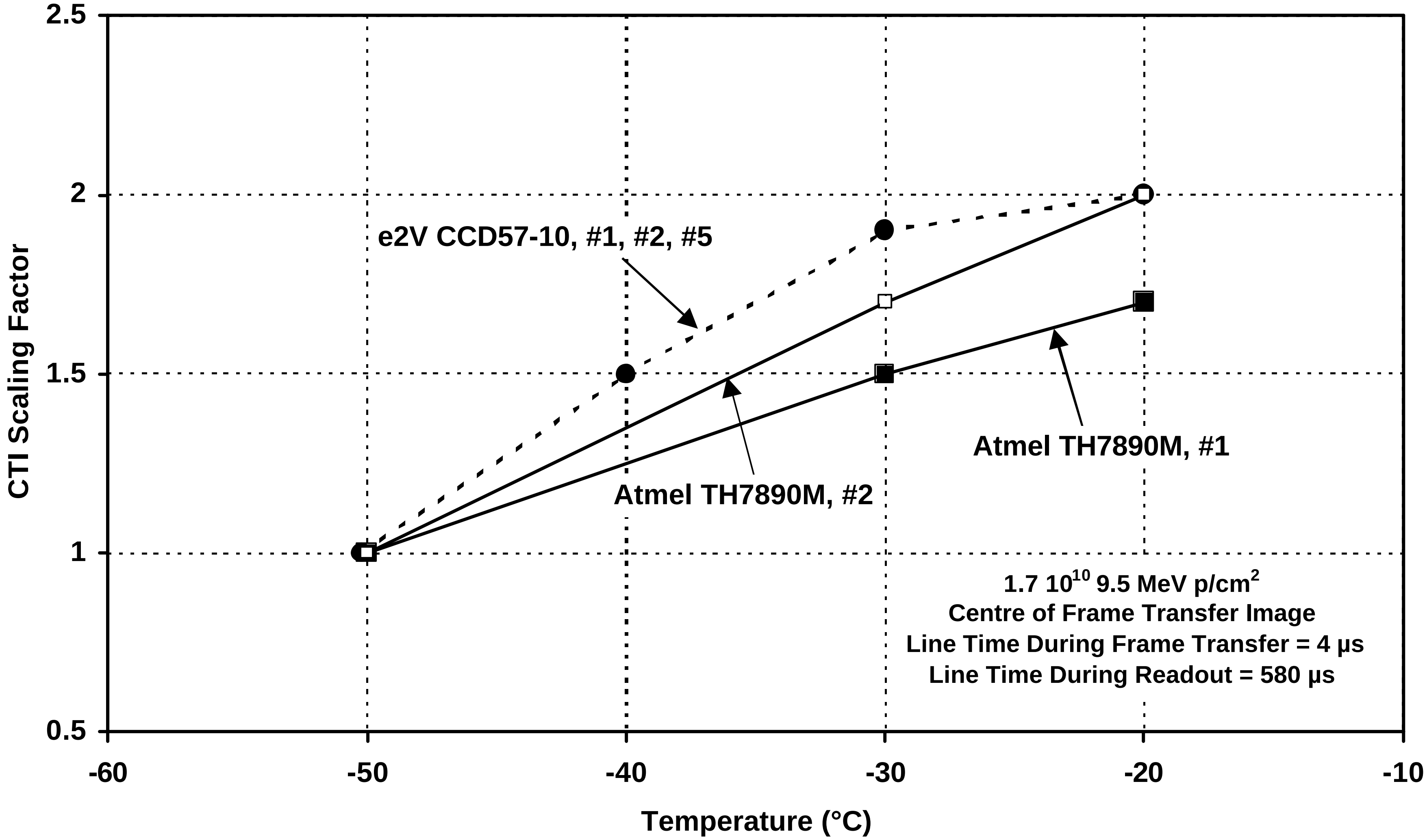
Proton-induced Dark Current



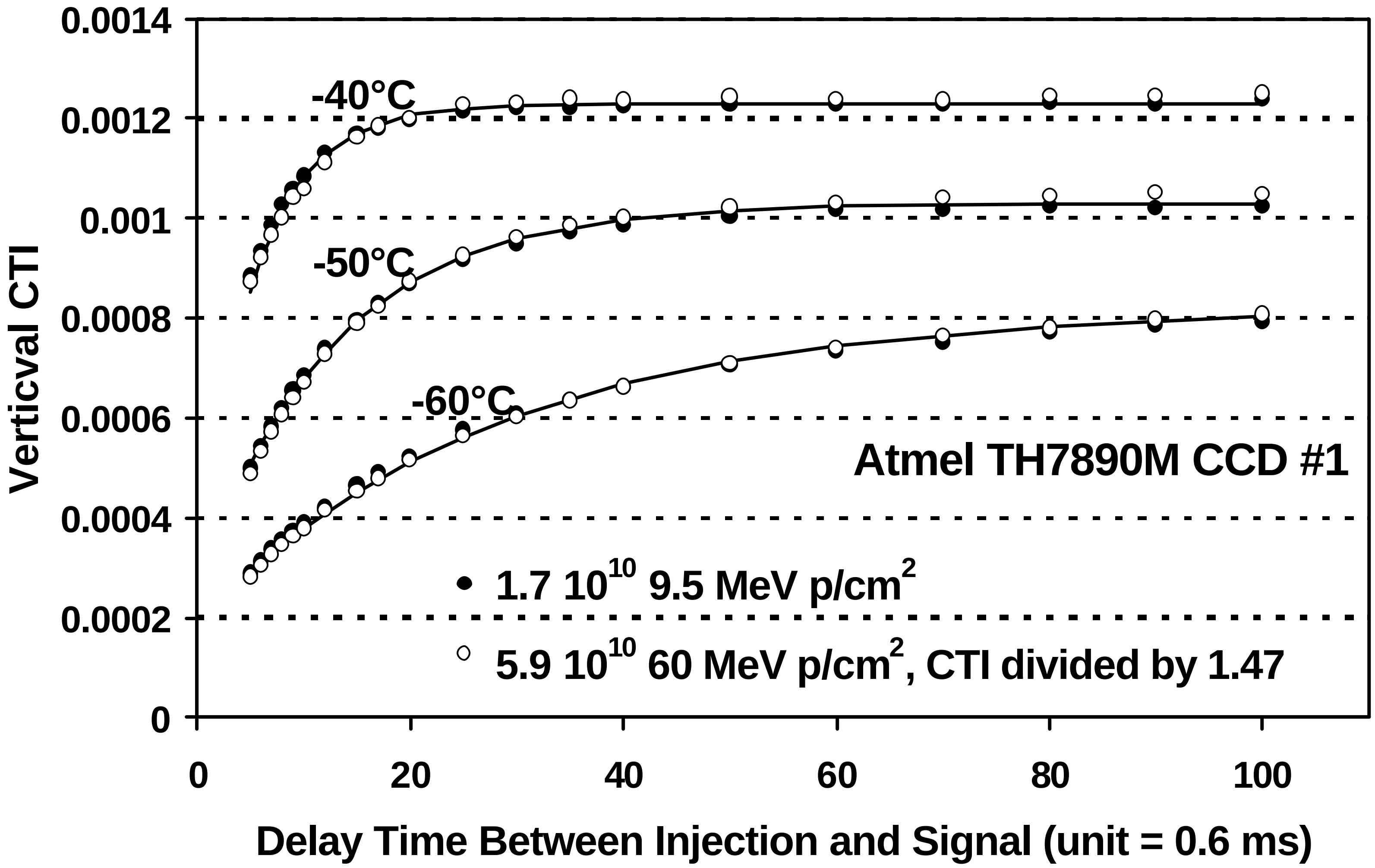
Charge Transfer Inefficiency



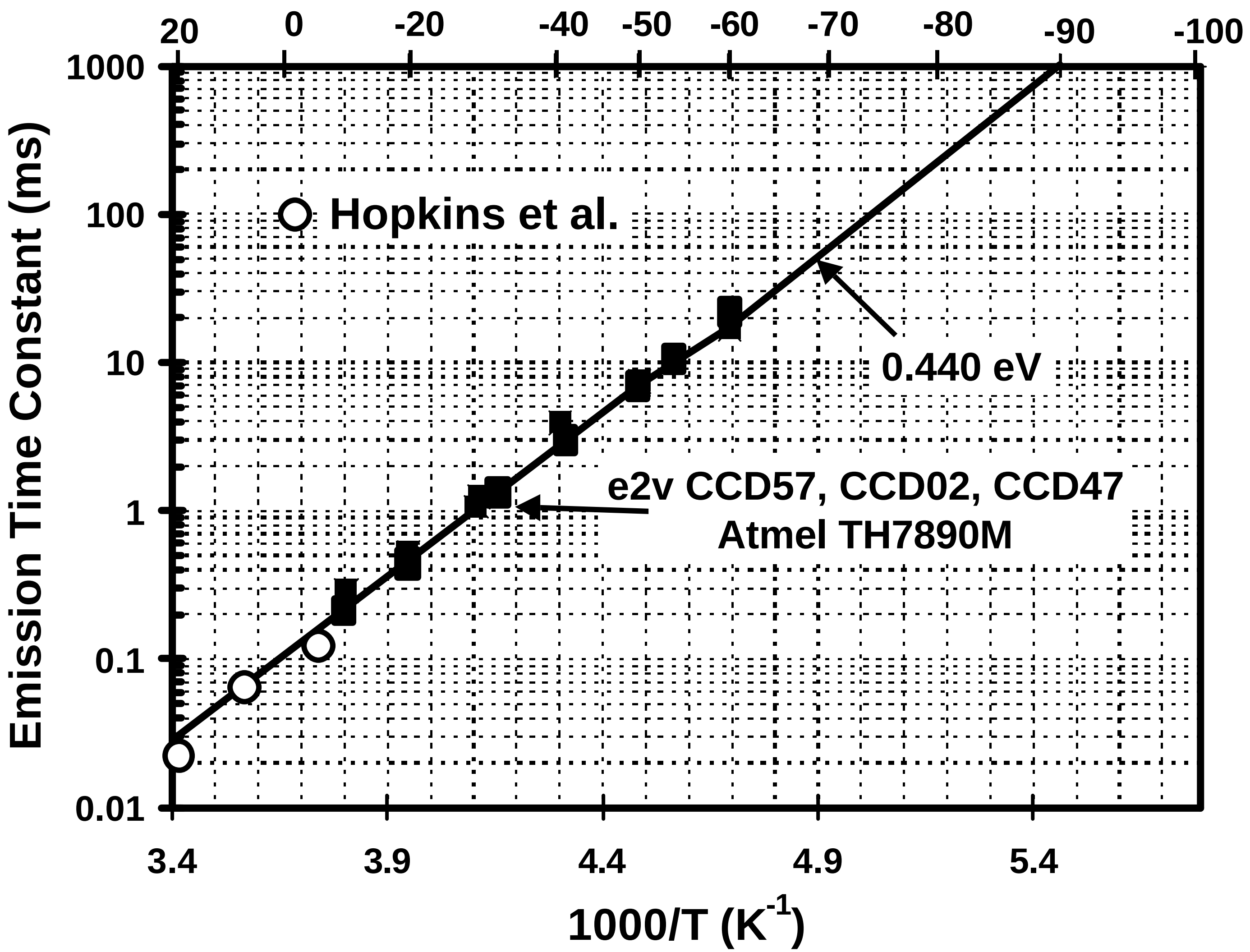
CTI Scaling Factors



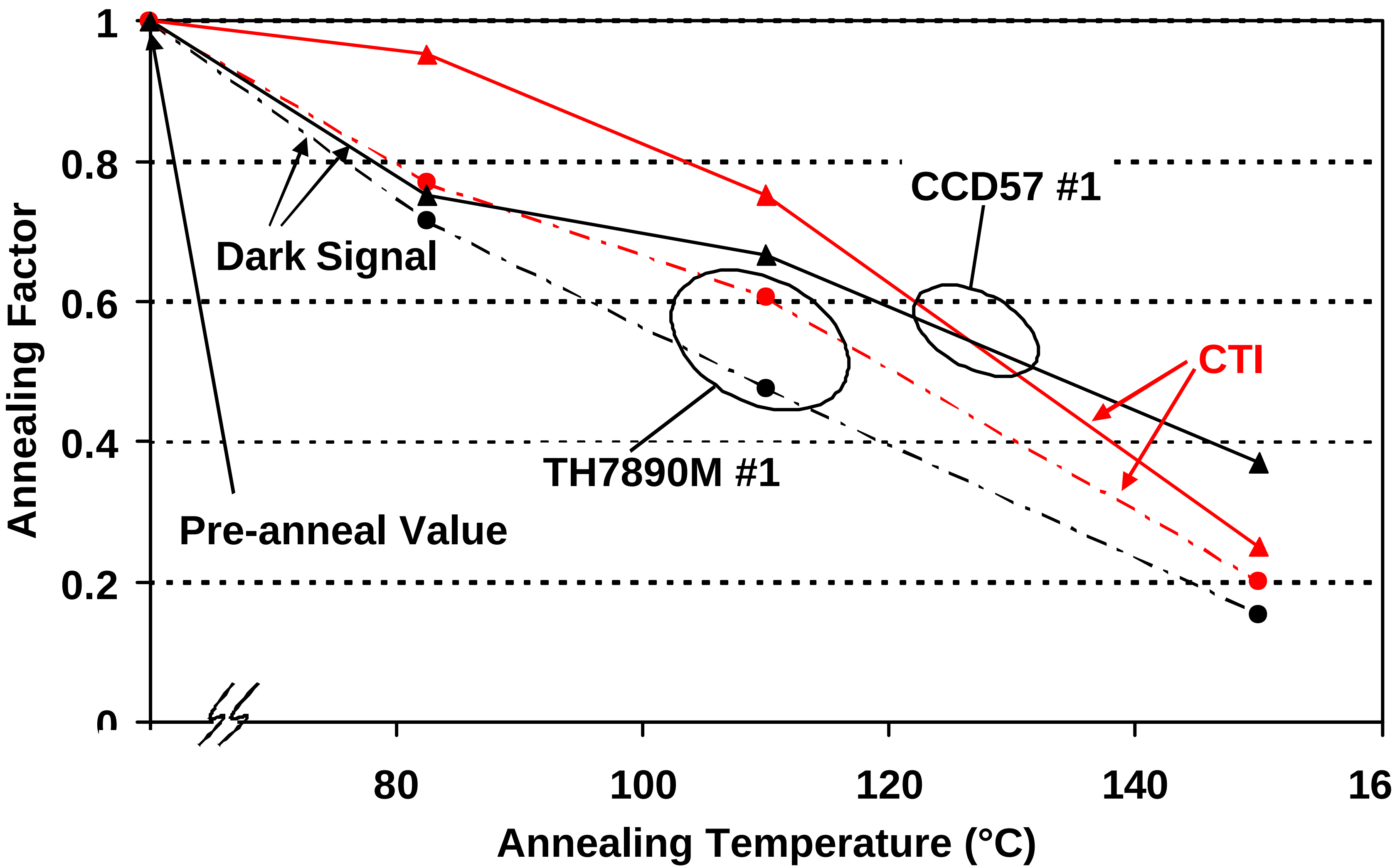
Charge Transfer Inefficiency



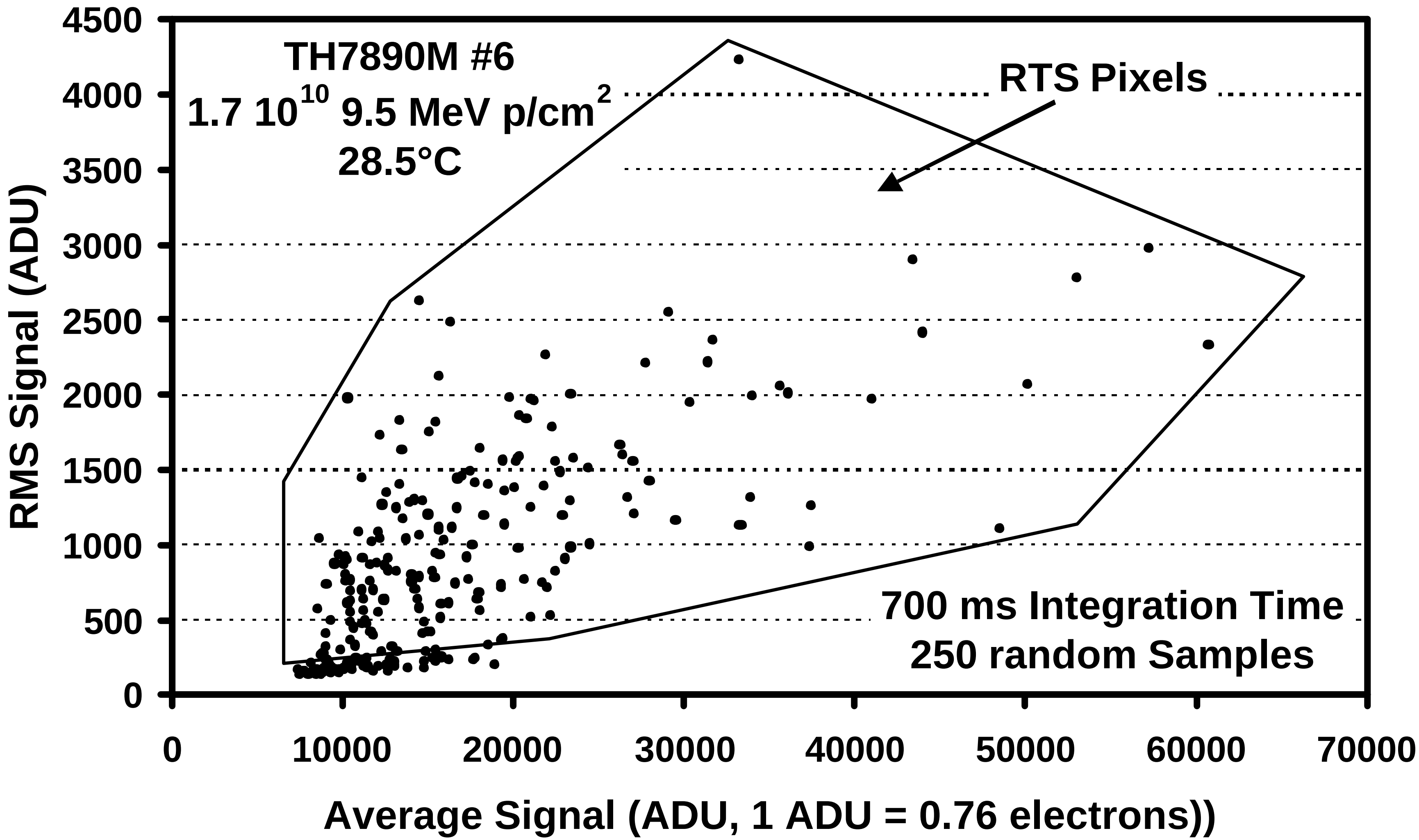
Trap Emission Times



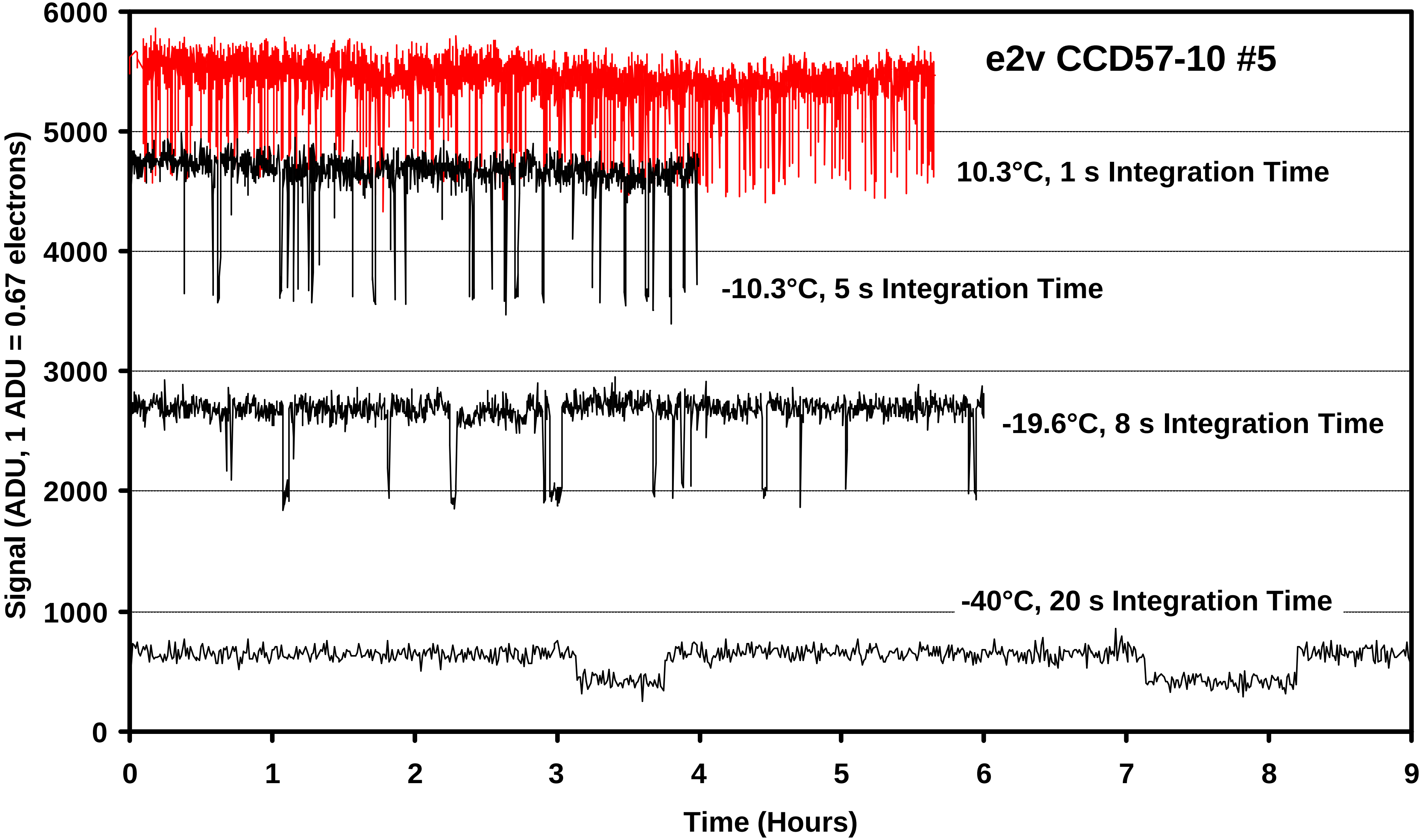
Annealing: 3 day steps



Random Telegraph Signals



Random Telegraph Signals



Conclusions (1)

- Ratio: $\frac{\text{damage at 10 MeV}}{\text{damage at 60 MeV}}$ = 1.8 (average dark current)
  2.3 (CTI) ← Prediction from Dale et al. NIEL

- NIEL scaling works well – very good first approximation
- At detailed level the defect inventory may change with energy – for dark current defects
- So far, CTI defects seem to scale with NIEL, but further work needed

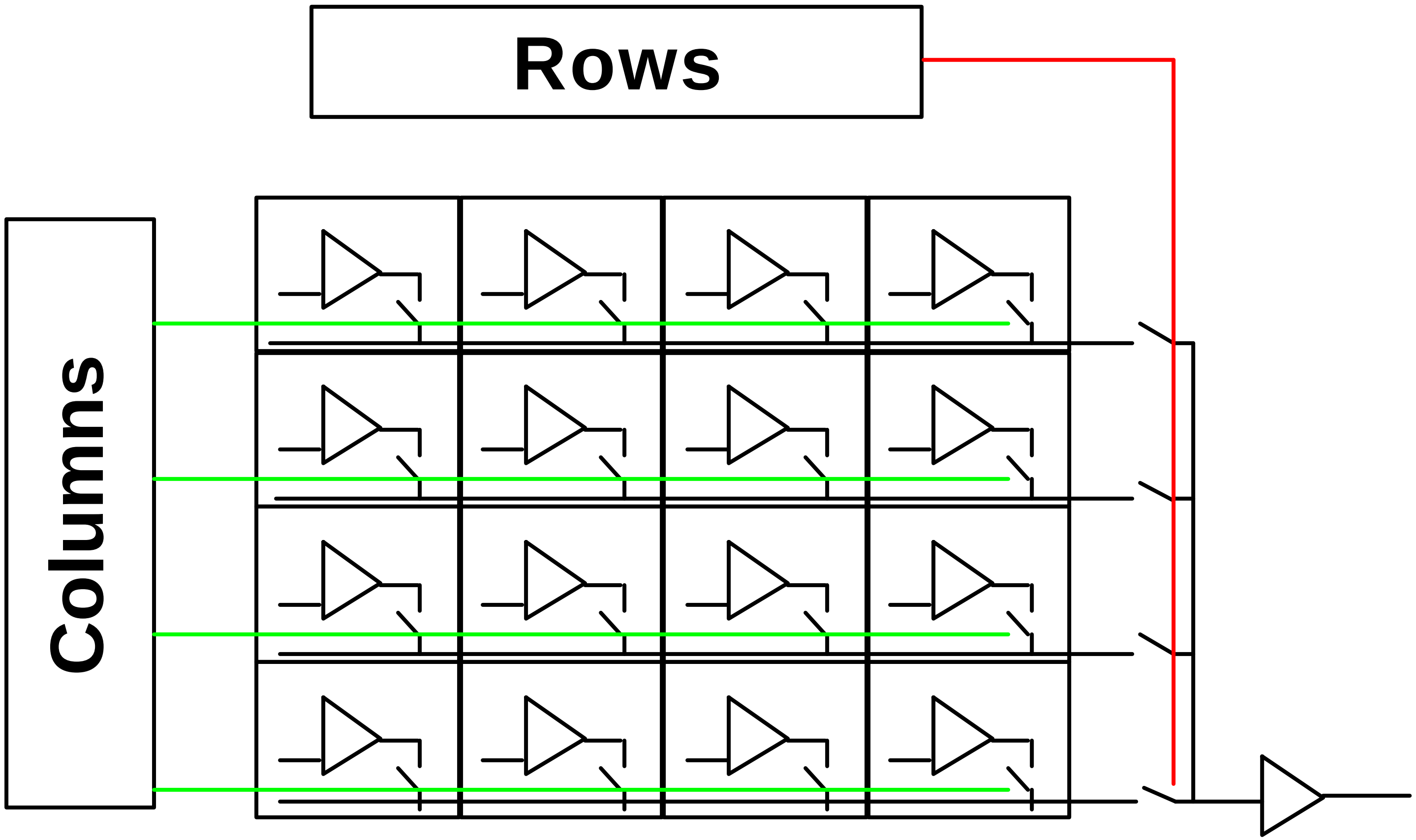
Conclusions (2): defects

- **CTI: main defect probably the E (P-V) centre**
  - Doping related: in p-channel CCDs get different defect
  - Energy level is correct
  - Consistent with annealing
- **Dark current : defect unknown**
  - Probably <u>not</u> dopant related (Srour and Lo, NSREC 2000)
  - Divacancy or vacancy/interstitial cluster ?
  - But anneals in range 100°C to 150°C, so probably not divacancy
  - Factor 100 higher dark current if mid gap (0.55 eV)
  - Some dark current defects are metastable (RTS)
  - RTS defects anneal also
  - Several studies have shown defect annealing
  - Several studies have shown 0.55 eV defects
  - Several studies have shown metastable defects

} Not at same time

APS

Background (1)



Background (1)

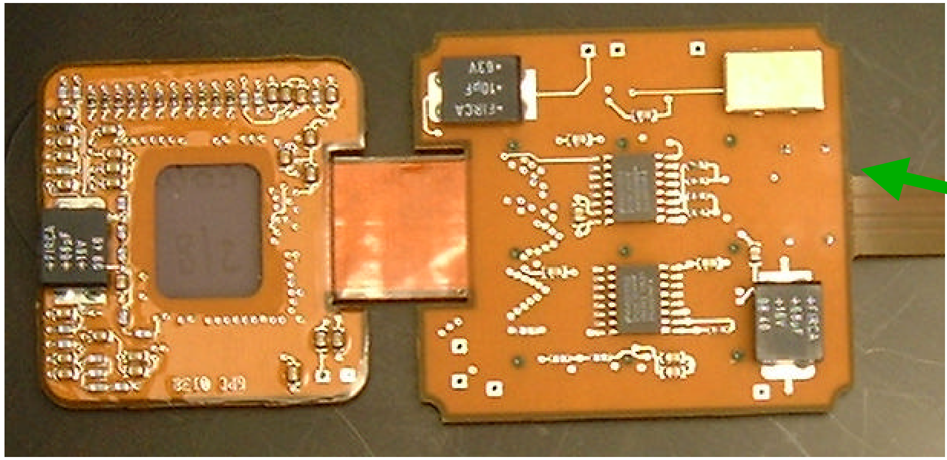
- Previous study investigated the 512 x 512 pixel ASCoSS APS from Fillfactory, Belgium
- New version is the STAR-250
  - standard 0.5 µm AMI Semiconductor (Oudenaarde)
  - hardened by design (for TID and SEL)
    - guard rings ➔ reduction in fill factor (63%)
  - 10-bit ADC (pixel rate up to 5 MHz)
  - fixed pattern noise (FPN) reduction circuits
  - four diodes per pixel
    - improves MTF and crosstalk

Background (2)

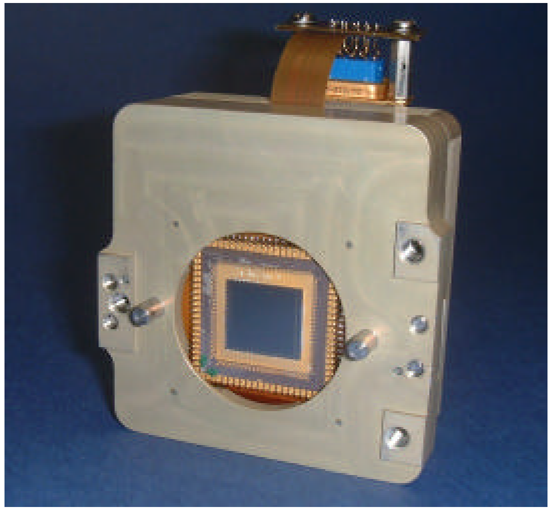
- **STAR-250 results previously presented by the manufacturer (Fillfactory)**
- **Results presented on video camera,**
  - **TID = 5.3 Mrd(Si)**
- **Nominal datasheet bias gives image lag effects**
- **Can trade-off lag with other performance parameters**
  - **trade-off affects radiation results - dark current spikes**
- **Additional data on responsivity and PRNU**
- **Heavy ion data for single event effects**

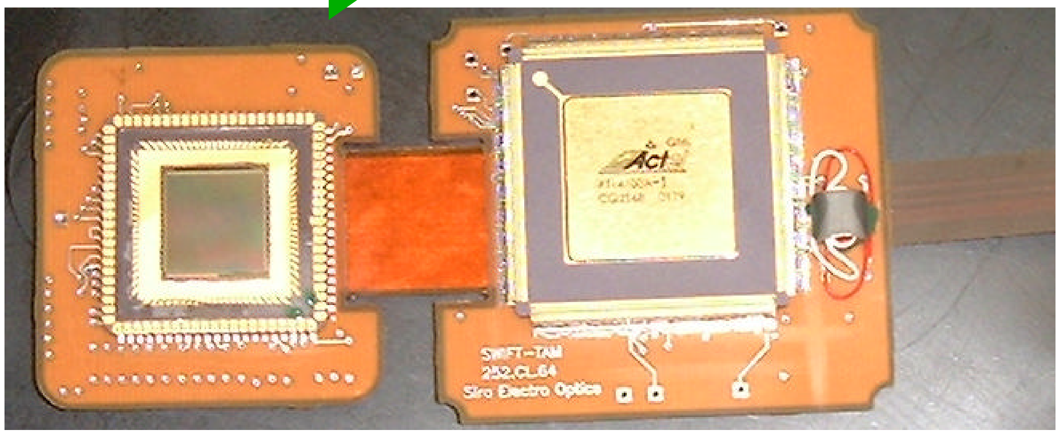
Motivation (1)

- **APS ➡ compact, low power instruments**



PCBs for Telescope Alignment Monitor on NASA's SWIFT X-ray Telescope





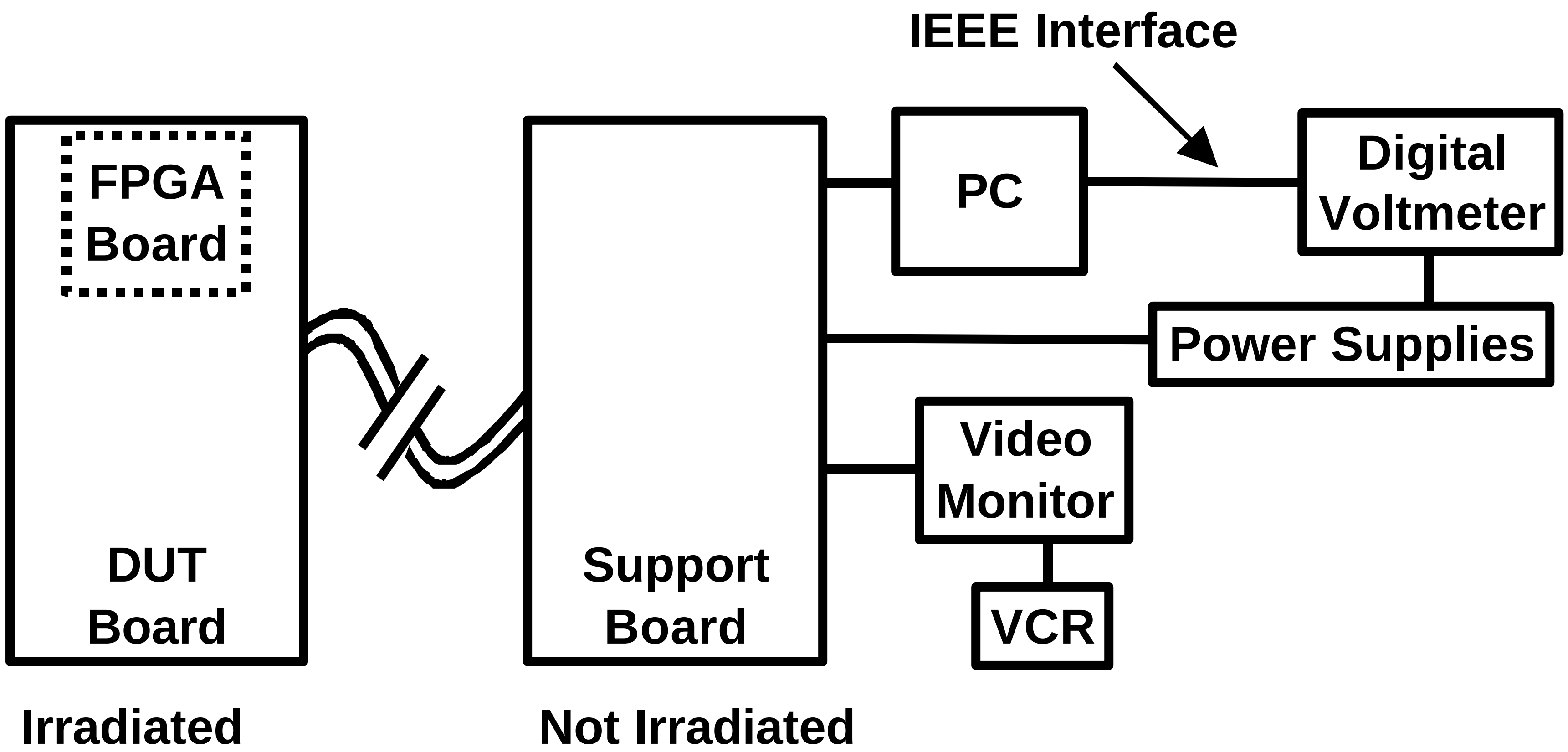
Motivation (2)

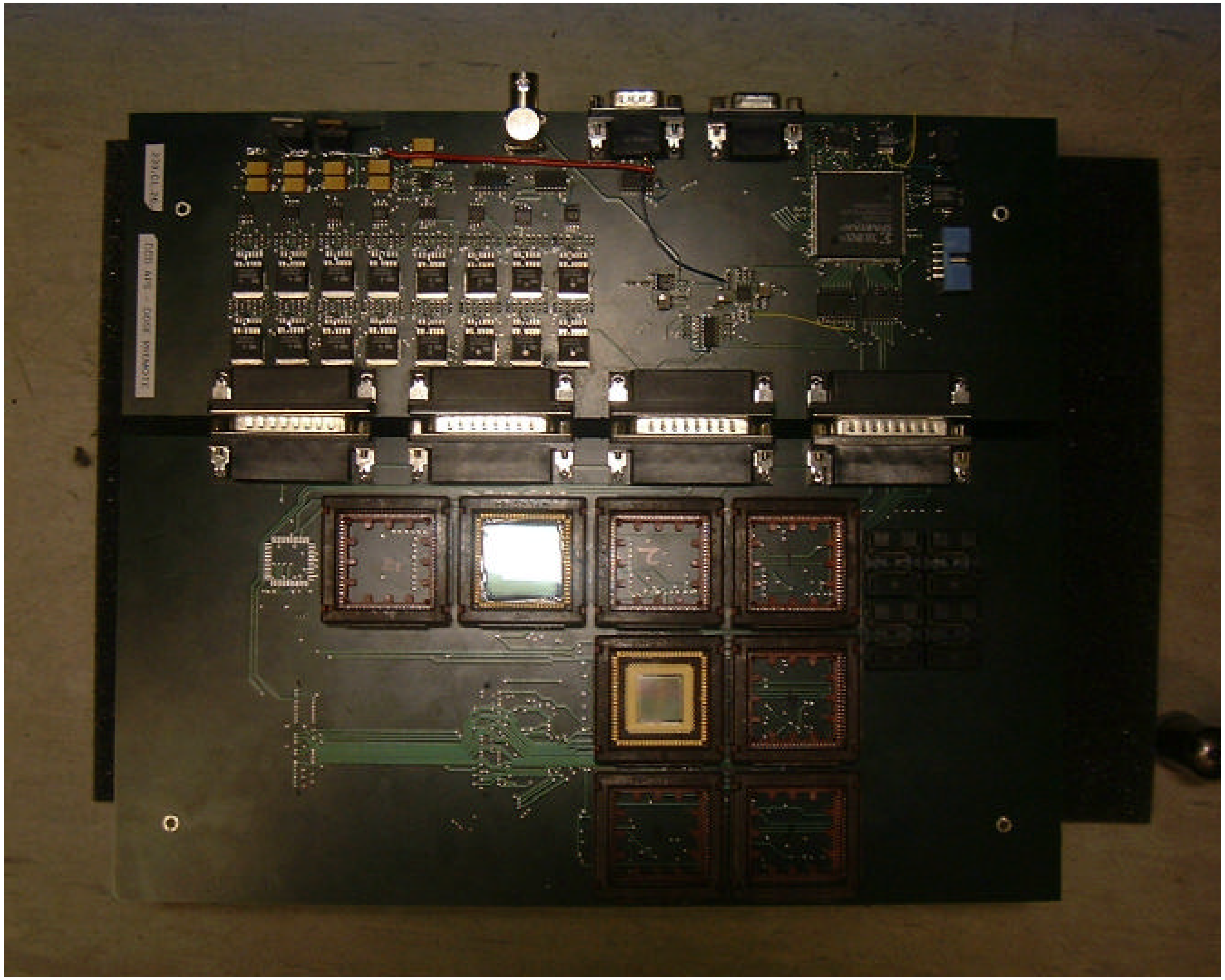
- Fast, windowed, readout
  - useful e.g. for intersatellite laser communications
- Better radiation performance than CCDs (which are limited to LEO)
  - no charge transfer (CTE) effects
  - thin gate oxide so no threshold voltage shifts
  - just have to protect against leakage currents and latch up (SEL)
- But need to test for the full range of radiation effects
  - TID
  - Displacement Damage
  - Single Event Phenomena

Experimental: Irradiations

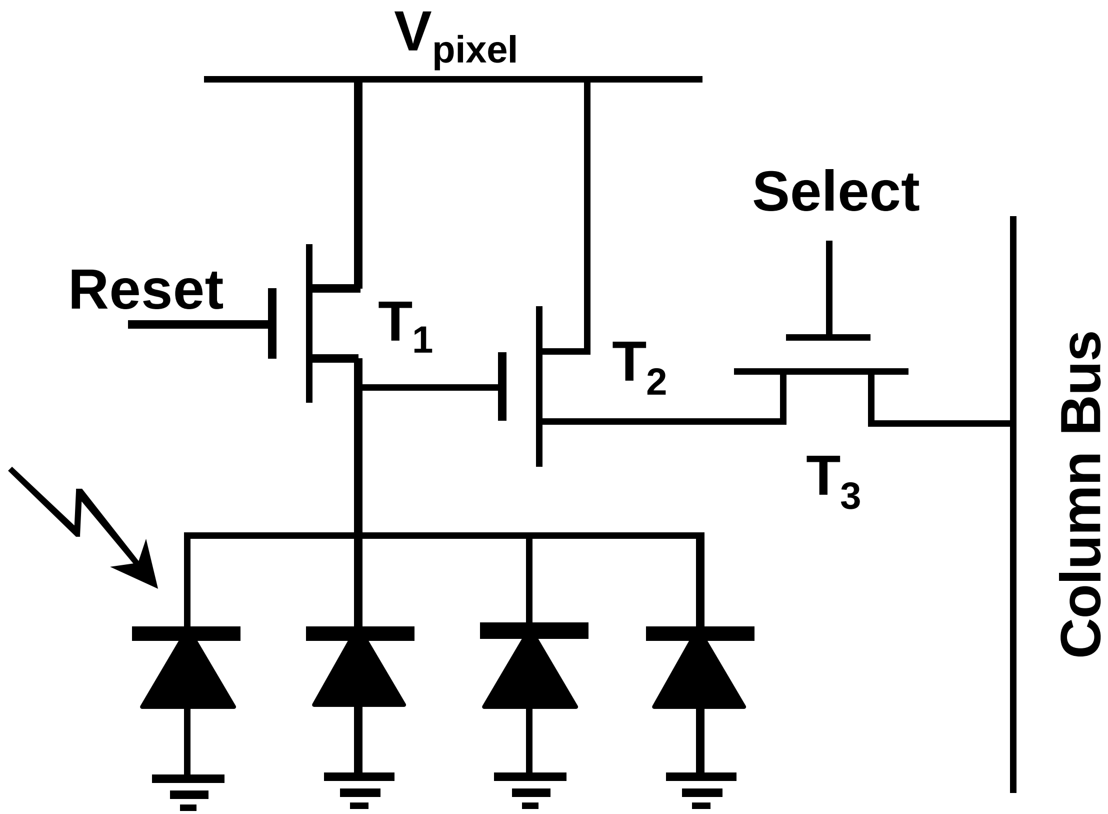
- Cobalt-60
  - ESTEC facility
  - ~ 3 krd(Si)/hour, 3 devices biased, 1 unbiased
  - maximum total dose = 79.2 krd(Si)
- 9.5 MeV proton
  - Ebis Iotron, Harwell, UK,
  - 2 devices, unbiased (pins shorted)
  - masking to get 0, 10 and 100 krd(Si)
- Heavy Ion
  - Heavy Ion Facility (HIF), Louvain-la-neuve, Belgium
  - highest LET: 68 MeV/(mg/cm^2) (Kr, 60° incidence)
  - 2 devices, also 2 IRIS-2 devices tested for SEL

Experimental: test equipment



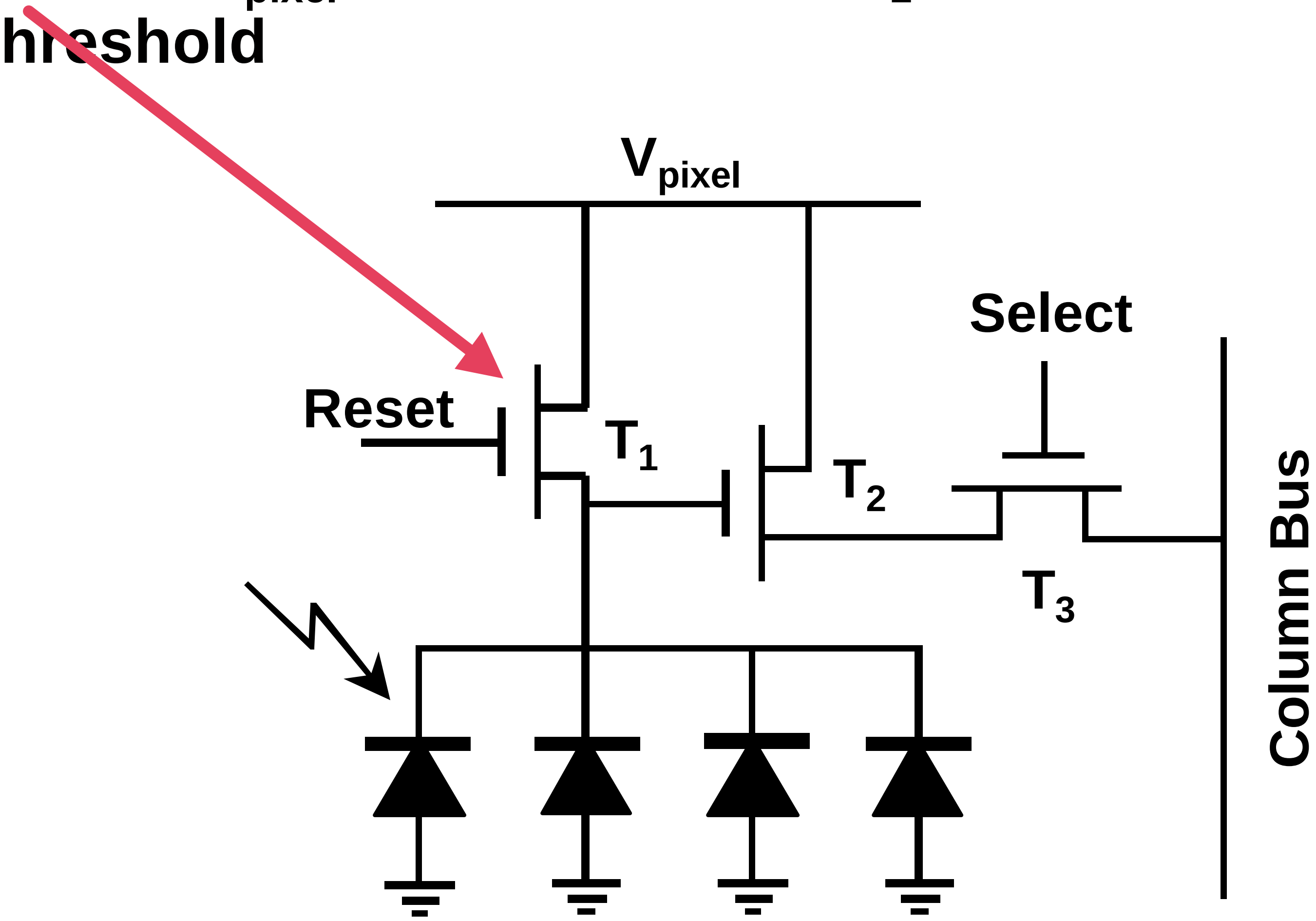


Pixel Architecture



Pixel Architecture

- Unless V_{pixel} is < roughly 4 V, T_1 operates sub-threshold



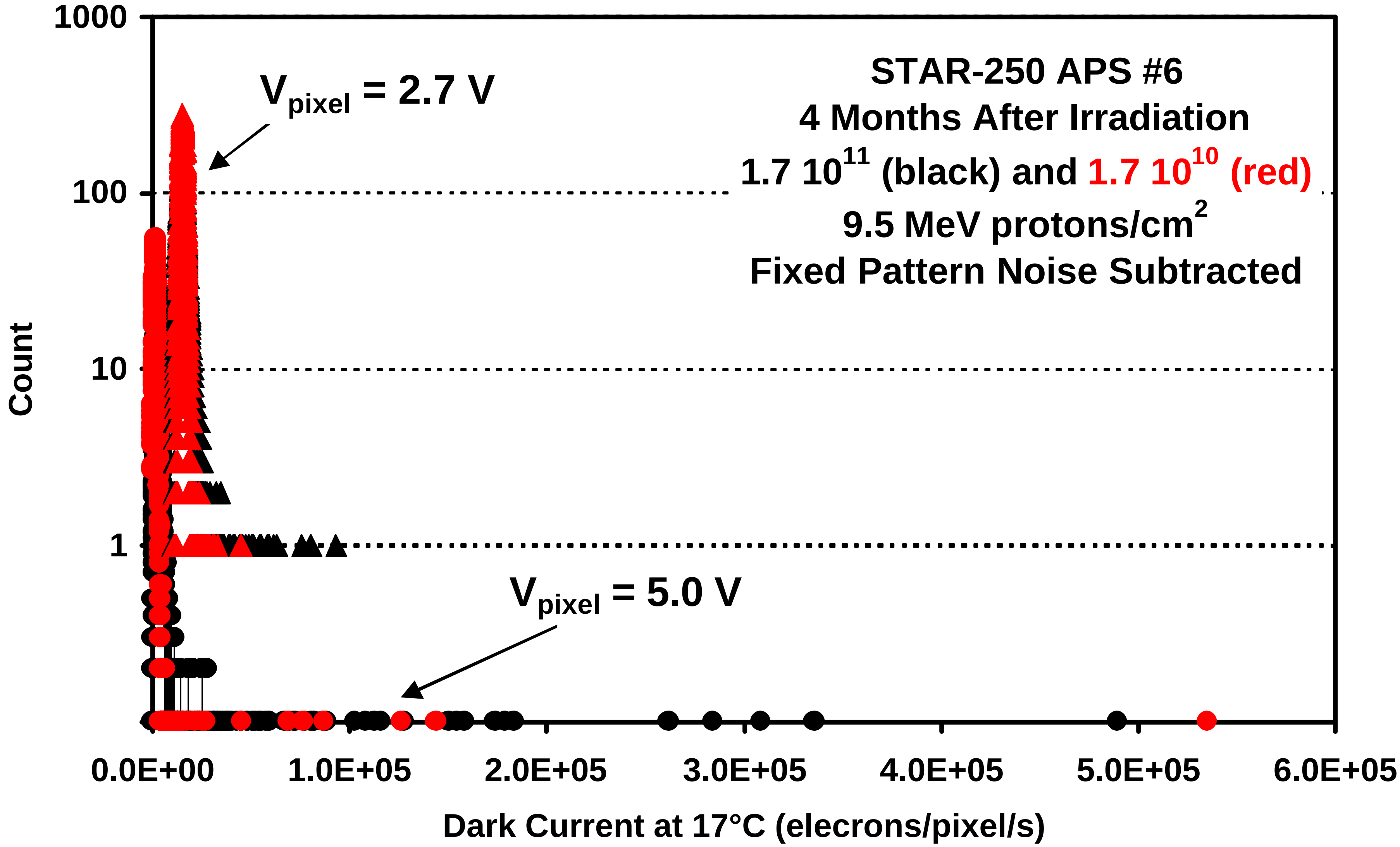
V_{pixel} trade-offs

Reducing V_{pixel} eliminates lag but:

- **Reduces gain**
- **Reduces full well capacity (both charge and voltage)**
- **Increases non-linearity**
- **Increases ‘fixed pattern’ non-uniformity (offsets)**
- **In theory, increases readout noise (by Ö2)**

- **Reduces proton-induced dark current spikes**

Results: proton-induced dark current



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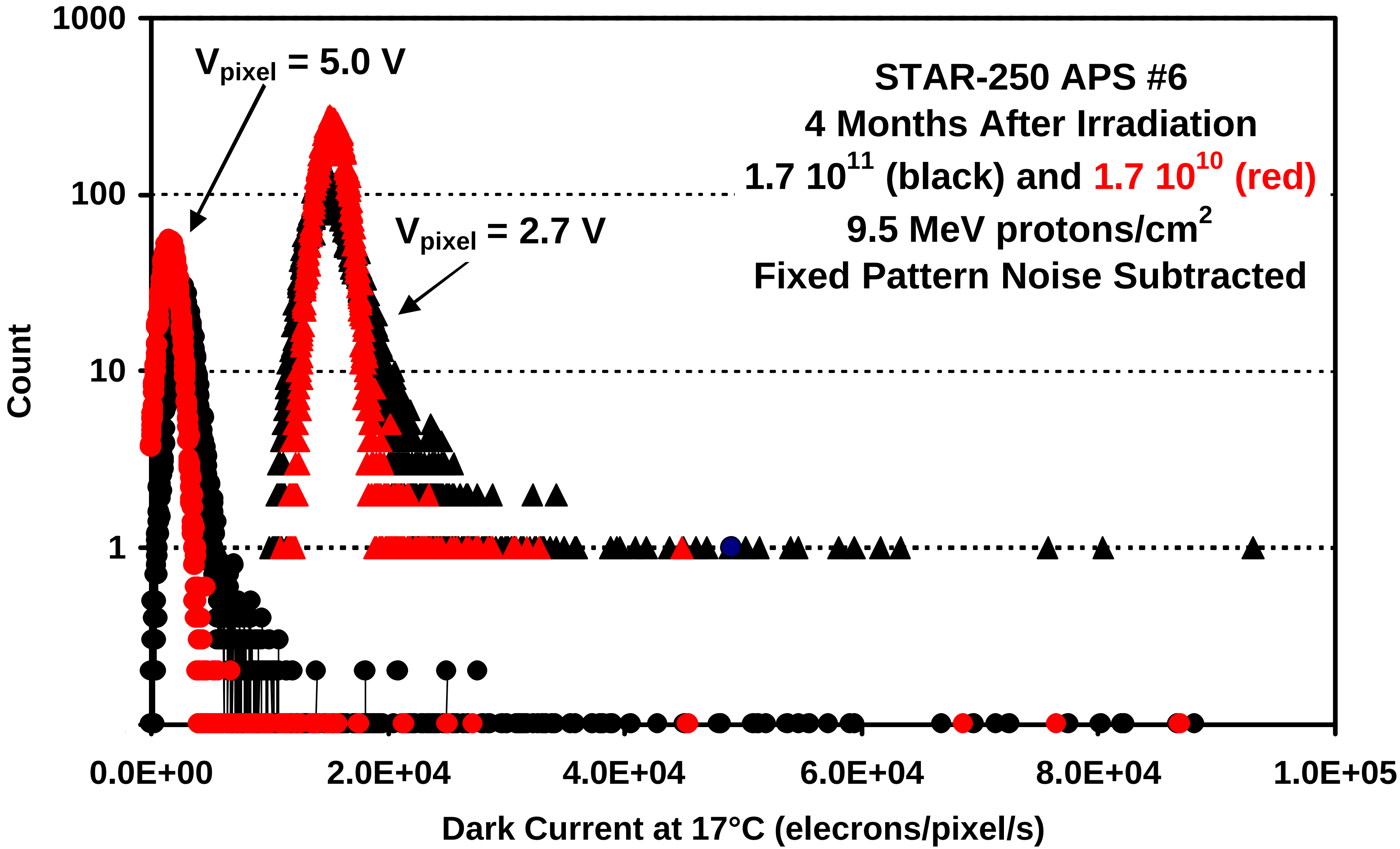
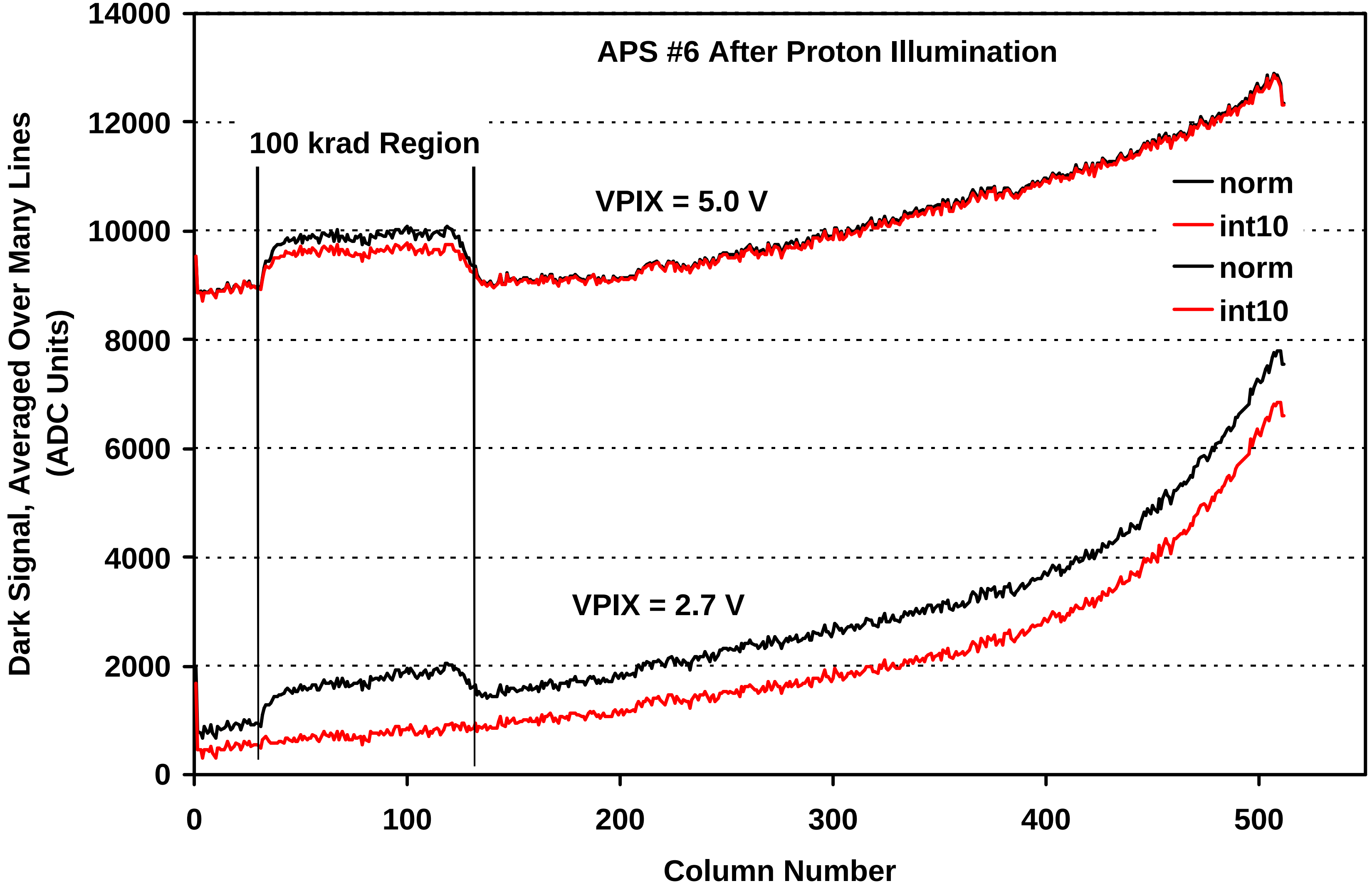
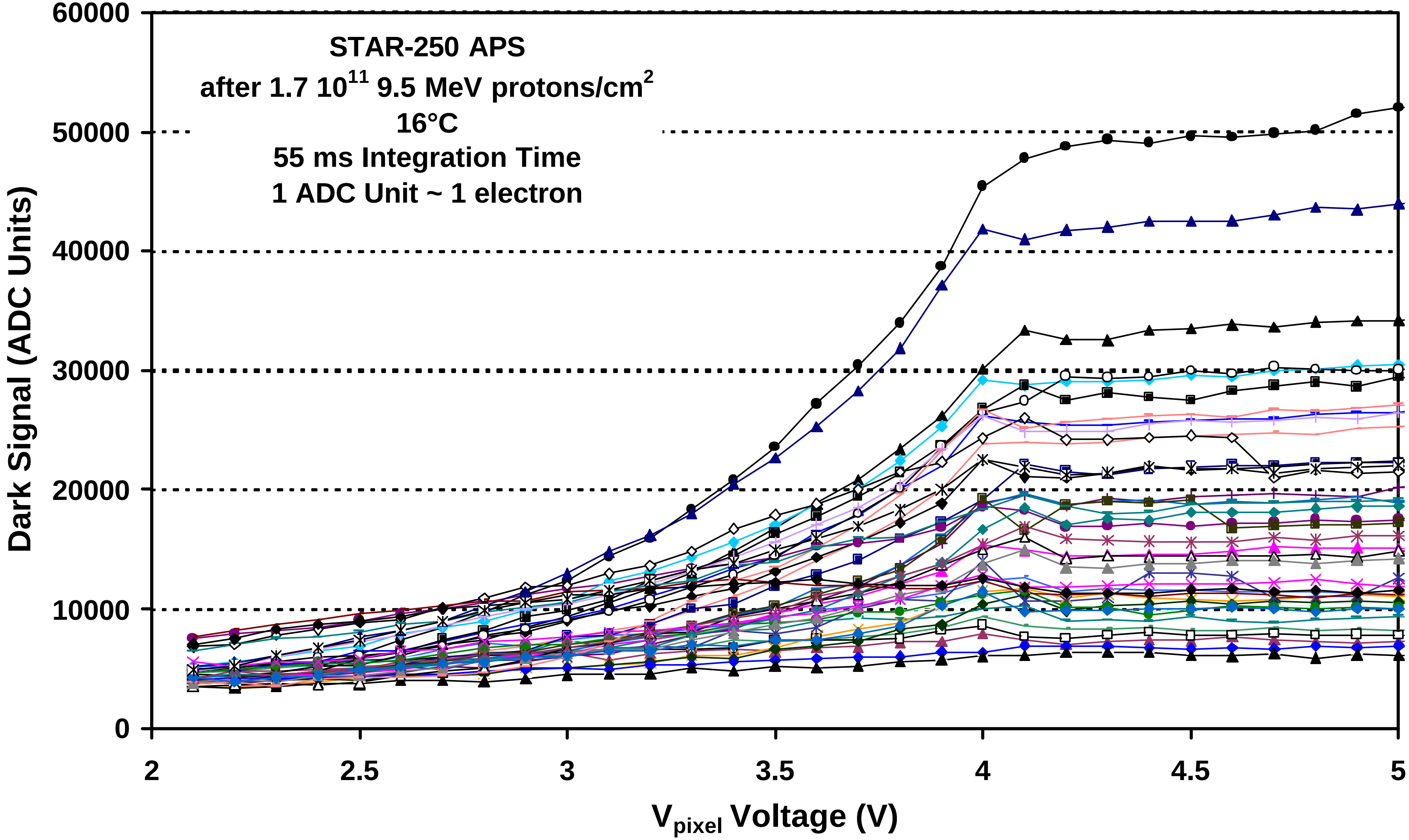


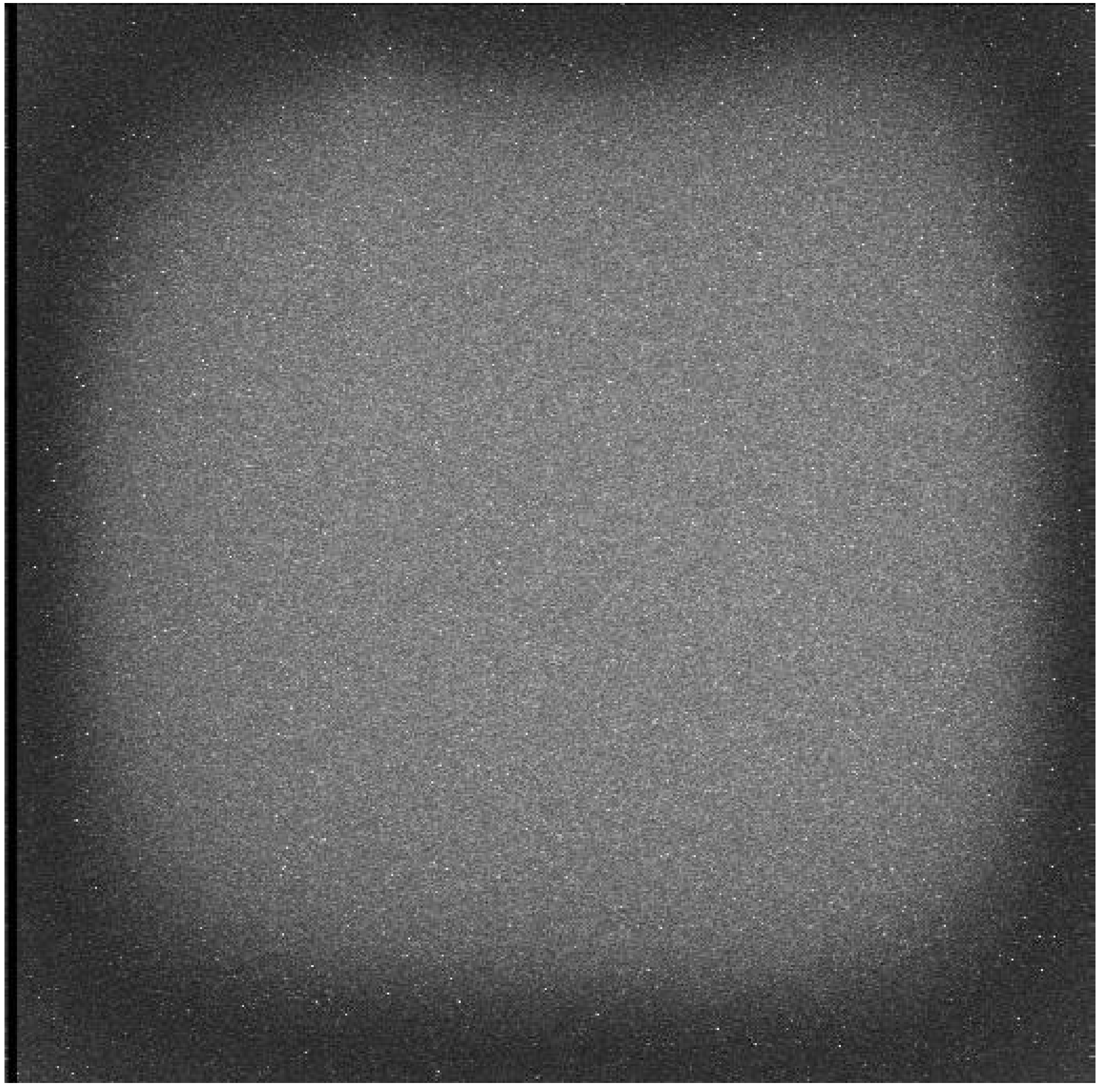
Horizontal profiles of Dark Images



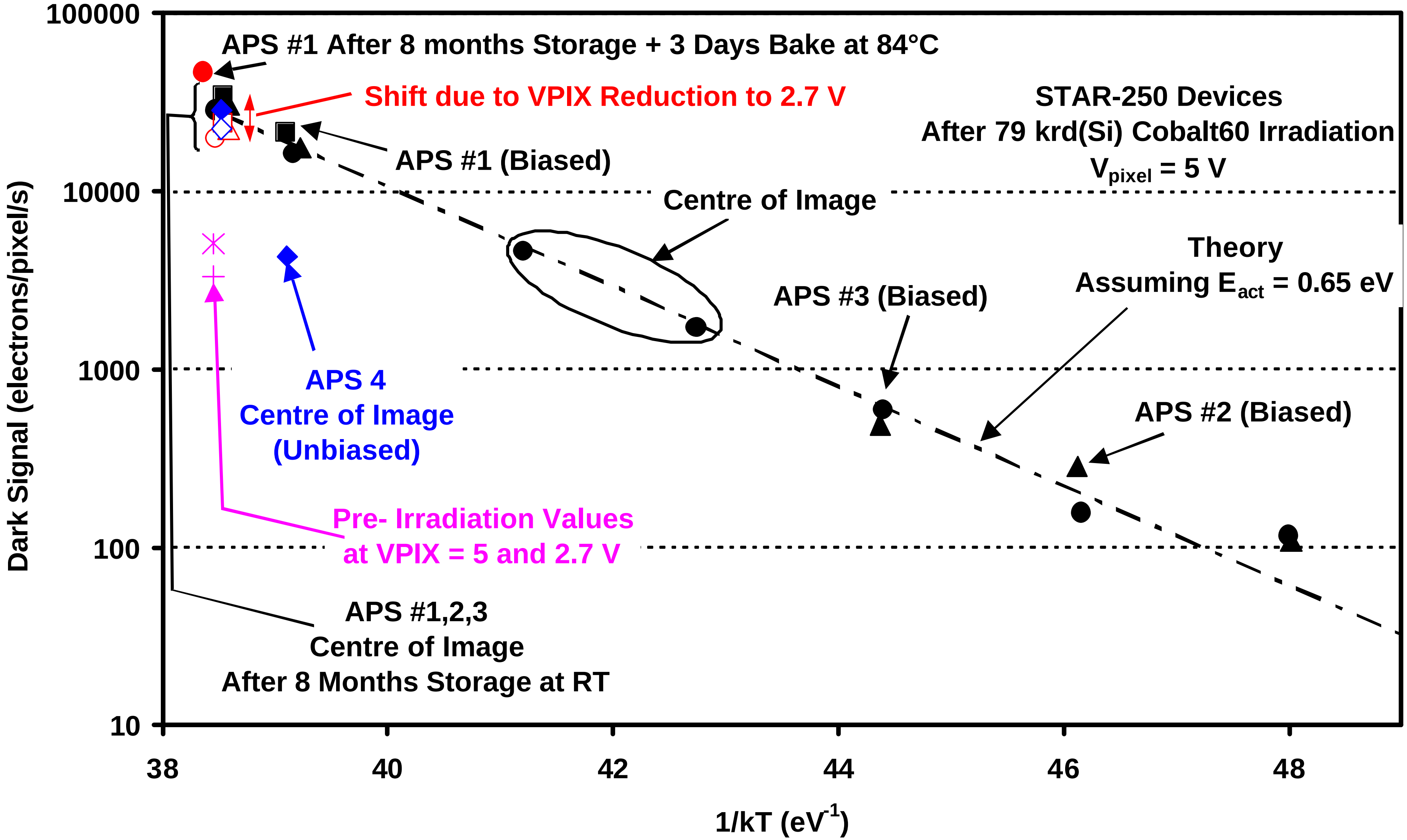
Results: proton-induced dark current



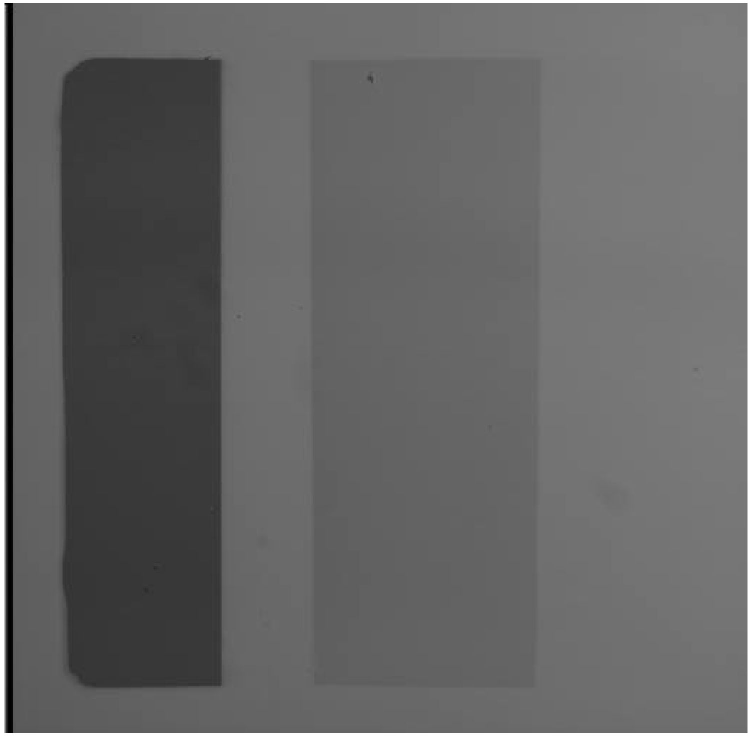
Results: Dark current due to TID

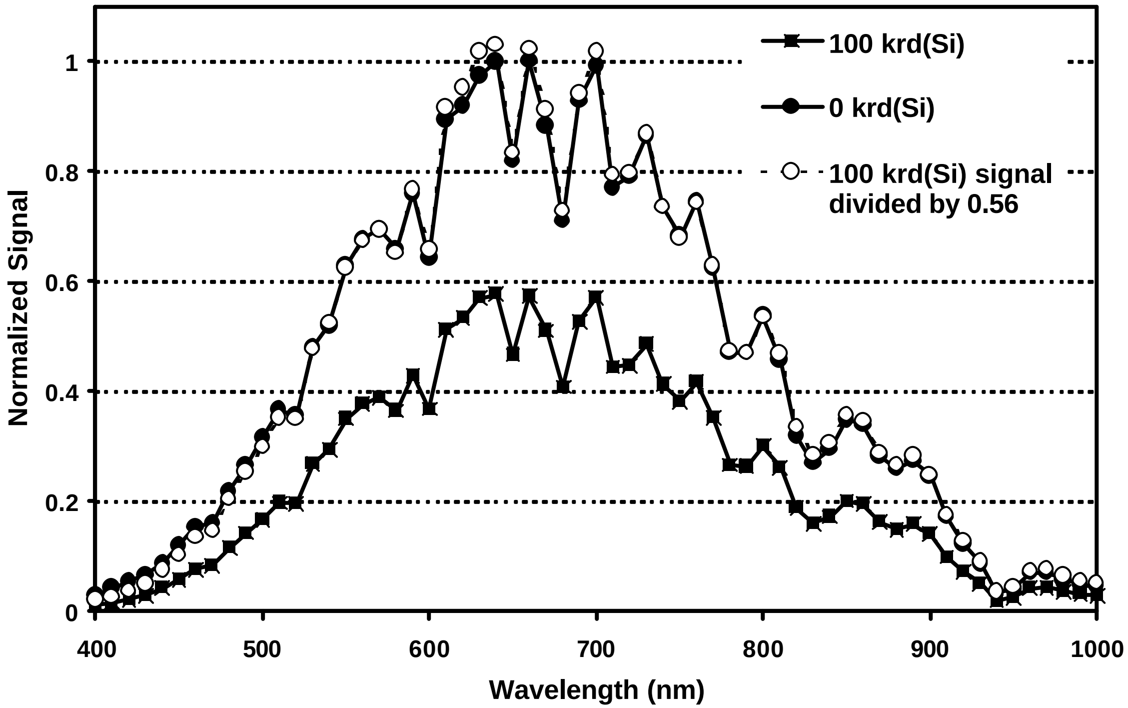


Results: Dark current due to TID



Results: decrease in responsivity, TID





- ❑ **Also get increase in PRNU**

Other TID results

- **Fixed pattern noise**
  - No significant change
- **Threshold voltage shift**
  - Measured by varying clocks under computer control
  - Negligible change after 80 krd(Si)
  - previously found 80 mV shift after 5.3 Mrd(Si)
- **Power supply currents**
  - Sensor currents increased from 22 to 29 mA but annealed back
  - ADC current stayed within 93 ± 2mA (frequency dependent)
- **ADC performance**
  - DNL and INL measured by varying output black reference voltage
  - No significant changes in performance
  - No missing codes

Results: Heavy ion testing

- **STAR-250 after 68 MeV/(mg/cm^2)**
  - **No SEL**
  - **No functional interrupts (from video monitor)**
  - **No large ADC errors (from histograms)**

  As expect:
  - **Transient noise events (all LETs): range ~ ± 40 ADU**
  - **Transient events in sensor**
- **IRIS-2 after 8 MeV/(mg/cm^2)**
  - **SEL and some 'low current' (mini-latch) events**
    - **Some events ~ 100 mA (typical operating current 43 mA)**
    - **Not known if device is functional after mini-latch**
      - **Implications for device testing**

Conclusions

- **Hardening by design successful for STAR-250**
  - **Most parameters unchanged after 80 krd(Si) and device operational up to several Mrd(Si) – TID dark current low**
  - **No SEL, functional interrupts or major transients at 68 MeV/(mg/cm^2)**
- **Need to reduce V_{pixel} to eliminate image lag**
  - **Reduces signal to noise ratio – probably not too significant for many applications**
  - **Reduces dark current spikes – important hardening effect**
- **Challenge for APS testing is to make sure all effects are covered**
  - **Test programme successful**
  - **For other sensors, may need to consider imaging performance during latch-up testing**