ACCEDE | ESCCON
2025 Seville - Spain
25 to 27th March
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Radiation tests on COTS TDI image sensor used in STEP Cube Lab-II satellite

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Outline

- Introduction and motivation
- Experimental
- Radiation tests
- Summary and conclusions

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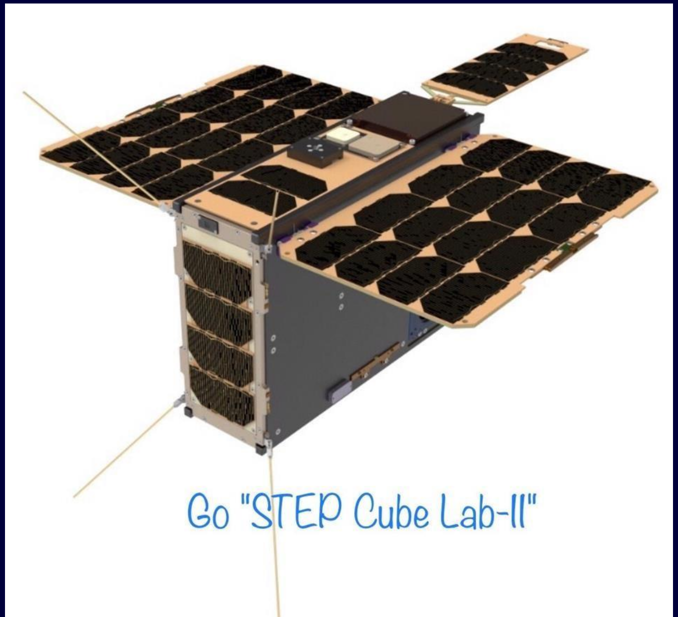
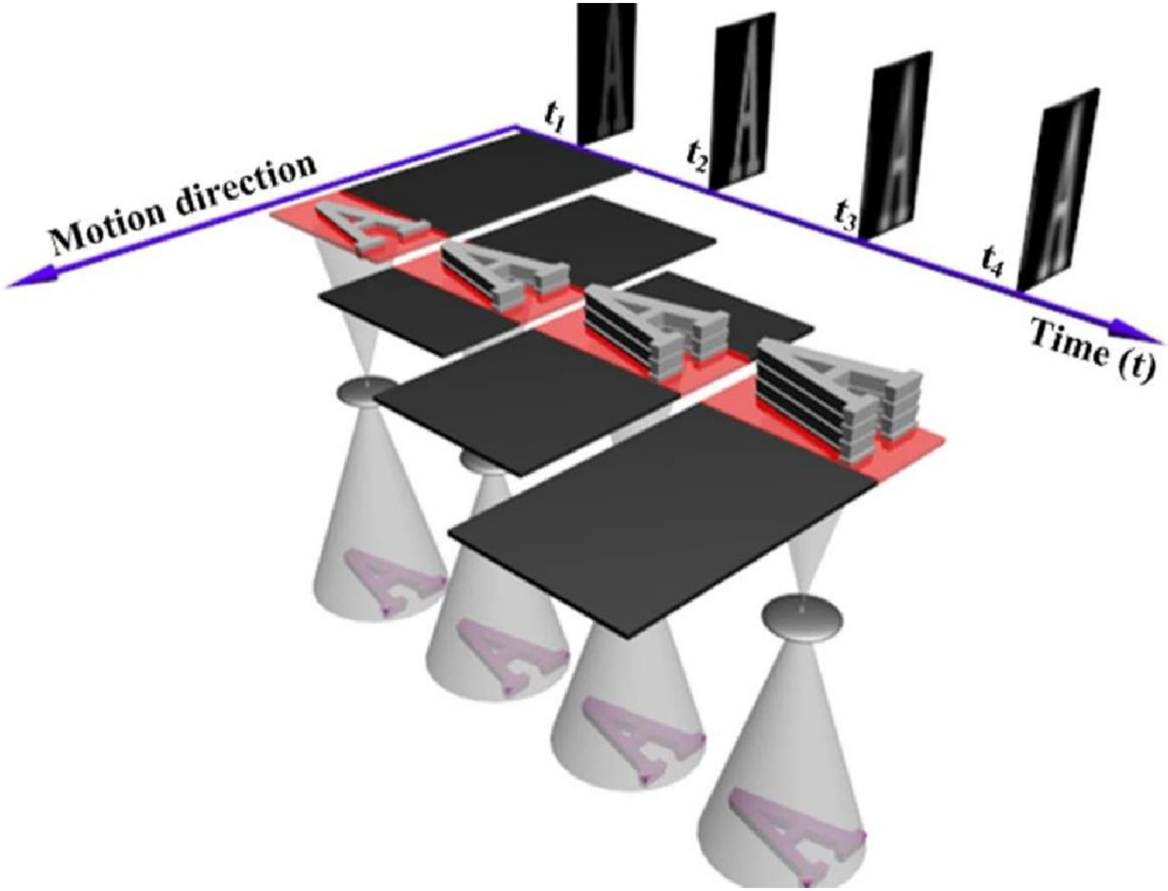
Motivation



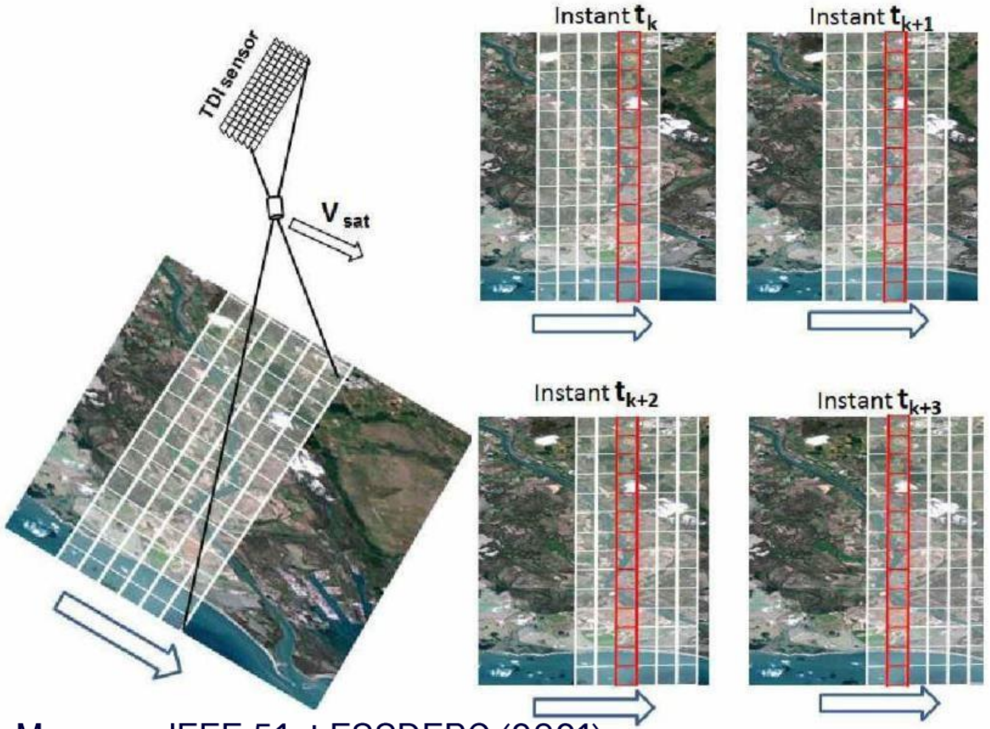
- NewSpace requires cheap components
- Earth Observation: land mapping, vegetation or oceans monitoring
- TDI matches perfectly the EO missions
- Scarce information about the radiation hardness of TDI CCD-on-CMOS

Time delay and integration image sensors



Li et al, Scientific Reports volume 9, Article number: 11319 (2019)

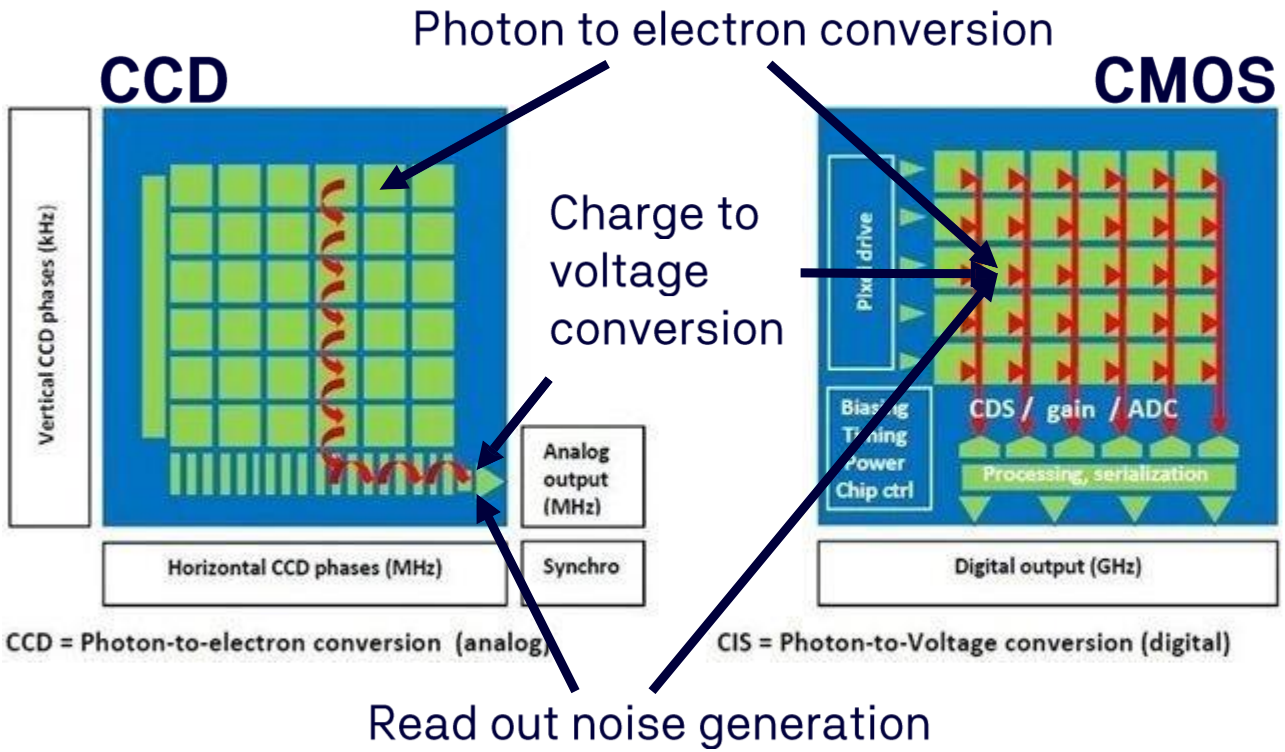
Perfect match for Earth Observation missions



Magnan, IEEE 51st ESSDERC (2021)

CCD vs CMOS

- More expensive
- Use more power
- Less digital noise
- Better in low light
- SEE tolerant



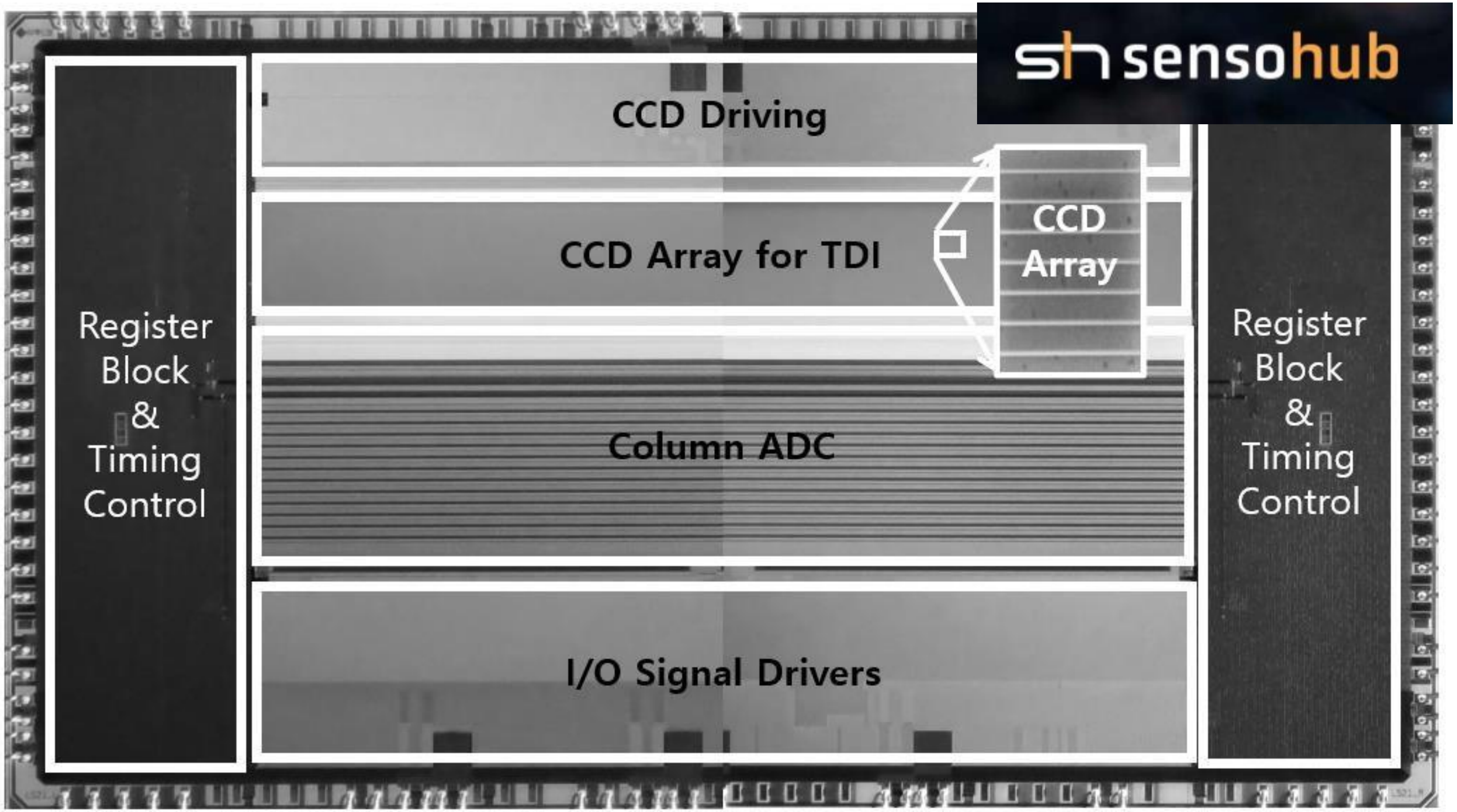
- Less expensive
- Use less power
- More digital noise
- Rolling shutter issues
- High fps rates
- TID tolerant

Adapted from Rakay et al., 25th ICCC (2024)

CCD-in-CMOS

Combines advantages of CCD and manufacturing profits of CMOS technology:

- low noise,
- high speed,
- low light imaging,
- lower power consumption.



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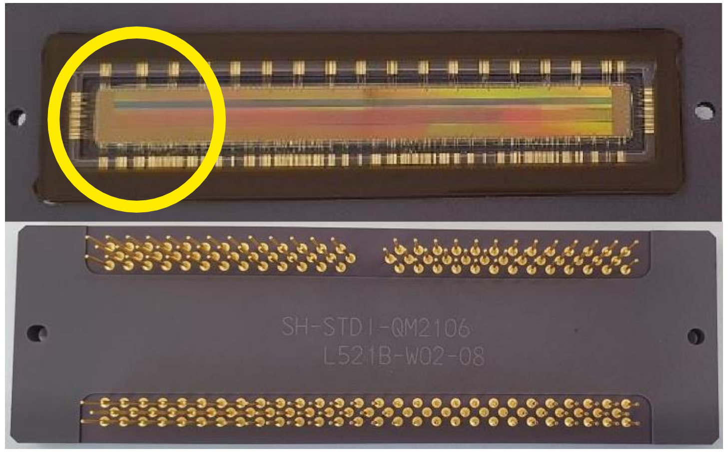
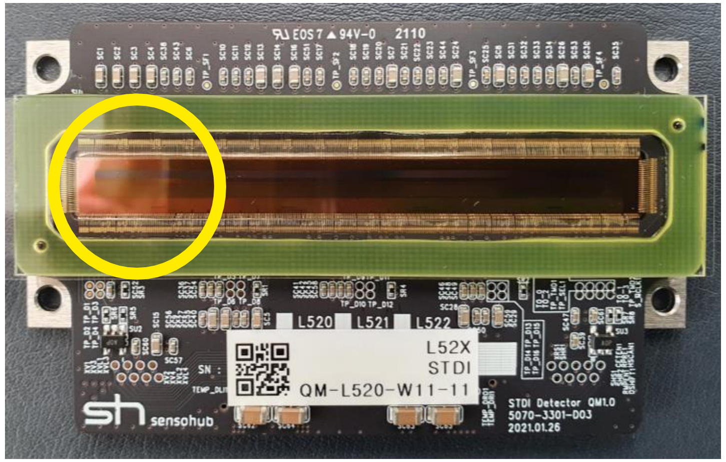
COTS Sensor SH9K7Ts from SensoHub

- CCD-in-CMOS technology
- Line rates of 30kHz and 12 bits
- 1 to 128 TDI stages selectable and 8960 pixels in a stage (67.12 mm)
- Full Well – 150 ke^-
- CTE – 99.99%
- Quantum efficiency 54% at 550 nm
- 32 x 80 Mbps LVDS readout system
- It was assembled in the camera of the small satellite STEP Cube Lab-II launched in 2022





Radiation tests

Single Event Effects

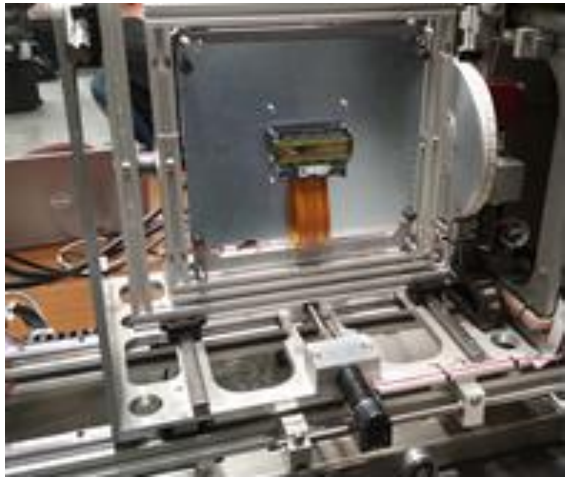
- HIF, UCL, Belgium
- LET range from 1.3 to 80 MeV·cm²/mg
- SEL, SEU, SET, SEFI
- 3 sensors, biased

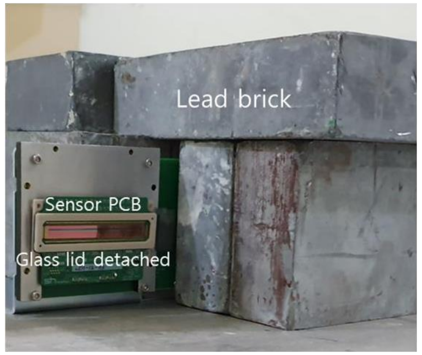
Displacement Damage

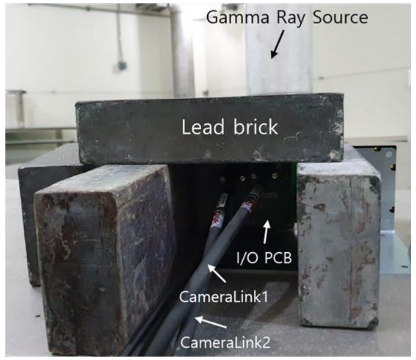
- LIF, UCL, Belgium
- Fluence $2 \cdot 10^{11}$ p/cm²
- 10 MeV – 3 sensors
- 50 MeV – 1 sensor
- All sensors biased

Total Ionizing Dose

- ARTI, KAERI, Korea
- 112 krad
- 12 sensors (5 biased and 7 non-biased)







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Single Event Effects

Single Event Latch-up (SEL)

- This event was monitored by means of the internal watchdog of the monitoring software and internal circuit on the test board.

Single Event Upset (SEU)

- Monitoring of the registers of image sensor to see if there was a bit flip.
- The patterns were compared to each other (LVDS signals) as bit error count.
- The changes/corruptions of the real images were accounted as an SEU.
- Additionally, the step changes in the currents were also accounted for this event. They occurred in a few instances and were not higher than 5% of the nominal current, coming back to pre-step values.

Single Event Functional Interrupt (SEFI)

- Any event which makes image sensor unresponsive (different from the SEL and SEU), which was mainly caused by SEU in control register. After this event, the camera was restarted.

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SEE – used heavy ions

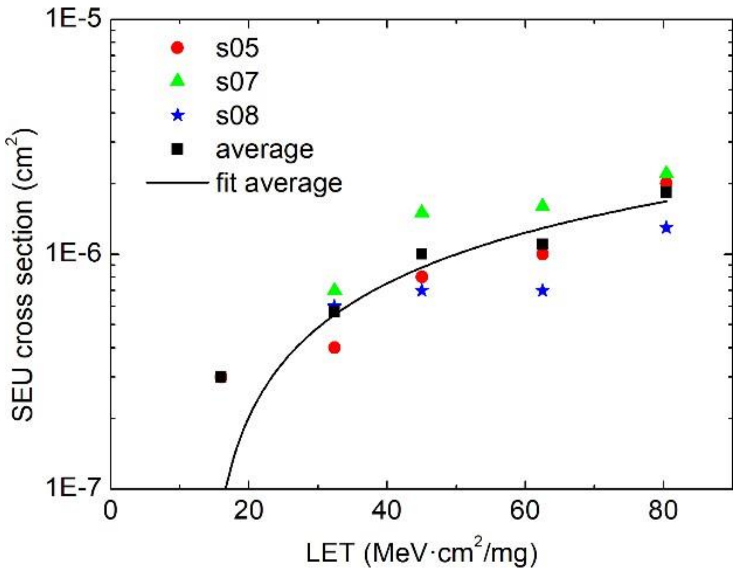
Ion	DUT Energy (MeV)	Range (µm Si)	LET (MeV·cm²/mg)	Tilt Angle (deg)	LET Final (MeV·cm²/mg)	TID (krad)
$^{13}C^{4+}$	131	269.3	1.3	0	1.3	0.21
$^{53}Cr^{16+}$	513	107.6	16	0	16.0	2.56
$^{84}Kr^{25+}$	769	94.2	32.4	0	32.4	5.18
$^{84}Kr^{25+}$	769	94.2	32.4	44	45.0	10.02
$^{124}Xe^{35+}$	995	73.1	62.5	0	62.5	10.00
$^{124}Xe^{35+}$	995	73.1	62.5	39	80.4	16.60

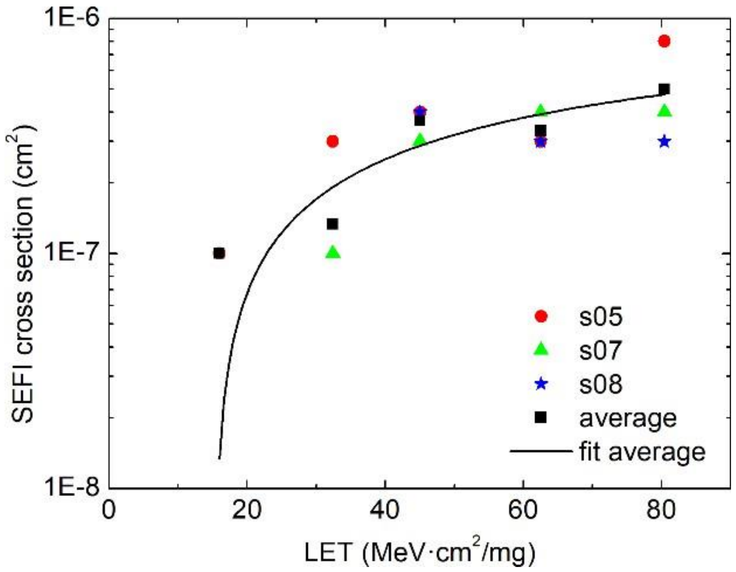
SEE – SEU and SEFI cross sections

- Cross section = number of events/fluence
- Weibull function to get fitting parameters for rates calculation

$$\sigma(x) = \sigma_0\left(1 - \exp\left[-\left(\frac{x-x_0}{W}\right)^S\right]\right)$$

- SEU cross section saturation $6.38 \cdot 10^{-6}$ cm^2
- SEFI cross section saturation is about one order of magnitude lower $8.53 \cdot 10^{-7}$ cm^2
- Sensors operated at 60°C in vacuum condition
- **No SEL observed**





SEE – SEU and SEFI rates – inputs for calculations

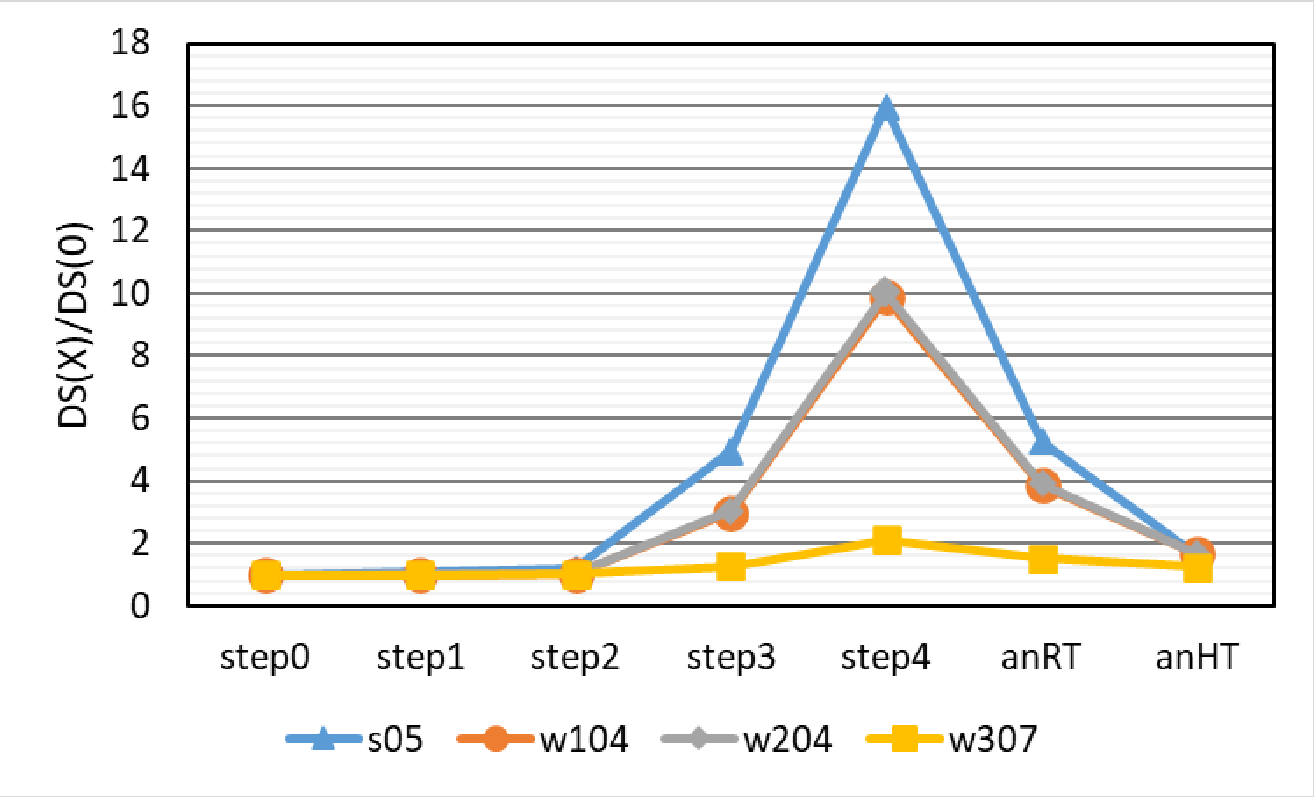
- Orbit: ISS (450 km) and STEP Cube Lab-II (700 km).
- Magnetic weather: quiet and stormy.
- Environment: solar minimum, worst week, and peak 5 minutes.
- Ions with Z number from 1 to 92.
- No shielding.
- Pixel size of 7 µm and depth of the sensitive volume of 6 µm.
- Number of bits in device: 32.
- CRÈME96 was used for SEE rates calculation.

SEE – rates calculation results

Magnetic weather	Solar Event	ISS		STEP Cube Lab-II	
		SEU	SEFI	SEU	SEFI
		(errors/device/day)			
Quiet	Solar minimum	1.80E-07	5.40E-08	6.34E-06	2.17E-06
	Worst week	2.11E-01	7.56E-02	5.90E+00	2.11E+00
	Peak 5 min	5.23E+00	1.89E+00	1.42E+02	5.18E+01
Stormy	Solar minimum	2.29E-06	7.81E-07	8.47E-06	2.91E-06
	Worst week	2.04E+00	7.29E-01	7.19E+00	2.57E+00
	Peak 5 min	4.92E+01	1.79E+01	1.73E+02	6.28E+01

Displacement damage

- No SEL observed
- 10 MeV (equivalent TID 111 krad):
  - Sample w104, w204
  - Sample s05 after SEE (+45 krad)
- 50 MeV (equivalent TID 32 krad):
  - Sample w307
- Strong increase of dark current
- Recovery after the annealing processes (240 h @ room temperature and 85 h @ 100°C)

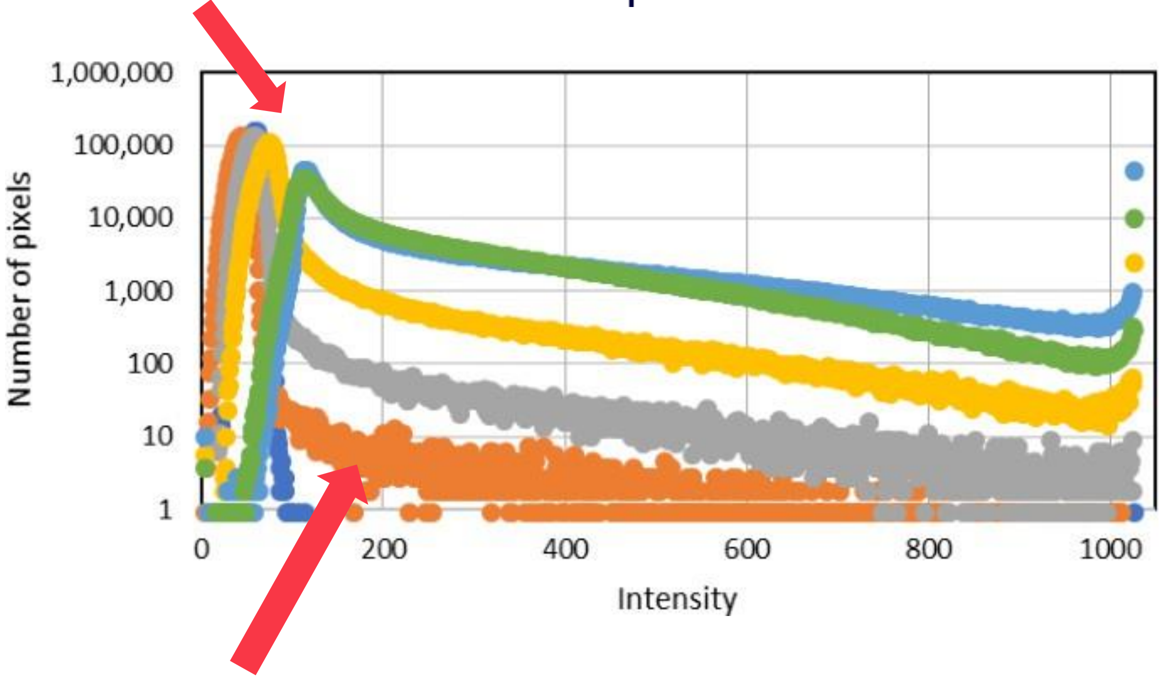


step0 – initial;
step1 – $1{\cdot}10^{9}$ p/cm^2;
step2 – $1{\cdot}10^{10}$ p/ cm^2;
step3 – $1{\cdot}10^{11}$ p/cm^2;
step4 – $2{\cdot}10^{11}$ p/ cm^2;
anRT – annealing at room temperature;
anHT – annealing at 85°C

DD histograms

Standard behavior

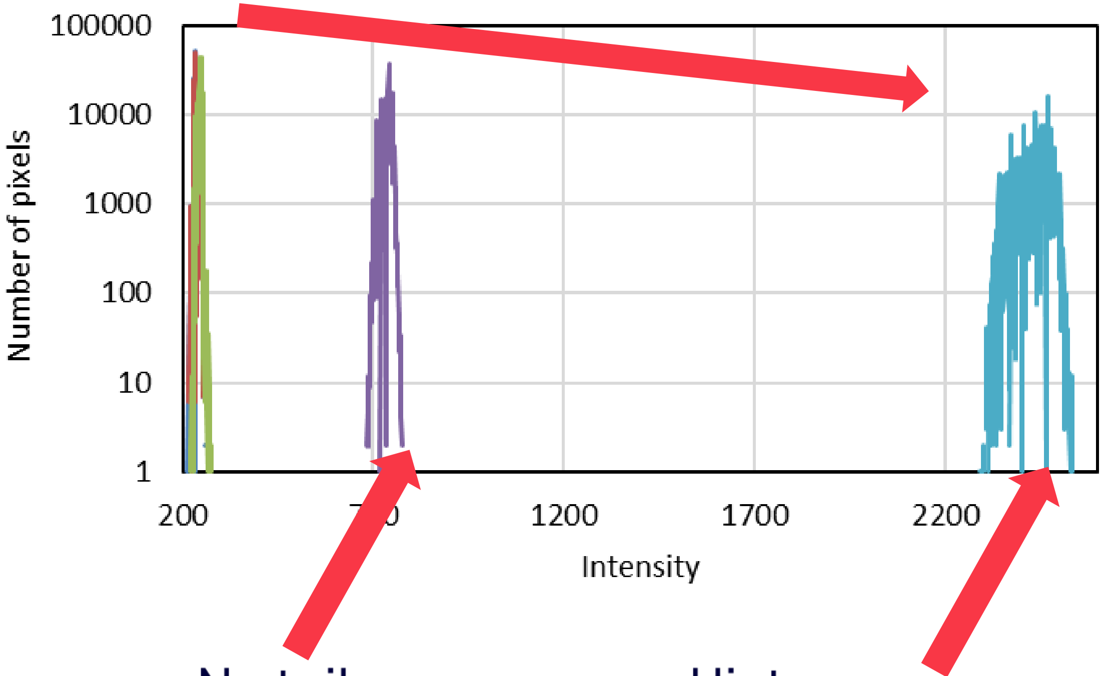
TID shift of maximum peak



DD induced tail

These devices

Strong shift of maximum peak

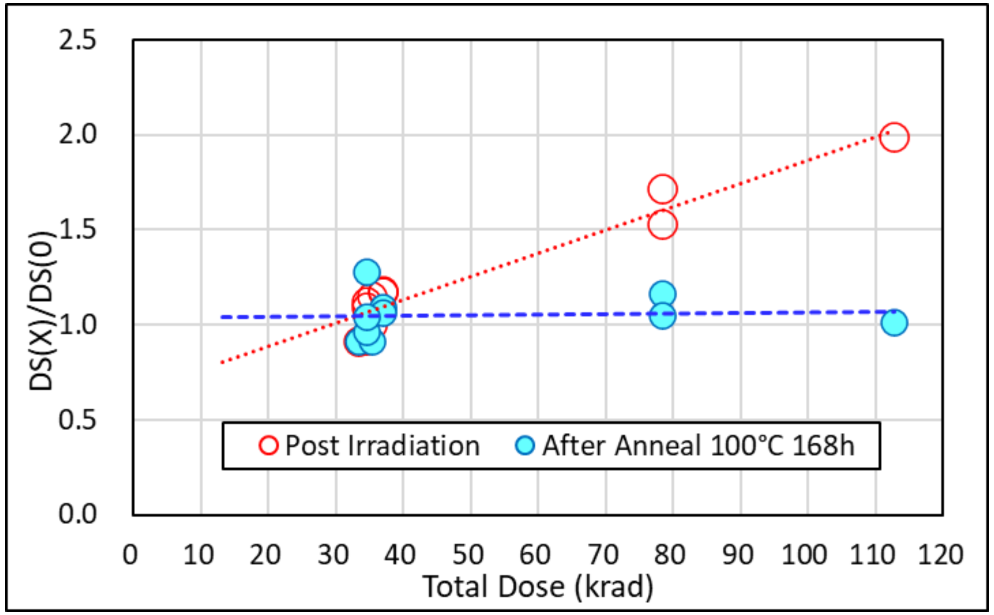


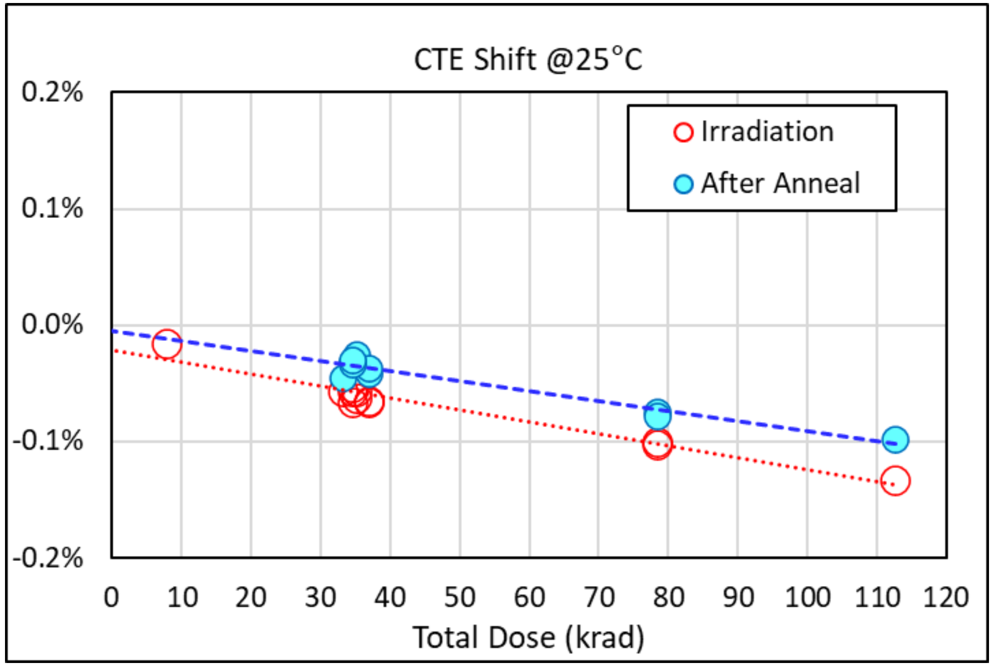
No tail

Histogram broadening

Total ionizing dose

- Total dose up to 112 krad
- 5 samples biased
- 7 samples unbiased
- Two times increase of dark current
- CTE decreased about 0.13%
- Recovery after the annealing for 168 h at 100°C





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Summary and conclusions

- TDI CCD-in-CMOS image sensors were tested for resilience to space radiation (SEE, DD, TID).
- No Single Event Latch-up (SEL) was observed up to a LET of 80 $MeV \cdot cm^2/mg$, even at elevated temperatures.
- Sensors withstood heavy ion fluxes up to 10,000 $ions/(s \cdot cm^2)$
- The SEU and SEFI rates were calculated for ISS and STEP Cube Lab-II orbits.
- Displacement damage testing showed dark signal changes with proton energy, but significant recovery occurred after annealing. Unusual histograms.
- TID tests revealed the crucial parameters degradation with radiation exposure, but dark current nearly fully recovered after annealing.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT; grant number: NRF-2018M1A3B3065997).

Thank you very much!