CNES/ESA Radiation Effects Final Presentation Days 2015

Radiation Effects on Digital CMOS Image Sensors using Microlenses and Color Filters

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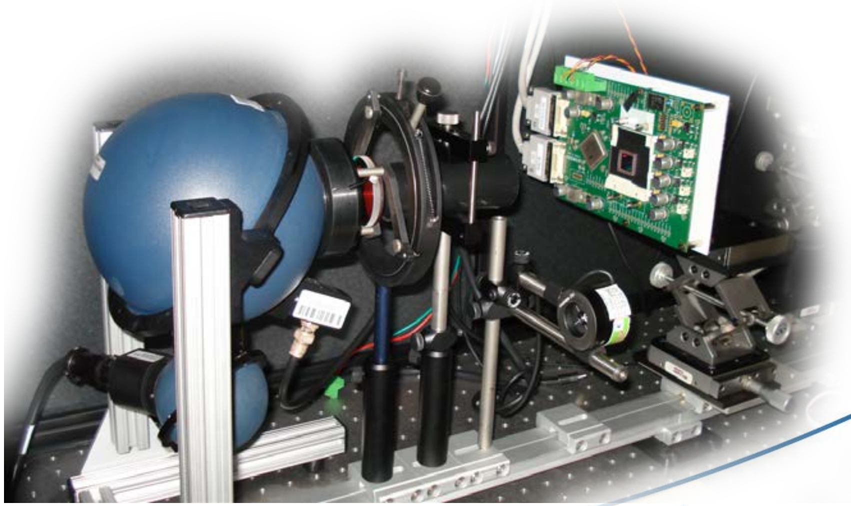
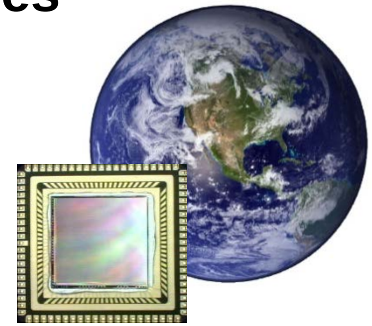
OUTLINE

- **CONTEXT OF THE STUDY**
- **CMOS IMAGER ARCHITECTURES**
- **PROTON-INDUCED PERMANENT EFFECTS**
- **HEAVY ION-INDUCED SINGLE EVENT EFFECTS**
- **CONCLUSIONS**

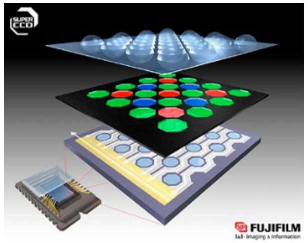


CONTEXT OF THE STUDY

- **CMOS Image sensors reach very good performances**
  - **Deep submicron technology**
  - **Process dedicated to imaging (→ pinned photodiode)**



- **CIS integrate CMOS electronic functions**
  - **Specific architectures, ADC, Registers, state machine**
- **Microlenses and color filters are widely used in commercial CMOS image sensors**
  - **Microlenses maintain the pixel quantum efficiency to counterbalance shrinking motivations**
  - **Color filters give direct access to colored images**

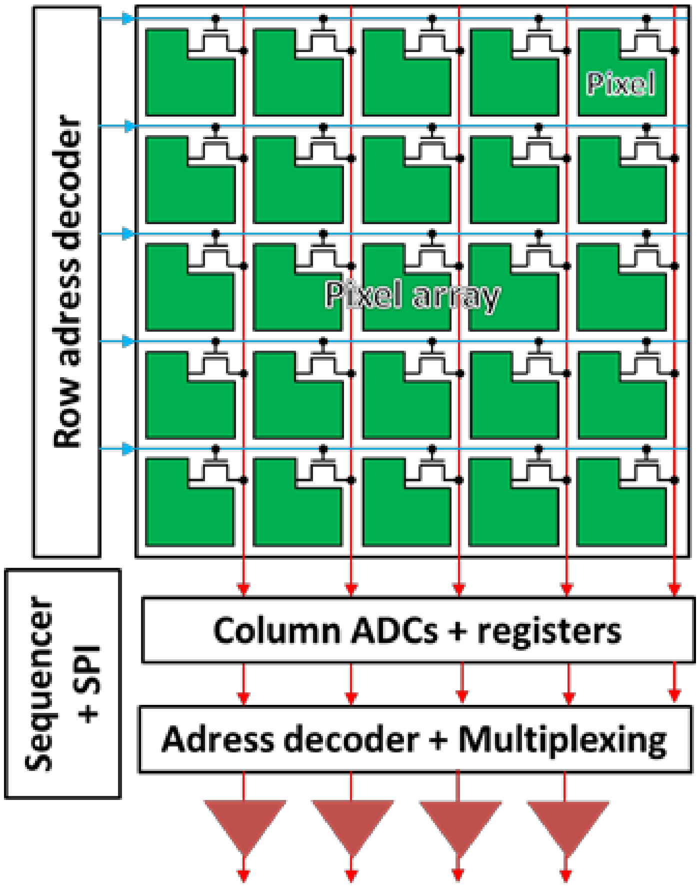


- **CIS are sensitive to space radiation environment**
  - **Few dedicated study concern Single event effects**
  - **No dedicated study focused on microlenses and color filters against space radiation**

DEVICE CHARACTERISTICS

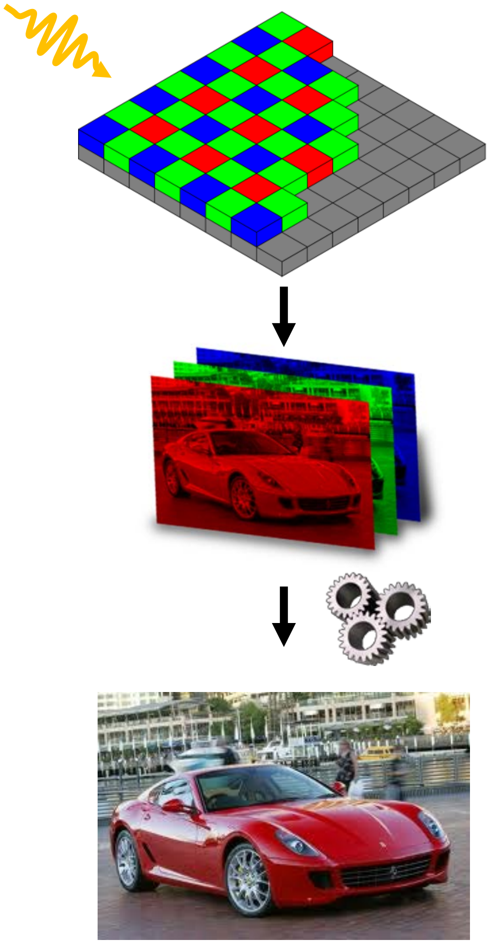
- **Device architecture**

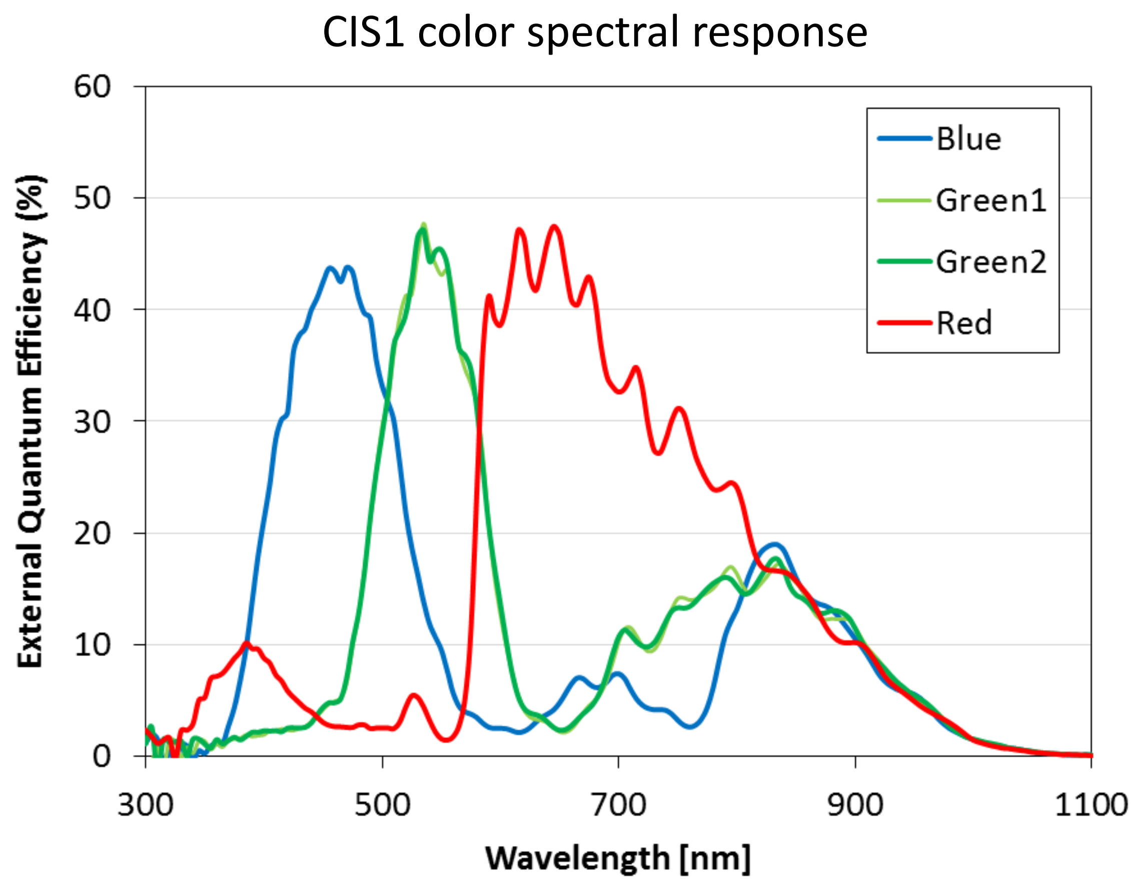
Imagers	CIS1	CIS2
Technology node	**180 nm**	**90 nm**
Pixel Pitch (µm)	5.5	1.4
Photodiode	**PPD**	**PPD**
Pixel isolation	STI	DTI
Epitaxial thickness (µm)	5 & 12	< 4
Array	2048 × 2048	2592 × 1944
Others	**µlenses, color filters**	**µlenses**
Irradiation	50 and 150 MeV Proton / Heavy ion	60 MeV Proton / γ-rays / Heavy ion



DEVICE CHARACTERISTICS

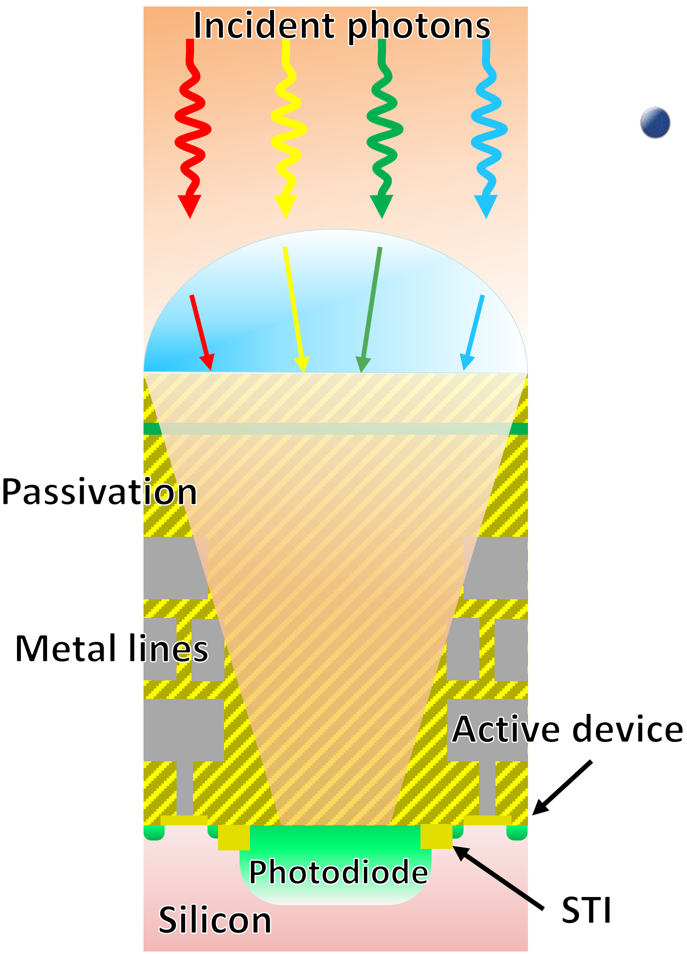
- **Color filter advantages**
  - **Selectable wavelength to build color image**

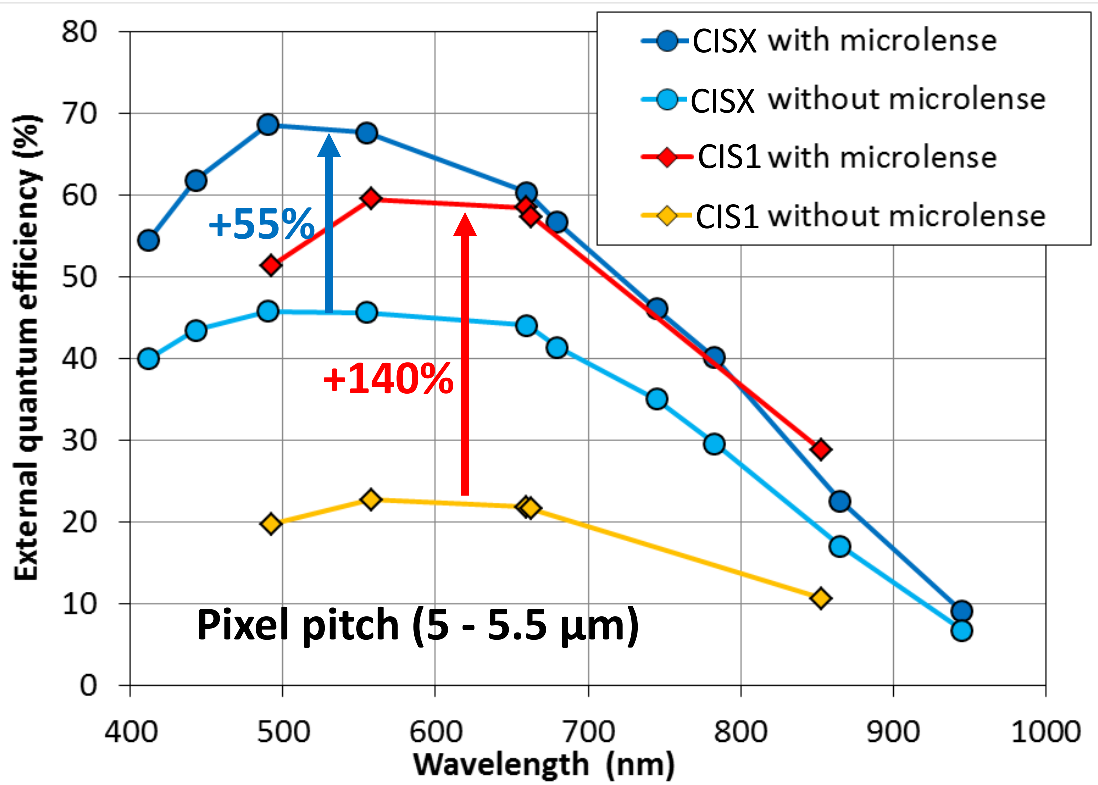




DEVICE CHARACTERISTICS

- **Microlense advantages**
  - **Focus the incident light to the photosensitive volume**
  - **Improve the External Quantum Efficiency (EQE)**





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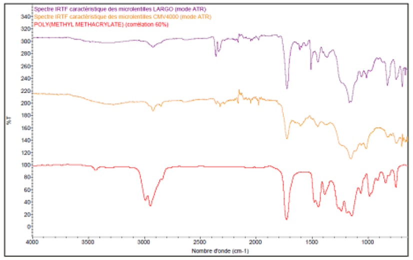
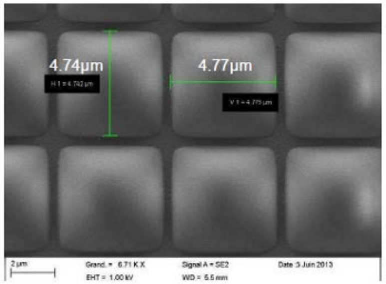
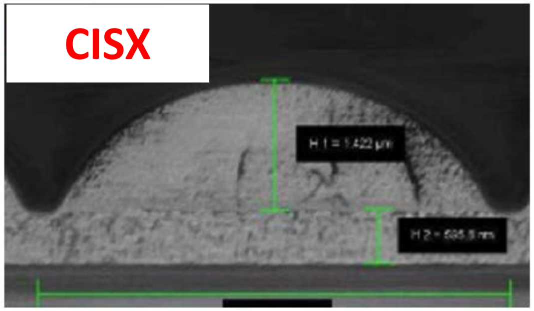
ENVIRONMENTAL TESTS

- **Physical analysis**
  - **Polymethylmethacrylate (PMMA)**

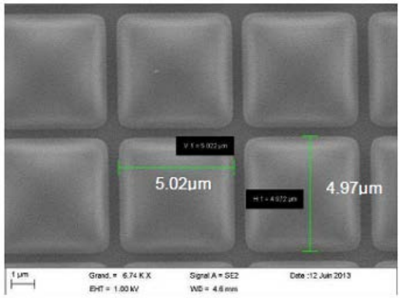


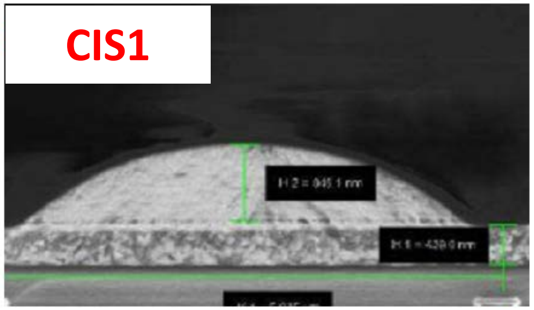
  - **Microlense CISX**
    - **Multilayer polymer: layer 595 nm**
    - **Surface 4.7 x 4.7 µm**
    - **Thickness 1,42 µm**





  - **Microlense CIS1**
    - **Single Layer polymer: 440 nm**
    - **Surface 5 x 5 µm**
    - **Thickness 0.845 µm**

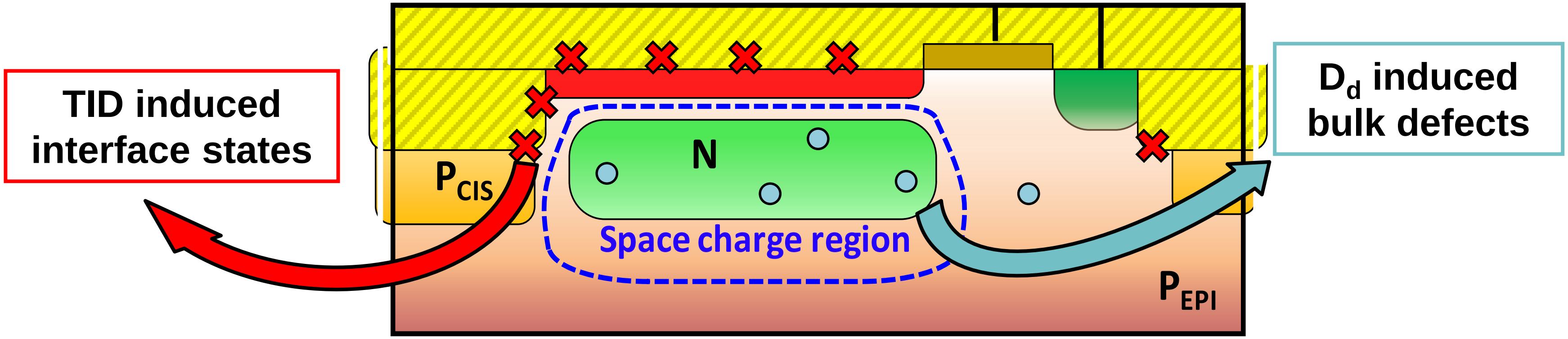




  - **Solvents: 10 minutes immerse in acetone and 10 minutes in ethanol**
    - **No physical evolution, no delamination was observed**

RADIATION-INDUCED DOSE EFFECTS

- **Radiation induced TID and DDD in CIS leading to dark current increase**
  - **TID induces trapped charges and interface states**
    - **TID effects are reduced using PPD → SCR is recessed from oxide**
  - **DDD induces bulk defects in silicon**
    - **Main issue in CIS using PPD → Hot pixels**

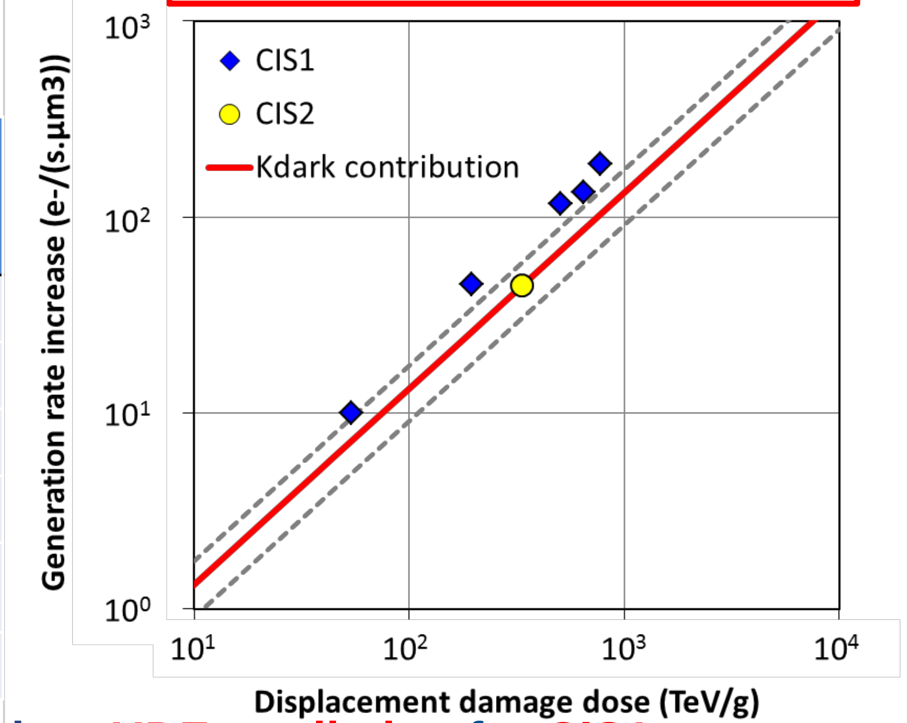


PROTON-INDUCED DOSE EFFECTS

- **Proportionality with DDD**
  - **Comparison with UDF (Srour 2000)**

$$\Delta I_{dark} = K_{dark} \cdot V_{dep} \cdot D_d$$

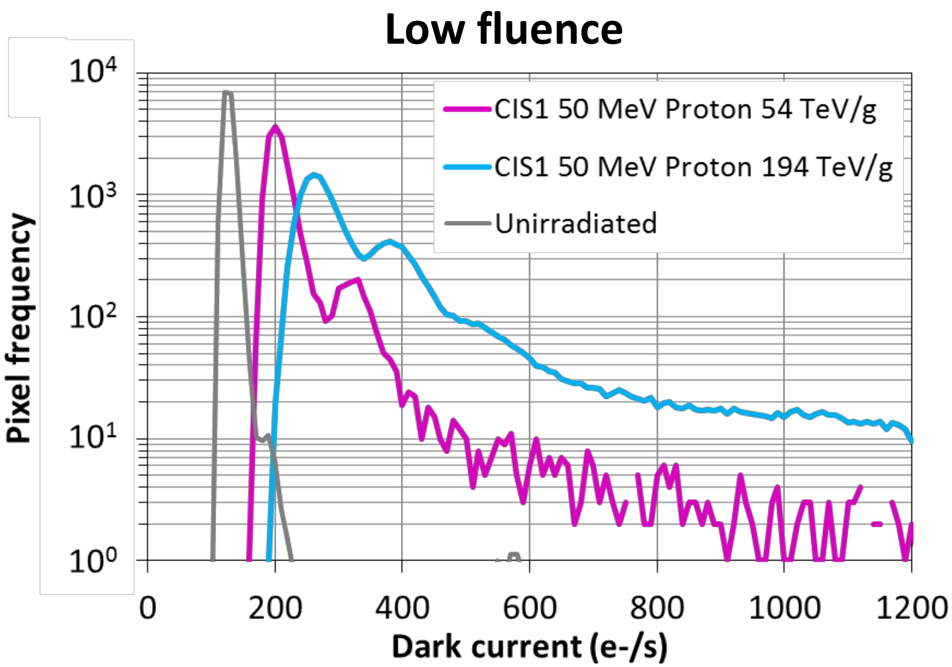
Irradiation type	Imagers	Fluence (cm^{-2}) / Dose rate	DDD (TeV/g)	TID (krad (SiO_2))
50 MeV proton	CIS1	1.4×10^{10}	54	2
50 MeV proton	CIS1	5×10^{10}	194	8
50 MeV proton	CIS1	1.3×10^{11}	504	20.5
50 MeV proton	CIS1	2×10^{11}	776	31.5
150 MeV proton	CIS1	3×10^{11}	645	21
60 MeV proton	CIS2	1×10^{11}	335	13.8

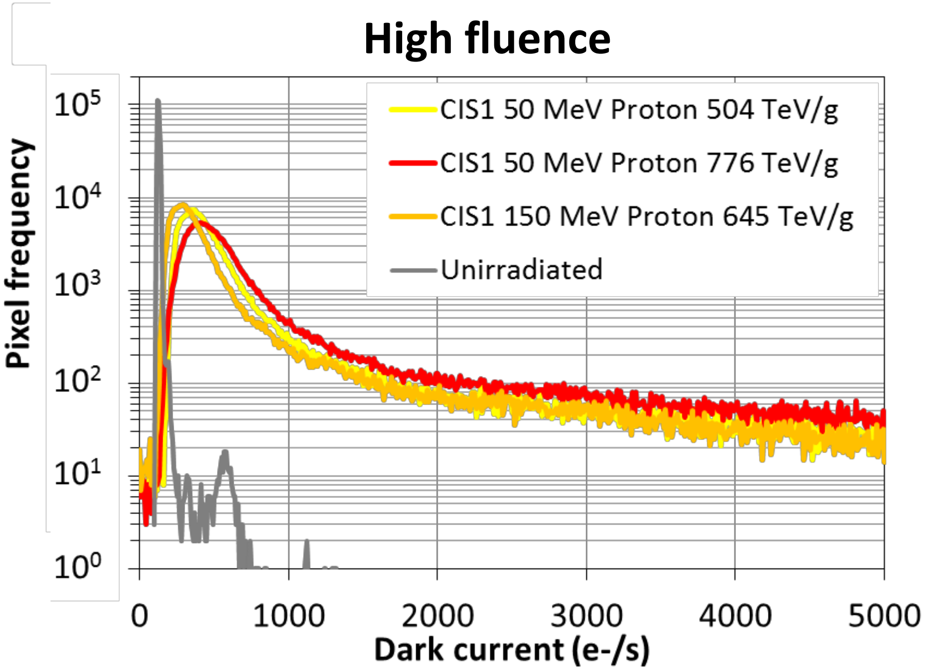


- **Mean dark current increase is higher than UDF prediction for CIS1**
  - **Proton-induced dark current is mainly attributed to DDD**
  - **TID effects are not negligible**
  - **Mean dark current increase is consistent with UDF predictions for CIS2**

PROTON-INDUCED DOSE EFFECTS

- **CIS1 dark current histograms after proton irradiation**
  - **TID shifts the entire pixel distribution**
  - **DDD induces hot pixel tail**





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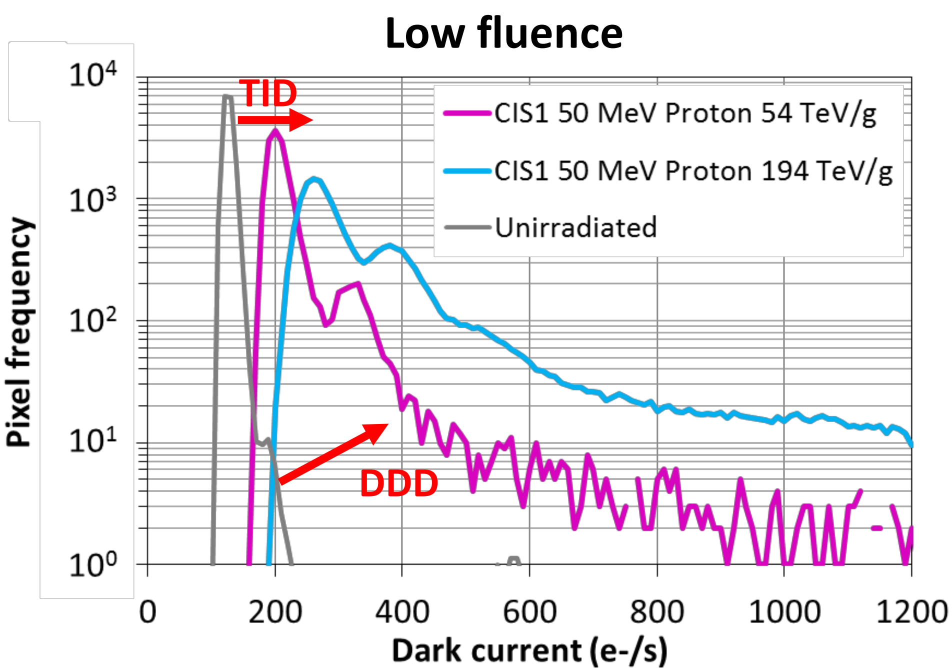
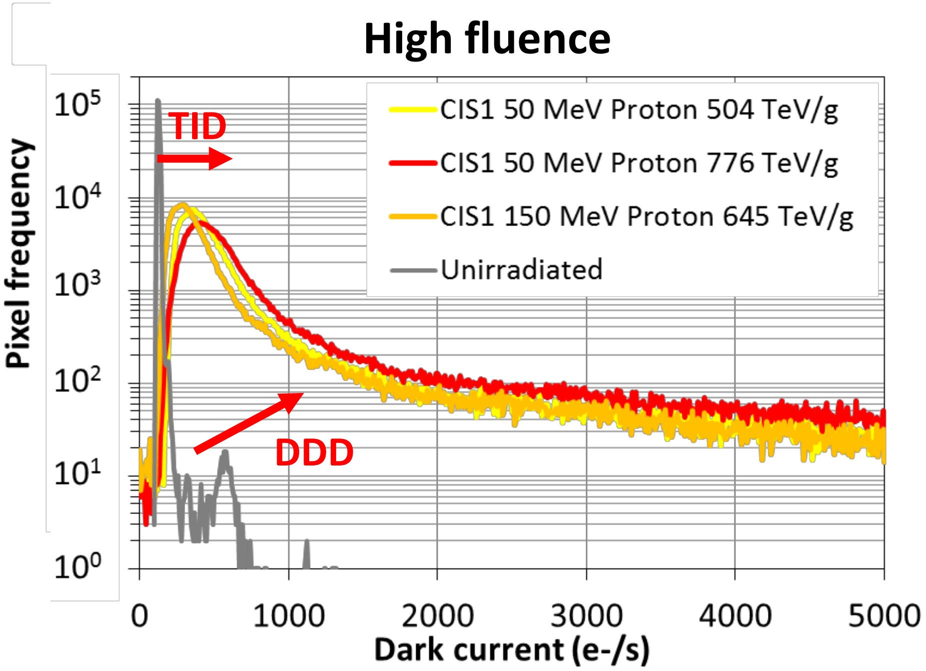
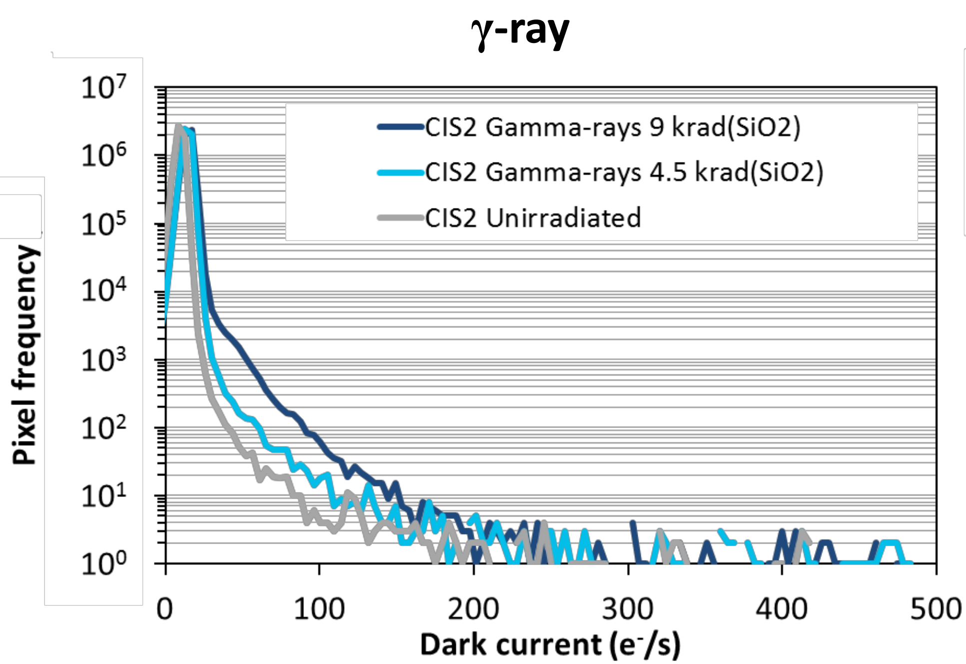


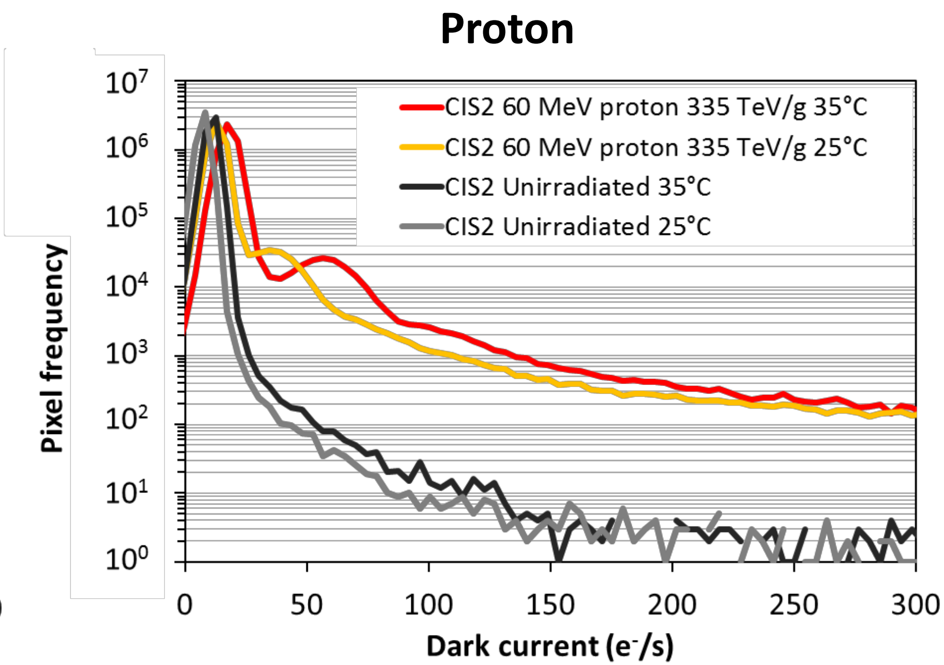


- **The degradation is mainly attributed to DDD**
- **TID-induced dark current is not negligible**

γ-RAY vs PROTON-INDUCED DOSE EFFECTS

- **CIS2 dark current histograms after γ-ray and proton irradiation**

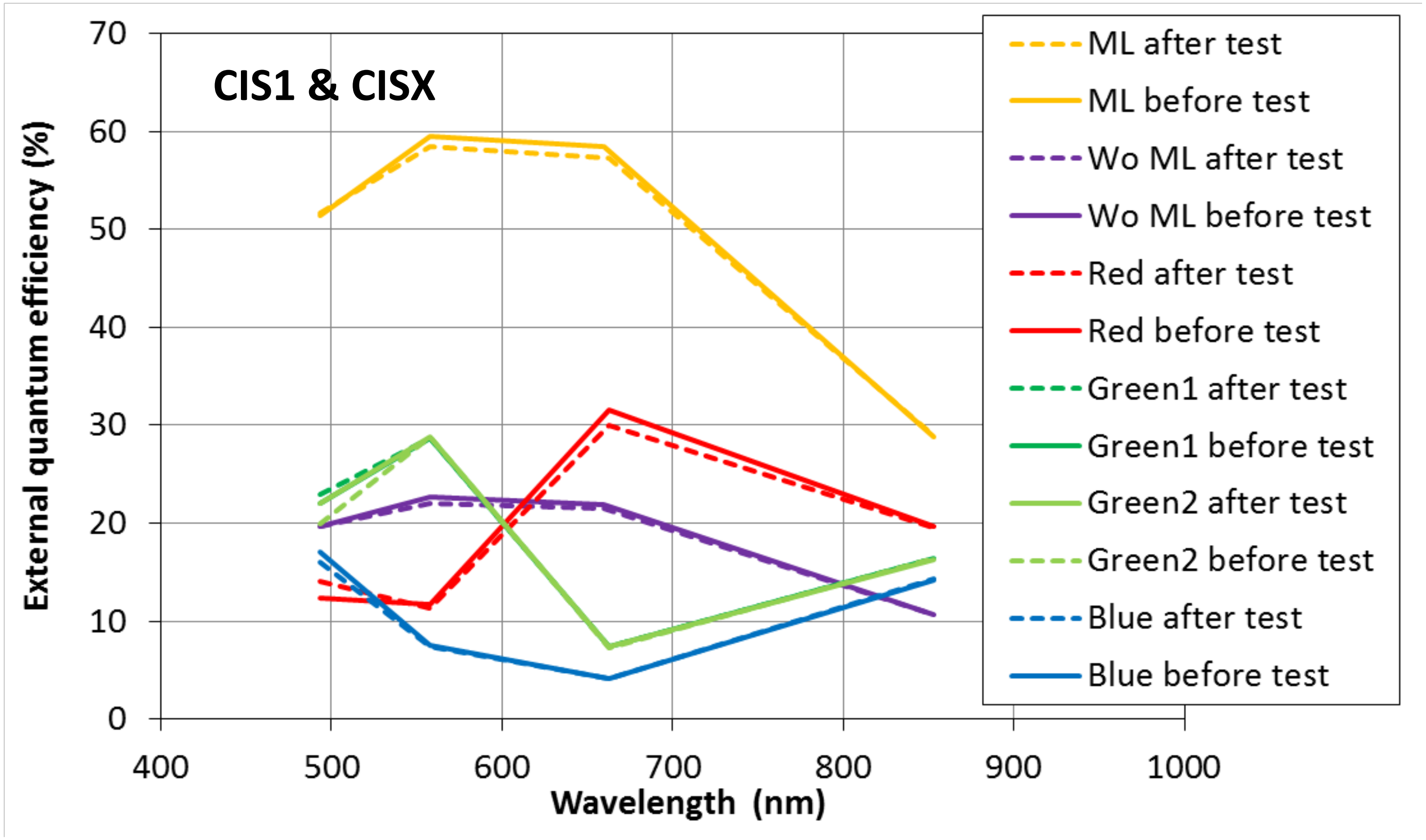




- **TID-induced dark current is negligeable in CIS2**
- **DDD-induced dark current is the main degradation mechanism**
  - **DCS peaks are observed and vary with temperature**

PROTON-INDUCED PERMANENT EFFECTS

- **Proton**
  - **50 MeV and 8.10^{11} cm^{-2} → TID 56 krad and DDD 3100 TeV/g**



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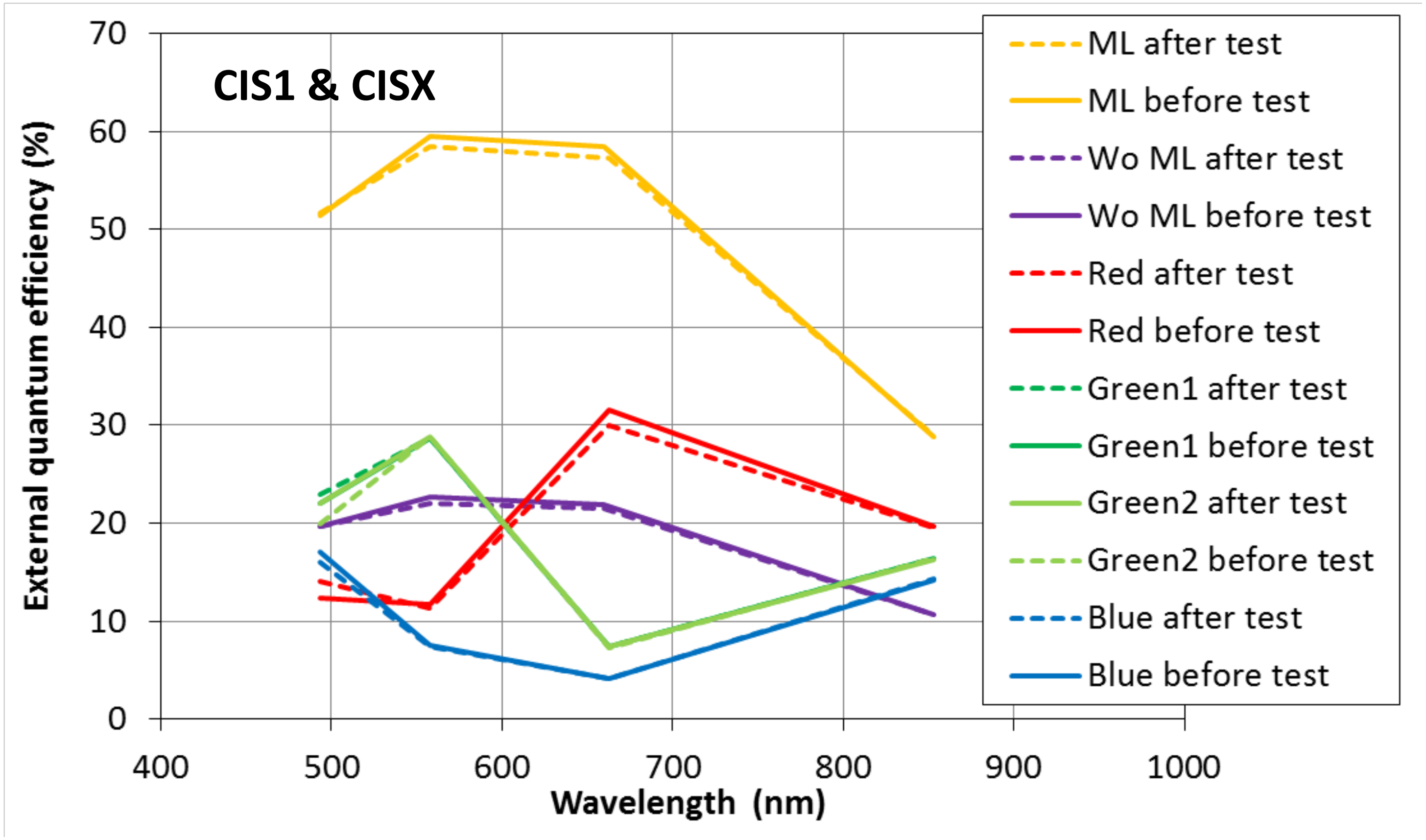


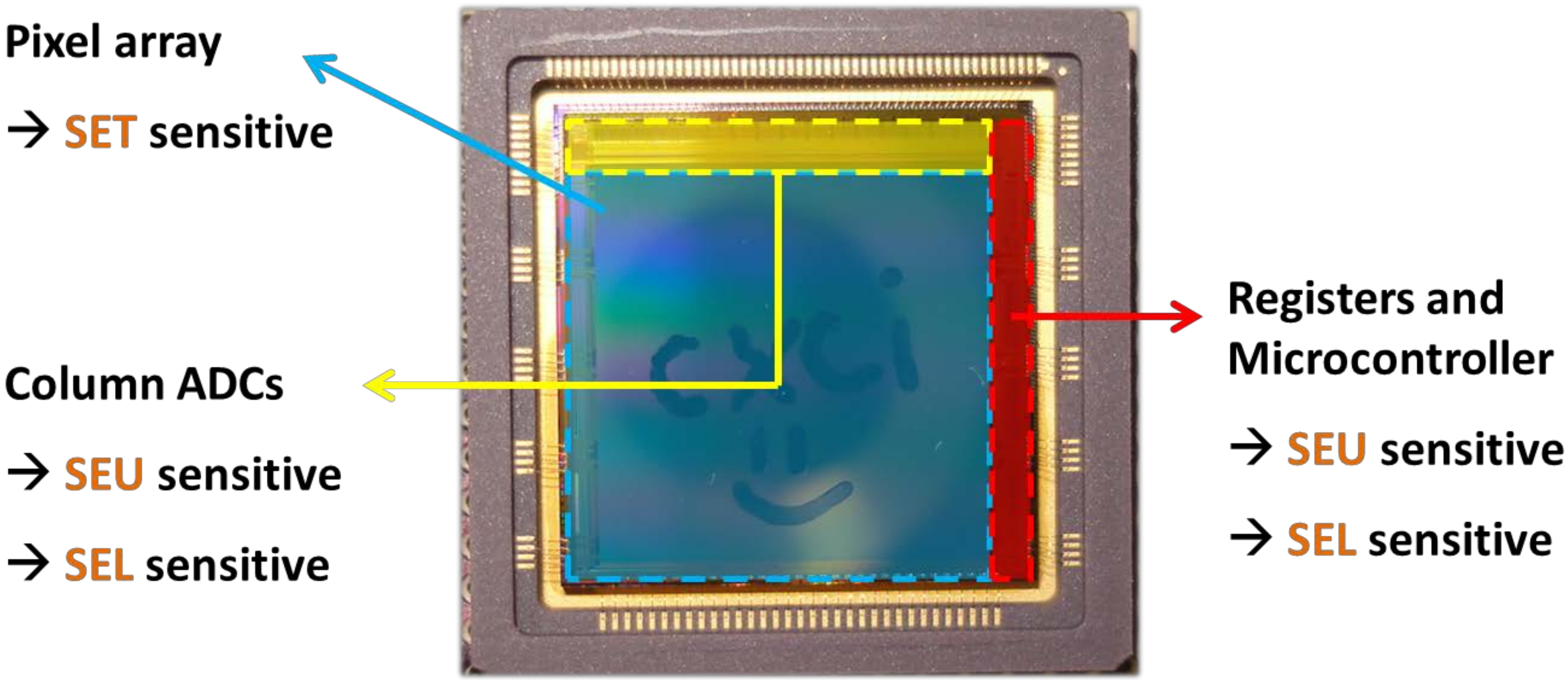
EQE variation < 5%

No parameter impacted on CIS1 and CISX

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **If you want to benefit from CMOS digital electronics**

→ You will have to deal with single event effects



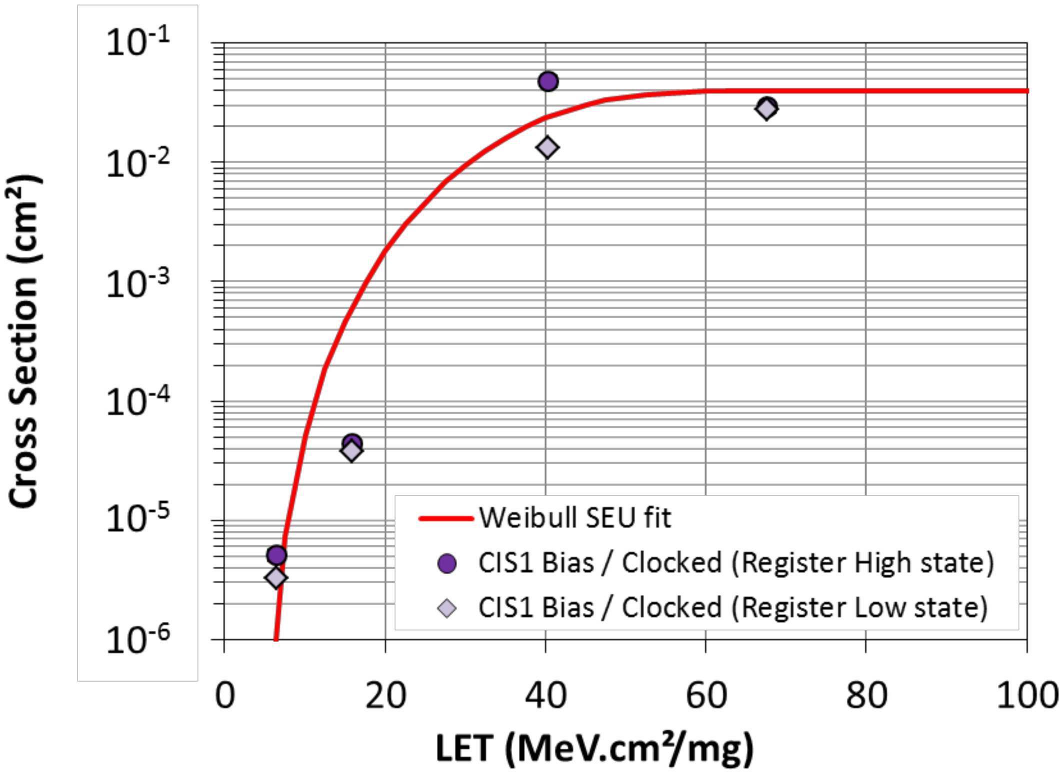
HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **The two cocktails of Université Catholique de Louvain were used to study SEE in CIS1**

Ions	Energie (MeV)	Max Flux ($p.cm^{-2}.s^{-1}$)	LET ($MeV.mg^{-1}.cm^{-2}$)	Range (µm Si)
UCL HIGH LET COCKTAIL (M/Q = 5)				
$^{124}Xe^{25+}$	420	$1,5.10^4$	67,7	37
$^{84}Kr^{17+}$	305	$1,5.10^4$	40,4	39
$^{40}Ar^{8+}$	151	$1,5.10^4$	15,9	40
$^{20}Ne^{4+}$	78	$1,5.10^4$	6,4	45
$^{15}N^{3+}$	60	$1,5.10^4$	3,3	59
UCL HIGH RANGE COCKTAIL (M/Q = 3.3)				
$^{83}Kr^{25+}$	756	$1,5.10^4$	32,6	92
$^{58}Ni^{18+}$	567	$1,5.10^4$	20,4	100
$^{40}Ar^{12+}$	372	$1,5.10^4$	10,2	117
$^{22}Ne^{7+}$	235	$1,5.10^4$	3	216
$^{13}C^{4+}$	131	$1,5.10^4$	1,1	292

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- Single Event Upsets



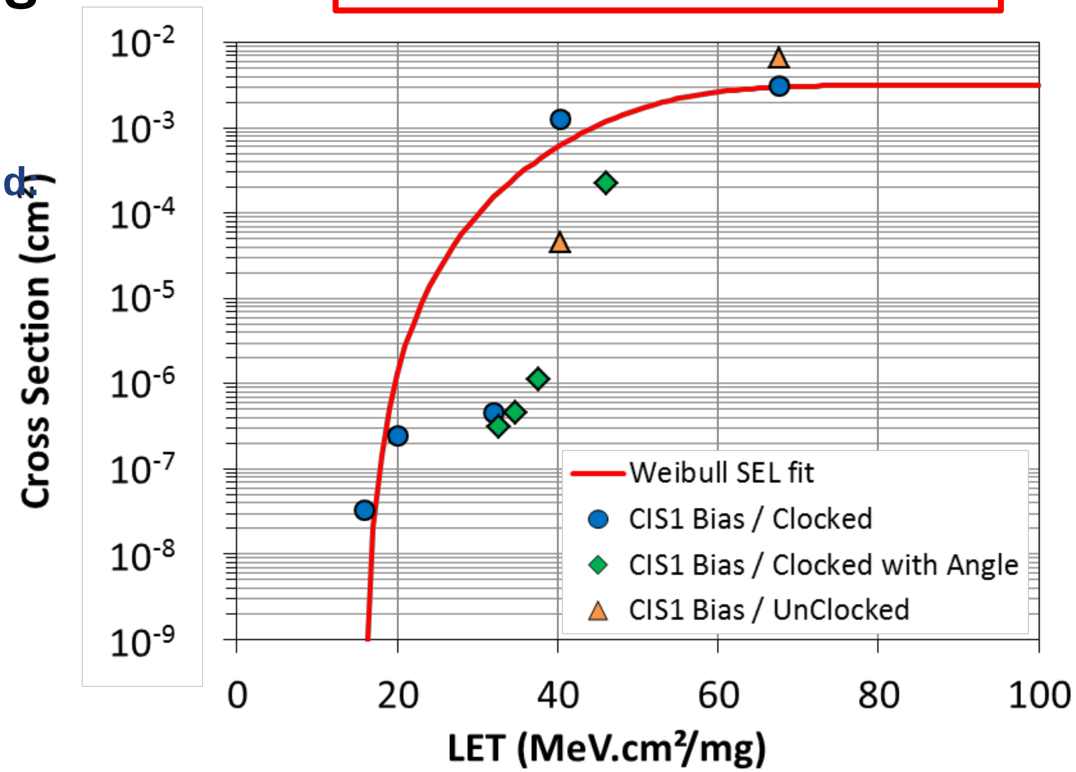
- Dedicated software has been developped
  - Write high or low state in the register
  - Read the state every 200 ms
  - Count the number of changes and re-write the initial value
- More than 30 were found
  - High and low state

- SEU cross section is not related to the register state (high or low states)

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **Single Event Latchups**
- **Controlled power supply**
  - **Fixed current detection threshold: 1.5 SV**
  - **Fixed current limit: 2 SV**
  - **Supply maintaining time : 1ms**
- **Test conditions**
  - **Biased with and without running mode (clocked)**
  - **Ion beam with tilted angle**

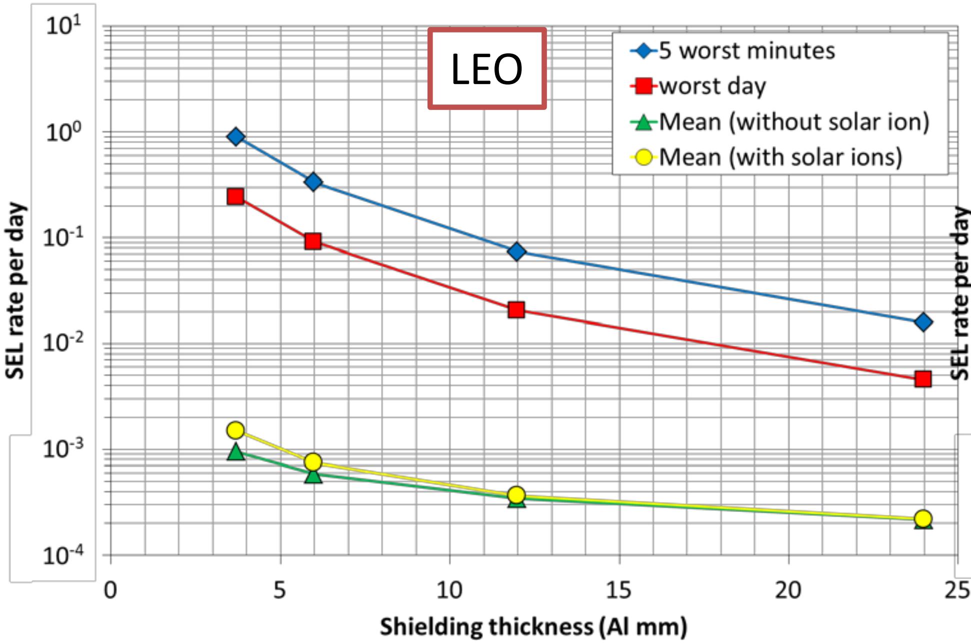
No Latchup detected on CIS2

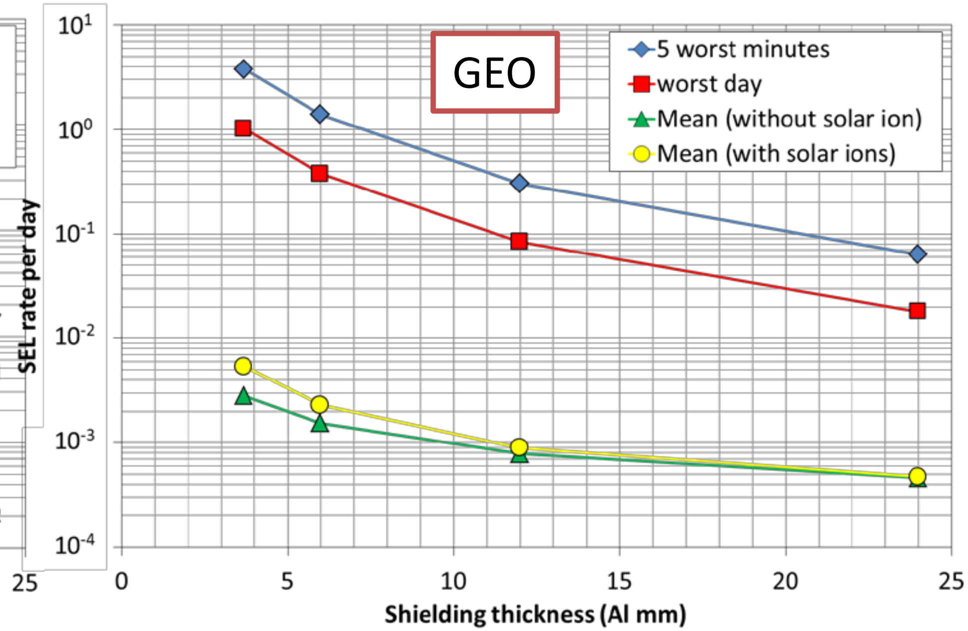


- **LET threshold around 17 MeV.cm²/mg and is slightly above the maximum LET protons can produce in silicon**
- **Tilted angle provide under estimated results for this device**

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **SEL results were computed with OMERE for Low and Geostationary Earth Orbits**





- **SEL occurrences are signifiant and an anti-latchup system is mandatory for such space missions**

CONCLUSION

- **Digital CMOS image sensors using different technologies were evaluated against radiations**
  - **Two CIS foundries using 180nm technology node**
  - **One CIS foundry using 90nm technology node**

- **Evaluation of CMOS microlenses and color filters against space radiation**
  - **Environmental tests were also done with good results (physical analysis, vacuum, humidity, UV irradiation…)**

- **Dose effects induced dark current increase mainly attributed to displacement damage**

- **Single event effects were studied**
  - **SEU are not related to high or low states**
  - **Latchups are found to be significant in CIS1 devices**

Thank you for your attention