CXCI

ESA-CNES Final Presentation Days 2013

Space Radiation-Induced Permanent and Single Event Effects in 4Mpixel Global Pipelined Shutter CMOS Image Sensors

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OUTLINE

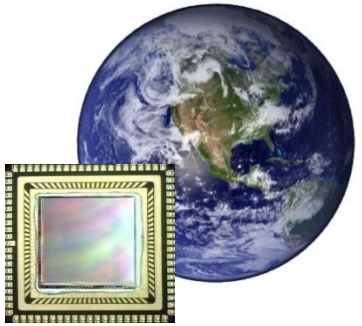
- CONTEXT OF THE STUDY
- CMOS IMAGER ARCHITECTURE
- PROTON-INDUCED PERMANENT EFFECTS
- HEAVY ION-INDUCED SINGLE EVENT EFFECTS
- CMOS IMAGER BEHAVIOR IN LOW EARTH ORBITS
- CONCLUSIONS AND FUTURE WORKS

CONTEXT OF THE STUDY

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

- **CIS integrates CMOS electronic functions**
  - Specific architectures, ADC, Register, state machine

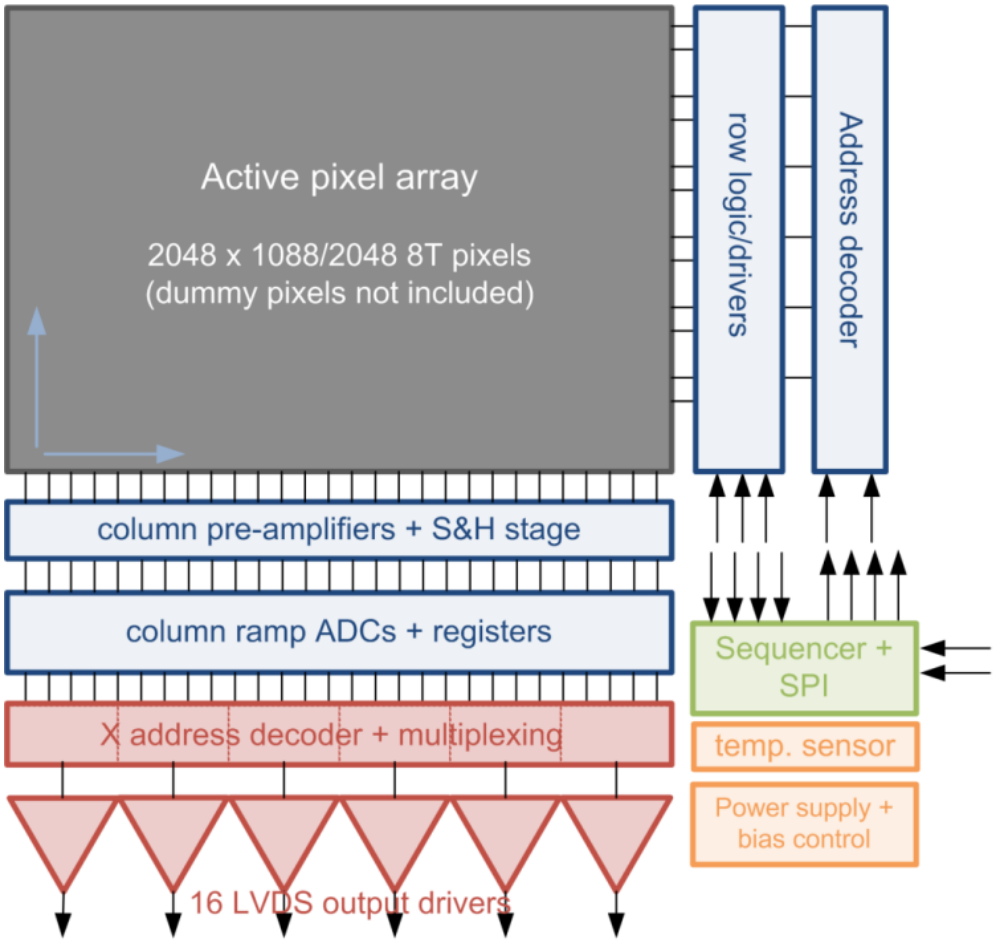
- **CIS could be used for scientific applications**
  - Space missions, nuclear physic,…
  - Need low and stable noise



- **CIS are sensitive to space radiation environment**
  - Permanent effects due to TID and D_d are on going work since the last decade
  - No dedicated study concerns Single event effects

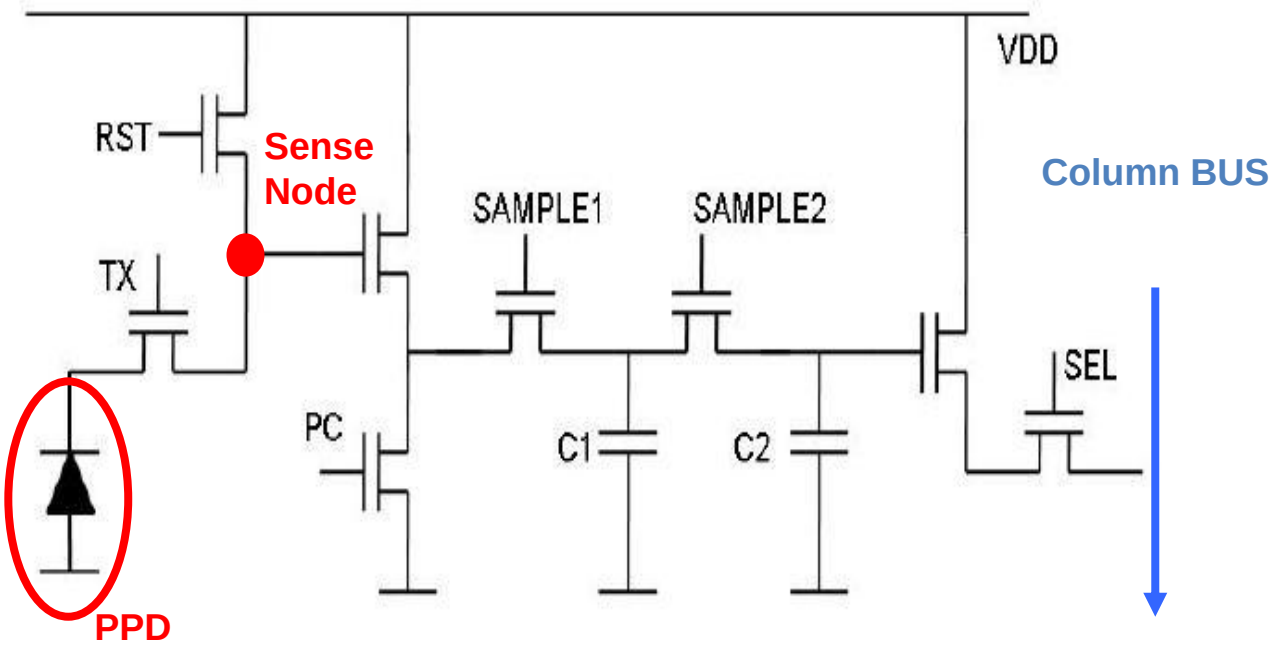
DEVICE ARCHITECTURE

- **Global architecture**
  - 2048 x 2048 pixels (5.5µm pitch)
  - Snapshot running mode → Same integration time for all pixels
  - 180 frames/sec
  - Global pipeline ADC are integrated (10 bit or 12 bit)
  - Registers, State machine and Microcontroller are integrated



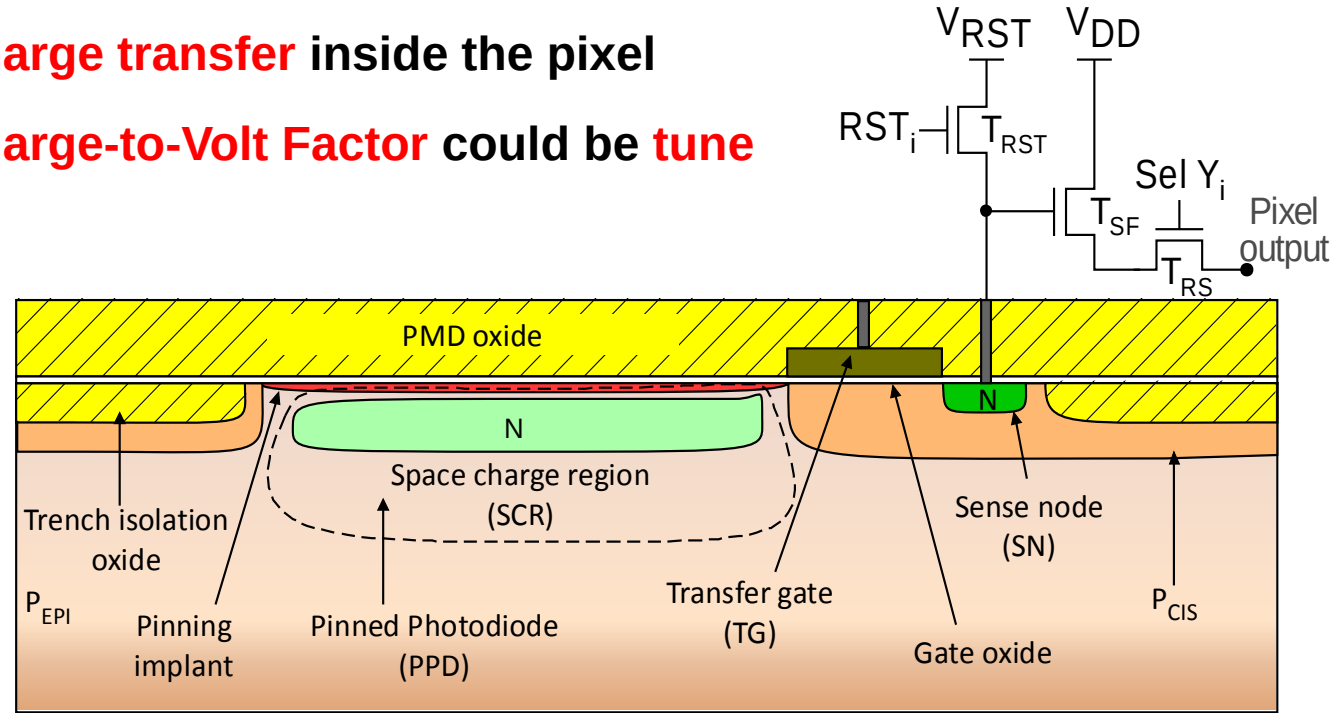
DEVICE ARCHITECTURE

- **Pixel architecture**
  - **8T pixel with in-pixel correlated double sampling**
    - **Reset noise is removed**
    - **Full well capacity and Fill Factor are reduced**



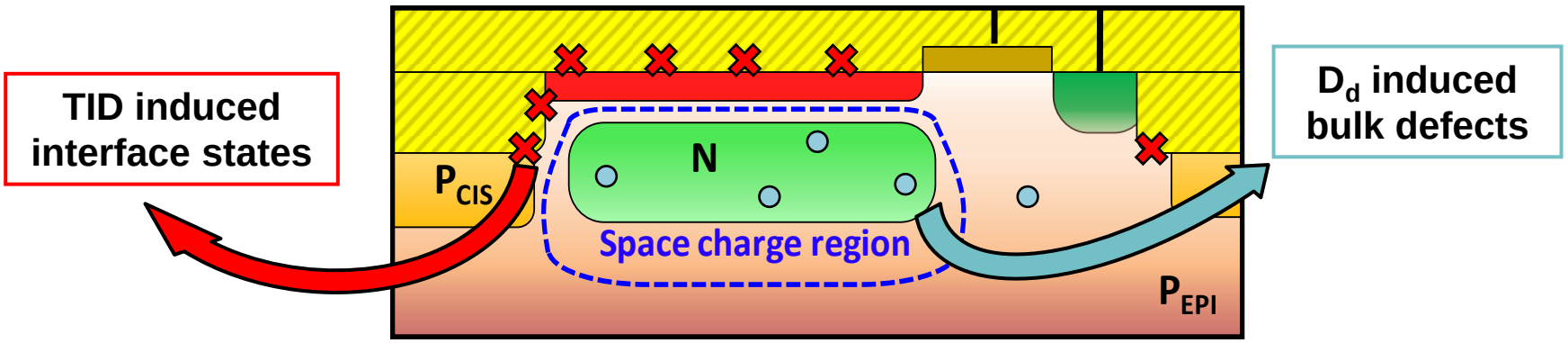
DEVICE ARCHITECTURE

- **Pixel architecture**
  - **8T pixel with in-pixel correlated double sampling**
  - **Pinned photodiode using additional transfer gate**
    - **$P^+/N/P^-$ sandwich → Space charge region are recessed from oxide**
    - **Charge transfer inside the pixel**
    - **Charge-to-Volt Factor could be tune**



PROTON-INDUCED PERMANENT EFFECTS

- **Protons induce TID and D_d in CIS leading to dark current increase**
  - **TID induces charge trapped and interface states**
    - **TID effects are reduced using PPD → SCR are recessed from oxide**
  - **D_d induces bulk defects in silicon**
    - **Main issue in CIS using PPD → Hot pixels**



PROTON-INDUCED PERMANENT EFFECTS

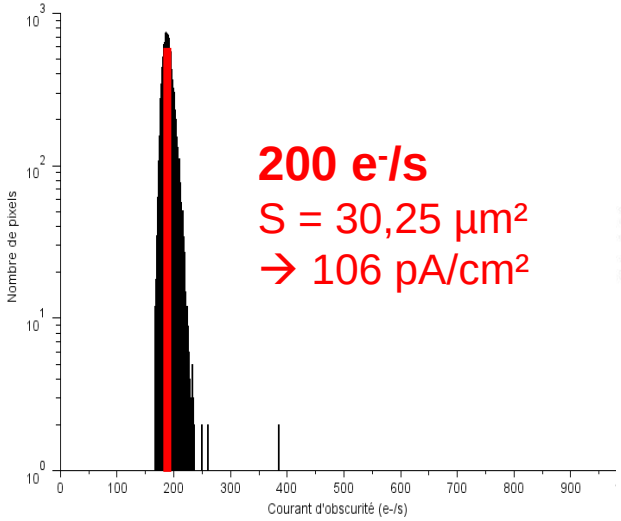
- **All tests at temperature controlled → 22°C**
- **100 averaged frames for each integration time**

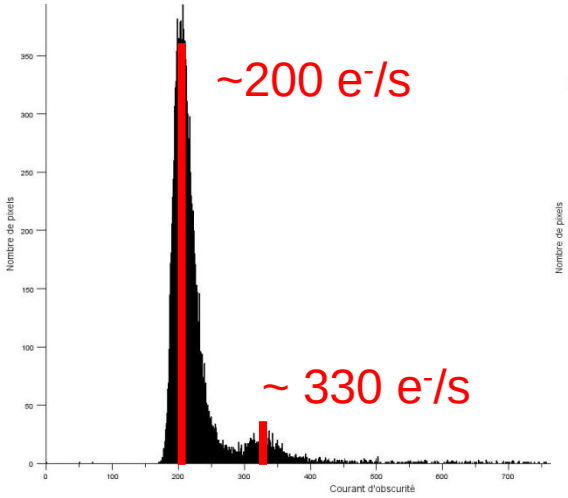
Proton test 1
- 2 device grounded
- E = 50 MeV
- F = 1.4 x 10^{10}p/cm²
- TID = 2,2 krad (SiO_2)
- D_d = 54 TeV/g

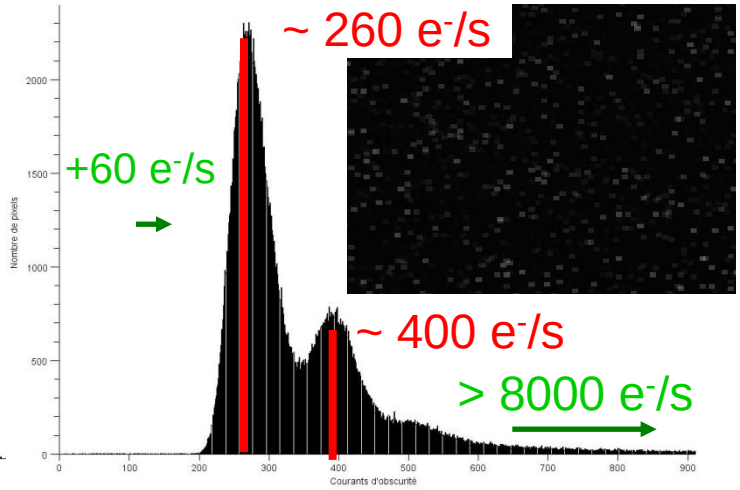
10 years LEO mission (800kms)

Proton test 2
- 2 devices grounded
- E = 50 MeV
- F = 5 x 10^{10}p/cm²
- TID = 8 krad (SiO_2)
- D_d = 194 TeV/g

→ ~ 5 x this LEO mission







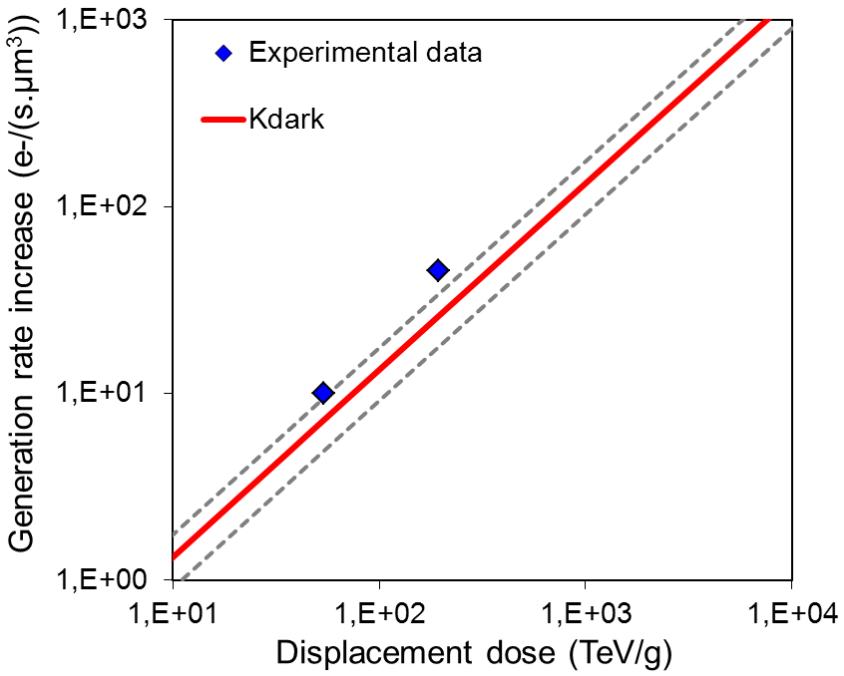
- **Only the dark current increases with doses**
- **LEO mission → I_{dark} < 9000 e-/s (4800 pA/cm²)**

→ Dark current increase due to Proton do not limit the CIS used for High Resolution Earth Imaging in LEO

PROTON-INDUCED PERMANENT EFFECTS

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

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



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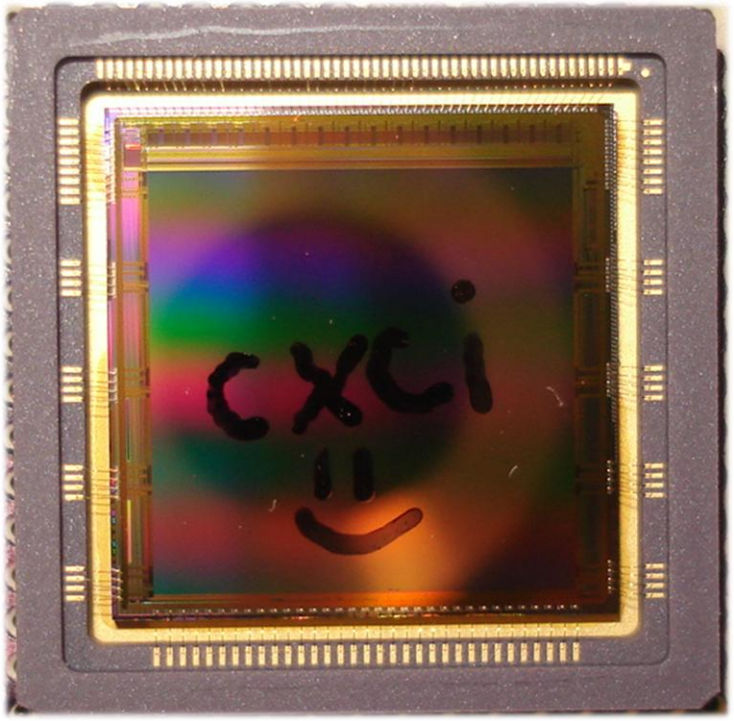
- **Mean dark current increase is higher than UDF prediction**
  - Proton-induced dark current is mainly attributed to D_d
  - TID effects are not negligible → Mainly due to transfer gate bias during integration *(See Goiffon, RADECS 2011)*

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **Single event effects occur in several parts of CIS integrating CMOS electronic functions**

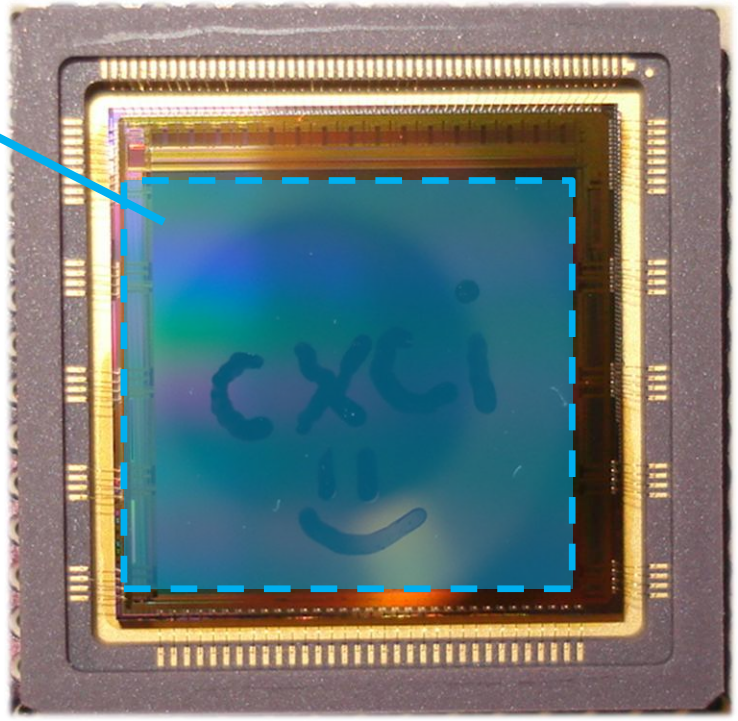


HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **Single event effects occur in several parts of CIS integrating CMOS electronic functions**

Pixel array

→ SET sensitive



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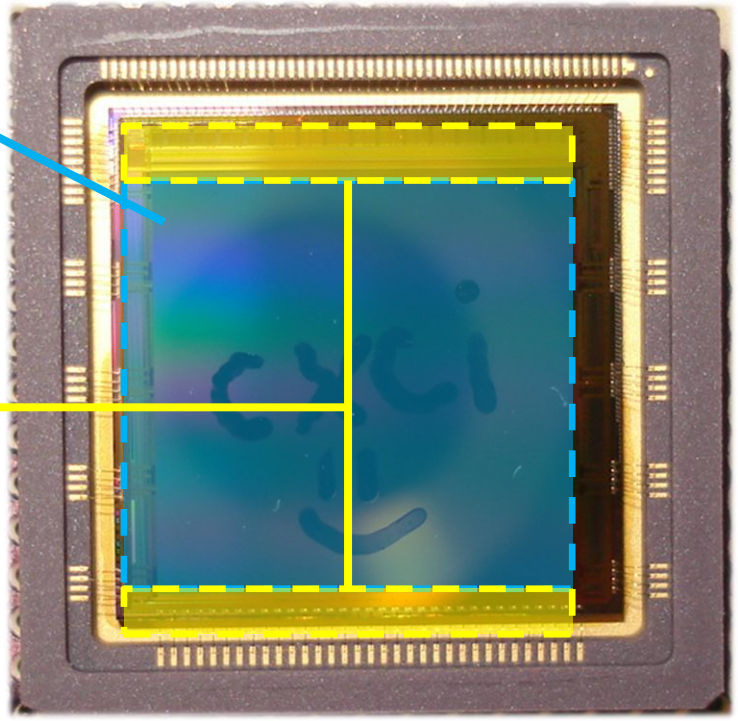

Column ADCs

→ SEU sensitive

→ SEL sensitive

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

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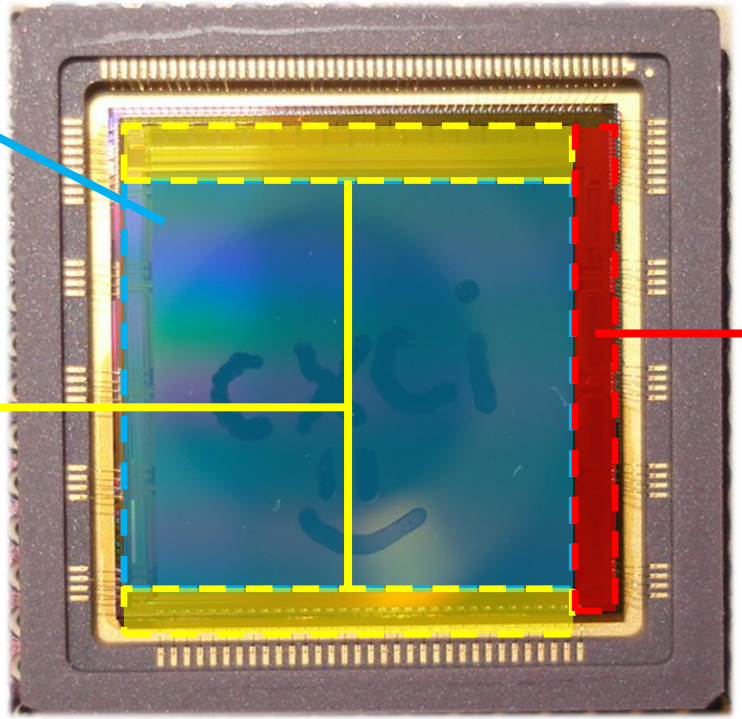
Pixel array

→ **SET** sensitive



Column ADCs

→ **SEU** sensitive

→ **SEL** sensitive

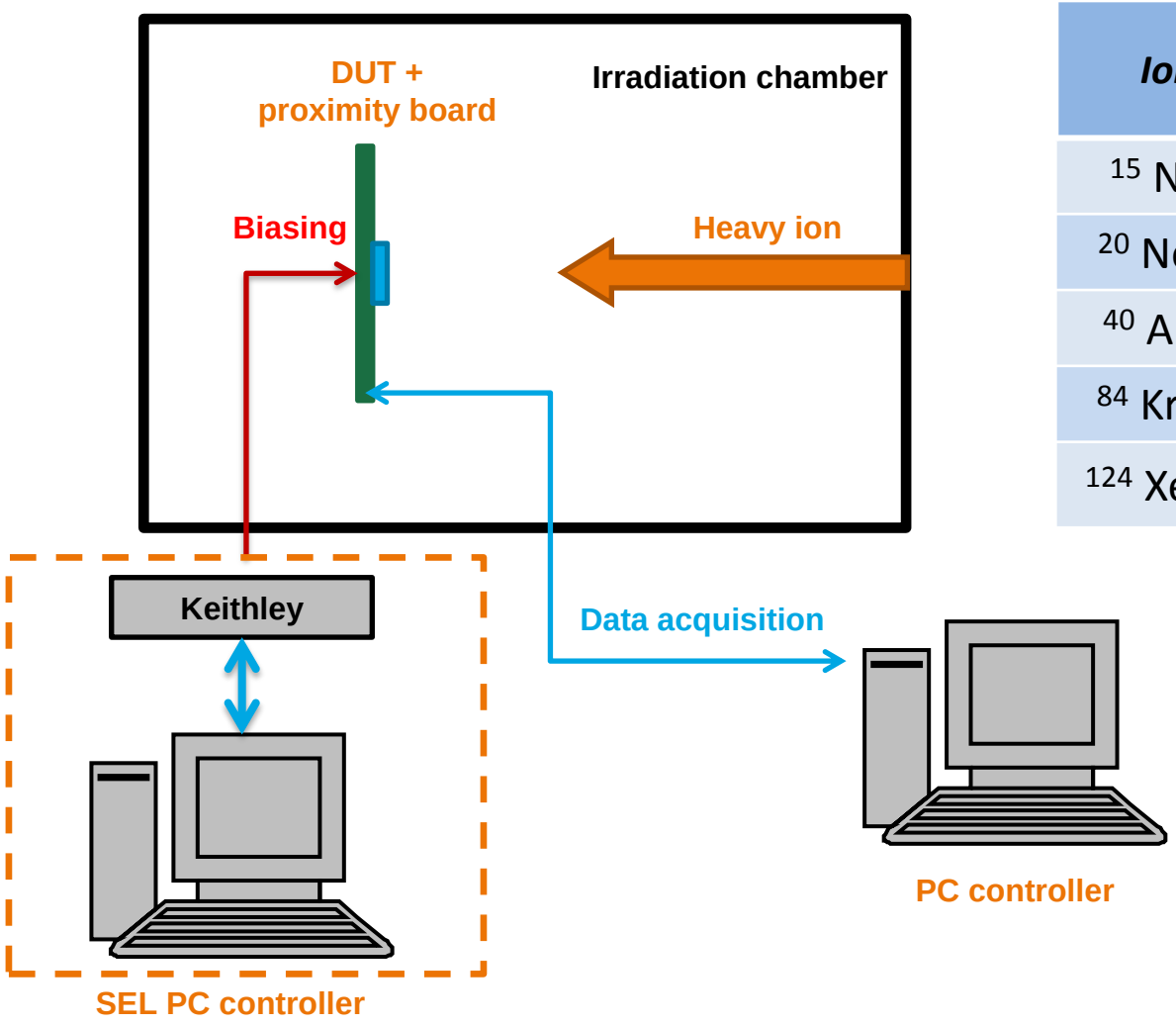
Registers and Microcontroller

→ **SEU** sensitive

→ **SEL** sensitive

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

Test bench setup



UCL High LET cocktail

Ion	*Range [µm Si]*	*LET [MeV/mg/cm²]*
$^{15}N^{3+}$	59	3.3
$^{20}Ne^{4+}$	45	6.4
$^{40}Ar^{8+}$	40	15.9
$^{84}Kr^{17+}$	39	40.4
$^{124}Xe^{25+}$	37	67.7

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

Software developed

Software 1: Frame per frame writing

- Count SEE (SET, SEU and SEL)

Software 2: 100 frame per 100 frame writing

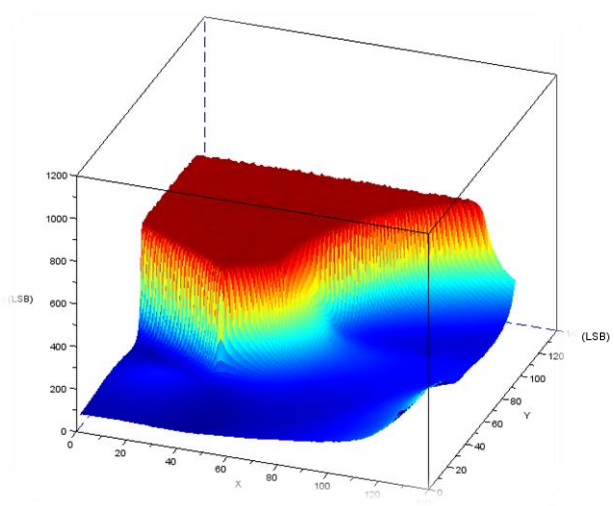
- Temporal degradation study (SET and SEU)

Software 3: Read and Write in Registers

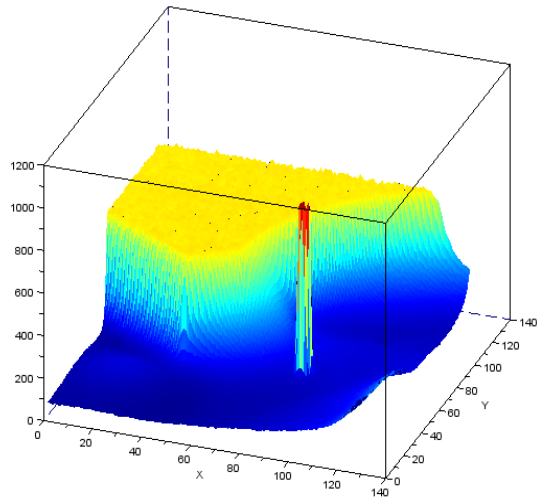
- Count SEU in registers (Sampling time = 200ms)

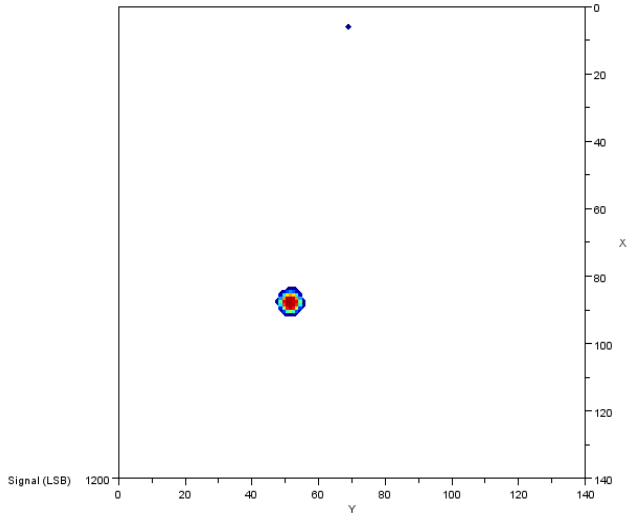
HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **SET analysis**
  - **Software 1: Frame per frame writing**
    - **Comparison of each frame to the reference image**
    - **SET detection threshold 3σ (reference image)**



Reference image
(100 frames averaged)

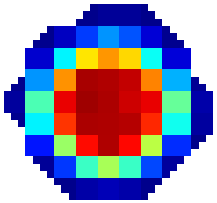




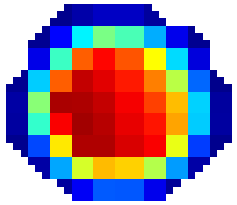
SET detection

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

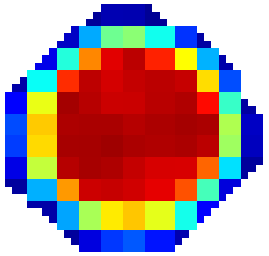
- **SET analysis**
  - **Software 1: Frame per frame writing**
    - **Comparison of each frame to the reference image**
    - **SET detection threshold 3σ (reference image)**
    - **Number of impacted pixels increase with LET**
      - **EPI = 5µm**
      - **Shallow trench isolation is used**



Azote
(3,3 MeV/mg/cm²)
~45 pixels



Néon
(6,4 MeV/mg/cm²)
~55 pixels

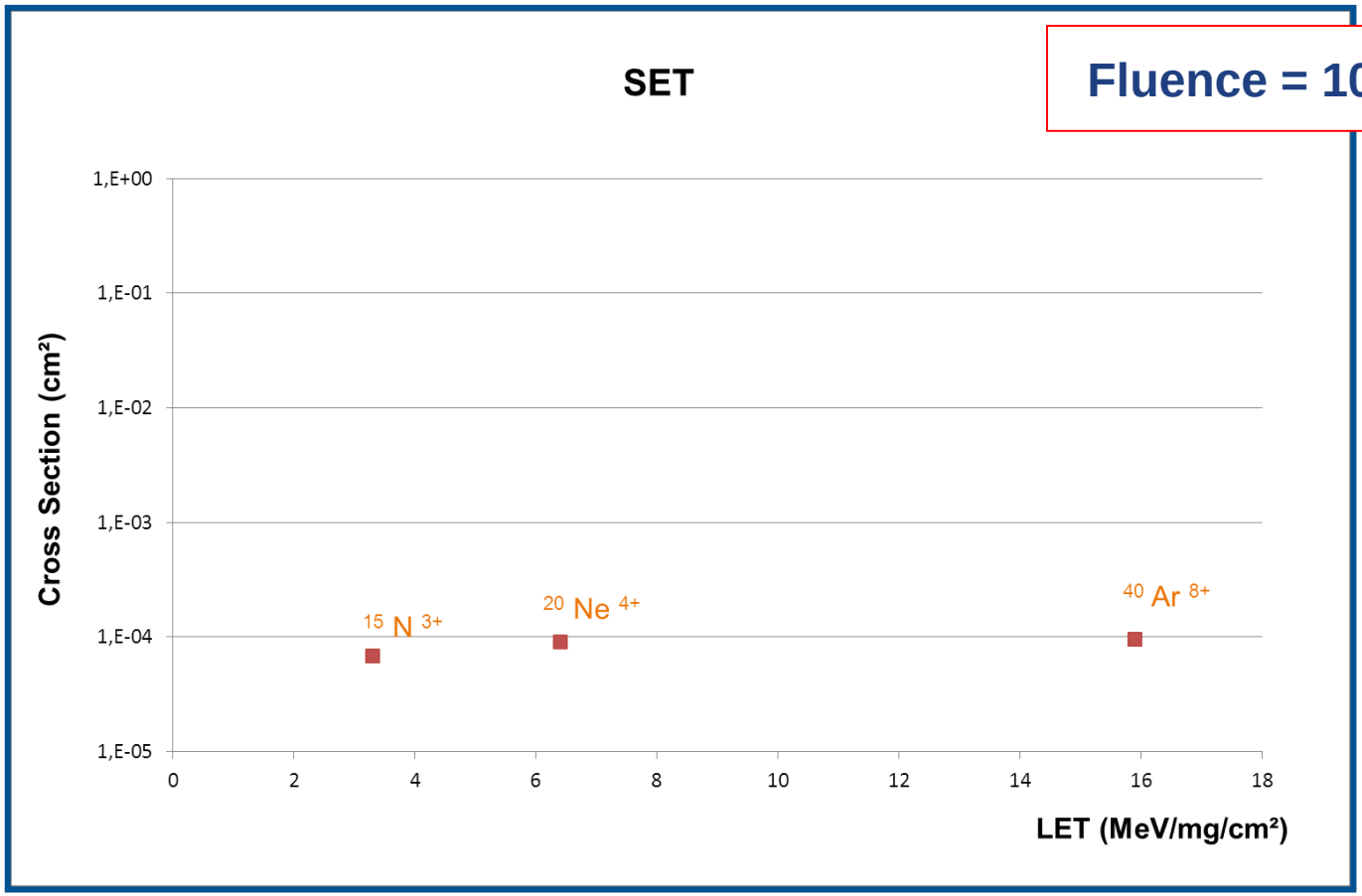


Argon
(15,9 MeV/mg/cm²)
~75 pixels

HEAVY ION-INDUCED SINGLE EVENT EFFECTS

SET analysis

- Cross section do not change significantly with LET

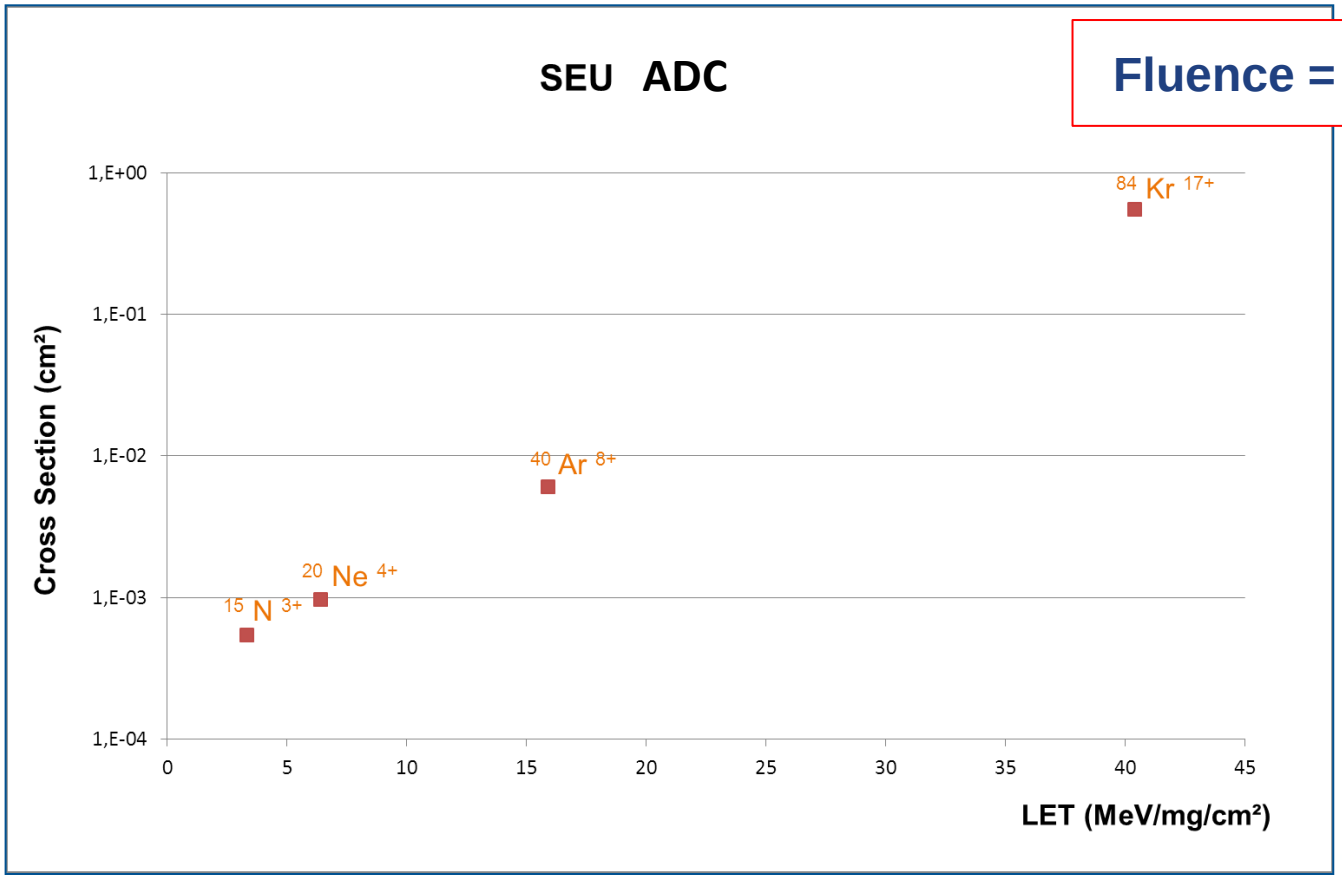


HEAVY ION-INDUCED SINGLE EVENT EFFECTS

SEU analysis

SEU in column ADCs: software 1

- Detection of isolated pixel → ADC SEU : **Numerous events**

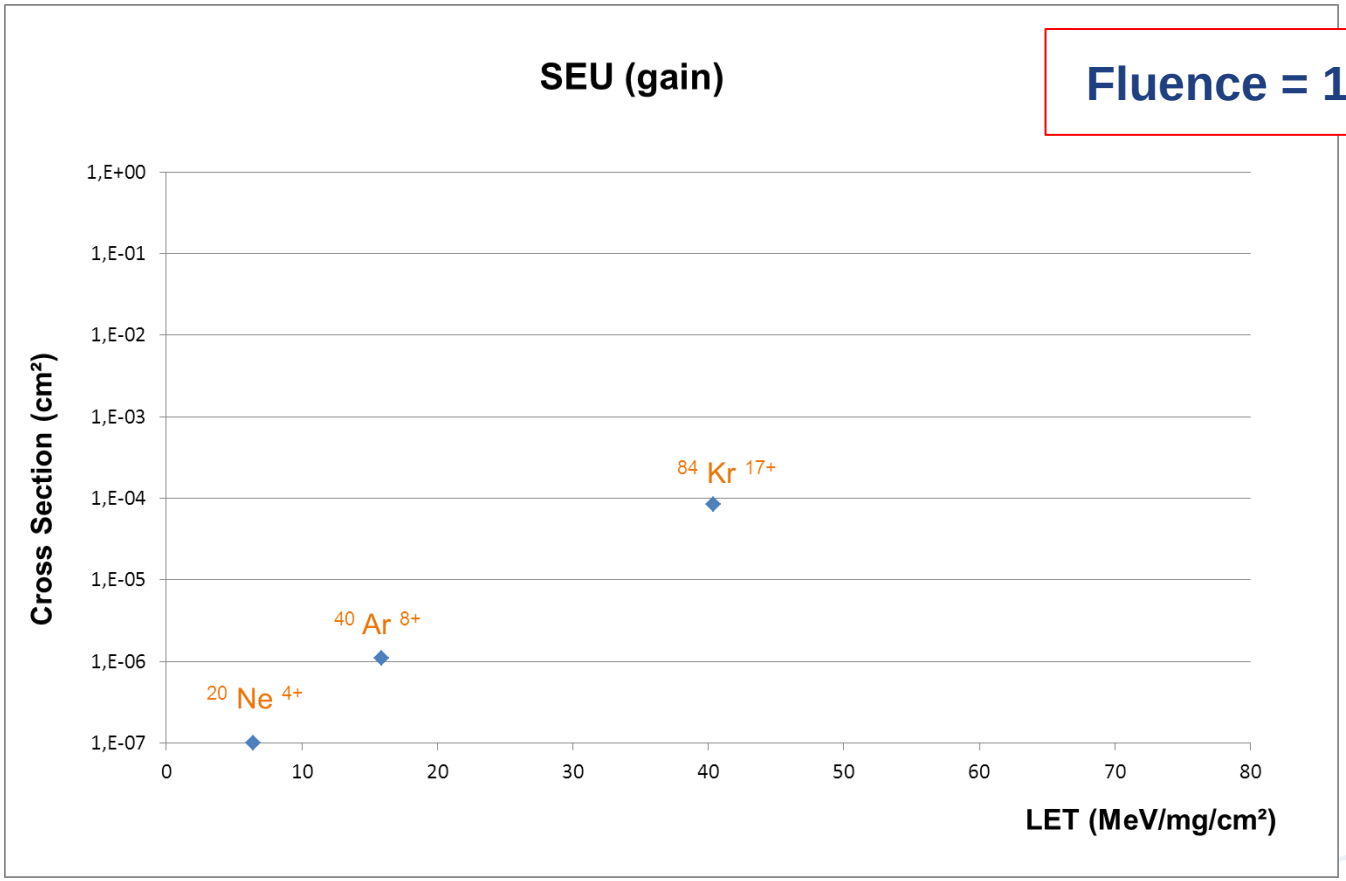


HEAVY ION-INDUCED SINGLE EVENT EFFECTS

SEU analysis

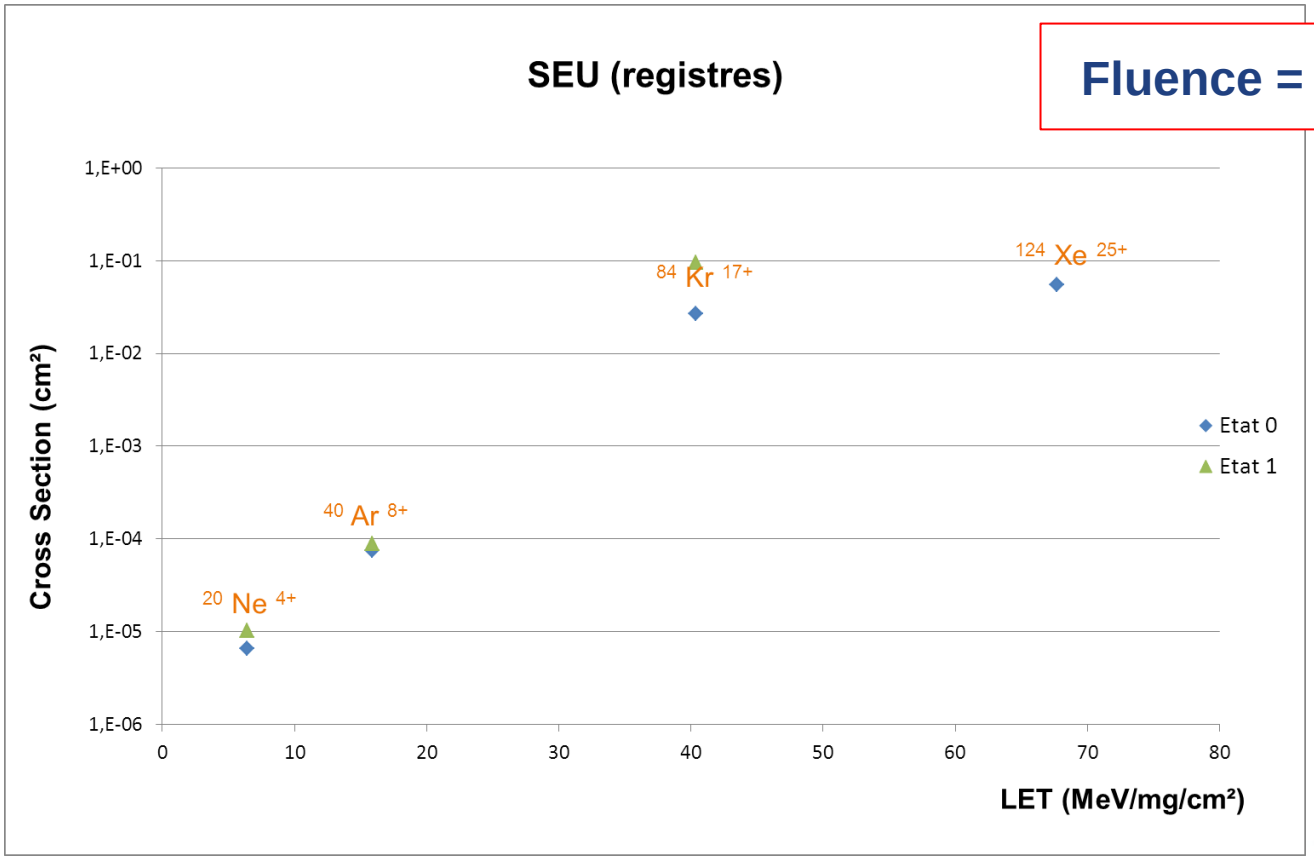
SEU in Gain register: software 1

- Detection of full image change → Gain SEU : **Rare event**



HEAVY ION-INDUCED SINGLE EVENT EFFECTS

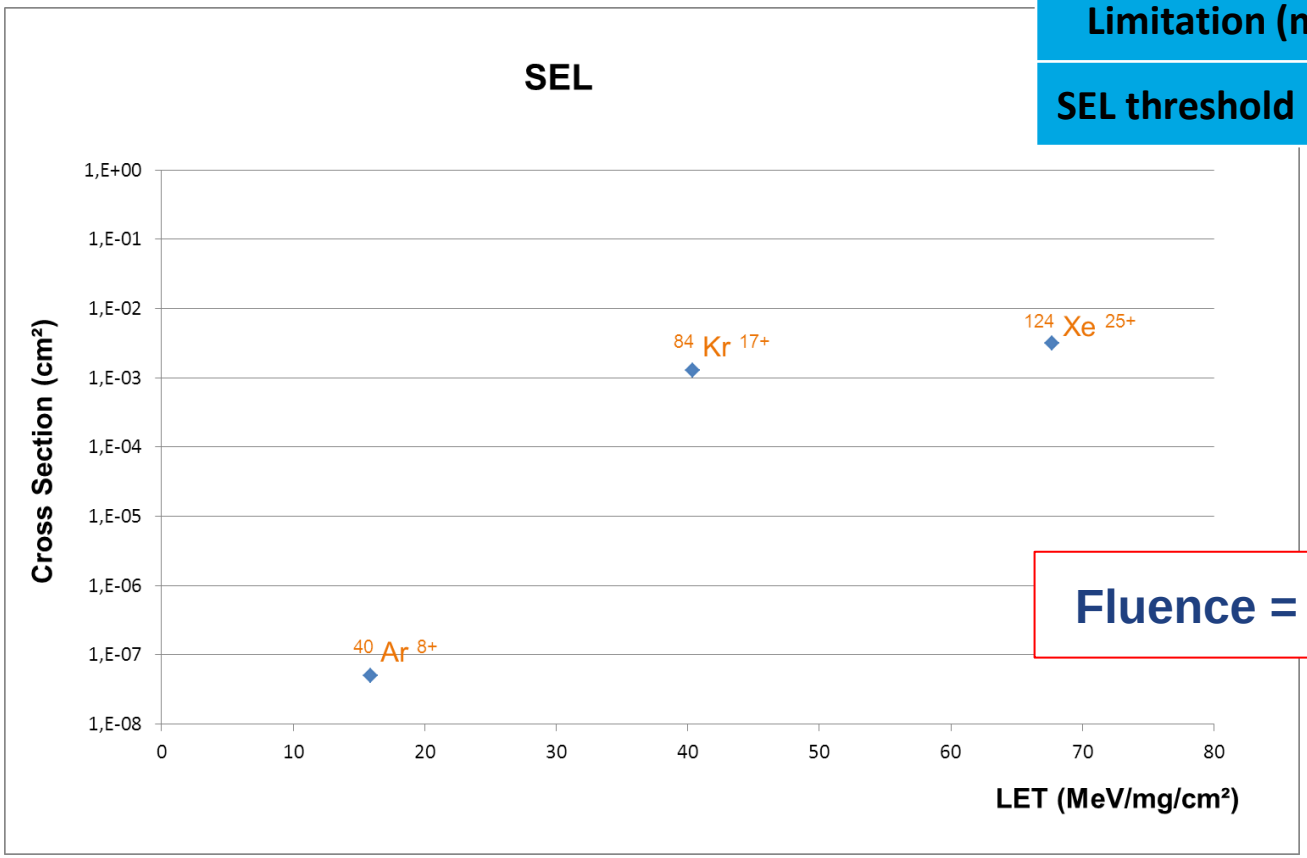
- **SEU analysis**
  - **SEU in registers: software 3**
    - **Register state: 0 and Register state: 1 → Same behavior**



HEAVY ION-INDUCED SINGLE EVENT EFFECTS

- **SEL analysis**
  - **SEU in registers: software 1 & 3**
    - **No SEL for N and Ne**

	Canal A1
Polarisation (V)	9
Current (mA)	330
Limitation (mA)	600
SEL threshold (mA)	500



Fluence = 10^7 p/cm²

CMOS IMAGER BEHAVIOR IN LOW EARTH ORBITS

SET results

- Heliosynchrone orbit - 700kms
- Full 2048 x 2048 pixel array – Device 30% ON

# SET / day			
Shielding	Wo eruption	Worse 24h	Worse 5mn
3,7mm d'alu	1,42E+00	3,46E+02	1,29E+03
6,0mm d'alu	7,98E-01	1,41E+02	5,20E+02
12mm d'alu	4,05E-01	3,49E+01	1,26E+02
24mm d'alu	2,33E-01	8,14E+00	2,87E+01

→ The occurrence do not significantly impact the mission

→ Possibility to reduce the number of impacted pixel using DTI

CMOS IMAGER BEHAVIOR IN LOW EARTH ORBITS

SEU results

- Heliosynchrone orbit - 700kms
- Full 2048 x 2048 pixel array – Device 30% ON

# SEU gain / day			
Shielding	Wo eruption	Worse 24h	Worse 5mn
3,7mm d'alu	1,06E-05	2,42E-03	8,88E-03
6,0mm d'alu	8,36E-06	8,10E-04	2,94E-03
12mm d'alu	6,27E-06	1,74E-04	6,18E-04
24mm d'alu	4,51E-06	4,37E-05	1,48E-04

# SEU ADC / day			
Shielding	Wo eruption	Worse 24h	Worse 5mn
3,7mm d'alu	2,57E+02	5,59E+04	2,07E+05
6,0mm d'alu	1,58E+02	2,44E+04	8,91E+04
12mm d'alu	8,91E+01	6,77E+03	2,43E+04
24mm d'alu	5,28E+01	1,79E+03	6,32E+03

→ The occurrence do not significantly impact the mission

→ Important number but only isolated pixel error: could be remove with QI software

CMOS IMAGER BEHAVIOR IN LOW EARTH ORBITS

SEU results

- Heliosynchrone orbit - 700kms
- Full 2048 x 2048 pixel array – Device 30% ON

# SEU registrers (State 1) / day			
Shielding	Wo eruption	Worse 24h	Worse 5mn
3,7mm d'alu	6,37E-02	1,53E+01	5,67E+01
6,0mm d'alu	3,67E-02	6,39E+00	2,34E+01
12mm d'alu	1,89E-02	1,62E+00	5,86E+00
24mm d'alu	1,07E-02	3,83E-01	1,35E+00

→ All register do not impact the image

→The occurrence do not significantly impact the mission

CMOS IMAGER BEHAVIOR IN LOW EARTH ORBITS

- **SEL results**
  - **Heliosynchrone orbit - 700kms**
  - **Full 2048 x 2048 pixel array – Device 30% ON**

# SEL / day			
Shielding	Wo eruption	Worse 24h	Worse 5mn
3,7mm d'alu	4,23E-04	1,08E-01	4,02E-01
6,0mm d'alu	2,57E-04	4,11E-02	1,51E-01
12mm d'alu	1,47E-04	9,36E-03	3,36E-02
24mm d'alu	9,18E-05	2,07E-03	7,23E-03

→ **Anti-Latchup system is mandatory for the mission**

→ **Shut down the system is required during solar eruptions**

CONCLUSIONS

- **Space radiations-induced permanent and single event effects are investigated in CIS fully integrated**
  - **Permanent effects are mainly due to displacement damage**
  - **Single event effects appear in CMOS electronic functions**
    - **SET in pixel array**
    - **SEU in column ADC and registers**
    - **SEL in numerical part**

- **CMOS Images Sensors fully integrated could be used for High Resolution Earth imaging in LEO**
  - **Permanent effects seem to do not limit the mission**
  - **Image correction could cancel isolated error pixel (due to ADC SEU)**
  - **SEU register are low and instrument availability stays in specification**
  - **Anti-Latchup system is required**

FUTURE WORKS

- **Guideline redaction could help the single event tests**
  - **Fixe the methodology to test the devices**

- **Complementary tests on this device**
  - **Single event study using proton irradiations**
  - **Test deeper EPI (12µm) → Observe the increase of SET impact size**
  - **Test other EPI resistivity → Observe SEL behavior**

- **Single event tests are on going work in other CIS device**
  - **Devices from other foundry**
  - **Devices using RadHard library**