RADIATION TESTS OF OPTOELECTRONIC DEVICES AND IMAGE SENSORS: ADVICE AND PITFALLS

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Template: 83230347-DOC-TAS-EN-009

GENERIC RETURN OF EXPERIENCE AND ADVICES ON SEE TESTING

RONAN MAREC

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Ref: Not referenced
Template: 83230347-DOC-TAS-EN-009

INTRODUCTION

Is this requirement can be apply in space project today ?

“No part sensitive to SEE”

INTRODUCTION

/// Today can we comply with such requirement : “No part sensitive to SEE” ?

- Today All Digital and Analog VLSI are more or less sensitive to SEE
- not possible to be compliant to such requirement except with a very specific radiation hardened device : huge effort & very expensive device

/// Solution : Analyses to demonstrate that EEE Device Sensitive to SEE can be used if :

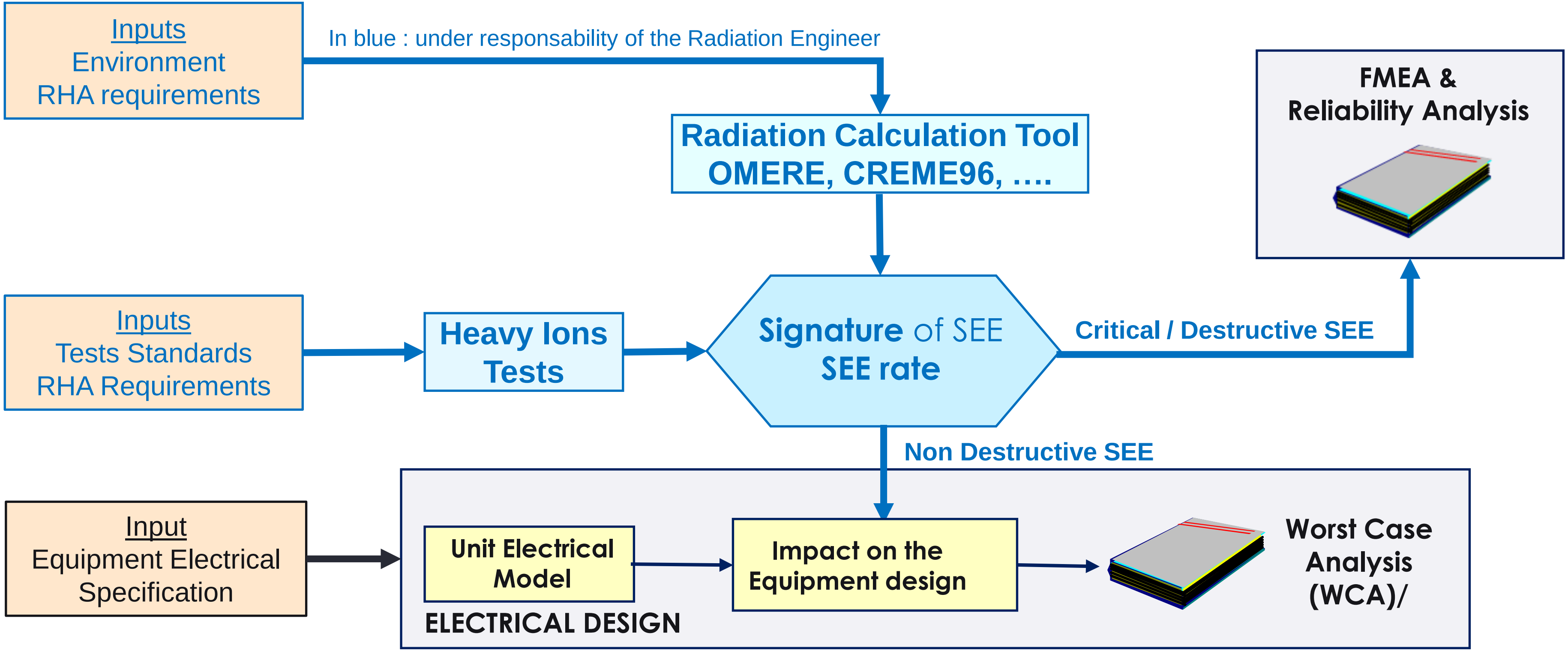
- SEE **Impact and Rate** are acceptable at equipment or system level : Availability / Reliability / FMEA
- Specific technics are applied to remove/mitigate effects

But we weed RELIABLE SEE DATA to perform such analyses

INTRODUCTION

What are reliable SEE Test Data ?

SEE RADIATION HARDNESS PROCESS IN SPACE PROJECT



In black : Checked during unit PDR/CDR – under responsability of Designer & RAMS Engineers

TRACEABILITY

/// Traceability provided in the Test Report

- Sample Serial Numbers, Date Code and Mask set
- Pictures of package, die and die marking, Die size in mm
- Device technology : e.g. FinFET TSMC 7 nm
- µcross-section : Depth of active region and dead layers

  either measured or from Manufacturer's data

/// SEE is done only during Evaluation Phase if

- Fligth traceabiltiy is identical to evaluation samples traceabilty
- Mask, technology shall be verified
- Part Change Notice (PCN) : to follow any change

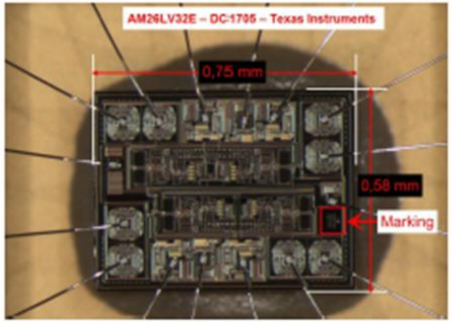
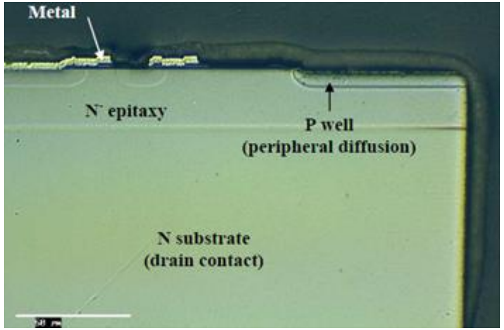


Figure 2: Internal overall view

Figure 3: Die marking

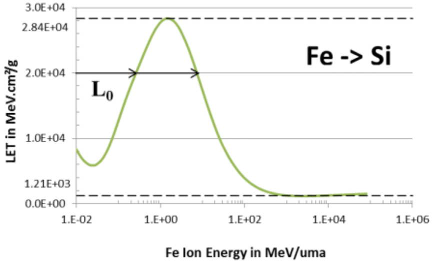


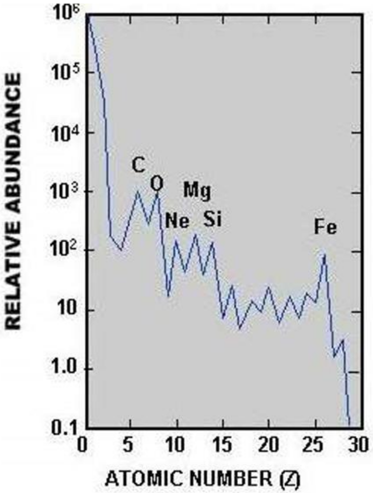
If data traceability is not known, Flight Mask shall be tested

HOW TO REPRODUCE GCR ENVIRONMENT ?

/// Impossible to reproduce the GCR space environment

- Very complex environment composed of high energy ions

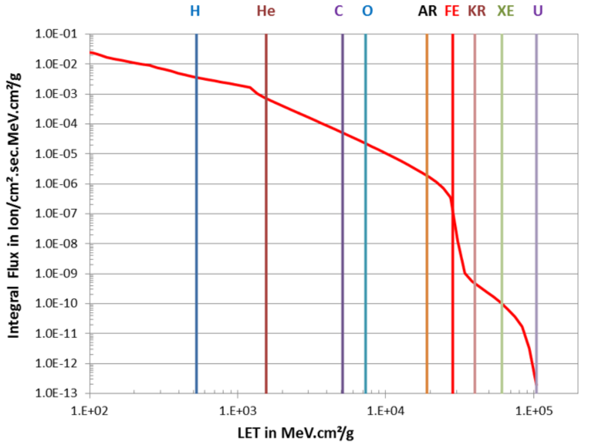




/// The solution :

- Linear Energy Transfer in Material : e.g. LET(Si)
- High energy may produce the same effect than low Energy
- Low energy ground facility can be used

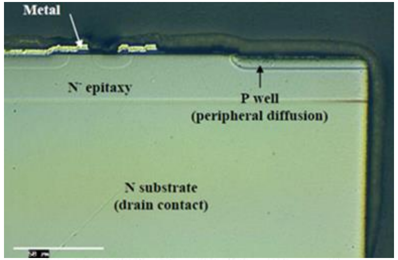
/// Environment defined by LET spectrum



/// Cyclotron are used to reproduce GCR environment

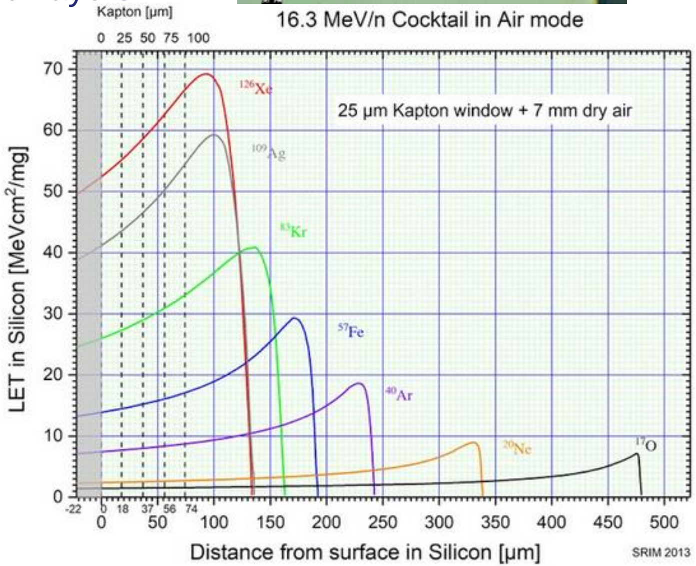
- Facility usually available in research context (University,..)
- UCL : 9 MeV/amu is operated in vacuum
- RADEF : from 9 to 22 MeV/amu is operated in vacuum or in air

SELECTION OF THE CYCLOTRON



/// Need to know the different layers of the DUT

- µsection and observation (SEM) in order to measure the thickness of layers



/// Bragg peak shall be beyond the active area of the DUT

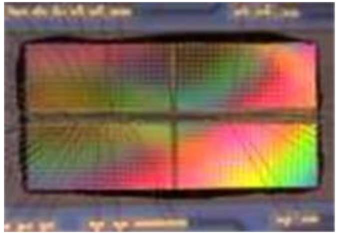
- Beam may quickly stopped when going through several layers
  - Kapton, Air, …
  - dead layer of device : metal, oxyde (in frontside) or Silicon (backside)
- OMERE (SRIM) used to calculate LET behind several layer in Si
- DUT may be prepared to remove some layers and comply with the requirements

Need to prepare samples for Heavy Ions Testing

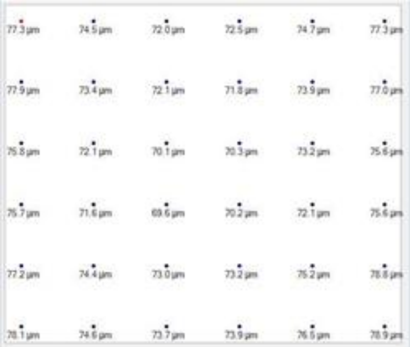
SAMPLE PREPARATION

/// Different solutions for delidding operation :

- Removing by mechanical or chemical operations the front side of the package when the die is top side in the package.



- Thinning the device by the back side by polishing or milling when the die is mounted back side in the package



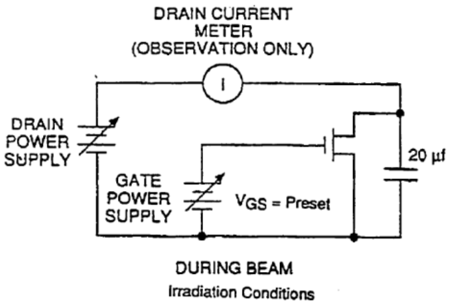
TEST CONDITIONS

/// /!\ Data shall cover all the different applications used in Flight

- Test to be done in the worst case condition for several use cases
- Test as you fly if only one application case

/// Test conditions applied during the test

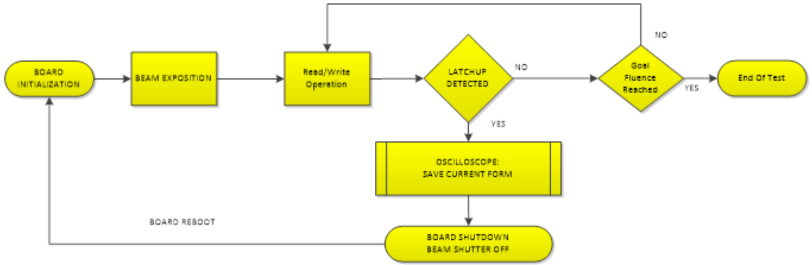
- Input voltages and/or input signal (waveform, pattern….) & output conditions
- Power supply Bias conditions
- Frequency & Data Sampling Rate
- T° : requirement may be different for NDSEE (Non Destructive) & DSEE (Destructive)
  - e.g; : SEL at upper T° used in application
- Number of bits, channels, IPs, memory size tested



MOSFET set-up from EIA/JESD57

/// Test Setup

- Information on how SEE are acquired during Test
- Test sequences described in a flowchart



FLUENCE AND FLUX

/// 2 criteria to stop the run

1. Fluence to 1 ^{E}7 ions/cm² : to be used to identify all type of events, included rare event, at higher LET
2. Only when all type events are known : run may be stopped when 100 events for each type of events are reached (without going up to 1^{E}7 ions/cm²)

/!\ Do not use only “100 events reached criteria” to perform your test

/// Flux

- High Risk if flux is too high :
  - To miss event : set up is not enough quick to detect and record all events
  - To create events that will not appear in space :
    - e.g. : MBU in memory word due to two or more ion hits in the same word between two different read cycle
- Selection of the flux : verification that same results are obtained with low and high flux before to use high flux

RULES FOR DATA POST PROCESSING

/// To consider **only as one event all impacts induced by a single heavy ion hit**

/// Classification with following criteria based on :

- level of criticality of the impact : Destructive (Reliability), critical at system level (FMEA), impact on the Availability (outage)
- end-user analysis : expected impact on the mission & Mitigation Technic put in place
  - e.g. : If an EDAC is used on a memory : event that can be corrected (SBU) and event not correctable (MBU)
- Signature of the event
  - Number of bits flipped in same time (NB they shall be counted only as one event)

    /!\ the number of flip bits can not be more than the total number of ions received
  - Signature linked to the architecture of the DUT : column, row, page,…..
  - For analog event : by duration or amplitude
  - ………

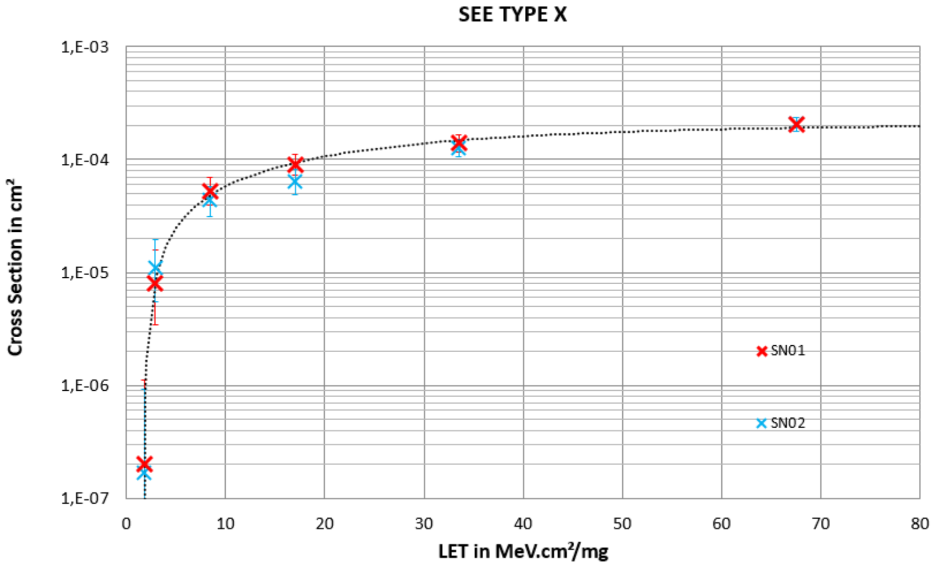
SIGNATURE OF EVENT & DEVICE CROSS SECTION VERSUS LET

/// For each type of SEE :

Detailed description of the signature of the event

NOK : « SEFI »

OK : Loss of functionality detected by a current consumption increase. This event can be recovered only with a Power OFF/ON cycle



Detailed device cross section versus LET

- at least 5 different values of LET used to determine carefully
  - LETth
  - Knee shape
  - Saturated cross section

WHAT ABOUT THIRD PARTY TEST DATA ?

/// Third party data (published paper, public database, manufacturer) shall be analysed carefully

- **TRACEABILITY** : detailed information available ? Identical to the Flight Lot ?
- **TEST COVERAGE** : Electrical conditions used during the test cover my application ?
- **EVENT SIGNATURE** Are all signature of events detailed in test report ?
- **CALCULATION RATE** : Are full device cross section versus LET available for each type of event ?
  - At least 5 ions used during test
  - At least 2 samples with same behaviour for NDSE
  - At least 3 samples with same behaviour for DSEE
- Test fully compliant with ESCC Basic Specification No. 25100 Issue 2 ?

/// If data available are not enough reliable, this data can be used as screening test but a new test shall be done

In any case of doubt, a new test shall be done

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Radiation Tests of Optoelectronic Devices and Image Sensors: Advice and Pitfalls

Matthieu Beaumel

#
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Y O U R
A M B I T I O N S

01

DISPLACEMENT DAMAGE DOSE TESTS ON CMOS IMAGE SENSORS

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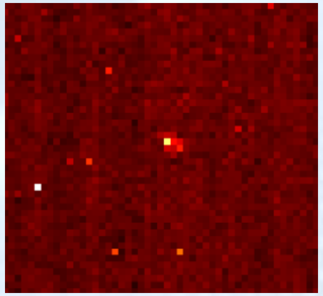
Displacement Damage Dose Effects

- As described this morning, Displacement Damage Dose (DDD) creates vacancies and more complex defects in the silicon lattice, which act as Shockley-Read-Hall generation centers in the pixel photodiode depletion regions.
- Large defects will create “hot pixels” or “spikes” in the image sensor area, characterized by dark current values several times higher than the main pixel population.
- Parameters most affected by DDD:
  - Dark Current
  - Dark Current Non-Uniformity (DCNU)
  - Parasitic Storage Node Leakage (PSNL) on global shutter CIS
  - Conversion factor for high irradiation levels (>1E12 60 MeV protons/cm^2)
  - Quantum efficiency for high irradiation levels (>1E12 60 MeV protons/cm^2)
- Dark Current Random Telegraph Signal (RTS) will also appear, especially in pixels with high dark current increase
  - Blinking pixels alternating between 2 or more dark current values (metastable states)



Non-Ionizing Energy Loss (NIEL) Scaling

- Displacement Damage Dose scales linearly with the Non-Ionizing Energy Loss (NIEL) of incident particles.
- The degradation scales linearly with DDD, especially mean dark current increase.

$$DDD = \Phi \times NIEL(E)$$

MeV/g (DDD) — #/cm² (Φ) — MeV.cm²/g (NIEL(E))

$$\Delta DC = \boxed{k_d} \times DDD = K_{dark} \times V_{dep} \times DDD$$

e-/s (ΔDC) — Exp. Result (k_d) — μm³ (V_{dep})

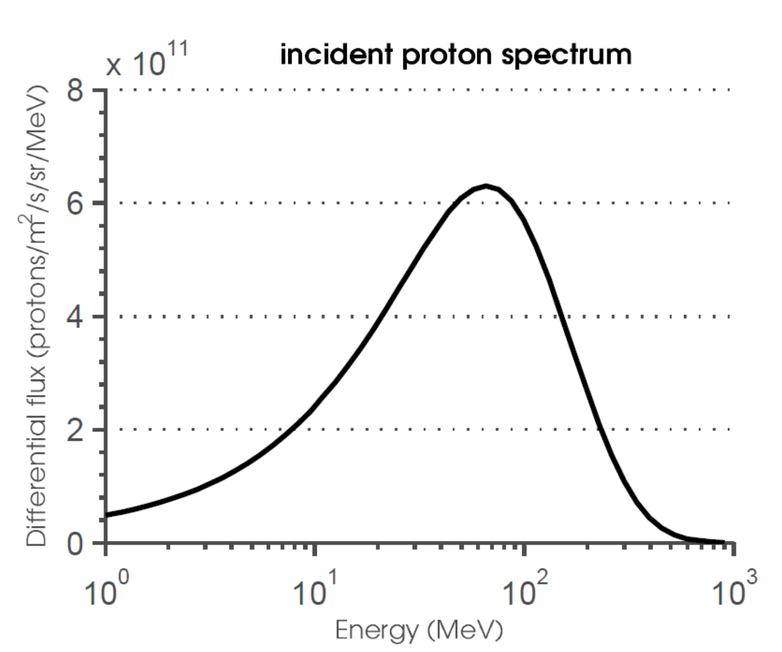
Universal Damage Factor (**Srour 2000**) (K_{dark})
≈1E-4 (e-/s) / (MeV/g) / μm³

- Displacement Damage Dose is therefore often expressed by an equivalent fluence of monoenergetic particles, which would cause the same amount of damage.
- **/!** As discussed by C. Inguimbert this morning, this holds true for hadrons (protons and neutrons) in silicon. For the same DDD, electrons cause significantly less degradation.
- **/!** Strong Electric fields will increase dark current generation through Poole-Frenkel effect and trap-assisted tunneling. Discrepancies are observed with "Universal Damage Factor" for fields >1E7 V/m
- Theoretical NIEL tables in silicon can be obtained from several sources (**G.P. Summers 1993, I. Jun 2003, Konobeyev 1992…**), with little differences in values compared to typical experimental accuracy.

Displacement Damage Dose Irradiations

- Readily available sources :
  - Protons from cyclotrons (typical energy: 10 to 200 MeV)
  - Neutrons from Deuterium-Tritium generators (energy: 14 MeV)
  - Fission neutrons from nuclear reactors (energy spectrum)
- /!\ Lower energy beams (e.g. 10 MeV) are often generated using beam degraders from higher energy beams.
  - This increases energy deposition straggling (variation in energy deposition in the CIS from particle to particle)
  - Lower energy beams also have a higher energy loss when crossing materials (front window of the CIS)
  - All these factors affect negatively the accuracy of the deposited DDD
- Recommended proton beam energy : **50 – 60 MeV**.
  - Range of 50 MeV protons in aluminum : 16 mm
  - Peak energy of Van Allen belt trapped protons through typical satellite shielding on LEO orbits
- /!\ Protons will also deposit Total Ionizing Dose
- Biasing conditions during irradiation: **unbiased** (no significant influence)

Incident proton spectrum incident on a star tracker image sensor on a 850 km LEO orbit



Displacement Damage Dose Test Levels

Earth observation mission:

LEO 850 km, 98° inclination
10 years lifetime
DDD: 3E10 50 MeV protons/cm^2

Geosynchronous telecom mission:

GEO 36000 km + Electrical Orbit Raising phase
15 years lifetime
DDD: 2E10 50 MeV protons/cm^2

Telecom constellation mission:

LEO 1200 km, 55° inclination
10.5 years lifetime
DDD: 1E11 50 MeV protons/cm^2

Europa Clipper mission:

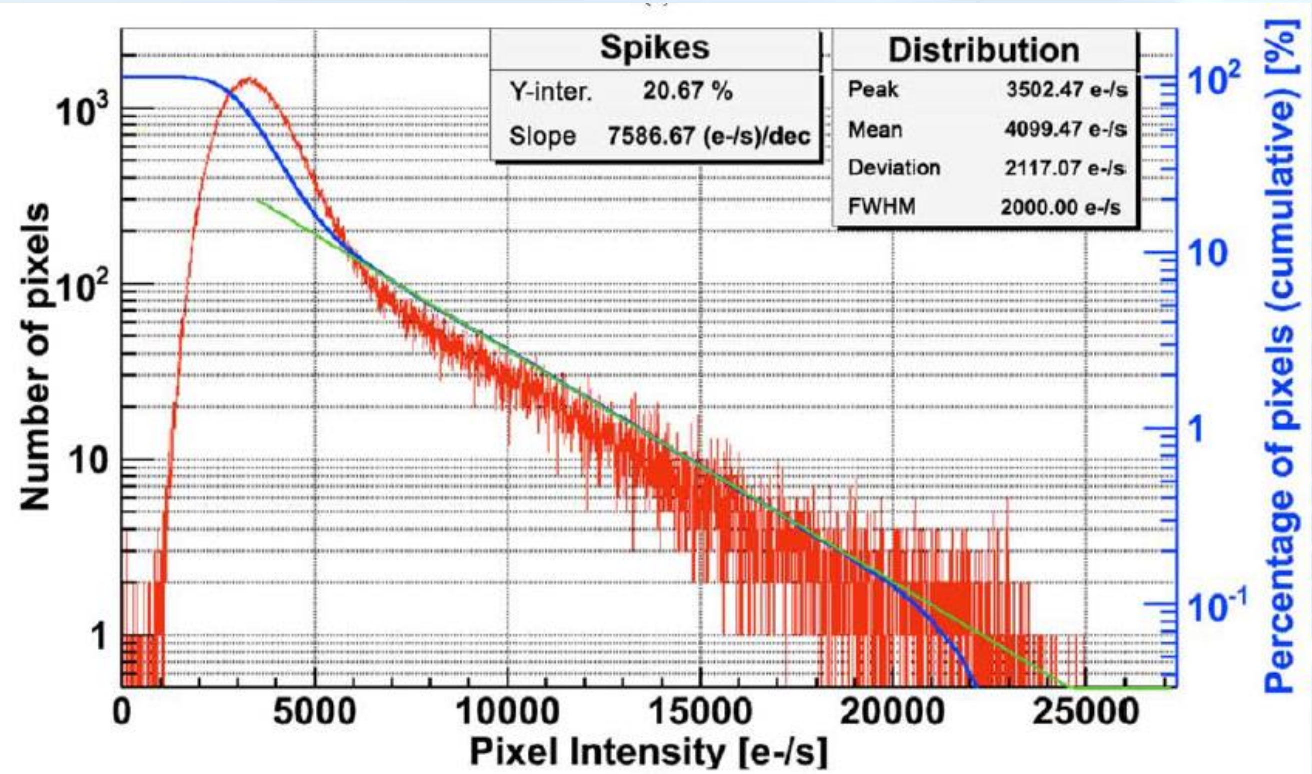
Fly-bys over Jupiter's moon Europa
DDD: 1E10 50 MeV protons/cm^2

/!\ Do not forget to add margins to cover part-to-part and lot-to-lot variations, up to x2

Dark Current Distribution Characterization

- The analysis of dark current increase distribution is the most straightforward way to assess DDD effects to the CIS.
- Mean dark current increase will be proportional to DDD.
- Hot pixels / spikes will appear as exponential-like distribution tail.
- This distribution tail appears as a straight line when plotted on a **lin-log** scale.
- This allows the extraction of the number of hot pixels (proportional to fluence) and the slope of the exponential distribution.
- This distribution has been extensively studied and can also be estimated from the photodiode depletion volume (**C. Virmontois 2012,** etc).

1 Mpixel 3T CIS irradiated with ~2E11 62 MeV protons/cm²



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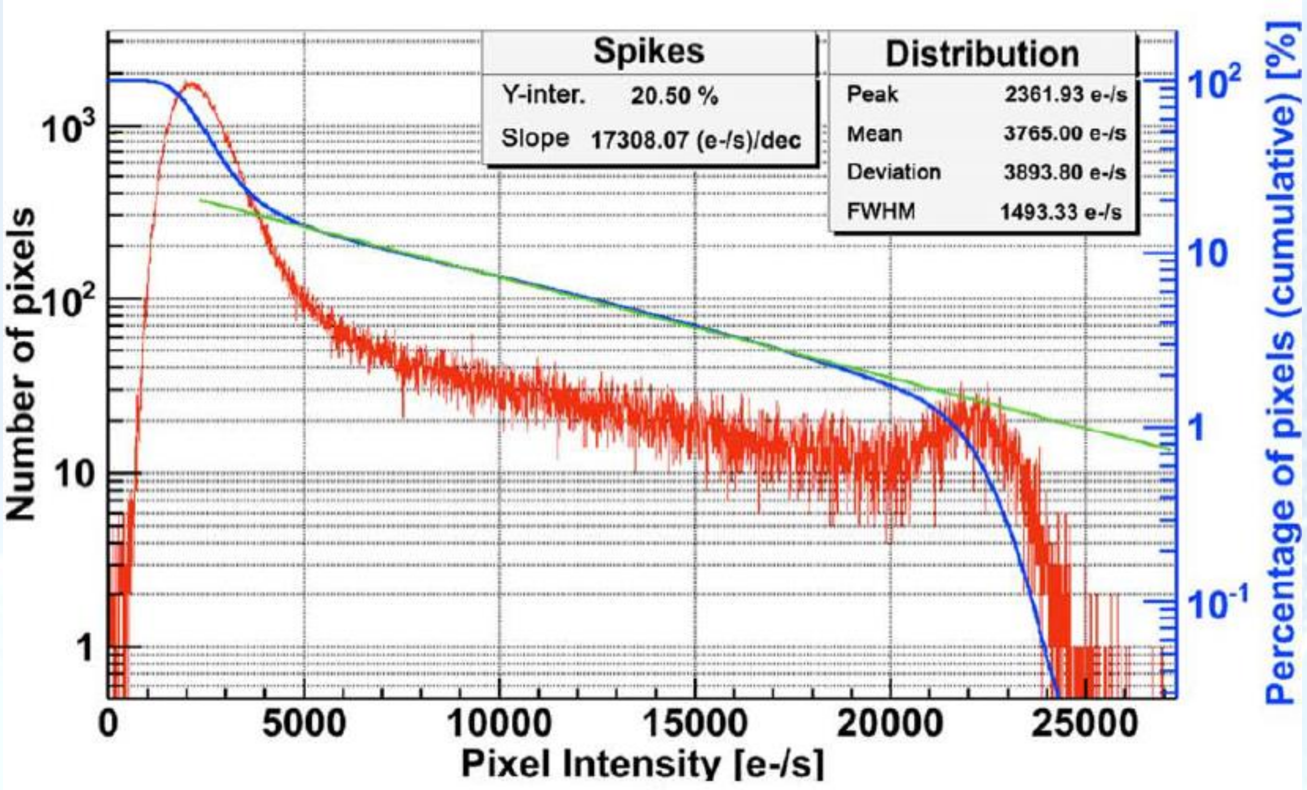


/!\ Beware of saturation effects when estimating mean dark current increase

Temperature effects

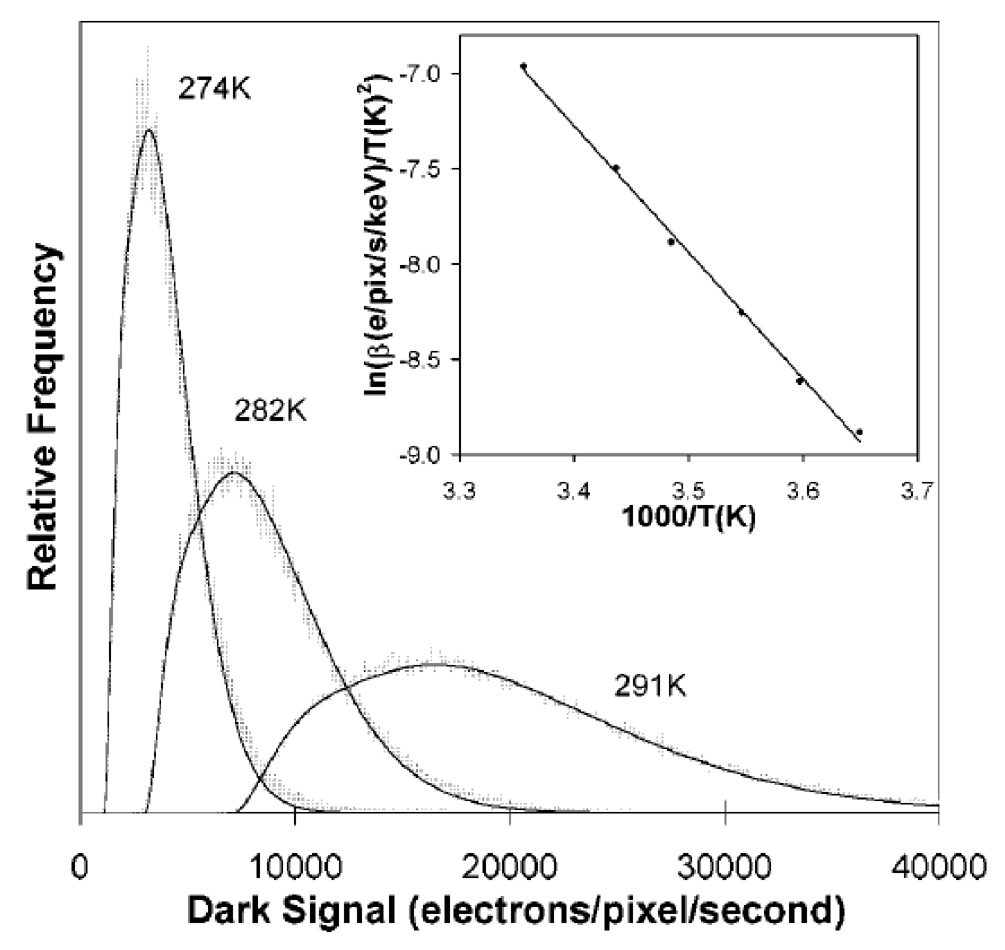
- Dark current is exponentially dependent on temperature (Arrhenius-like law).

$$DC \propto \exp\left(-E_a/k_bT\right)$$

- /!\ Accurate knowledge of the CIS temperature during dark current measurements is therefore critical.

- Activation energy of the dark current increase law should be assessed by performing measurements at several temperatures.
  - This allows dark current increase to be determined for a range of operating temperatures
  - Typical activation energy of DDD defects in silicon: **0.63 – 0.82 eV**
  - Corresponding dark current doubling temperature near room temperature : **7°C – 9°C**

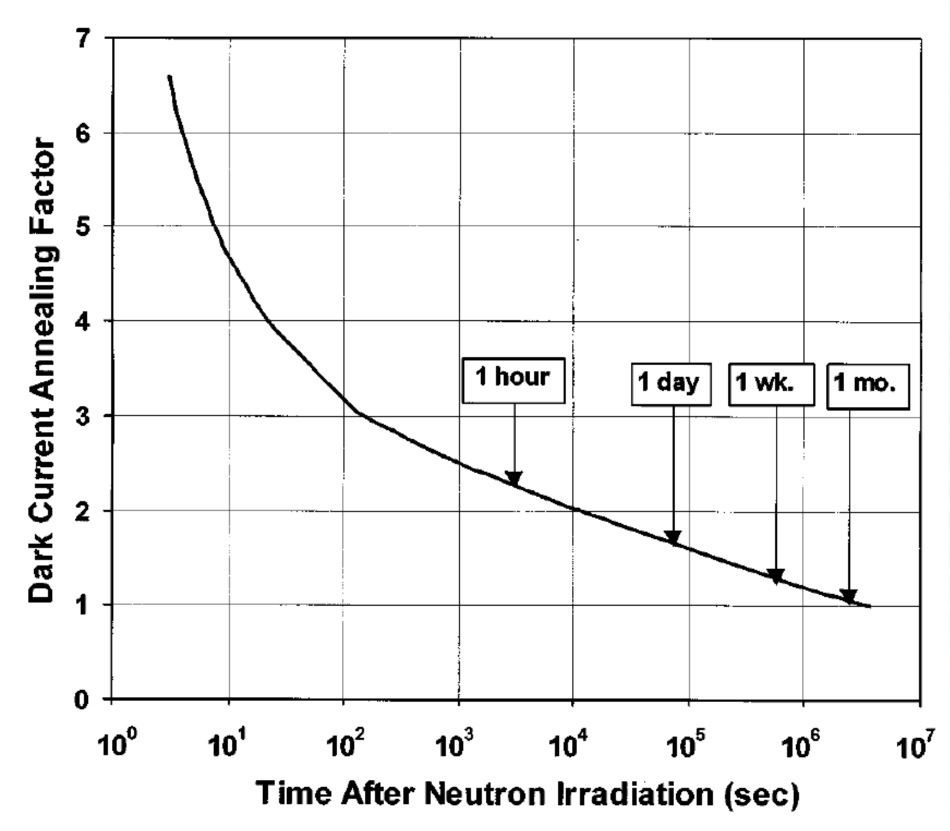
/!\ Field enhancement effects will lower the activation energy: all pixels may not have the same dark current activation energy



Dark current dependence on temperature, CCD irradiated with 3.4E10 60 MeV protons/cm²
(M. Robbins 2000)

Displacement Damage Annealing

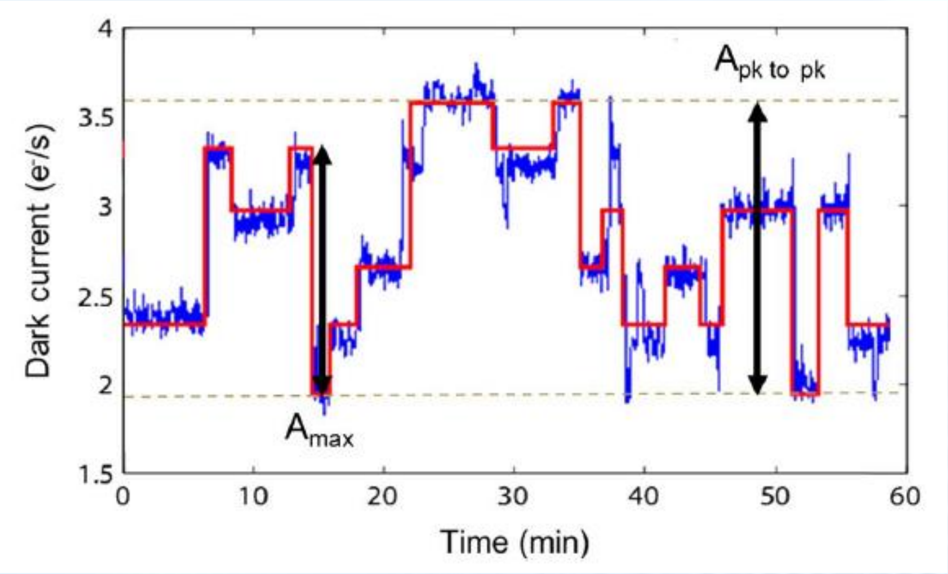
- Dark current-induced displacement damage first anneals very quickly at room temperature, then reaches a pseudo-plateau.
- /!\ Depending on the intended application, dark current measurements can be not very representative if performed straight after the irradiation.
- In any case, the time duration between the irradiation and the measurements must be carefully recorded
- Typical time for measurements: 3 weeks after irradiation.
- Depending on the intended application temperature, a high temperature annealing step after irradiation can be interesting, as temperatures above 70°C greatly anneal DDD-induced dark current. Typical annealing time at high temperature : 1 week.
- /!\ CIS intended to be used in low temperature applications (typically <-50°C) must be irradiated at the application temperature, otherwise room-temperature annealing effects may cause an underestimation of the degradation at the intended temperature.



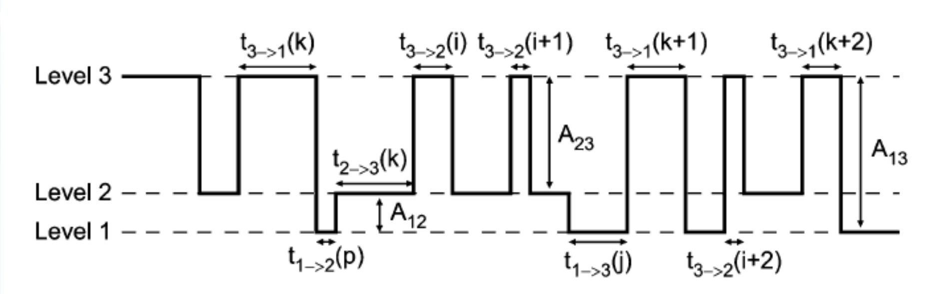
Annealing factor from Srour 2000, normalized to 1000h

Random Telegraph Signal (RTS)

- Random Telegraph Signal (RTS) pixels exhibit blinking behaviour: their dark current values will switch between 2 or more “semi-stable” states.
- Hot pixels with high dark current are the most likely to exhibit RTS, but weakly damaged pixels can also be subject to RTS.
- /!\ Depending on the intended application, it can be a matter of lesser interest or critical for performance
  - On average, RTS will not change the dark current distribution or the associated shot noise
  - However, RTS will greatly impair the ability to perform pixelwise dark current correction through dark current mapping
- /!\ Characterizing RTS requires long test sequences (recording images during several hours and a few seconds period)
- Standard technique for detection and characterization of RTS pixels : **Edge detection technique** (**V. Goiffon 2009**)
- This allows to characterize for each RTS pixel
  - Number of levels
  - Transition amplitudes
  - Inter-transition periods



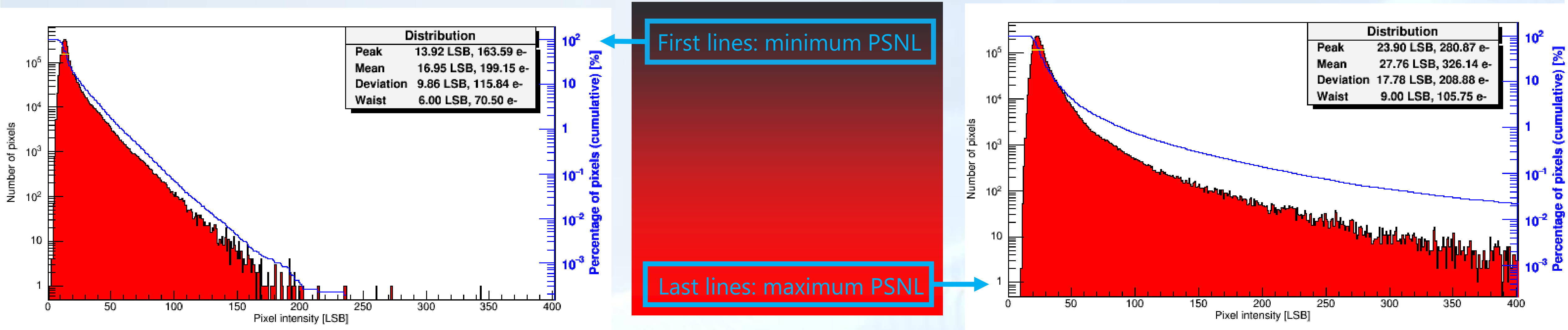
Example of multi-level RTS from C. Virmontois 2013



RTS parameters extraction from V. Goiffon 2009

Parasitic Storage Node Leakage (PSNL)

- PSNL is the equivalent of dark current in the memory node on a Global Shutter CIS (accumulated between the end of integration time and the readout of the line).
- /!\ On large Global Shutter CIS, DDD-induced PSNL can be a dominant contributor.



Global shutter CIS irradiated to ~4E11 1 MeV n/cm²

- CIS performing double sampling / correlated double sampling in the voltage domain are expected to be less sensitive to such effects, but this is not always the case…
- In such cases, perform measurements with different integration times / line readout times to be able to selectively cancel DC or PSNL contribution.

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02

TOTAL IONIZING DOSE TESTS ON CMOS IMAGE SENSORS

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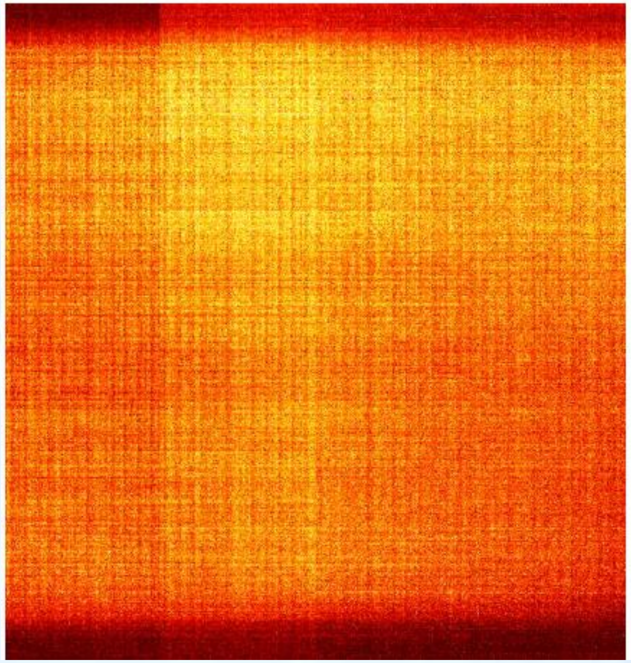
Total Ionizing Dose Effects

- Total Ionizing Dose creates charges trapped in the CIS oxides and interfaces traps.
- Interface traps in contact with the pixel photodiode depletion region will cause the increase of dark current.
- The CIS Read-Out Integrated Circuit (ROIC) electrical characteristics will degrade.
- Parameters most affected by TID:
  - Dark Current
  - Dark Current Non-Uniformity (DCNU)
  - Parasitic Storage Node Leakage (PSNL) on global shutter CIS
  - Fixed Pattern Noise (FPN)
  - Charge Transfer Efficiency / Lag in pinned photodiode pixels
  - Full Well Capacity (FWC) in pinned photodiode pixels
  - Readout noise
  - Conversion factor
  - Quantum Efficiency
- As for DDD, Dark Current Random Telegraph Signal (RTS) will also appear.

Total Ionizing Dose Irradiation

- Readily available sources:
  - Cobalt-60 (1.33, 1.25 MeV gamma rays)
  - X-Rays tubes (typically from 10 to 100 keV)
- Cobalt-60 is usually preferred over X-rays because of several advantages:
  - Very high penetration depth in materials (half value layer in Aluminum: 6.8 cm), good resulting homogeneity
  - Higher charge yield (more representative of electrons in orbit)
  - However, much higher dose rates can be achieved with X-rays
- /!\ Be wary of TID equilibrium issues with Cobalt-60:
  - Co-60 gammas create Compton electrons in silicon with ~1 MeV energy
  - Such electrons have a range of ~1 mm and can “escape” the silicon if no or very thin surrounding materials are present
  - This can create a strong overestimation of the deposited TID (factor ~2…)
  - **With Co-60, always irradiate packaged dice**
- Biasing conditions during irradiation: **biased** (worst-case for ROIC) and **unbiased** (not required for PPD, but can be worst-case for newer structures).
- No enhanced low dose rate sensitivity (ELDRS) reported in CIS.

2 Mpixel CIS dark current map at 30 krad after Co-60 irradiation



Total Ionizing Dose Test Levels

Earth observation mission:

LEO 850 km, 98° inclination
10 years lifetime
TID: 4 krad

Geosynchronous telecom mission:

GEO 36000 km + Electrical Orbit Raising phase
15 years lifetime
TID: 6 krad

Telecom constellation mission:

LEO 1200 km, 55° inclination
10.5 years lifetime
TID: 20 krad

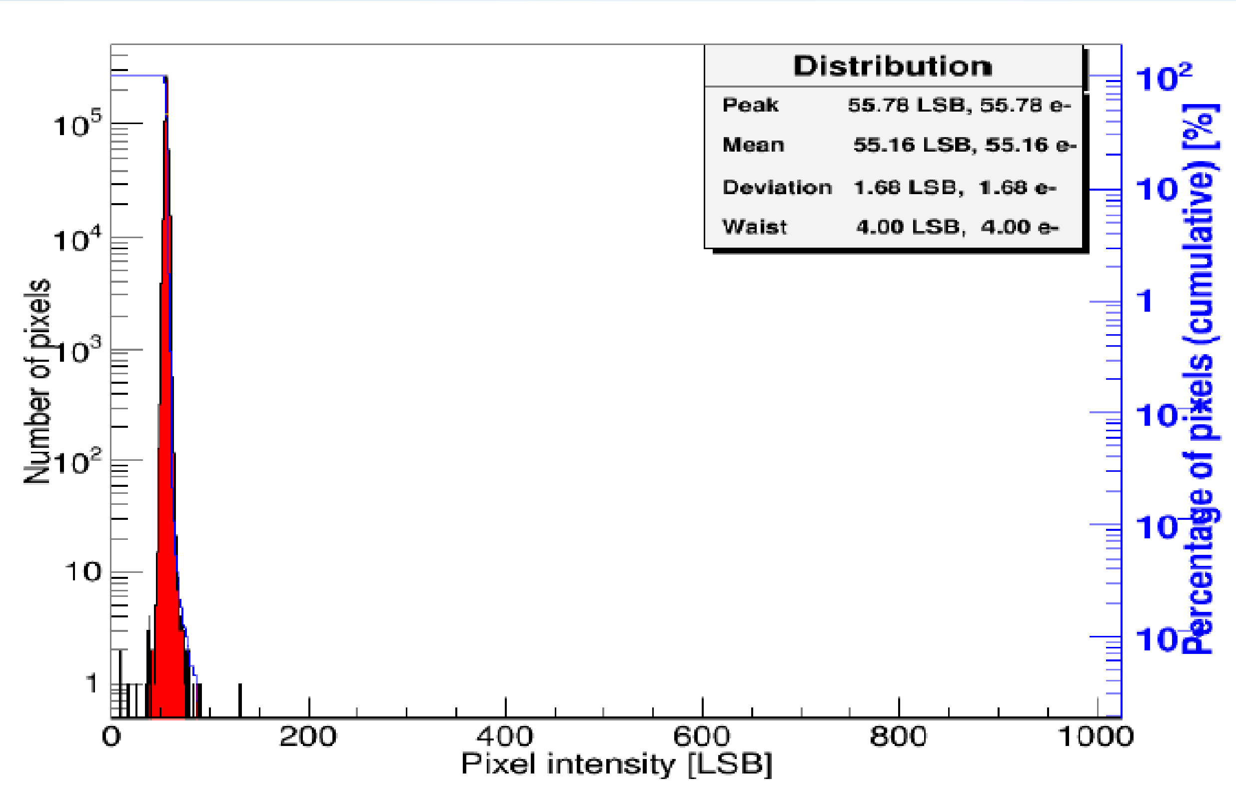
Europa Clipper mission:

Fly-bys over Jupiter’s moon Europa
TID: 50 krad

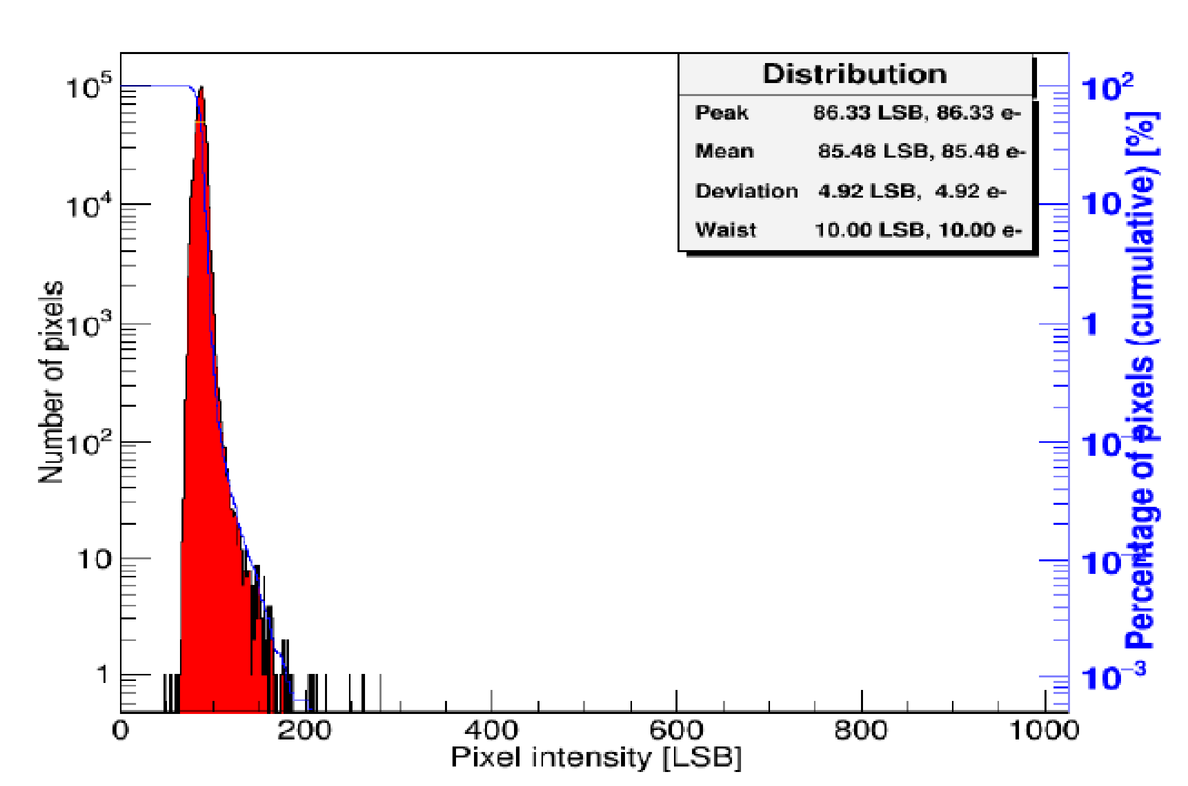
/!\ Do not forget to add margins to cover part-to-part and lot-to-lot variations, up to x2

Dark Current Distribution Characterization

- In contrast to DDD damage, TID will induce a more uniform increase of dark current.
- /!\ TID effects can be non-linear as higher levels are reached:
- **Do not extrapolate TID degradation at higher doses.**
- **Be very careful when interpolating TID degradation between large TID levels steps.**



Initial 2 Mpixel CIS dark current distribution



2 Mpixel CIS dark current distribution at 30 krad

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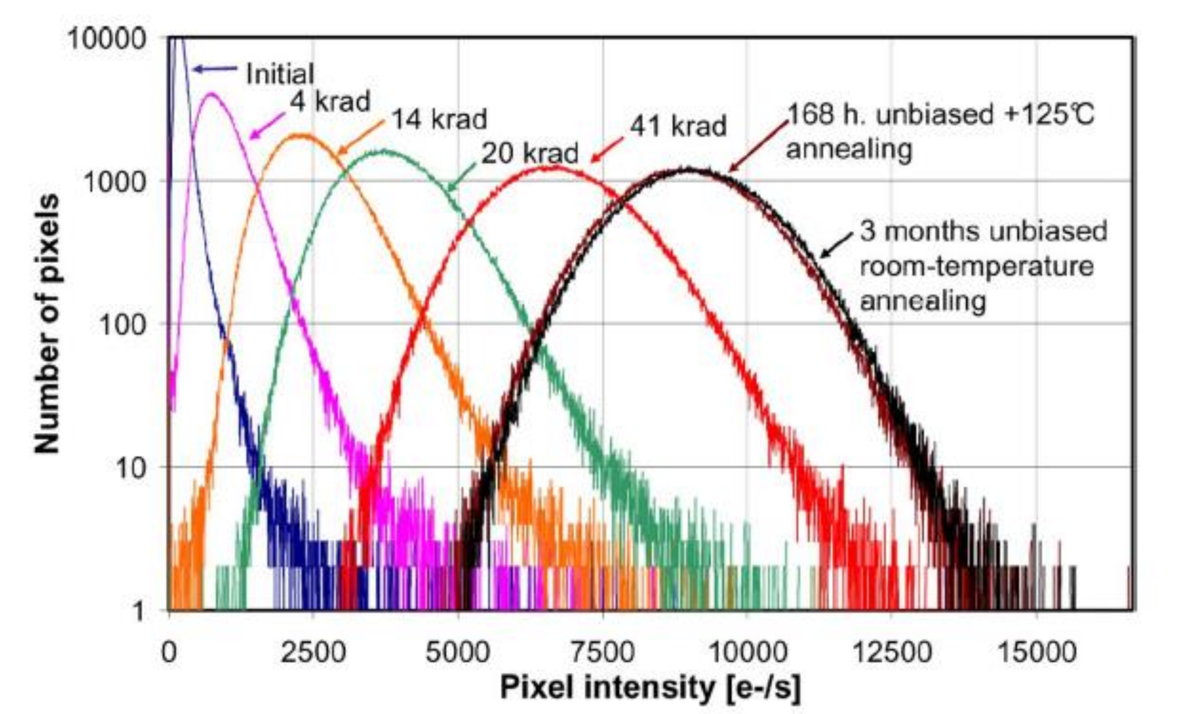
Total Ionizing Dose Annealing

- /!\ In some cases, reverse annealing (increase of degradation at the end of irradiation) has been observed on CIS.
- TID irradiation standards such as ESCC 22900 or MIL-STD-883 TM1019 mandate accelerated annealing (100°C during one week) at the end of the irradiation to characterize these effects.
- It is a good practice to perform this annealing step
- Of course, it can also reduce the degradation through the de-trapping of oxide charges



Reverse annealing on 1Mpixel 3T CIS

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