SERESSA 2022

5th to 9th of December at CERN, Geneva

Introduction to OMERE: a tool for space environment and radiation effects on electronics devices

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Tests & radiations

Agenda

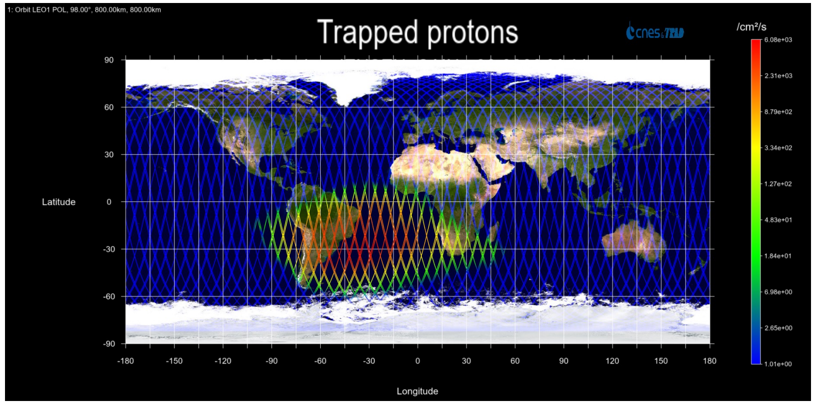
- ❑ Introduction
- ❑ SEE rate calculations
- ❑ OMERE SEE module
- ❑ Calculation example

Introduction

TRAD & OMERE

- TRAD benefits of more than 20 years of expertise in radiative environments and provides advanced services to help companies predict and minimize radiation effects on their products and systems.

  - Test services
  - Component selection
  - Engineering support
  - Software solutions →

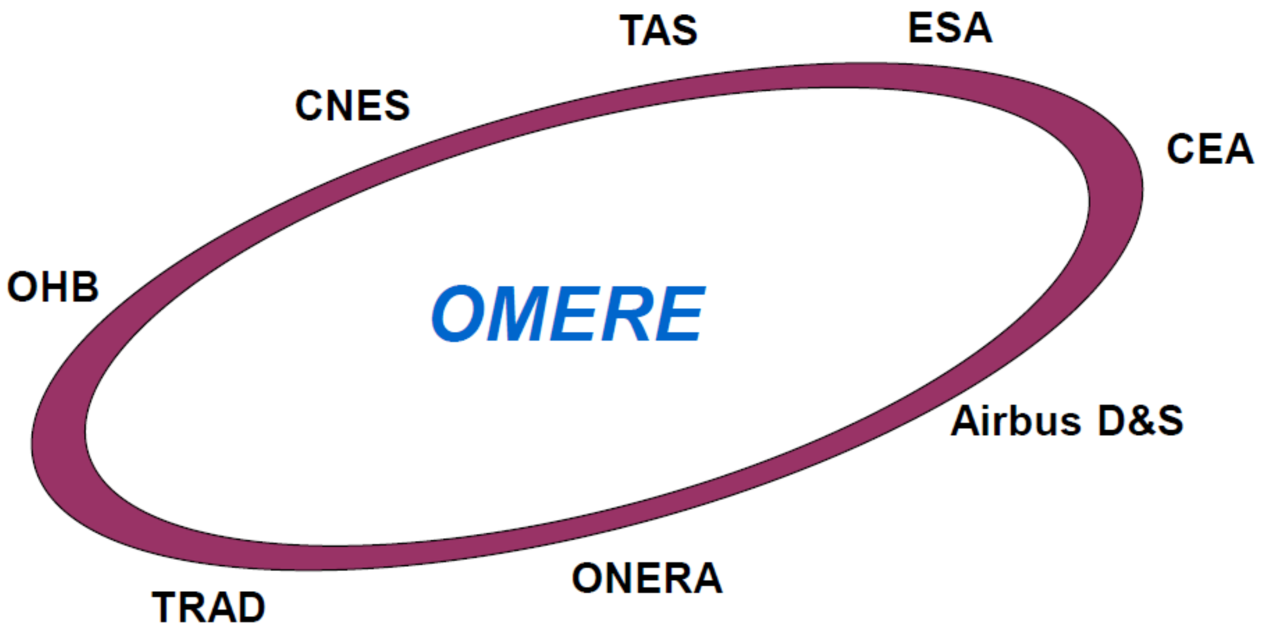


OMERE is the ultimate freeware for radiation environment calculation !

- ✓ Space Environment modelling
  - ✓ Trapped particles
  - ✓ Solar particles
  - ✓ Galactic Cosmic Rays
- ✓ Cumulative effects
  - ✓ Dose / Displacement damage depth curves
- ✓ Single Event Effects
  - ✓ SEE rate calculation
- ✓ Solar cells degradation
- ✓ Interplanetary missions

The OMERE software

- ❑Developped by TRAD with CNES support
- ❑Conceived to meet industrial requirements
- ❑Partnership of european actors



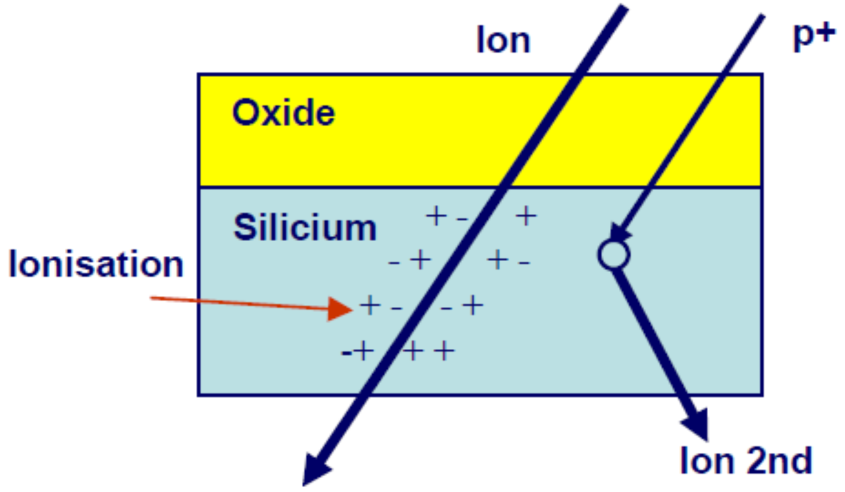
Introduction

❑A Single Event Effect is
- An isolated event taking place in an active device
- Due to only one energetic particle strike

❑A Single Event Effect can be
- Destructive
- Non-destructive

❑Single Event Effect are caused by
- Heavy ions
- Protons

❑The environment contributions to the SEE are
- Trapped protons
- Solar particles (protons and ions)
- Cosmic rays



Introduction

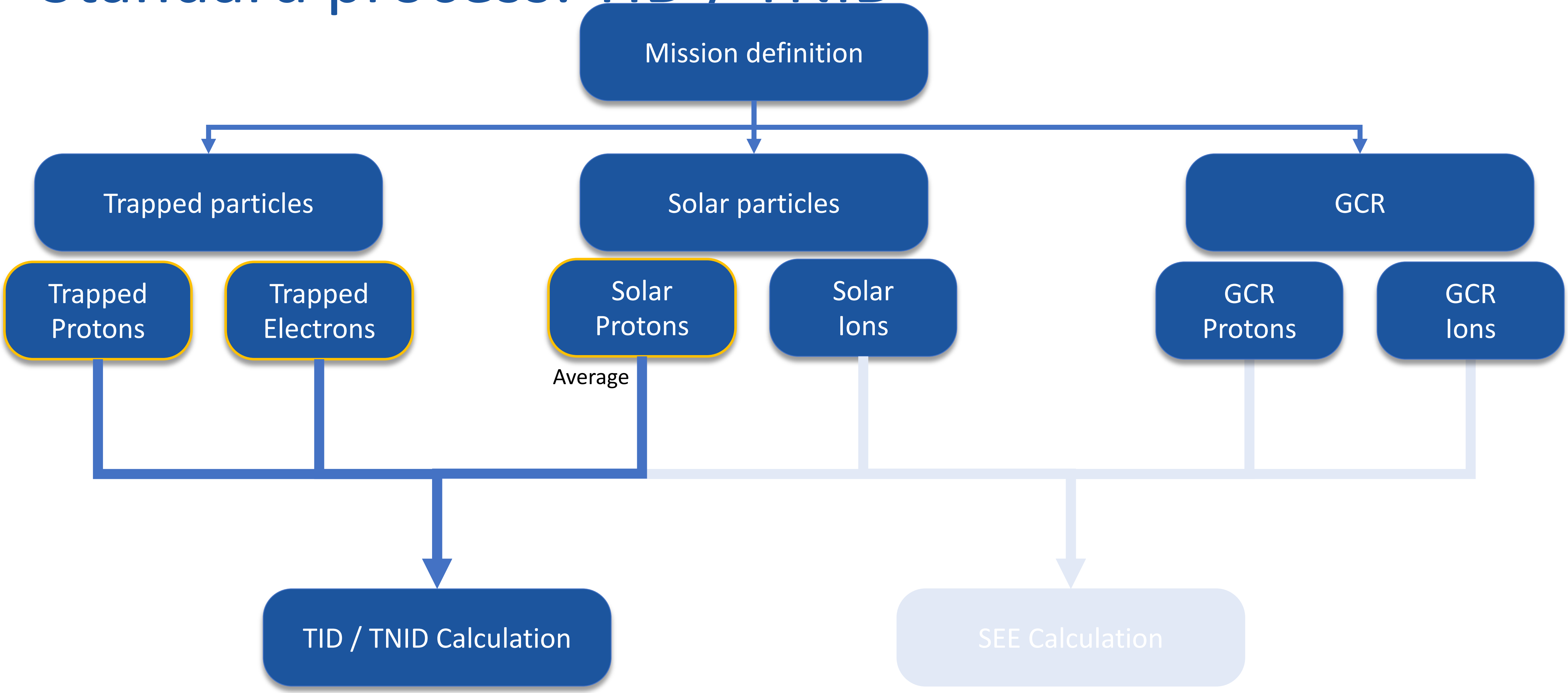
- **Non-destructive effects**
  - SEU (Single Event Upset)
    - A change of state induced, that may occur in digital, analog, and optical components, these are “soft” errors in that a reset or rewriting of the device causes normal device behavior thereafter
  - MBU (Multiple Bit Upset)
    - An event inducing the corruption of several bit in the same word/memory address
  - MCU (Multiple Cell Upset)
    - An event induced by a single energetic particle that causes multiple upsets or transients during its path through a device or system
  - SET (Single Event Transient)
    - Transient perturbation in analog devices
  - SEFI (Single Event Functional Interrupt)
    - Functionality loss in complex devices

Introduction

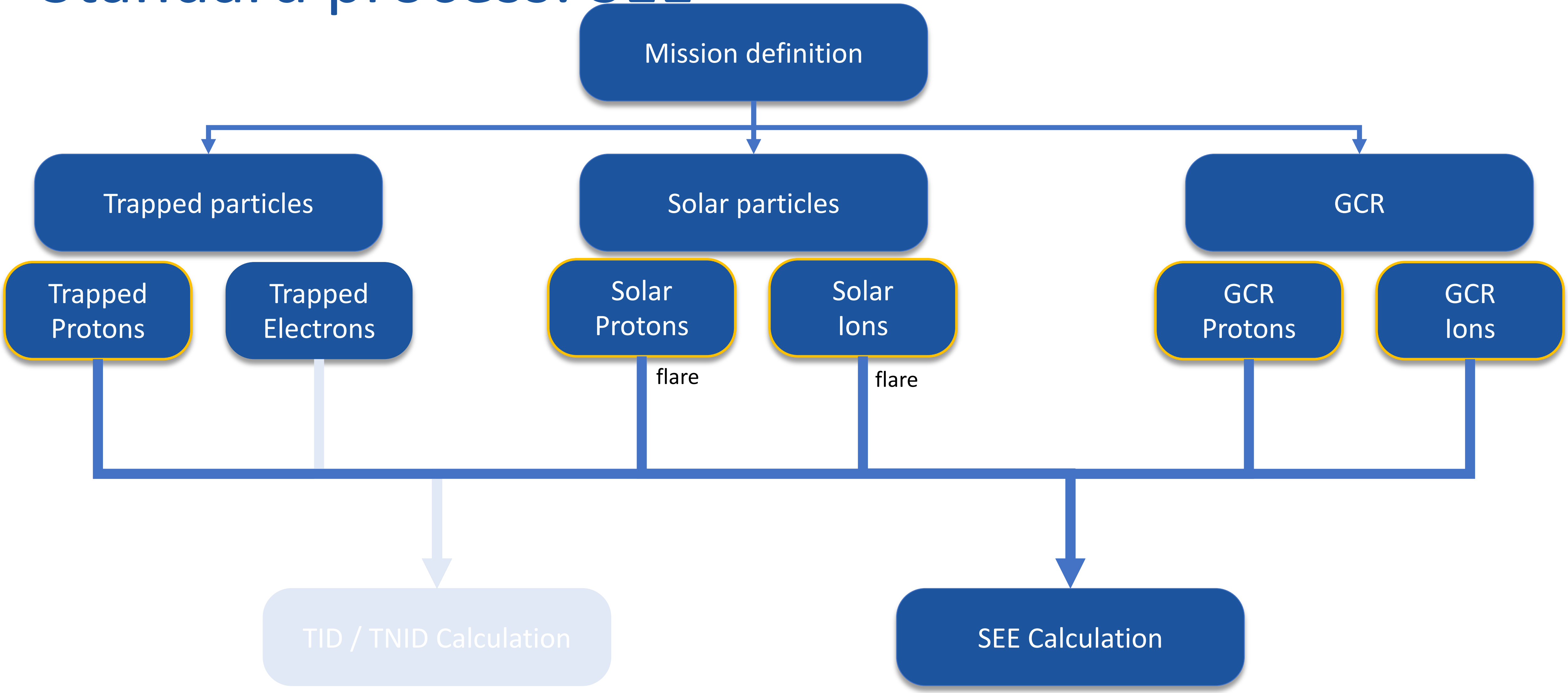
- **Destructive effects**

  - SHE (Single Hard Error or Stuck Bit)
    - An SEU which causes a permanent change to the operation of a device, like a stuck bit in a memory.
  - SEGR (Single Event Gate Rupture)
    - An ion induced condition in power Mosfet which may result in the formation of a conducting path in the gate oxide.
  - SEB (Single Event Burnout)
    - A condition which can cause device destruction due to a high current state in a power transistor.
  - SEDR (Single Event Dielectric Rupture)
    - Destructive event occuring in FPGA, AOP…
  - SEL (Single Event Latch-up)
    - A condition which causes loss of device functionality due to a single event induced high current state, that may (or may not) cause permanent damage, but requires power reset of the device to resume normal operation.

Standard process: TID / TNID



Standard process: SEE



SEE rate calculation

SEE Basic Mechanisms and Model

- Charge deposition and collection
  - There are plenty of different SEE that can potentially occur in a device
  - They are all initiated by the same scheme
    - An energetic particle passes through the device
    - Energy is transmitted to the semi-conductor by ionization
    - A large amount of charge is generated on the ion path
    - The generated charge is collected and leads to an event

- SEE are « isolated » events taking place in a device, caused by only one particle strike
  - The SEE sensitivity is not represented by an irradiation level (like for TID/TNID)
  - The SEE sensitivity is represented by a probability of occurrence
    - Specific to the event type
    - Specific to the device

SEE Basic Mechanisms and Model

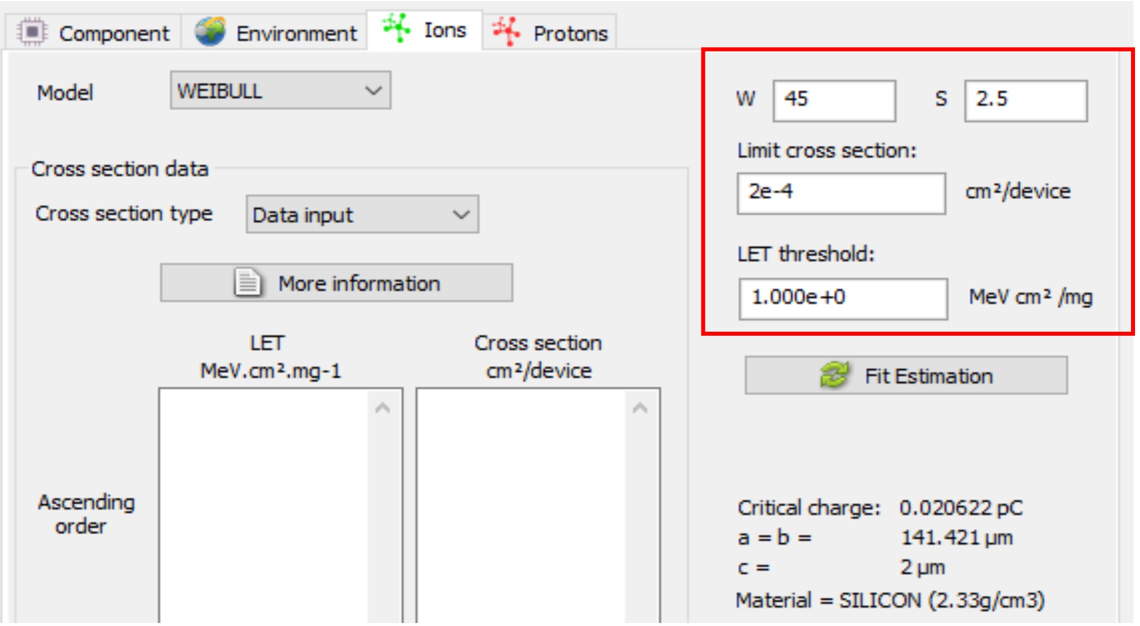
- This probability is called the device Cross Section
  - The device cross section represents the sensitivity of a device to a given SEE under specific conditions. It is the experimental ratio of counted events divided by received ions
  - The cross section is represented as a function of
    - The LET under heavy ions
    - The energy under protons

$$\sigma = \frac{event\_number}{fluence} = \frac{\#}{\phi}$$

- LET concept
  - Linear Energy Transfer
  - The LET characterizes the amount of energy that a particle yields along its path in the matter
  - The higher the LET, the more the energy deposition in the device is important
  - LET and Energy are two different things…

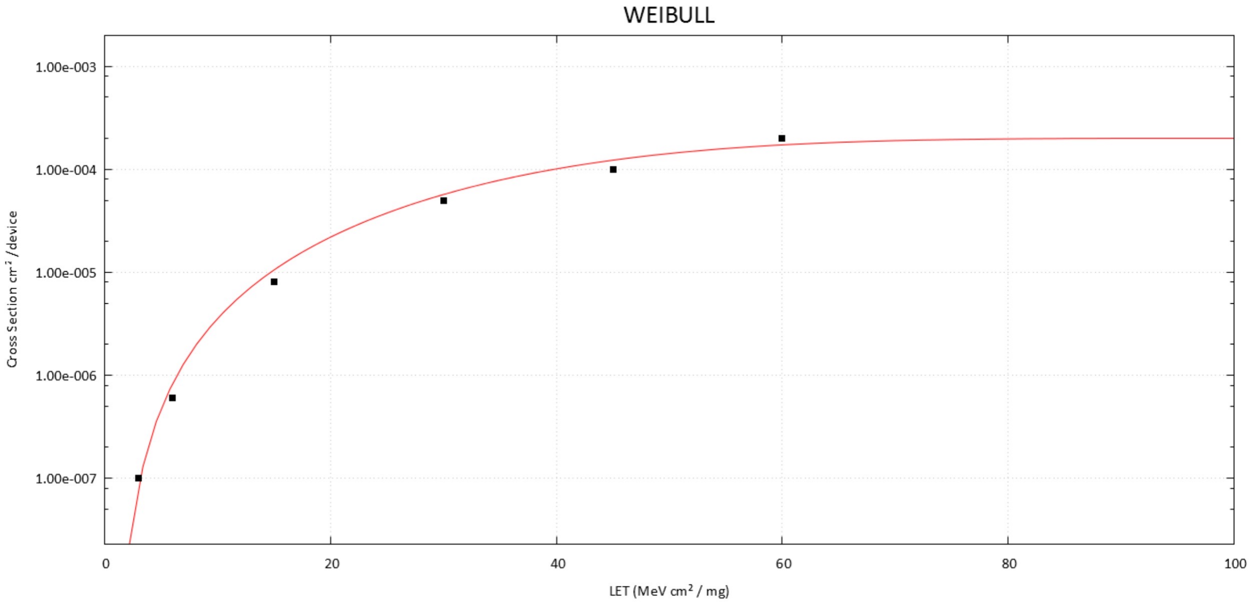
Cross section

$$F(L)=\sigma_0\left[1-exp\left(-\left(\frac{L-L_0}{W}\right)^S\right)\right]$$



- Weibull fit parameters
  - W (width)
  - S (shape)
  - σ_{SAT} (saturated cross section)
  - L_{th} (threshold LET)

- Weibull curve
  - Weibull distribution (red curve) fitted to the test data (black dots)

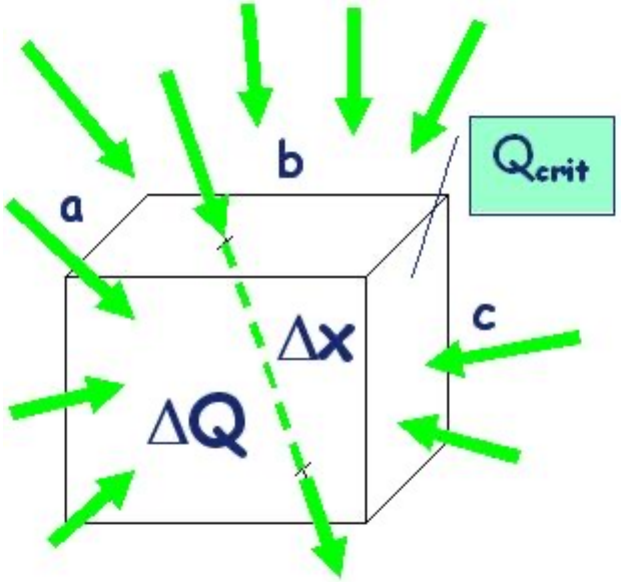


SEE caused by Ions: CREME and RPP Method

- CREME (Cosmic Ray Effect on Electronics)
  - Adams, 1986

- Assumption
  - Rectangular Parallelepiped (RPP) sensitive volume
  - Constant LET all along ion path
  - Qcrit critical charge of this sensitive volume
  - If $Q_{dep} > Q_{crit}$ then an event occur

- CREME enables to calculate the SEU rate in a given sensitive volume characterized by a specific LET threshold
  - Calculation parameters
    - a, b and c
    - L_{th}



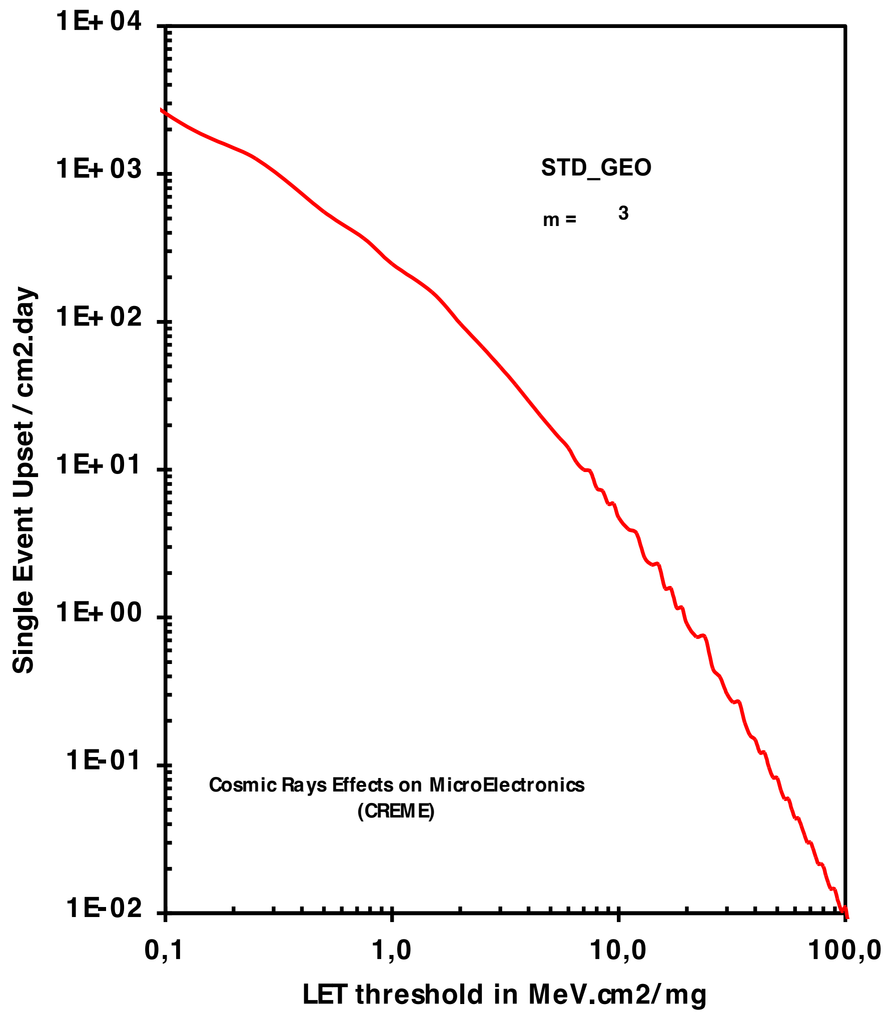
$$\Delta Q \geq Q_{crit}$$

$$\Delta Q \propto \Delta E = LET_{Si}^{ion}(E) \cdot \Delta x$$

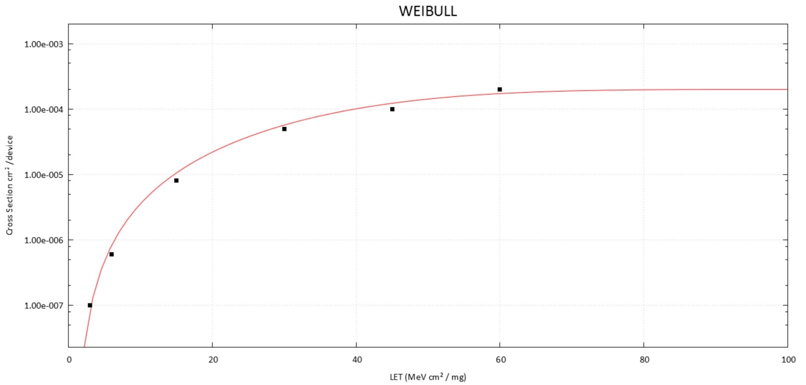
Single Cell Rate

- For a given sensitive volume
  - The SEU rate is calculated with the UPSET module of CREME86 (included in OMERE)

- For the entire device
  - The single-cell rate is correlated to the device under-irradiation response with OMERE



Interpretation of Data



- LET threshold (or on-set LET)
  - Minimum LET for which an event can occur
- All cells do not have the same LET threshold in a device
  - Progressive increase of the cross section curve
- The information of the SEE susceptibility of the entire device (including all cells) depending on the LET is given by the cross section curve
  - The rate for one sensitive volume (one L_{th}) is calculated at all LET and integrated over the whole cross section curve
- This SEE rate is calculated by OMERE
  - With the CREME rate calculated for one cell with a specific LET threshold
  - Taking into account the whole device sensivity as a function of the LET

Interpretation of Data

- Weibull distribution

$$\Sigma(L)=\Sigma_0\left[1-\exp-\left(\frac{L-L_0}{W}\right)^S\right]$$

- Number of cells for which
  - Lth < L

$$N(L)=N_0\left[1-\exp-\left(\frac{L-L_0}{W}\right)^S\right]$$

- LET threshold distribution

$$\zeta(L)=\frac{dN(L)}{dL}$$

- CREME rate (at each LET)

T(L) CREME

- Device SEE rate
  - Integration over the whole cross section curve

$$\tau=\int_{L_0}^{\infty}\mathrm{T}(L)\zeta(L)dL$$

SEE Caused by Protons

❑Proton cross section

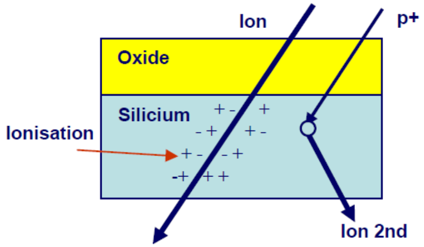
- Only one particle type (proton)
- No need to use the LET
- Proton-caused SEE are indirect
  - No geometry/angle effect taken into account
- Cross section expressed as the function of the incident energy

❑Proton SEE rate

- Product of the cross section multiplied by the flux at each energy

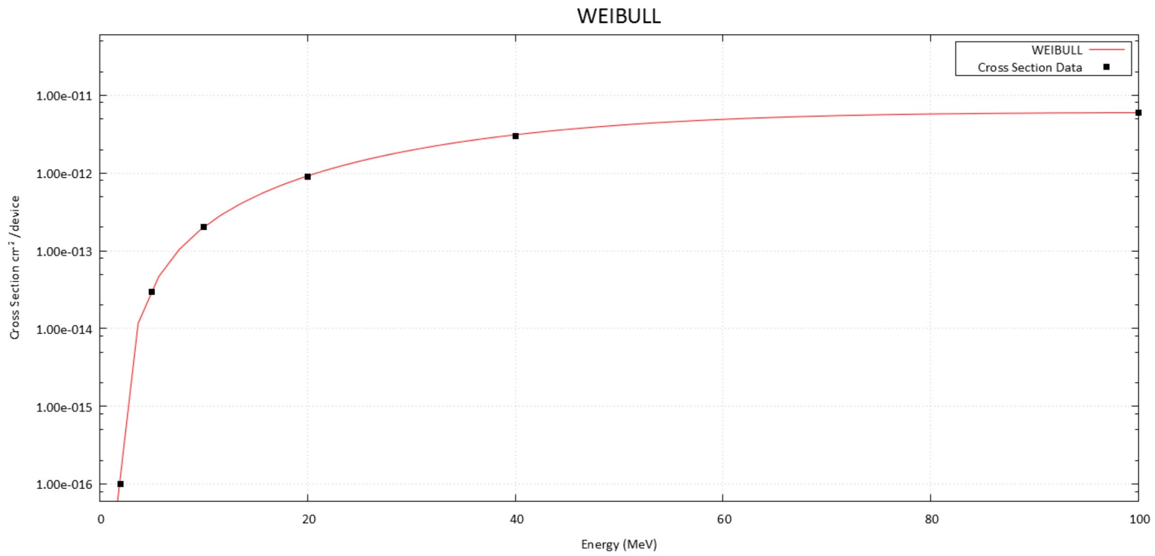
$$\tau_{p+} = \int_{E_0}^{\infty} \varphi(E)\Sigma(E)dE$$

❑Device considered as potentially sensitive to protons if the heavy ion LET threshold is smaller than 15 $MeV.cm^2.mg^{-1}$



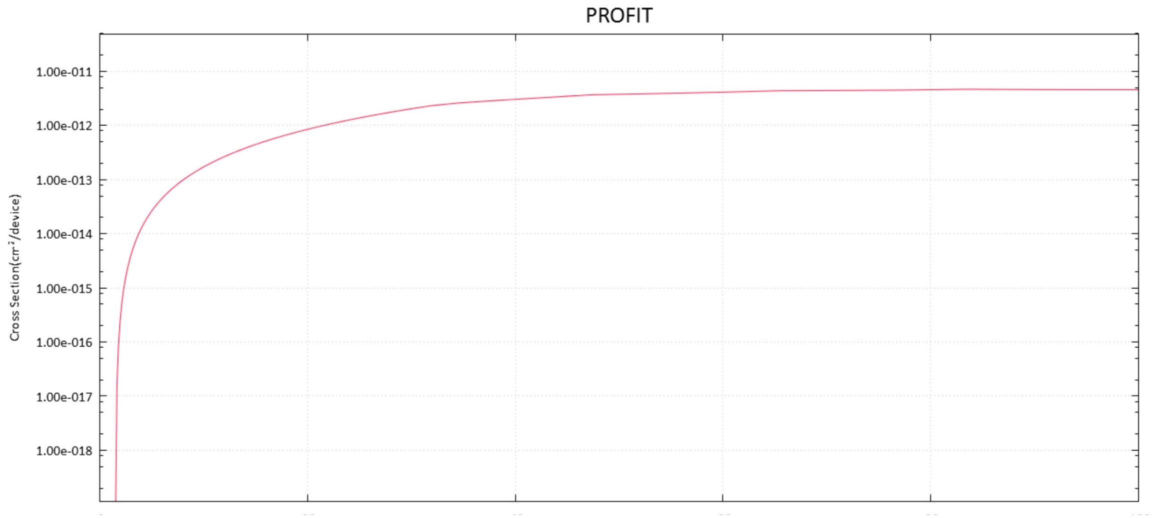
SEE Caused by Protons

- ❑ Proton cross section test data (black dots) fitted to a Weibull distribution (red curve)



- ❑ The proton cross section can be deduced from the heavy ion cross section
  - PROFIT *P. Calvel, et al. December 1996.*
  - SIMPA *B. Doucin, et al. June 1994.*
  - METIS *C. Weulersse, et al. April 2011.*

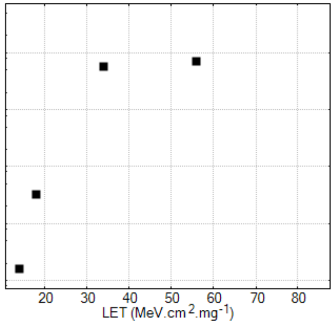
    → Dedicated to SEU rates on SRAMs



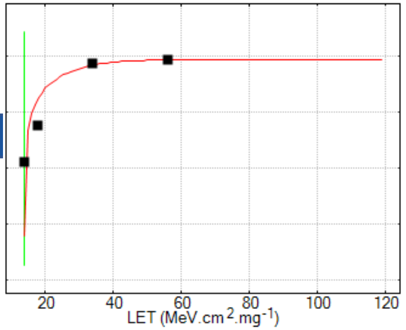
SEE Rate: Heavy ion summary

Number of cells easy to define for SEU on memories.

For other cases, (i.e. destructive events) **1 cell gives worst-case results**

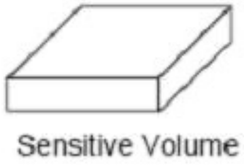


Heavy ion sensitivity
(test data)

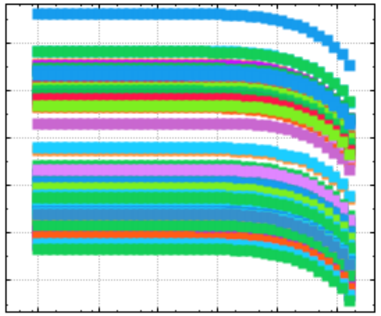


Heavy ion sensitivity
(Weibull Fit)

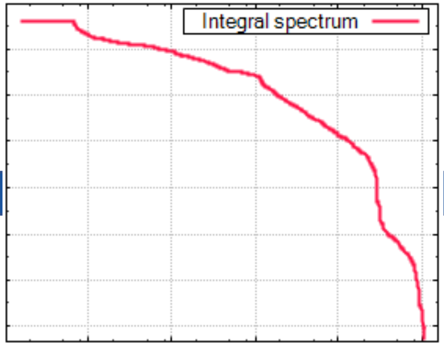
ERROR RATE



Device description
(number of sensitive cells
and SV depth)

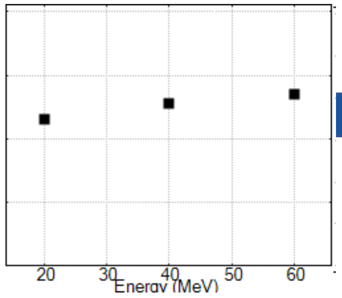


Space environment
(Integral fluxes)

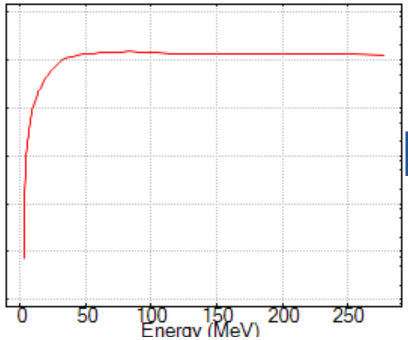


Space environment
(LET spectrum)

SEE Rate: Proton summary



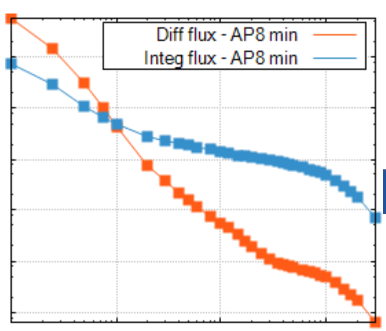
Proton sensitivity
(test data)



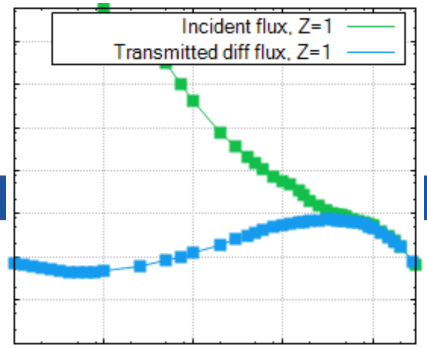
Proton sensitivity
(Weibull Fit)

ERROR RATE

$$\tau_{p+} = \int_{E_0}^{\infty} \varphi(E)\Sigma(E)dE$$



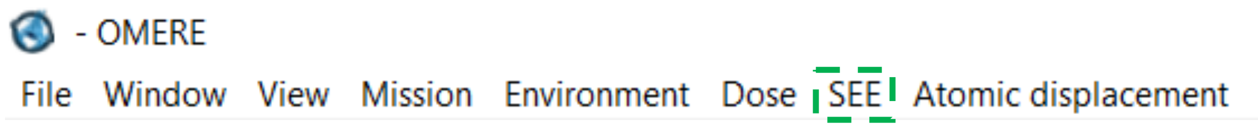
Space environment
(Incident flux)



Space environment
(Transported flux)

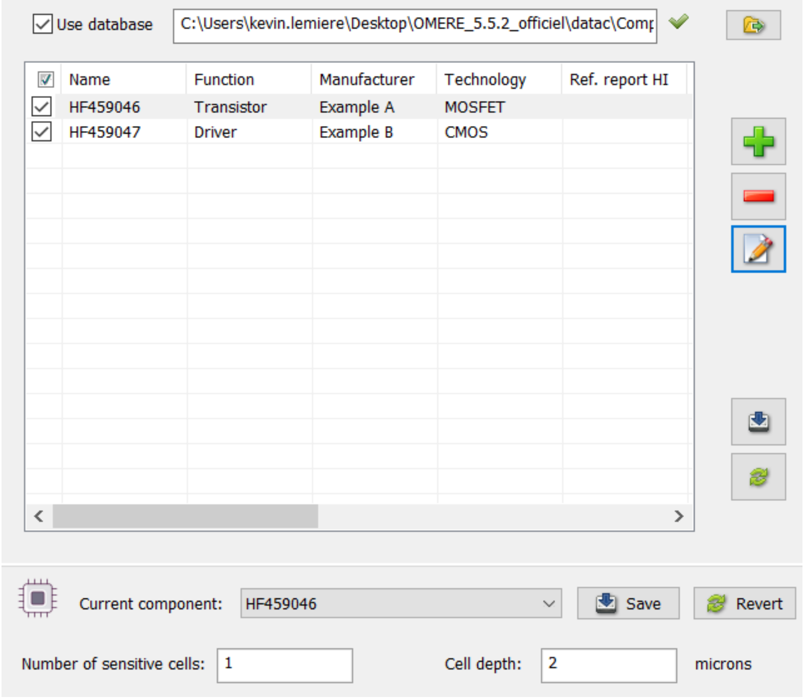
OMERE SEE Module

OMERE SEE module



❑The SEE rate is calculated considering:

- LET spectrum for ions / Transported flux for protons
- Cross sections data (Weibull fit, experimental data…)
- Calculation parameters: Number of sensitive cells and cell depth



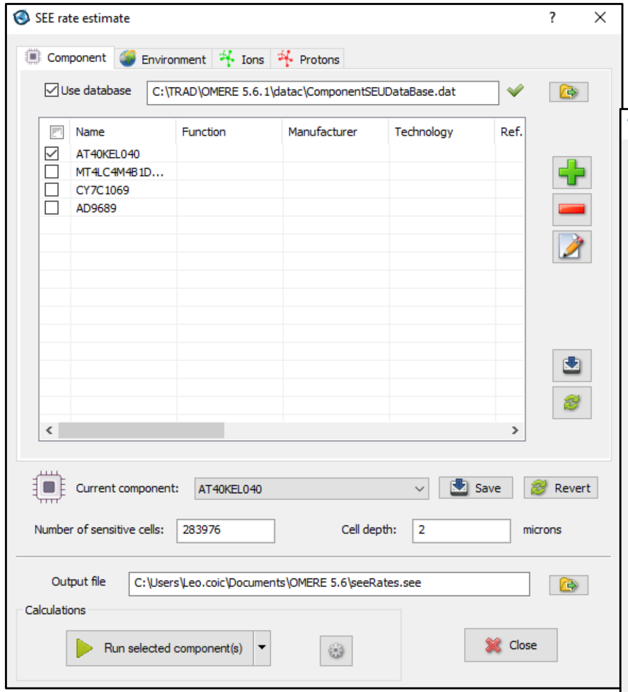
❑Inputs: energy spectra

- *From mission*: the LET spectrum and transported proton flux are calculated considering the mission and models selected in the environment tools, have to choose the shielding thickness
- *From files*: user directly inputs the LET spectrum and the transported proton flux

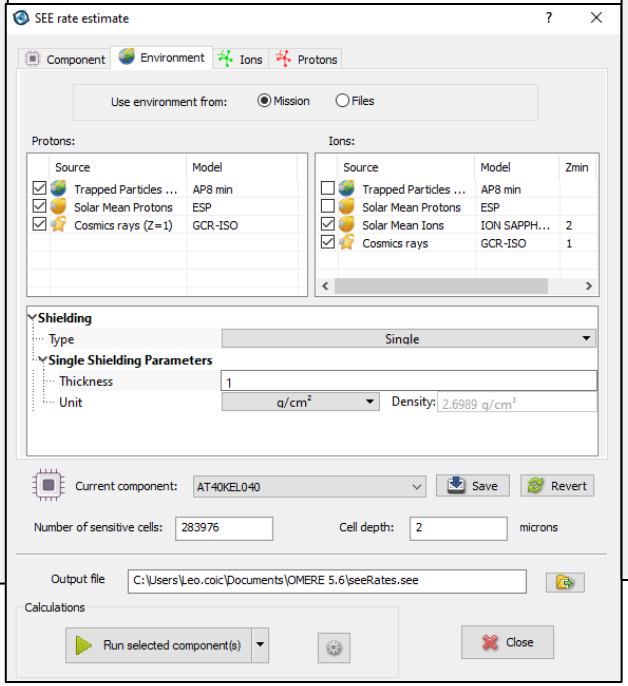
❑Output:

- The SEE rate is computed for each source of particles

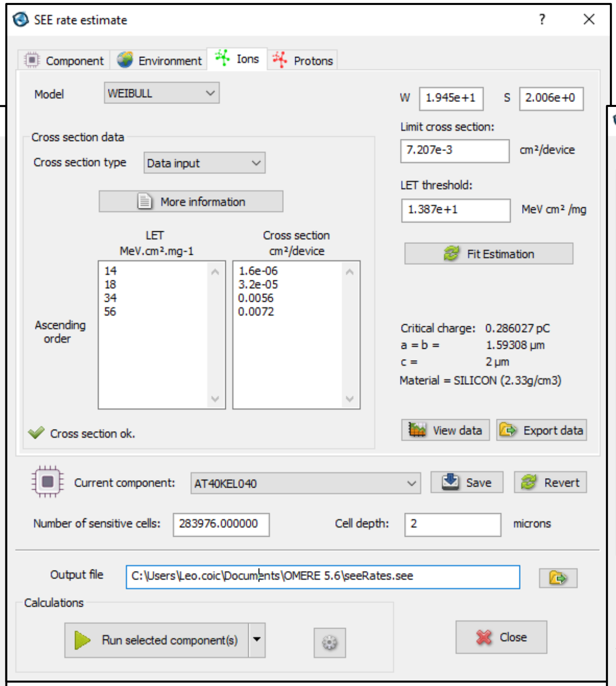
OMERE SEE module



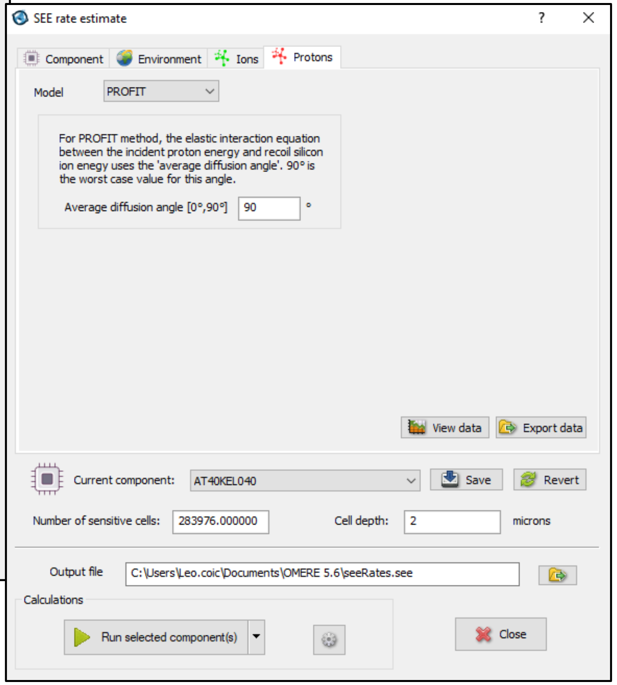
Component Database



Environment definition



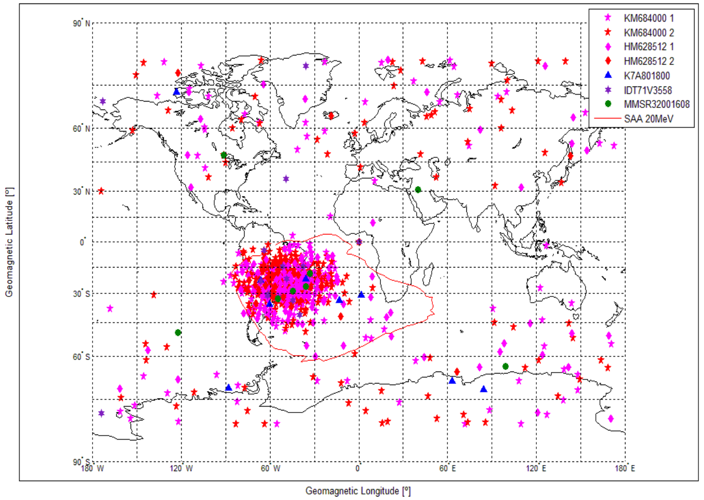
Heavy Ion Cross-section



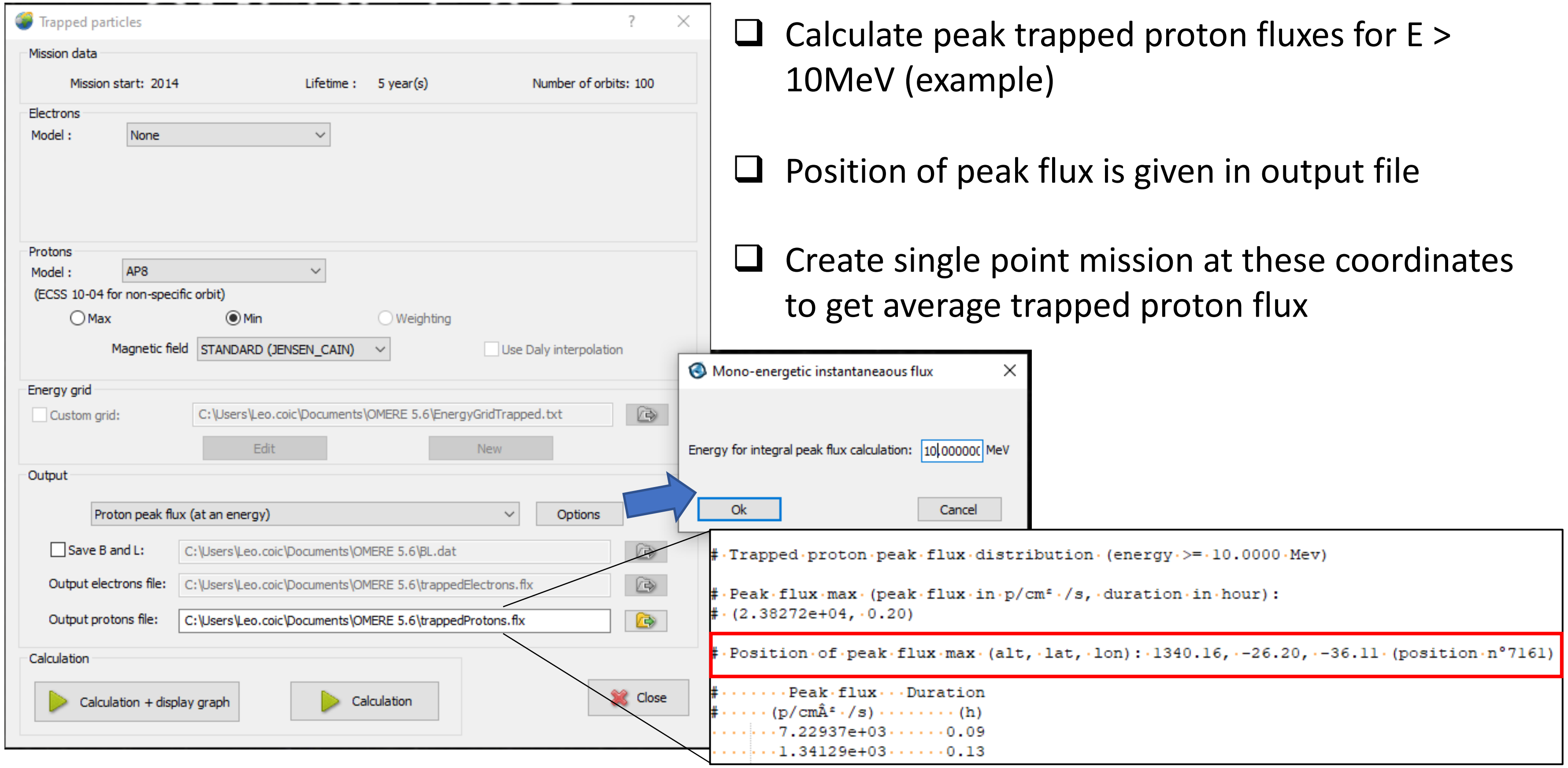
Proton Cross-section

Specific case: SAA peak trapped proton flux

- LEO or EOR missions: Crossing the SAA → High flux of trapped protons



SEU occurrences on several memories for a LEO mission



- Calculate peak trapped proton fluxes for E > 10MeV (example)
- Position of peak flux is given in output file
- Create single point mission at these coordinates to get average trapped proton flux

Calculation example

SEE rate calculation exercise I

- Mission specification

Orbit Inclination Lifetime Nominal launch date	MEO, 1000 km, 26768 km 63,4° 5 2012

- Environment specification (out of flare)

Electrons	Deselect all
Trapped protons	AP8 MIN
GCR	GCR ISO H to U

To be transported behind 1g/cm²

- Example FPGA SEU test data
  - 283976 bits → 283976 sensitive volumes

LET (MeV.cm2.mg-1)	σ (cm2.dev-1)
14	1,6E-6
18	3,2E-5
34	5,6E-3
56	7,2E-3

SEE rate calculation exercise II

❑Mission specification

Orbit Inclination Lifetime Nominal launch date	1336km circular 66° 5 2014

❑Environment specification

Trapped protons	AP8 MIN
GCR protons	GCR ISO H to H
GCR ions	GCR ISO He to U
Solar flare (WD) protons	CREME96 H to H
Solar flare (WD) ions	CREME96 He to U

To be transported behind 1g/cm²

❑Example SRAM SEL test data

- How many sensitive volumes?

LET (MeV.cm2.mg-1)	σ (cm2.dev-1)
5	2E-05
10	2E-02
20	1,2E-01
32	2E-01

Heavy-ion data

Weibull parameter	Value
W	25
S	1,5
σsat (cm²/dev)	3,0E-8
Eth (MeV)	25

Proton data

SEE rate calculation exercise III

- Mission specification

Orbit	800Km Peak Proton flux
Longitude	-30°
Latitude	-30°
Duration	5 minutes (~0,0035 days)

- Environment specification

Electrons	Deselect all
Trapped protons	AP8 MIN

To be transported behind 1g/cm²

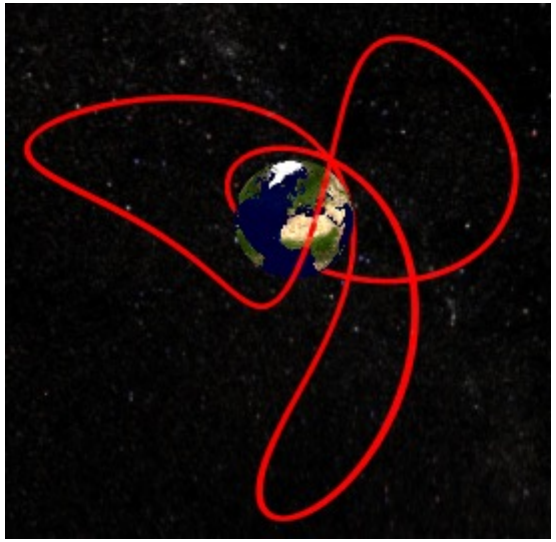
- Example DRAM SEU proton test data
  - How many sensitive volumes?

Proton Energy (MeV)	σ ($cm^2.bit^{-1}$)
20	2,1E-15
40	3,7E-15
60	5,1E-15

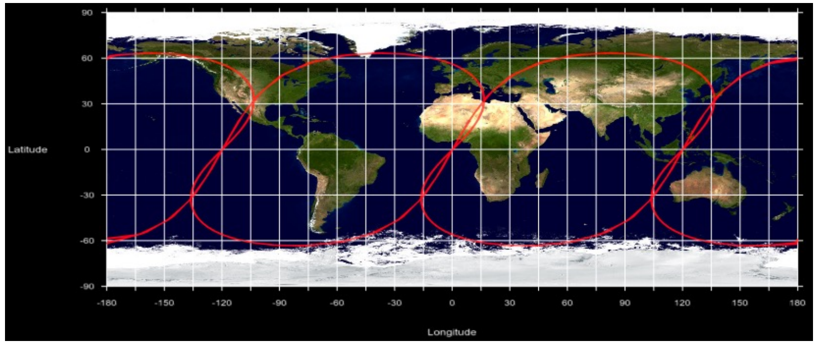
Calculation example solution

SEE rate calculation solution I

- Example FPGA SEU rate for the MEO mission
  - 283976 sensitive volumes



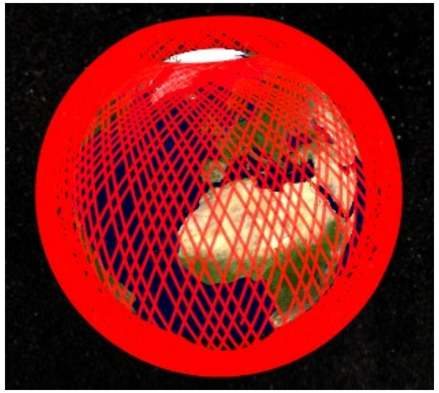
Heavy ion total rate	Proton total rate	Total rate
/device/day	/device/day	/device/day
1.1E-04	1.2E-06 (PROFIT 90°)	1.1E-04

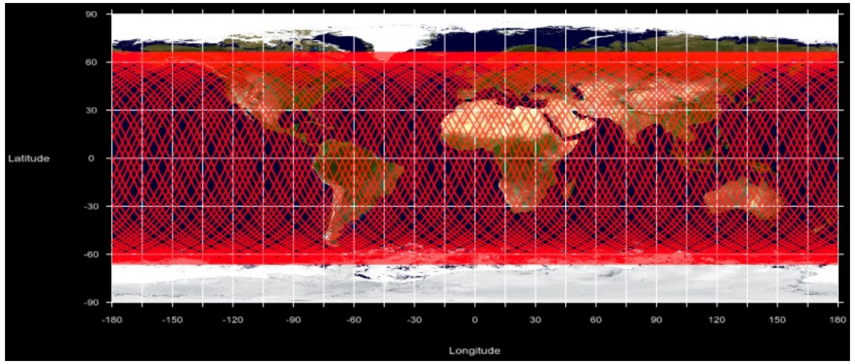


SEE rate calculation solution II

- Example SRAM SEL rate for the LEO 1336km mission
  - 1 sensitive volume (because SEL)

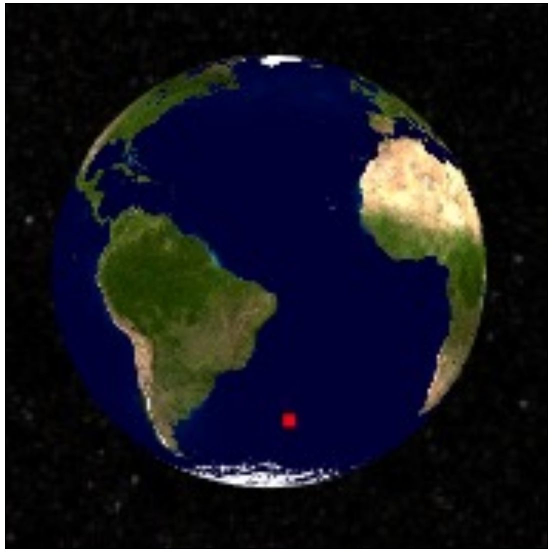
out-of-flare			during flare				
Trapped proton	GCR		Trapped proton	Solar particles		GCR	
	HI	proton		HI	proton	HI	proton
/dev/day	/dev/day	/dev/day	/dev/day	/dev/day	/dev/day	/dev/day	/dev/day
1.72	0.14	3.83E-3	1.72	39.2	3.64	0.14	3.83E-3





SEE rate calculation solution III

- Example DRAM SEU rate peak proton flux LEO 800Km
  - 1 sensitive volume (because rate /bit)



Proton Peak rate	Proton Peak rate
/bit/day	/bit/5m
2.26E-6	7.91E-9

x0,0035