A Simulation Tool
to Predict Displacement Damage Effects in Electronic Components

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Project Objective

- Design and implementation of a software simulation tool (pilot-study) allowing

  - to calculate displacement damage effects in semiconductors induced by external radiation

  - to estimate the resulting parameter degradation in electronic circuit components.

- Aim: Reduce (expensive) ground tests of electronic components to be specified for space missions.

Basic Pre-requisites

Possible radiation effects in semiconductors

- Transient ionisation effects (*electron-hole pairs*)
  Exceeding a critical charge may result in SEUs
  (latch-up, burnout, gate rupture)

- Long-term ionisation effects *(electron-hole pairs)*
  Trapped immobile charges may cause permanent parameter changes
  (shift of threshold voltage, e.g. in MOSFETs)

- Atomic displacement effects *(interstitial-vacancy)*
  Primary knock-on atoms (PKAs) and secondary displaced atoms, both resulting in Frenkel pairs and subsequent defect formation may cause serious parameter degradation
  (CCD dark current, LED light output, max. power of solar cells …)

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Displacement Damage

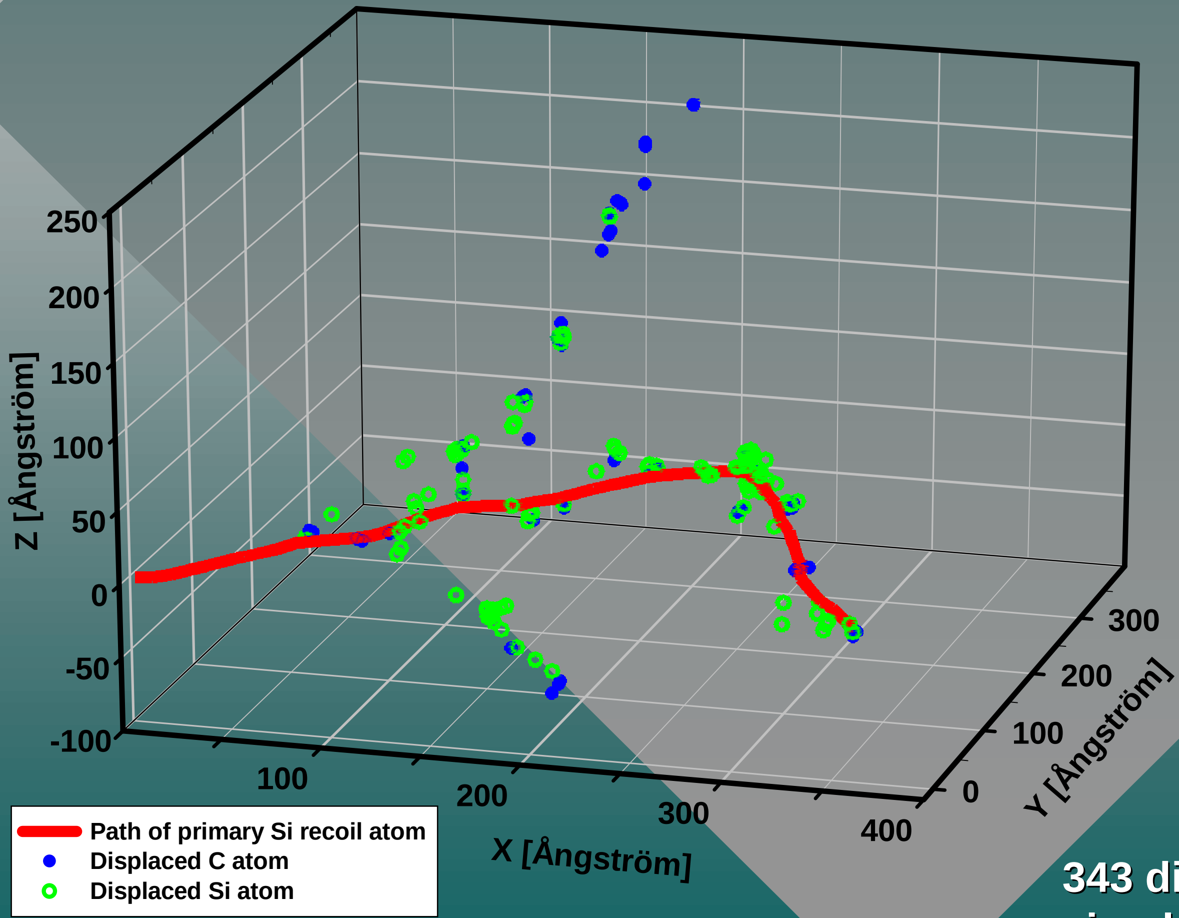
Component	Lifetime Degrad.	Carrier Removal	Charge Trapping	Mobility Degrad.
Si MOS Transistors & ICs				S
CCDs		P	P	
Si Bipolar Transistors & Linear ICs	P	S		
Photodetectors	P			
LEDs & Laser Diodes	P			
pn Junctions	P	P	P	
JFETS		P	P	S
GaAs Transistors & ICs		P		S

Accord. to: C.J. Marshall and P.W. Marshall, NSREC Short Course 1999, Norfolk, VA (1999)

P **Primary failure** **S** **Secondary failure**

Atom Displacement in SiC

Path of a 30 keV primary Si recoil starting at (0,0,0) in a SiC lattice and creating displaced C and Si atoms



343 displacements simulated with SRIM

NIEL Scaling Concept

Ionising	**Non-Ionising**
• **LET**	• **NIEL**
• **Dose** D	• **Displ. Damage Dose** D_d
• D = LET$\times\Phi$	• D_d = NIEL$\times\Phi$

- **In many cases surprisingly good linear relationship between NIEL and device degradation (e.g. max. power output of solar cells).**
- **For the same NIEL value, device degradation often is the same, independent of particle type and energy.**

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NIEL Scaling (I)

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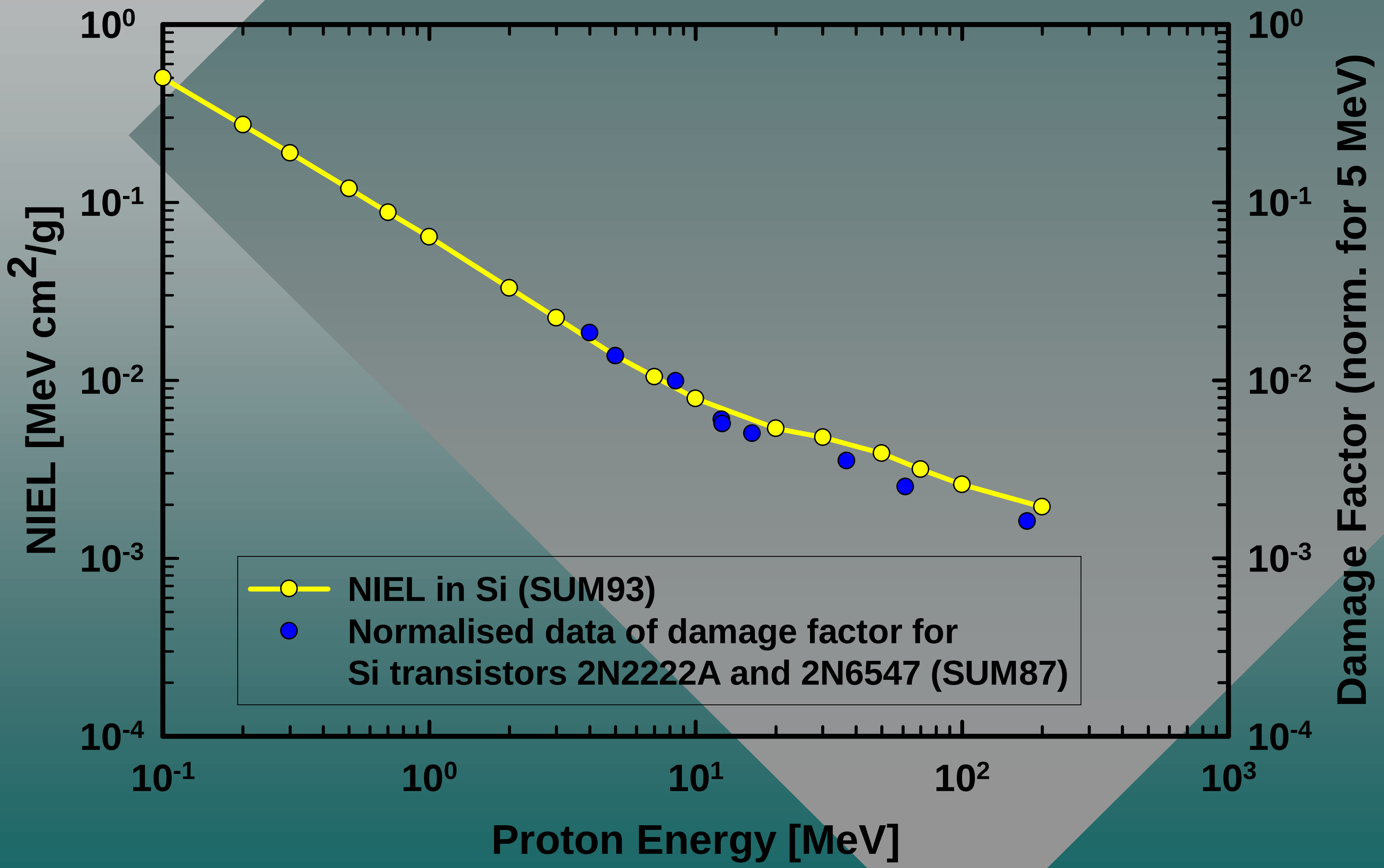
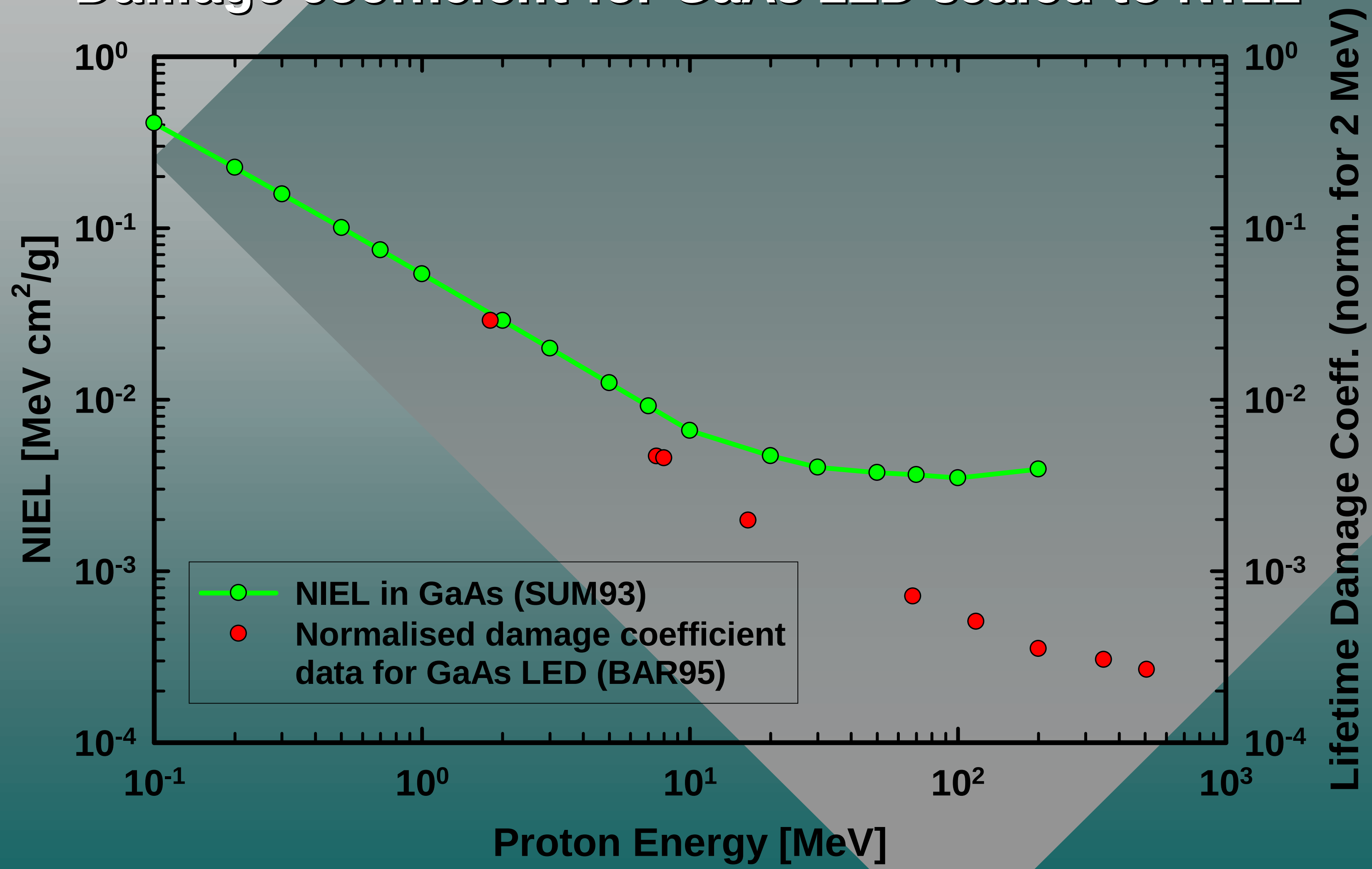
Damage factors for Si transistors scaled to NIEL



NIEL Scaling (II)

Damage coefficient for GaAs LED scaled to NIEL



Scheme of Space Radiation

Primary radiation environment

SPENVIS / Orbit generator & fluence models

Spacecraft shield & device shield

Secondary radiation environment

SPENVIS / MULASSIS

Active volume of irradiated component

Non-ionising energy loss (NIEL)

Resulting displacement damage

Parameter degradation

Simulation Tool

GEANT 4

Steps of Prediction Process (I)

(1) Irradiate device under well-defined conditions (*monoenergetic particles, normal incidence, total dose …*)

(2) Measure resulting device degradation

(3) Calculate device degradation as a function of displacement damage dose based on the irradiation experiment

Steps of Prediction Process (II)

(4) Define radiation environment for specific space mission

(5) Calculate radiation environment behind shielding

(6) Calculate displacement damage dose for mission

(7) Estimate onboard device degradation based on results of step 3 and step 6

Simulation Tool / User Interf.

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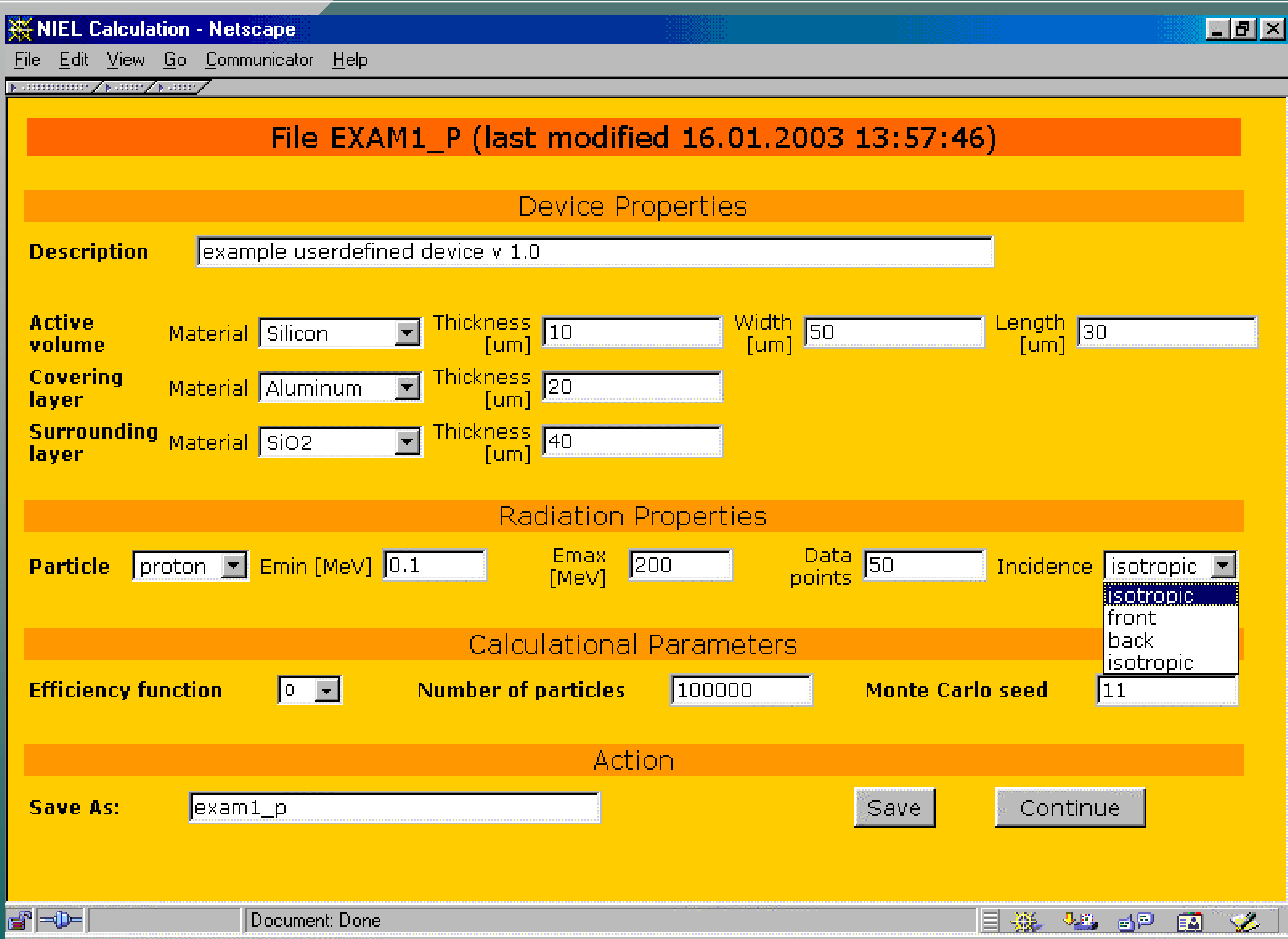
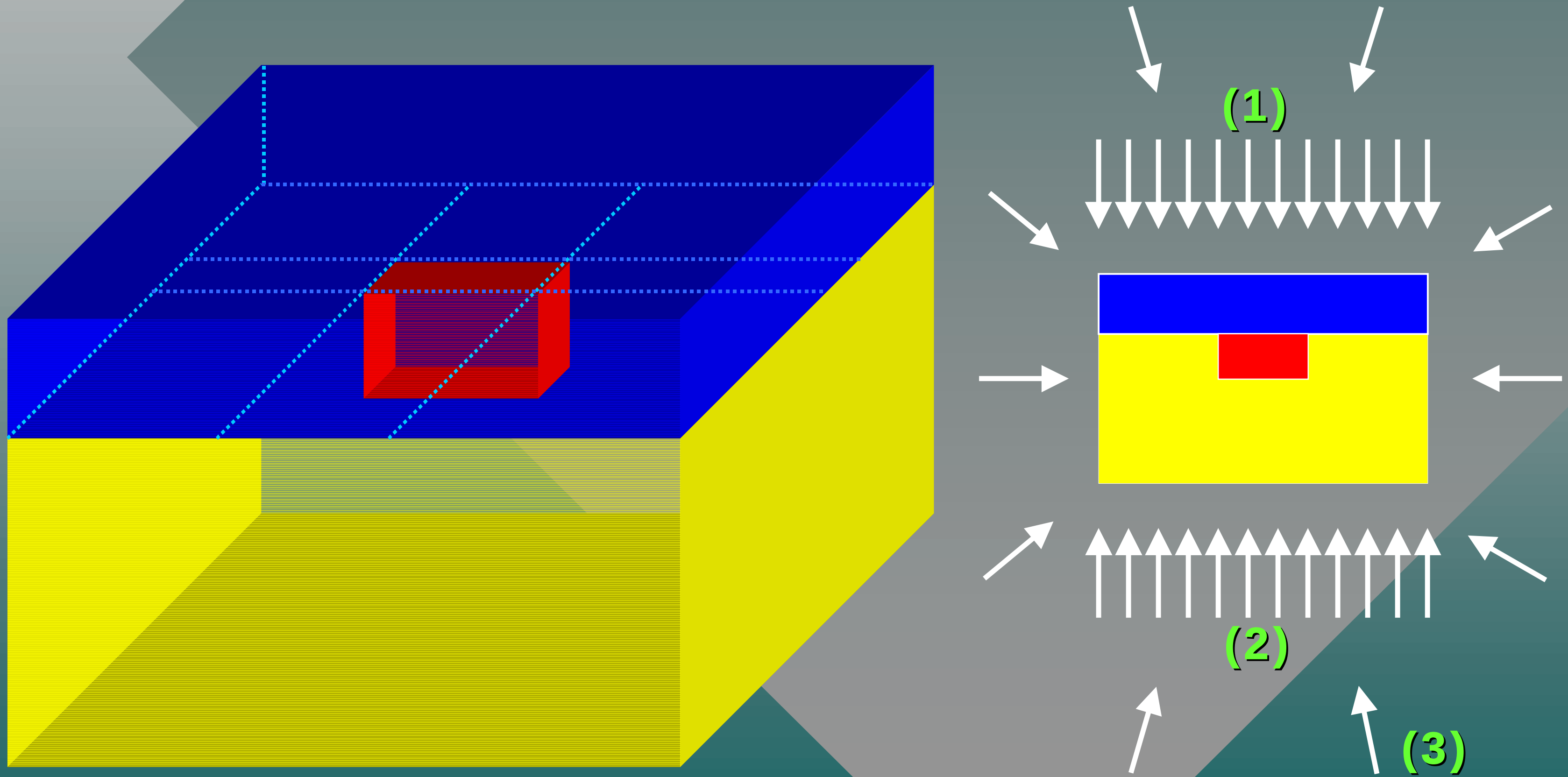


Irradiation Geometry

Geometry options of the simulation tool allow particle irradiation from front (1), back (2) and isotropic (3)



Active volume **Covering layer** **Surrounding layer**

NIEL Calculation (I)

Processes to be considered

- **All interactions between space radiation environment and arbitrary semiconductor material (in a spacecraft), that transfer sufficient energy to an atom to leave its lattice site (≈ 21 eV in Si)**

Max. Energies to be considered (near Earth)

- **Protons:** E<300 MeV
- **Electrons:** E<10 MeV
- **HZE:** E<300 MeV/nucleon
- **Second. Neutrons:** E<300 MeV

Min. Energies to be considered (to displace Atoms in Si)

- **Protons:** ≈ 150 eV
- **Electrons:** ≈ 220 keV
- **Second. Neutrons:** thermal, since (n_{th},γ) may cause recoils (e.g. (n_{th},γ) in Si leading to ≈ 1.28 keV recoils)

NIEL Calculation (II)

Algorithmic approach

- **Contribution of a given recoil to NIEL:**

$$NIEL(E) = \frac{N_A}{A} \int_{T_{\min}}^{T_{\max}} dT\, Q(T)\, \xi(T)\, T \left(\frac{d\sigma}{dT} \right)_E$$

E	**Kinetic energy of impinging particle**
T	**Kinetic energy of recoil or fragment**
$d\sigma/dT$	**Differential partial cross section for recoil creation**
Q(T)	**Fraction of T being lost by non-ionising processes (Lindhard partition)**
$\xi(T)$	**Empirical efficiency function (optional)**
N_A/A	**Number of atoms per gram**

NIEL Calculation (III)

Additional requirements

- Use GEANT 4 physical models to gain the kinematics of the generated recoils and fragments
- Consider non-equilibrium conditions in small volumes by following up the recoils in a larger volume
- Improve statistics of non-elastic events responsible for fluctuations of energy deposition (e.g. causing pixel-to-pixel variation of the dark current signal in CCDs) by biasing during Monte-Carlo calculation

Presently, we are checking out the appropriate GEANT 4 physical interaction modules