WP8: SEE simulation capabilities for FLUKA.CERN

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https://indico.cern.ch/e/radnext-2024

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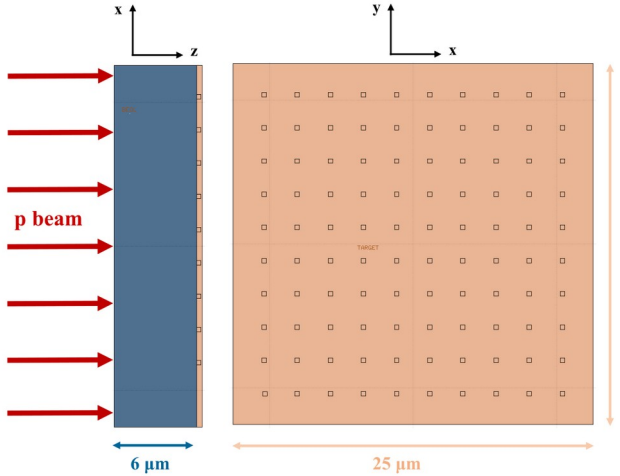
Outline

- Monte Carlo simulations of Single Event Effects
- FLUKA.CERN v4 – The current, 4th generation
- FLUKA.CERN v5 – The next, 5th generation
- The G4SEE toolkit
  - Capabilities
  - User guides, tutorials
  - Validation
- Ongoing & Future Work
- Summary

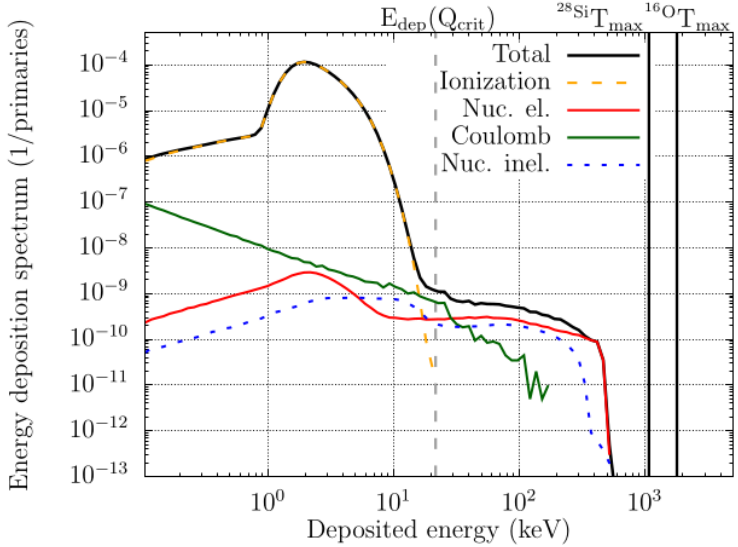
Monte Carlo simulations of SEEs

SEE rate prediction based on a single rectangular parallelepiped (RPP) or Integral RPP models, using Monte Carlo (MC) particle transport simulation tools to get energy deposition due to particle-matter interactions along each trajectory



Images by Alexandra-Gabriela Serban (CERN)

RPP simulation geometry (10 x 10 RPPs) for a proton irradiated SRAM memory in FLUKA v4 [1], visualized using Flair GUI



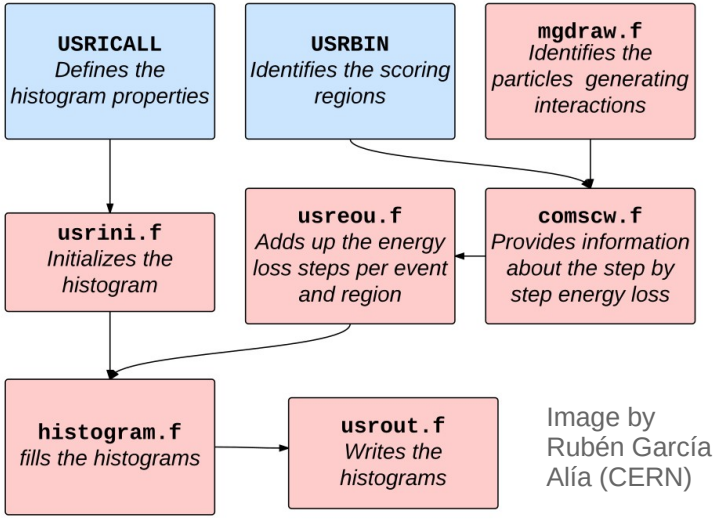
Energy deposition distribution of 8 MeV protons in the SRAM memory's RPPs simulated with FLUKA v4 [1]; Contribution of various interactions of primary protons, and critical charge (Q_{crit}) value of SRAM cell are shown [1]

[1] A.-G. Serban et al., *"Nuclear elastic scattering of protons below 250 MeV in FLUKA v4-4.0 and its role in SEU production in electronics,"* arXiv:2312.12300 [physics.comp-ph], 2023

FLUKA.CERN v4

Website: https://fluka.cern

- **Multi-purpose MC particle transport simulation package** developed by the FLUKA.CERN collaboration [2]
- **SEE scoring capabilities are limited:**
  - Biasing (non-analog MC runs) for single event scoring to reduce variances was not implemented
  - Multi-group neutron transport (Recently the point-wise treatment was added too)
  - Neutron-induced secondary charged particles were not produced and tracked explicitly
- **Custom event-by-event scoring user routine [3]** was developed by Ketil Røed (Uni. of Oslo) and Rubén García Alía (CERN)
  - This user routine was used for simulation on prev. slide, and many other simulation studies in CERN R2E project
  - It is not part of FLUKA v4 package (!)
- **These served as motivation of this work**



Schematic diagram of the FLUKA input cards (blue) and custom user routines (red) used in the event-by-event energy deposition scoring with FLUKA v4 [3]

[2] FLUKA collaboration: *"New Capabilities of the FLUKA Multi-Purpose Code"*, Front. Phys., 2022
[3] R. García Alía: "*Radiation Fields in High Energy Accelerators and their impact on Single Event Effects*", PhD thesis, 2014

FLUKA.CERN v5

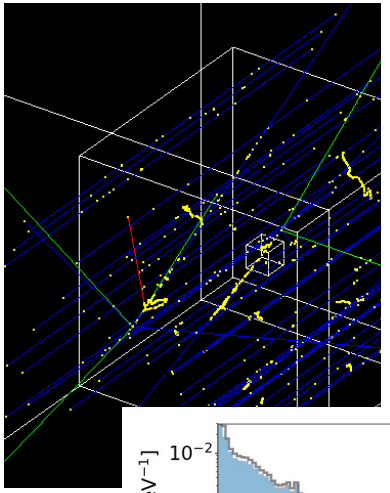
Website: https://fluka.cern

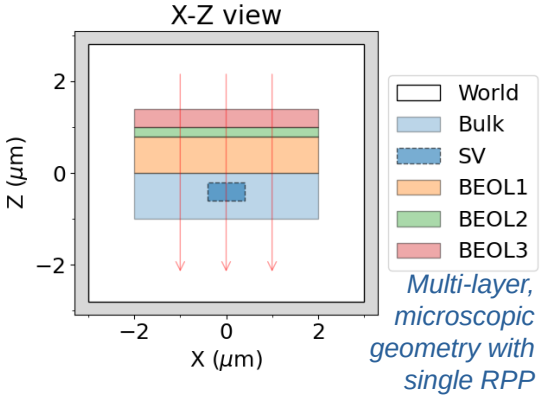
- Physics performance of FLUKA v4 is being improved and extended continuously
- Concurrent development activity is ongoing for several years now [4]:
  - 1st devel. stage: **Moira, a new application** has been developed as an exploratory prototype, which already reached a sufficient level of maturity
  - 2nd devel. stage: Currently, Moira is being distributed internally for testing and further developments as **the new, 5th generation of FLUKA: the FLUKA v5**
- FLUKA v5 code is **written in C++**, its architecture has evolved substantially into **a modular and maintainable structure**
- Based on the **Geant4 (G4) simulation framework**, enabling the use of all the G4 physics models directly, plus FLUKA hadron inelastic physics too
- **All FLUKA v4 capabilities are being implemented** in this G4-based application (geometry, transport, scoring, biasing, v4 physics models, etc.)
- Full compatibility the Flair GUI

[4] G. Hugo on behalf of FLUKA.CERN collaboration, *"Latest FLUKA developments"*, in Proc. SNA+MC 24, Paris, France (2024)

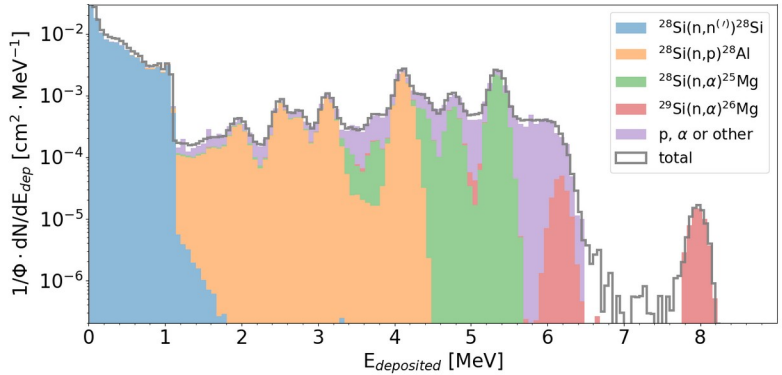
The G4SEE toolkit

- **G4SEE** is a **Geant4-based Monte Carlo Single Event Effect** (SEE) simulation toolkit [5]
- **Direct and indirect event-by-event energy deposition scoring** in a microscopic, user-defined sensitive volume enabling SEE cross-section (rate) estimation
- **Focusing on SEEs**, while remaining as **general** and **user friendly** as possible
- **Free and open-source**, therefore available for the whole radiation effects community for a wide variety of use cases
- **G4SEE scoring features are being progressively integrated to FLUKA v5**, which is relatively easy and straightforward thanks to the fact both are G4-based applications





Multi-layer, microscopic geometry with single RPP

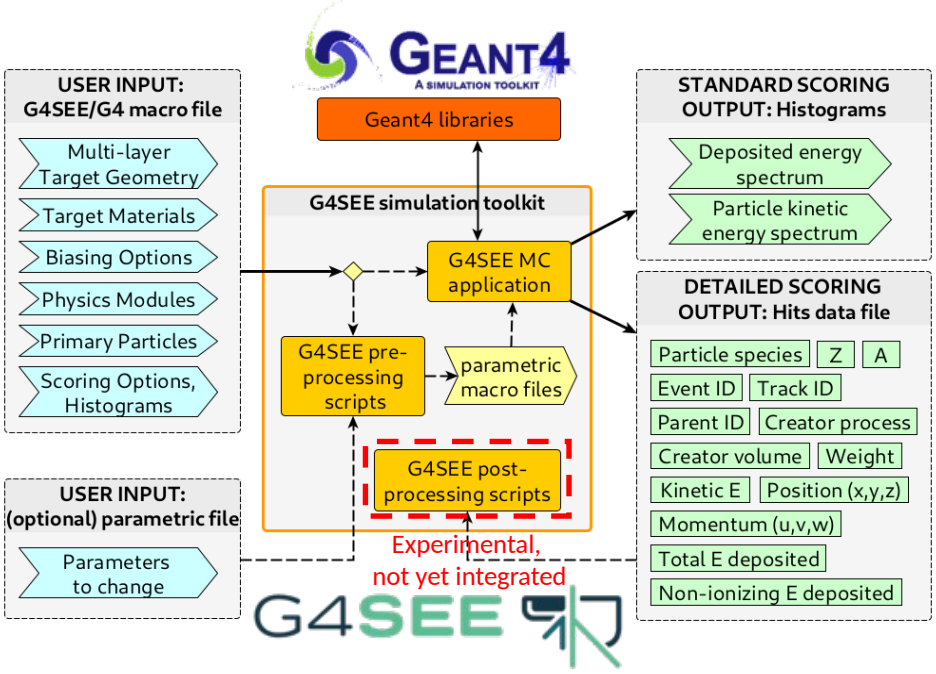


[5] Dávid Lucsányi et al., *"G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements"*, in IEEE TNS, 2022

G4SEE / Capabilities

- User input via a Geant4-style text file (macro)
- Simplified, multi-layered target geometry with custom user-defined materials
- Users-built, modular physics list with user-defined production range cuts for secondary particles
- Arbitrary primary particle source
- Particle interaction biasing (microscopic XS)
- Simple “standard” scoring of the event-by-event total $E_{deposited}$ in SV, and $E_{kinetic}$ of particles entering or produced in SV (filtered by particle species)
- Advanced “detailed” scoring of all individual particle hits in SV, saved to a CSV output file + Grouping e^-, e^+ and y particles produced per event to reduce verbosity and size of output file
- Auxiliary pre- and post-processing scripts to add extra functionalities

[5] Dávid Lucsányi et al., *"G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements"*, in IEEE TNS, 2022



High-level architecture of the G4SSE toolkit with user inputs and outputs, and the two types of scoring mechanisms: Standard and Detailed scoring [5]

G4SEE / User guides, tutorials

Tutorial: commands how to run the G4SEE simulation with input macro file, then merge and plot histograms, and finally obtain SEU cross-section in function of critical charge for an SRAM cell

Website:
cern.ch/g4see
Source code in GitLab:
gitlab.cern.ch/g4see
Online documentation:
g4see-docs.web.cern.ch
Open-access paper:
DOI link
RADMEP 2023 lecture:
RADMEP Indico page
SERESSA 2022 lectures:
SERESSA Indico page
User Forum:
g4see-forum.web.cern.ch

```
#################
### Geometry

# BULK COMMAND
/SEE/geometry/Bulk
# SV COMMAND
/SEE/geometry/SV
```

Silicon is defined as the material of Bulk vol.

Dimensions (width and thickness) of a volume

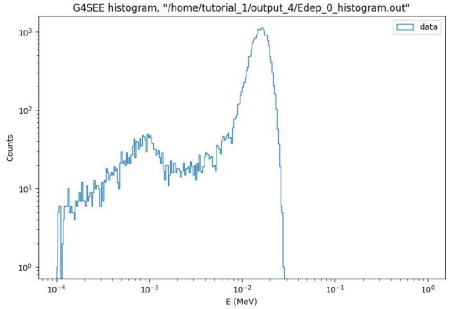
Enable/Disable biasing for a given volume

Name of given Back End Of Line (BEOL) layer

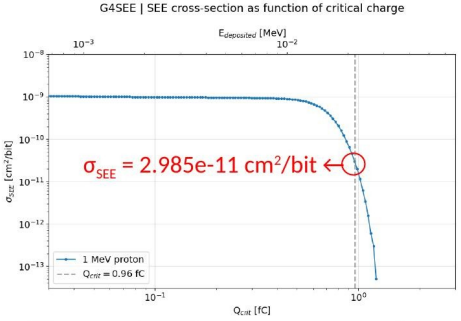
```
MATERIAL
G4_Si
POSITION unit
0 0 0 nm

WIDTH unit    THICK unit    BIAS
6 um          1 um          false
WIDTH unit    THICK unit    BIAS
310 310 nm    310 nm        false
```

Commands in G4SEE Docker container (CLI)

```
:/home# cd tutorial_1/ && mkdir output_4 && cd output_4/
:/home/tutorial_1/output_4# g4see ../tutorial_1-4.mac > stdout.log
:/home/tutorial_1/output_4# mergeHistograms .
:/home/tutorial_1/output_4# python $G4SEE_BUILD/scripts/g4see.py plot Edep_0_histogram.out
:/home/tutorial_1/output_4# python $G4SEE_BUILD/scripts/g4see.py see-xs ../config_1-4.yaml
```



Event-by-event energy deposition distribution, contribution of δ-electrons produced outside SV at lower E_{dep} values



SEE cross-section estimation at 1 MeV proton beam energy (assuming Q_{crit} = 0.96 fC) based on MC simulated E_{dep} histogram

```
# ##################################### #
# YAML config file for Tutorial 1.4     #
# ##################################### #

see-xs:

  # Input parameters
  conversion_factor:      0.022469    # MeV/fC
  critical_charge:        0.96        # fC

  # List of Edep histograms
  data:
    - path:               Edep_0_histogram.out
      label:              '1 MeV proton'
      primary_number:     2e+5
      beam_area:          1e-8    # cm2 (1x1 um2)

  # XS plot config
  xs_plot:
    xlim:                 [3e-2, 3e+0]
    ylim:                 [None, 1e-8]
    figsize:              [10, 7]
```

YAML config file

Validation / SEU cross-sections

- Monoenergetic neutron-induced event-by-event total (inelastic) energy deposition distributions were compared in 1.2–17 MeV energy range [5]
- Monoenergetic proton-induced SEU cross-sections of two 65nm SRAM memories have been measured experimentally, which then were compared to both G4SEE and FLUKA v4 simulation results obtained using the RPP modelling approach [6] → very good agreement
- Significant discrepancy between Geant4 (used by G4SEE) and FLUKA v4 nuclear elastic scattering was discovered at 2–10 MeV proton energies [6], triggering development of new nuclear elastic scattering model for FLUKA v4 [1]

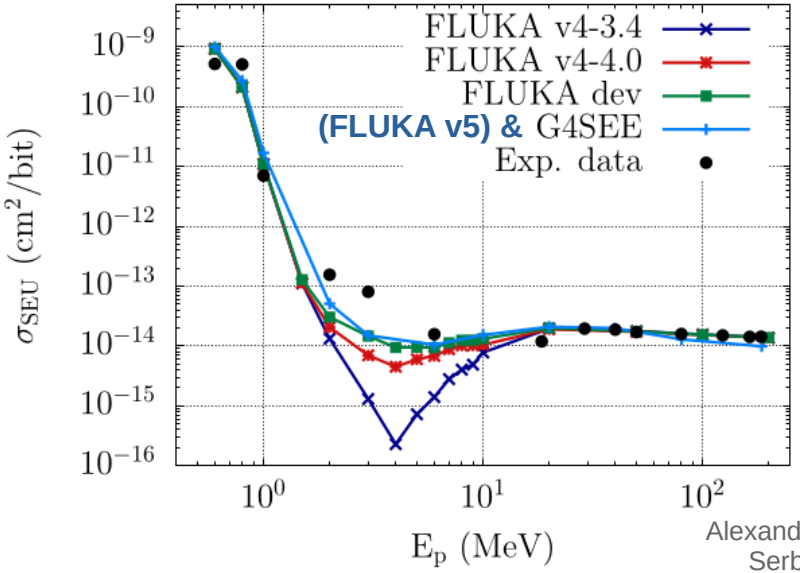


Image by Alexandra-Gabriela Serban (CERN)

*Simulated and experimental cross-sections of **proton induced SEUs** in 65-nm ISSI SRAM as function of proton beam energy [1,6]*

[1] A.-G. Serban et al., *"Nuclear elastic scattering of protons below 250 MeV in FLUKA v4-4.0 and its role in SEU production in electronics,"* arXiv:2312.12300 [physics.comp-ph], 2023
[6] Andrea Coronetti et al., *"Proton direct ionization upsets at tens of MeV"*, in IEEE TNS, 2022

Ongoing and future work

- **Maintainance of the G4SEE toolkit:**
  - New scoring features (LET scoring, Energy deposition per interaction scoring) implemented recently for G4SEE will be released soon [7]
  - Then, the maintenance and development of the standalone, open-source G4SEE toolkit continues only with minor changes and fixes
- **Development of FLUKA v5:**
  - All G4SEE features not already available in FLUKA v5, are being merged into FLUKA v5, avoiding duplication of effort and source code to maintain [4]
  - Cross-comparison studies between the FLUKA and Geant4 physics models
- **Both the G4SEE and FLUKA v5 user communities will benefit from the merging**

[4] G. Hugo on behalf of FLUKA.CERN collaboration, *"Latest FLUKA developments"*, in Proc. SNA+MC 24, Paris, France (2024)
[7] Eva Fialová, *"Development and validation of new features for the G4SEE radiation effect simulation toolkit"*, MSc Thesis, May 2024.

Summary

- **SEE simulation features** have been implemented based on the **Geant4** Monte Carlo simulation framework
- These are currently being merged into the new, **5th generation of FLUKA.CERN (FLUKA v5)** Monte Carlo simulation package, **based on the Geant4 simulation framework**
- This SEE simulation module has been released as a free and open-source, standalone toolkit called **G4SEE, the Geant4-based Single Event Effect simulation toolkit**
- Experimental validation studies with neutron and proton irradiated devices (SRAM memories, silicon diode detector) have been performed successfully
- **The G4SEE toolkit**, its **user guides and** simulation **tutorials are disseminated** within the community of radiation effects in electronics
- **RADNEXT WP8 Task 8.6 (*Integration of SEE event-by-event scoring in FLUKA*)** → DONE
  Find more details in **RADNEXT Milestone M8.3 (*Validation of FLUKA SEE module*) Report**

Thanks for your attention!

Questions?