RADMEP workshop

4–8 December 2023, CERN

Introduction to G4SEE

a toolkit for simulating radiation effects in electronics

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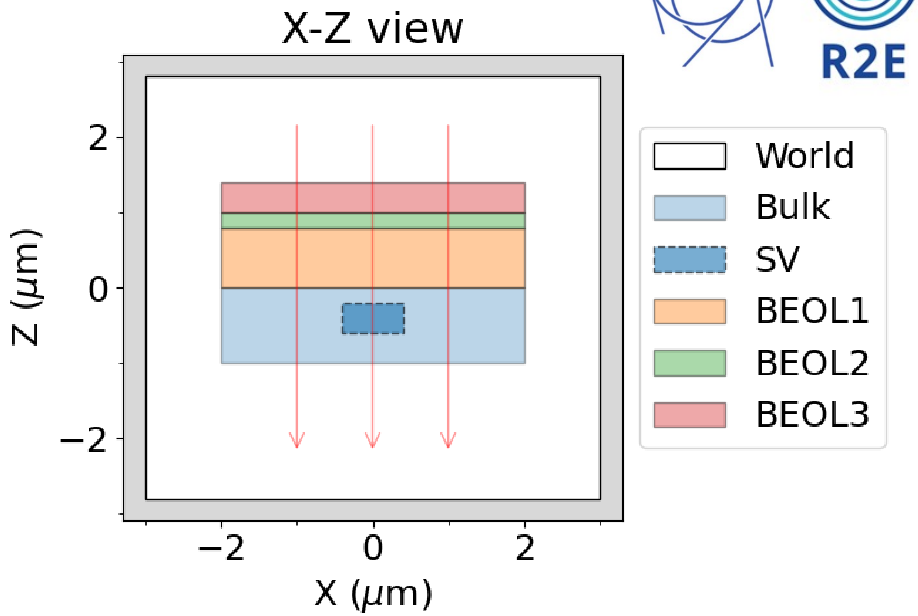
Agenda

- Introduction to G4SEE toolkit:
  - An open-source toolkit
  - Capabilities
  - User support & community
- Tutorial #1:
  - The simulation case: Proton-induced SEUs in SRAM memory
  - 1.1) General, Input/Output
  - 1.2) Geometry
  - 1.3) Primary particles, Scoring
  - 1.4) Scoring, SEE cross-section
- Tutorial #2:
  - The simulation case: Neutron interactions in Silicon (SRAM/diode)
  - 2.1) Geometry, Primaries, Scoring and Physics
  - 2.2) Biasing (non-analog Monte Carlo)
  - 2.3) Detailed Scoring
- Validation of the G4SEE toolkit with mono-energetic neutrons

Introduction – An open-source toolkit

- G4SEE is a Geant4-based Monte Carlo Single Event Effect (SEE) simulation toolkit [1]
- Free and open-source, available for the whole radiation effects community for a wide variety of use cases
- It is being developed in CERN Radiation To Electronics (R2E) project, but developers, contributors and beta testers outside CERN are also welcome!
- Progressive integration of features into FLUKA.CERN 5, but G4SEE remains also as a standalone toolkit for the community



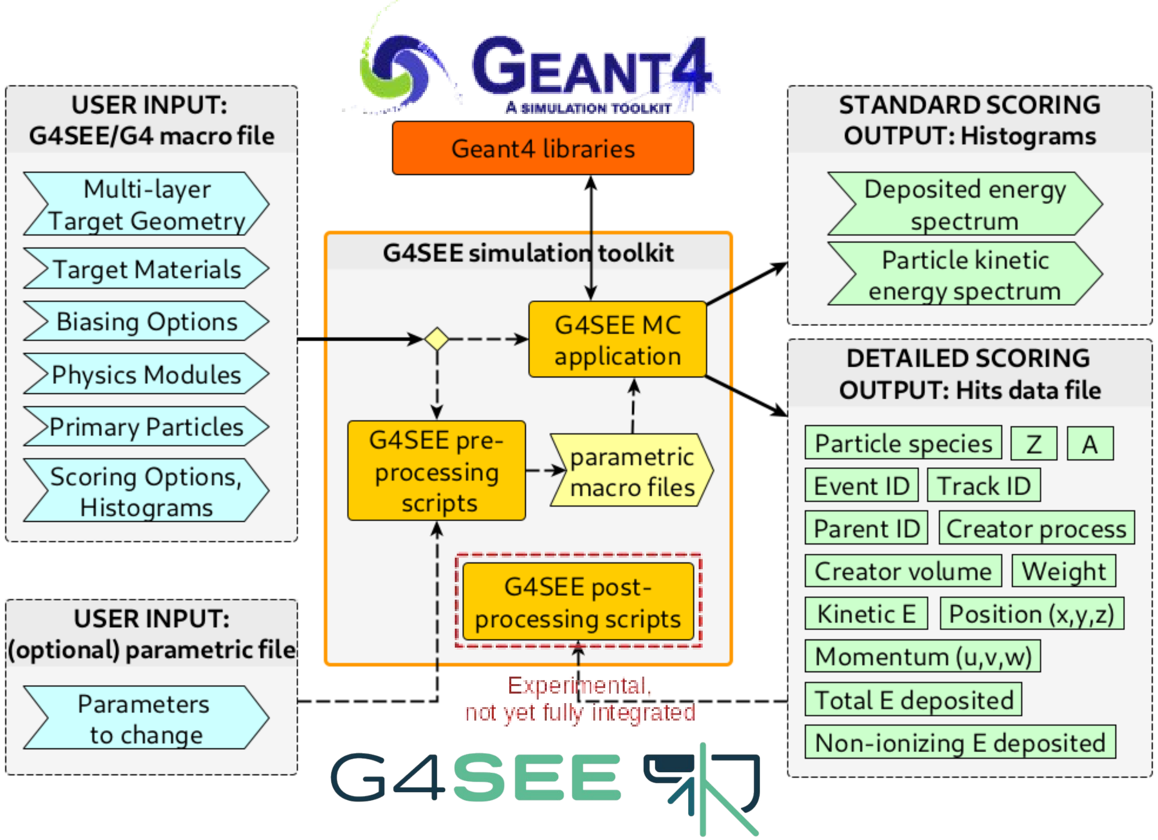
Multi-layer, micro-metric geometry used in a G4SEE simulation to obtain energy deposition in Sensitive Volume (SV), a single RPP (cuboid) models the component's SV

Reference (open-access)

[1] Dávid Lucsányi et al., "G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements," in *IEEE TNS*, vol. 69, no. 3, March 2022, [(link)]

Introduction – Capabilities

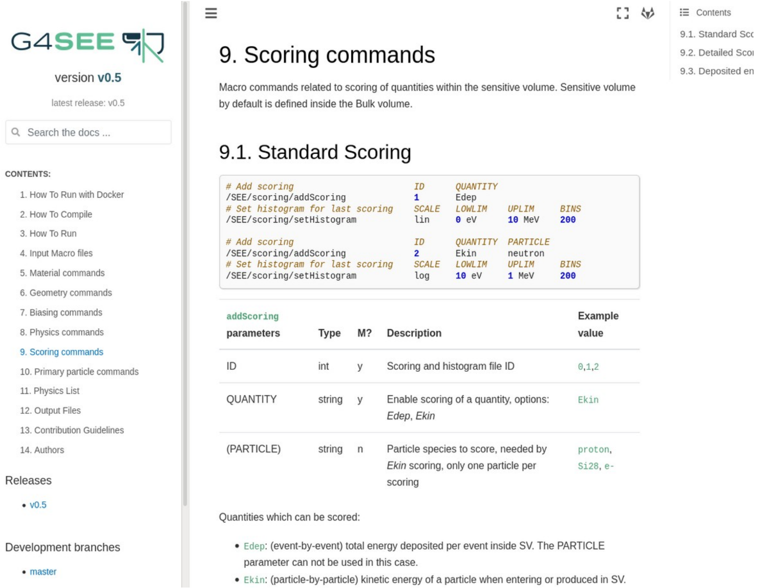
- Enables to study SEEs on a very low-level focusing on radiation-matter interactions
- Extracting low-level information relevant for SEEs, event-by-event and/or particle-by-particle, based on the needs of users
- Direct and indirect energy deposition scoring in a micro-metric, user-defined sensitive volume (RPP model) ⇒ SEE cross-section (or rate) estimation
- Primary motivation and use cases so far were neutron- and proton-induced SEEs (relevant at CERN environments)



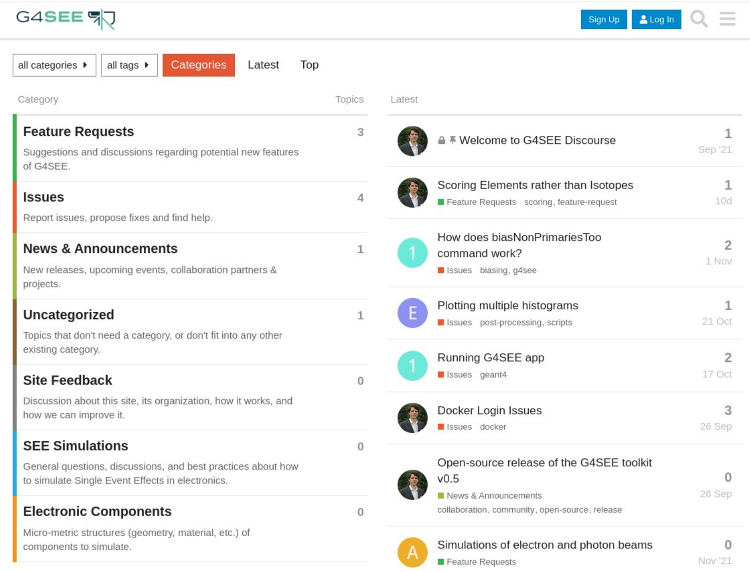
High-level architecture of the G4SSE toolkit with user inputs and outputs (ASCII files)

Introduction – User support & community

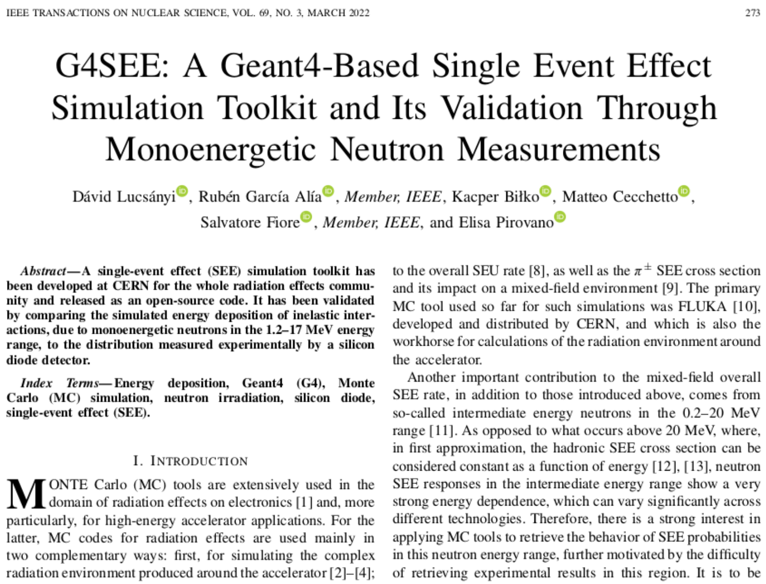
G4SEE documentation: g4see-docs.web.cern.ch



G4SEE community forum: g4see-forum.web.cern.ch



G4SEE paper in IEEE TNS: [doi.org/10.1109/TNS.2022.3149989](doi.org/10.1109/TNS.2022.3149989)



G4SEE website: g4see.web.cern.ch

Contact: g4see.toolkit@cern.ch

Introduction – Get the toolkit!

- See slides about installation guidelines on [Indico page]
- Options to run G4SEE toolkit on your computer:

Using Docker *(recommended)*

- After Docker installation, pull the latest, **G4SEE v0.5.2** Docker image
- Run a Docker container based on G4SEE v0.5.2 image (with shared folder)

CLI commands to run on host computer to start G4SEE Docker container

```
$ docker pull gitlab-registry.cern.ch/g4see/g4see:v0.5.2_G4-11.1.3
$ export DISPLAY=:0.0
$ xhost +local:docker
$ docker run -it -h g4see -e DISPLAY=$DISPLAY -v /tmp/.X11-unix:/tmp/.X11-unix \
             -v /host/path/to/shared_folder:/home \
             gitlab-registry.cern.ch/g4see/g4see:v0.5.2_G4-11.1.3
root@g4see:/home# cp –r $G4SEE_BUILD/examples/tutorial_1 /home
```

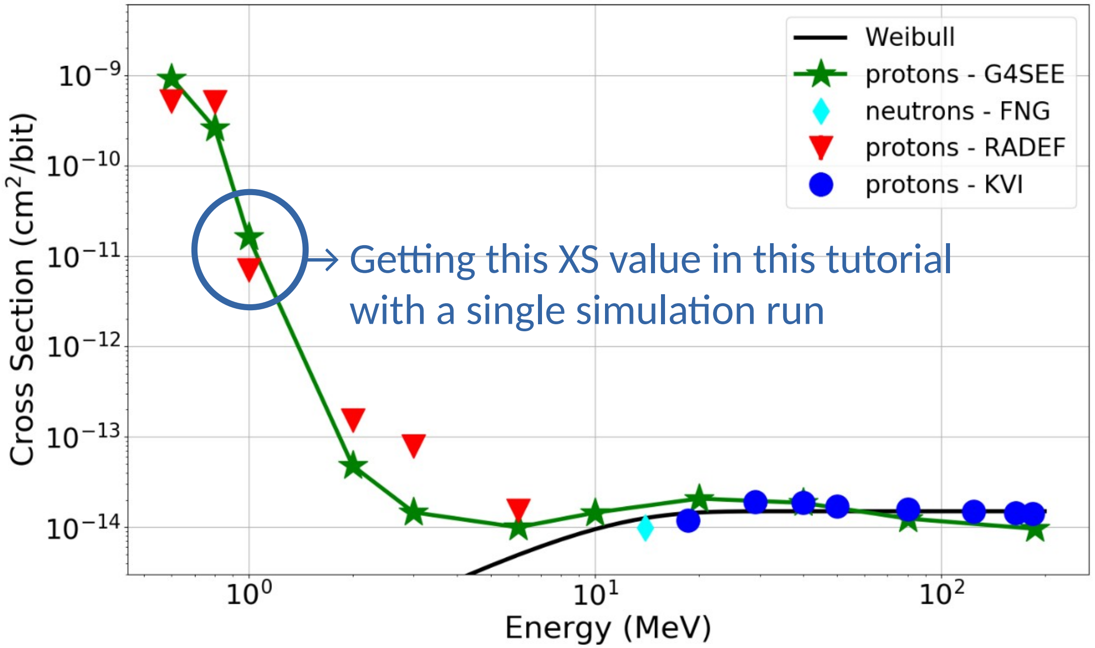
Forward display from the Docker container (optional)

Share a folder between host and Docker container!

Once inside running Docker container, copy tutorials to shared /home folder!

Tutorial #1 – ISSI SRAM & protons [2]

- **DUT:** ISSI SRAM memory cell (65nm)
- **Effects:** Single Event Upsets
- $Q_{critical}$ = 0.96 fC (≈ 21.6 keV) → for SEU XS calculation
- **Facilities:** RADEF, PARTREC
- **Primary particles:** beam of protons
- **Physics:** direct ionization
- **Scoring:** standard ($E_{kinetic}$ and $E_{deposited}$)
- Tutorial files in GitLab (link)



Cross-section of proton induced SEUs in 65nm ISSI SRAM as function of proton beam energy [2]

Reference (open-access)

[2] Andrea Coronetti *et al.*, "Proton direct ionization upsets at tens of MeV", in *IEEE TNS*, 2022, (link)

Tutorial 1.1 – General, Input/Output

- To run G4SEE, a G4-style macro (UI) file is needed as input, with general G4 and G4SEE-specific UI commands
- Open the *tutorial_1-1.mac* input macro file:

Optional commands

```
#################
### General G4 commands

/run/printProgress                  1
/run/numberOfThreads                4
/control/cout/ignoreThreadsExcept   0

/random/setSeeds                    1234, 4321

/tracking/verbose                   1

#################
### Geometry

# BULK COMMAND                      MATERIAL             WIDTH unit      THICK unit      BIAS
/SEE/geometry/Bulk                  VACUUM               10 um           10 um           false
# SV COMMAND                        POSITION unit        WIDTH unit      THICK unit      BIAS
/SEE/geometry/SV                    0 0 -4.5 um          1 1 um          1 um            false

#################
### Initialize
/run/initialize

#################
### Run
/run/beamOn                         100
```

Mandatory commands

General Geant4 (G4) macro commands can be also used

Multi-threading related commands

Seeds for random number generator (if you want to reproduce exact same results multiple times)

Increasing verbosity (from 0 to 1), use only for few events when testing your macro!

G4SEE-specific commands ('/SEE/...') to define geometry (see Tutorial 1.2)

These are macro (UI) commands with multiple parameters in a single line
One command = one line
Comments start with # character

Initialization of a G4 simulation

Last command: start N=100 primary particles (default: "geantino" virtual particles)

Tutorial 1.1 – General, Input/Output

- Run a simulation with this macro file, then check the output files of G4SEE:

Commands in G4SEE Docker container (CLI)

```
:/home# cd tutorial_1/ && mkdir output_1 && cd output_1/
:/home/tutorial_1/output_1# g4see ../tutorial_1-1.mac > stdout.log
:/home/tutorial_1/output_1# ls
```

* Optional redirection to file

```
root@g4see:/home/tutorial_1/output_1# ls
g4see.out  n_event_t0.out  n_event_t1.out  n_event_t2.out  n_event_t3.out  stdout.log
root@g4see:/home/tutorial_1/output_1#
```

- **G4/G4SEE stdout** (redirected to **stdout.log**):
  - Material information
  - List of all particles and their processes
  - List of all physics models enabled
  - Production thresholds (a.k.a. Range cuts)
  - [optional] Steps of each particle track (a.k.a. G4Track info)
- **g4see.out** – useful info about simulation run, like G4 and G4SEE versions, running time, random seeds, number of primary particles, macro file
- **n_event_t<j>.out** – number of events run by a specific thread/job
- No scoring was added yet, so no actual data has been scored and written to file (see Tutorial 1.3)

Tutorial 1.2 – Geometry

- Let's define a simplified geometry for a target SRAM cell (Bulk, SV and BEOL volumes)!
- Open the *tutorial_1-2.mac* input macro file:

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

# BULK COMMAND                        MATERIAL             WIDTH unit     THICK unit    BIAS
/SEE/geometry/Bulk                    G4_Si                6 um           1 um          false
# SV COMMAND                          POSITION unit        WIDTH unit     THICK unit    BIAS
/SEE/geometry/SV                      0 0 0 nm             310 310 nm     310 nm        false
# BEOL COMMAND                        MATERIAL             WIDTH unit     THICK unit    BIAS     NAME
/SEE/geometry/BEOL/addLayer           G4_SILICON_DIOXIDE   6 um           6 um          false    Oxide
```

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

(X,Y,Z) position of a SV (scoring) volume inside the Bulk (relative to Bulk cube's top center point)

SV can by asymmetric in size along X and Y axes

Any predefined material from G4 material database can be used here
Users can also define custom materials, like elements, compounds and mixtures

One can add arbitrary number of BEOL layers on top of each other, but only a single Bulk and SV for now

Tutorial 1.2 – Geometry

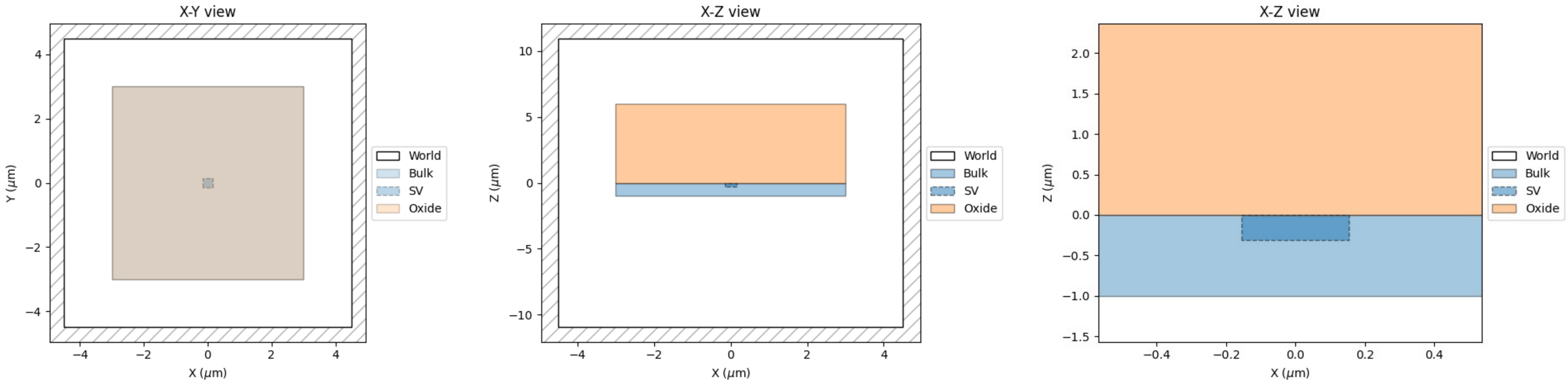
- Run a simulation with this macro file, and check changes in stdout (materials and particle tracks)!

Commands in G4SEE Docker container (CLI)

```
:/home# cd tutorial_1/ && mkdir output_2 && cd output_2/
:/home/tutorial_1/output_2# g4see ../tutorial_1-2.mac > stdout.log
:/home/tutorial_1/output_2# less stdout.log
:/home/tutorial_1/output_2# python $G4SEE_BUILD/scripts/g4see.py view ../tutorial_1-2.mac
```

* press q to exit 'less'

- Visualize geometry using G4SEE 'view' script:



Top (X-Y), side (X-Z) and zoomed-in (X-Z) view of simulated ISSI SRAM memory cell, proton beam will have –Z direction

Tutorial 1.3 – Primary particles, Scoring

- We can also define a simple mono-energetic proton beam (or any arbitrary particle source distribution)
- Add scoring commands to record and write to file binned kinetic energy values of protons
- Open the *tutorial_1-3.mac* input macro file:

Any G4 General Particle Source (GPS) command can be used in a G4SEE macro file, there is no limit in source definition

```
#################
### Primaries

/gps/particle               proton
/gps/ene/mono               1 MeV
/gps/ene/sigma              25 keV
/gps/direction              0 0 -1
/gps/pos/type               Plane
/gps/pos/shape              Rectangle
/gps/pos/centre             0 0 10 um
/gps/pos/halfx              0.5 um
/gps/pos/halfy              0.5 um
```

- Particle species (/gps/particle)
- Mean and std. deviation of energy (/gps/ene/mono, /gps/ene/sigma)
- Particle direction (mono-directional, -Z direction)
- Shape and type of source (point/surface/volume)
- Position of source's center
- Half dimensions of source plane (now it's only 1×1 μm² plane to save time)

Energy and angular distributions can be user-defined functions or read directly from ascii file

Two types of scoring mechanisms implemented:
- Standard: Ekin or Edep;
- Detailed (see later)

```
#################
### Scoring (standard)

/SEE/scoring/addScoring       0      Ekin     proton
/SEE/scoring/setHistogram     lin    0 MeV    2 MeV    200
```

Scoring definitions

- Kinetic energy scoring for protons (particle-by-particle scoring) file name id: 0 --> 'Ekin_0_hist_tN.out'
- Binning of histogram for previously defined scoring (linear binning from 0 to 2 MeV in 200 bins, other option is log binning)

Tutorial 1.3 – Primary particles, Scoring

- Run a simulation with a proton beam, while scoring energy of each proton:

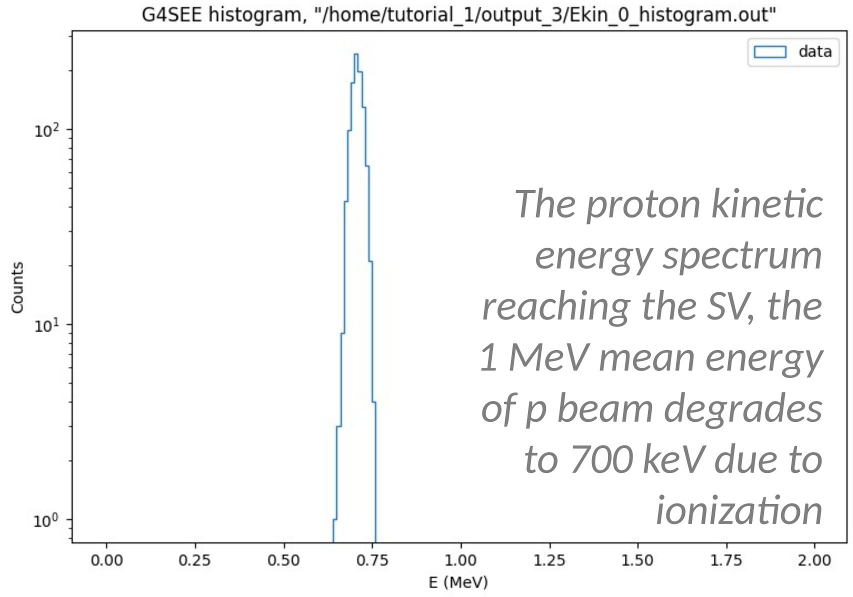
Commands in G4SEE Docker container (CLI)

```
:/home# cd tutorial_1/ && mkdir output_3 && cd output_3/
:/home/tutorial_1/output_3# g4see ../tutorial_1-3.mac > stdout.log
:/home/tutorial_1/output_3# mergeHistograms .
:/home/tutorial_1/output_3# ls
:/home/tutorial_1/output_3# python $G4SEE_BUILD/scripts/g4see.py plot Ekin_0_histogram.out
```

- Merge histogram files of the multiple threads into a single histogram!
- Only the kinetic energy of protons entering (or produced) in the SV is scored
- Plot histogram using G4SEE 'plot' script

Merged histogram of scored proton kinetic energy values, during merging std. deviation of each bin is also calculated

Ekin	Counts	StdDev(corr)
underflow	0	0
overflow	0	0
0.000e+00	0	0
...	...	...
6.300e-01	0	0
6.400e-01	0	0
6.500e-01	1.000e+00	5.000e-01
6.600e-01	6.000e+00	1.000e+00
6.700e-01	4.100e+01	5.315e+00
6.800e-01	8.600e+01	4.359e+00
6.900e-01	1.710e+02	4.500e+00
7.000e-01	2.450e+02	1.147e+01
7.100e-01	1.960e+02	6.325e+00
7.200e-01	1.190e+02	2.986e+00
7.300e-01	6.300e+01	1.258e+00
7.400e-01	1.900e+01	2.872e+00
7.500e-01	2.000e+00	5.774e-01
7.600e-01	0	0
7.700e-01	0	0



Tutorial 1.4 – Scoring, SEE cross-section

G4SEE

- Let's add energy deposition scoring as well, similarly to kinetic energy scoring!
- Open the *tutorial_1-4.mac* input macro file:

```
/SEE/scoring/addScoring            0       Edep
/SEE/scoring/setHistogram          log     100 eV  1 MeV    300

/SEE/scoring/dumpHistogramsAfter   10000

#################
### Run
/run/beamOn                        200000
```

- `Edep`: Deposited energy scoring per event for all particles (event-by-event scoring) file name id: 0 --> 'Edep_0_hist_tN.out'
- `300`: Logarithmic binning with 300 bins
- `10000`: After how many simulated events we want to dump histograms to file
- `200000`: By increasing the primary particle number, we can get better statistics

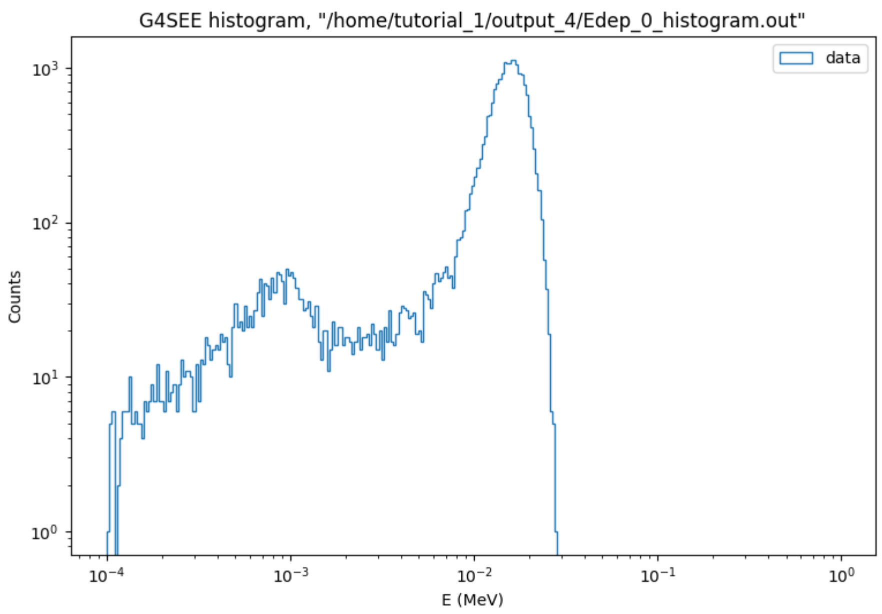
- Run the bit longer simulation (1-2 min), then merge histograms and create Edep histogram plot:

Commands in G4SEE Docker container (CLI)

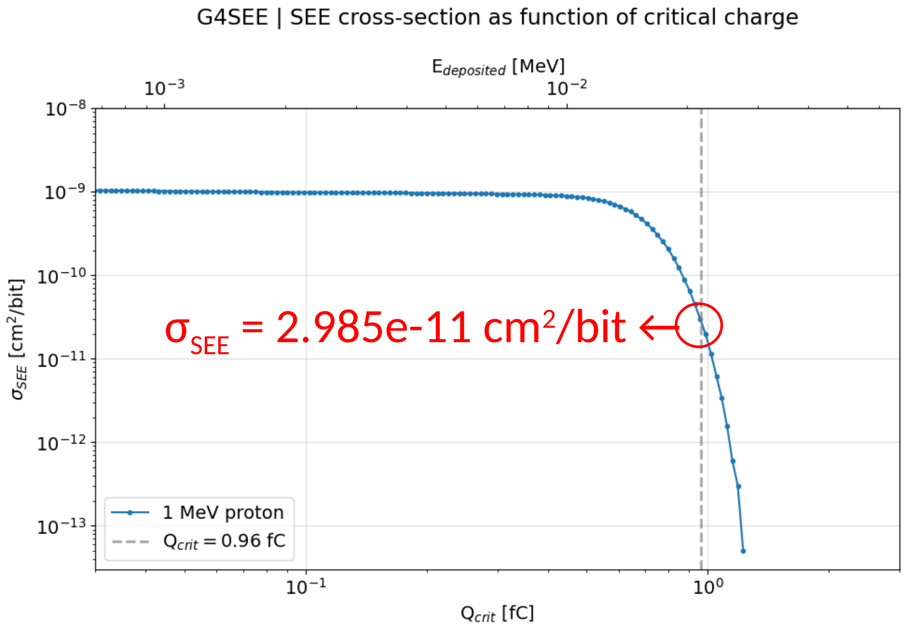
```
:/home# cd tutorial_1/ && mkdir output_4 && cd output_4/
:/home/tutorial_1/output_4# g4see ../tutorial_1-4.mac > stdout.log
:/home/tutorial_1/output_4# mergeHistograms .
:/home/tutorial_1/output_4# python $G4SEE_BUILD/scripts/g4see.py plot Edep_0_histogram.out
:/home/tutorial_1/output_4# python $G4SEE_BUILD/scripts/g4see.py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

Tutorial 1.4 – Scoring, SEE cross-section

- By running the 'see-xs' script, one can obtain the SEE cross-sections in function of critical charge based on the inverse cumulative sum of energy deposition distribution --> SEE cross-section (and rate) estimation if we know $Q_{critical}$
- The script 'see-xs' needs a YAML config file with input parameters and plotting options



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



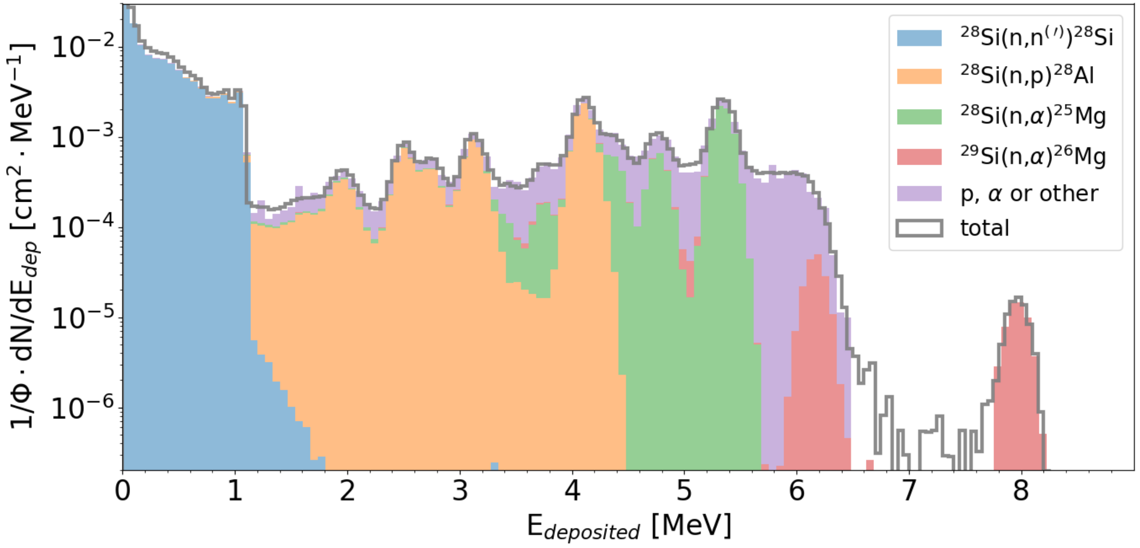
SEE cross-section estimation at 1 MeV proton beam energy (assuming Q_{crit} = 0.96 fC) based on MC simulated E_{dep} histogram

```yaml
# ######################################## #
# 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

Tutorial #2 – Neutrons in Silicon [1,3]

- **DUTs:** ISSI SRAM cell (40nm) / Si diode detector
- **Effects:** SEUs / Single Event Transients
- **Facility:** PTB (PIAF)
- **Primary particles:** 1.2, 2.5, 5, 8, 14.8, 17 MeV mono-energetic neutrons
- **Physics:** nuclear reactions
- **Scoring:** standard & detailed
- Tutorial files in GitLab (link)



Contribution of different nuclear reactions to energy deposition distribution of 8 MeV neutrons in natural Silicon [1]

Reference (open-access)

[1] Dávid Lucsányi et al., "G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements," in *IEEE TNS*, vol. 69, no. 3, March 2022, (link)

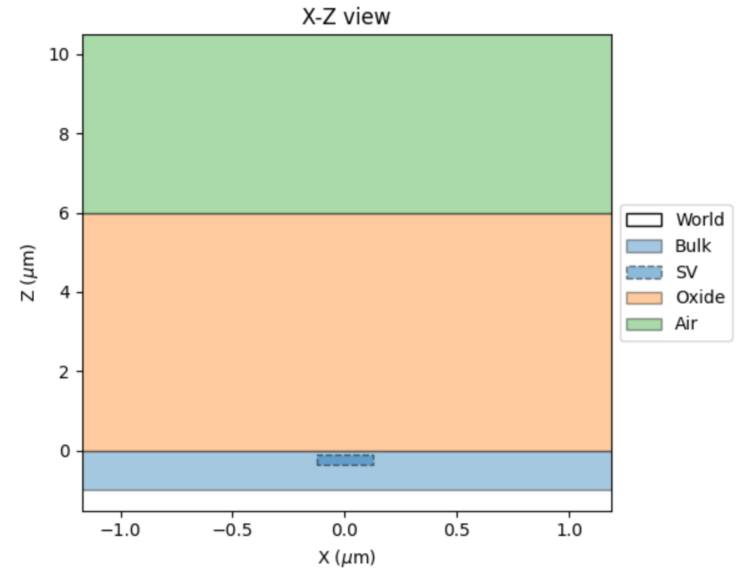
[3] Matteo Cecchetto et al., "0.1–10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments", in *IEEE TNS*, vol. 68, no. 5, May 2021, (link)

Tutorial 2.1 – Geometry, Primaries, Scoring

G4SEE

- Open the *tutorial_2-1.mac* input macro file:

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

# BULK COMMAND                  MATERIAL            WIDTH unit      THICK unit      BIAS
/SEE/geometry/Bulk              G4_Si               6 um            1 um            false
# SV COMMAND                    POSITION unit       WIDTH unit      THICK unit      BIAS
/SEE/geometry/SV                0 0 -100 nm         250 250 nm      250 nm          false
# BEOL COMMANDS                 MATERIAL            WIDTH unit      THICK unit      BIAS      NAME
/SEE/geometry/BEOL/addLayer     G4_SILICON_DIOXIDE  6 um            6 um            false     Oxide
/SEE/geometry/BEOL/addLayer     G4_AIR              6 um            1 cm            false     Air
```




```
#################
### Primaries

/gps/particle          neutron
/gps/ene/type          Gauss
/gps/ene/mono          8 MeV
/gps/ene/sigma         85 keV
/gps/pos/type          Point
/gps/pos/centre        0 0 1 cm
/gps/direction         0 0 -1
```

```
#################
### Scoring - Standard

# Energy deposited
/SEE/scoring/addScoring        0      Edep
/SEE/scoring/setHistogram      log    1 keV     20 MeV     200

# Kinetic energy
/SEE/scoring/addScoring        0      Ekin      neutron
/SEE/scoring/setHistogram      lin    0 keV     10 MeV     200
/SEE/scoring/addScoring        1      Ekin      gamma
/SEE/scoring/setHistogram      lin    0 keV     10 MeV     200
```

Tutorial 2.1 – Physics

- Add elastic and inelastic hadronic physics to the simulation, since so far we had EM physics models only

```
###############
### Physics

# Physics modules
/SEE/physics/addPhysics          G4EmStandardPhysics_option4
/SEE/physics/addPhysics          G4HadronElasticPhysicsHP
/SEE/physics/addPhysics          G4HadronPhysicsFTFP_BERT_HP

# Particle production range cuts
/SEE/physics/setElectronCut      1 um
/SEE/physics/setGammaCut         1 mm
/SEE/physics/setHadronCut        1 nm
```

Adding G4 physics modules to put together a full G4 physics list:

Default physics, highest accuracy general EM physics in G4 (no need to add here explicitly)

Hadron **elastic** physics with High Precision (HP) neutrons models

Hadron **inelastic** physics with HP neutron models

HP models are strongly recommended for <20 MeV neutrons!

See full list of physics options in G4SEE docs!

Secondary particles with expected range below the defined range cuts are not produced, its E is deposited on the spot instead, it can save computational time!

- Running the simulation with 300k neutron primaries, we get an empty Edep histogram (only a single event!)
- Simulation running time increases proportionally with primary particle number and particle interactions

Commands in G4SEE Docker container (CLI)

```
:/home/tutorial_2# mkdir output_2 && cd output_2/
:/home/tutorial_2/output_1# g4see ../tutorial_2-1.mac > stdout.log
:/home/tutorial_2/output_1# mergeHistograms . --delete
:/home/tutorial_2/output_1# less Edep_0_histogram.out
```

Tutorial 2.2 – Biasing

G4SEE

- Let's increase statistics, by running a non-analog Monte Carlo simulation using a biasing (variance reduction) technique!
- G4SEE has microscopic XS biasing implemented to artificially increase probabilities of certain particle interactions
- Open the *tutorial_2-2.mac* input macro file:

```
###############
### Biasing
# (Biasing has to be also enabled for the volumes above!)

/SEE/biasing/biasParticle          neutron
/SEE/biasing/biasProcess           hadElastic
/SEE/biasing/biasProcess           neutronInelastic
/SEE/biasing/biasFactor            1000
```

Particle species to be biased (by default biasing only applies to primary particles)

Physics process(es) to be biased

The σ(E) function is multiplied by this factor, increasing interaction probability with 3 orders of magnitude

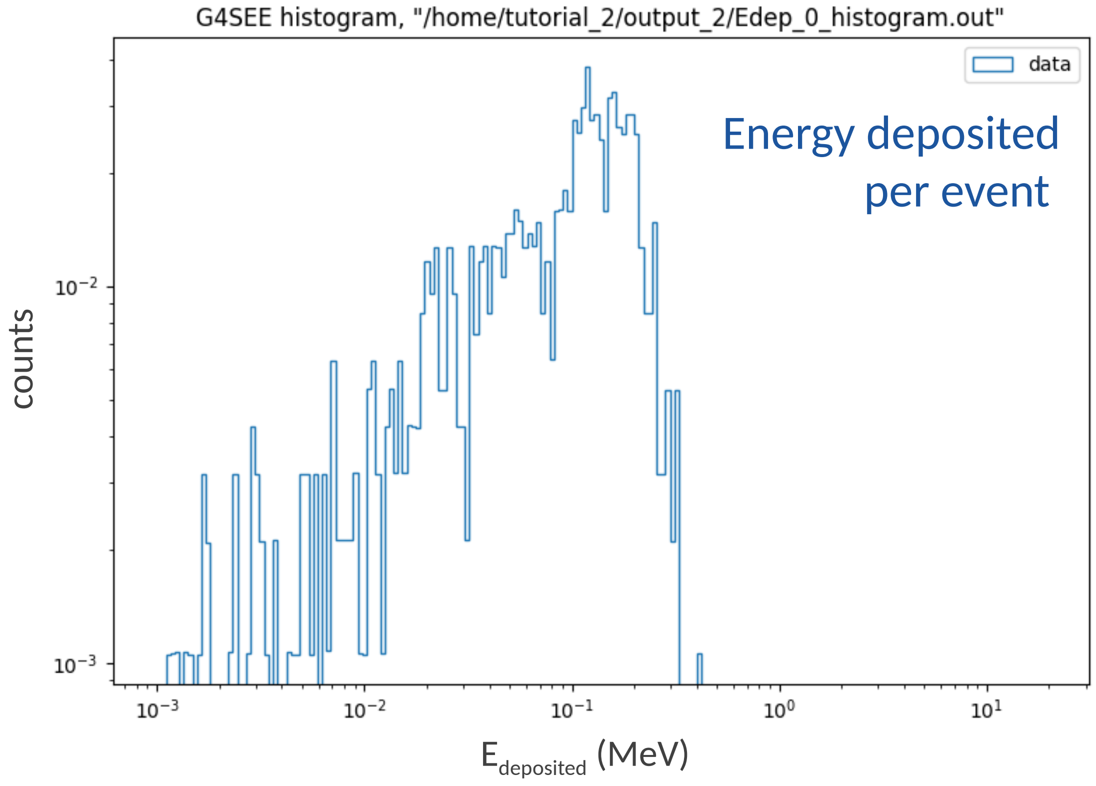
```
################
### Geometry

# BULK COMMAND            MATERIAL           WIDTH unit    THICK unit    BIAS
/SEE/geometry/Bulk        G4_Si              6 um          1 um          true
# SV COMMAND              POSITION unit      WIDTH unit    THICK unit    BIAS
/SEE/geometry/SV          0 0 -100 nm        250 250 nm    250 nm        true
# BEOL COMMANDS           MATERIAL           WIDTH unit    THICK unit    BIAS     NAME
/SEE/geometry/BEOL/addLayer  G4_SILICON_DIOXIDE  6 um      6 um          true     Oxide
/SEE/geometry/BEOL/addLayer  G4_AIR             6 um       1 cm          false    Air
```

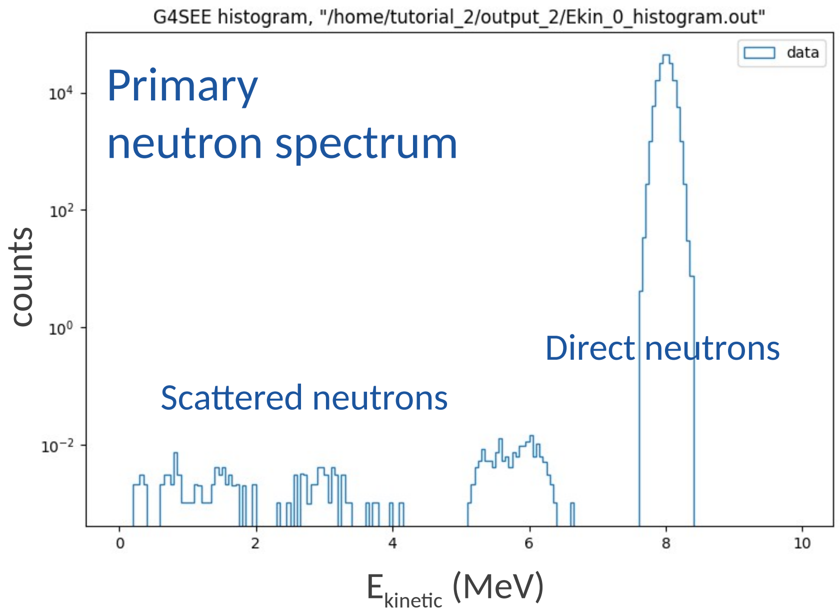
Don't forget to enable biasing for the volumes here!

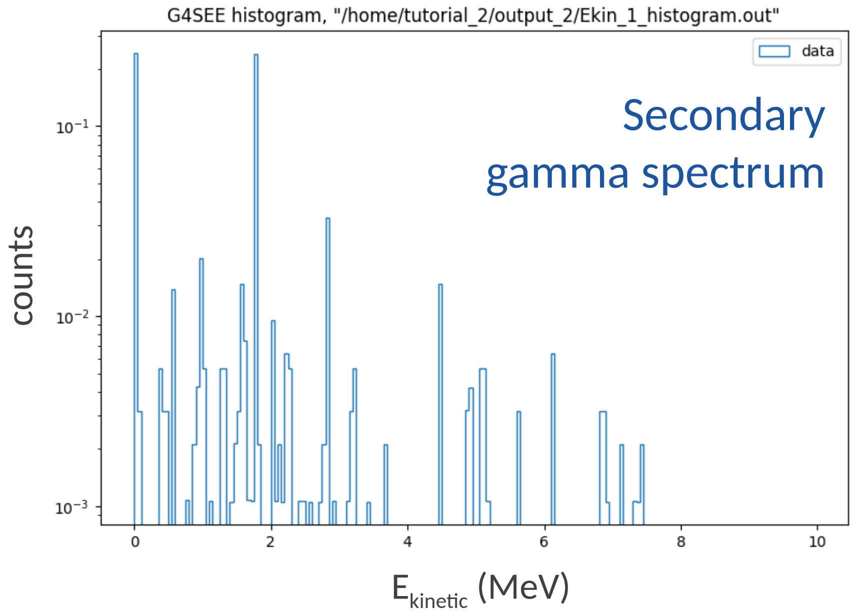
Use biasing cautiously, since it is very easy to over-bias a simulation, producing non-valid results!
To avoid this, run at least once without any biasing (with high pp number) for validation

Tutorial 2.2 – Biasing

- Running similarly as before (300k pp), but now we get counts in histograms thanks to the applied XS biasing
- Histogram counts are weighted to correct for artificial increase in interaction probabilities, so results should be in agreement with an analog Monte Carlo simulation (no biasing)







Tutorial 2.3 – Detailed Scoring

- Open the *tutorial_2-3.mac* input macro file:

```
#################
### Scoring - Detailed

/SEE/scoring/detailed                       true       # default: false

# Kinetic energy threshold for individual particle scoring
/SEE/scoring/detailed/e-/setThreshold       10 keV     # default: 10 keV
/SEE/scoring/detailed/gamma/setThreshold    100 keV    # default: 100 keV

# Grouping method used for particles below kinetic energy threshold
/SEE/scoring/detailed/e-/groupByAncestor    false      # default: false

# Printing option
/SEE/scoring/detailed/printPrimary          false      # default: true
/SEE/scoring/detailed/setCSVFormat          false      # default: true

# Scored quantities and information particle-by-particle
/SEE/scoring/detailed/addTrack      true
/SEE/scoring/detailed/addParent     true
/SEE/scoring/detailed/addEkin       true
/SEE/scoring/detailed/addProcess    true
/SEE/scoring/detailed/addEdep       true
/SEE/scoring/detailed/addCounts     true
/SEE/scoring/detailed/addZ          true
/SEE/scoring/detailed/addA          true
/SEE/scoring/detailed/addVolume     true
/SEE/scoring/detailed/addEexc       true
```

Enabling detailed (particle-by-particle) scoring
note: output data files can easily have very large size!

Kinetic energy threshold: above this energy $e^-/e^+/\gamma$ particles are scored individually, but below this energy they are grouped together (single line in output file)

If 'true', then grouping $e^-/e^+/\gamma$ particles based on their ancestor particles to get total contribution of every secondary hadrons

Primary particles are not printed to output data file, because we are not interested and/or want to save disk space

Use 'true', using CSV format saves disk space!

Which quantities to print to output data file

Commands in G4SEE Docker container (CLI)

```
:/home/tutorial_2# mkdir output_3 && cd output_3/
:/home/tutorial_2/output_3# g4see ../tutorial_2-3.mac > stdout.log
:/home/tutorial_2/output_3# ls
:/home/tutorial_2/output_3# less Hits_t0.out
```

Tutorial 2.3 – Detailed Scoring

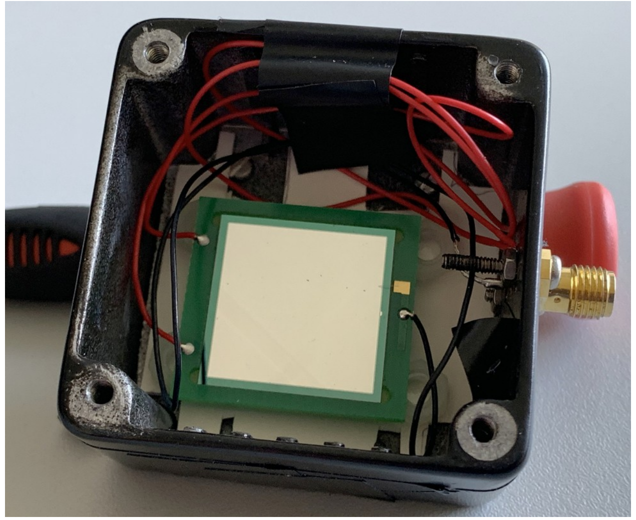
event	particle	weight	Z	A	track	parent	E_kin	process	volume	E_dep	counts
377	alpha	1.055e-03	2	4	2	1	3.8826e+00	b(neutronInelastic)	Sensitive	2.5712e-02	1
377	Mg25	1.055e-03	12	25	3	1	1.5530e+00	b(neutronInelastic)	Sensitive	2.4899e-02	1
377	g(e-)	nan	0	0	-1	nan	nan	ionIoni	Sensitive	5.4009e-03	5
490	neutron	1.053e-03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].9415e+00	b(neutronInelastic)	Sensitive	0	1
490	Si28	1.053e-03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].4732e-01	b(neutronInelastic)	Sensitive	1.2955e-01	1
490	gamma	1.053e-03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].7778e+00	b(neutronInelastic)	Sensitive	0	1
732	O16	1.069e-03	8	16	2	1	1.0890e+00	b(hadElastic)	Oxide	1.3268e-01	1
914	gamma	1.057e-03	0	0	4	1	4.8919e+00	b(neutronInelastic)	Bulk	0	1
914	gamma	1.057e-03	0	0	5	1	1.7790e+00	b(neutronInelastic)	Bulk	0	1
1212	neutron	1.077e-03	0	1	2	1	5.2899e+00	b(neutronInelastic)	Bulk	0	1
1257	O16	1.048e-03	8	16	3	1	1.2290e-01	b(neutronInelastic)	Oxide	9.4224e-02	1
1342	neutron	1.072e-03	0	1	2	1	3.9277e-01	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	3	1	5.1945e+00	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	4	1	1.4963e+00	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	5	1	4.7253e-01	b(neutronInelastic)	Sensitive	0	1
1342	Si30	1.072e-03	14	30	6	1	3.3550e-01	b(neutronInelastic)	Sensitive	1.3925e-01	1
1428	O16	1.050e-03	8	16	3	1	5.6249e-02	b(neutronInelastic)	Oxide	4.4397e-02	1
1536	Si28	1.066e-03	14	28	2	1	4.7965e-02	b(hadElastic)	Sensitive	4.7965e-02	1
1565	Al28	1.067e-03	13	28	3	1	4.7900e-01	b(neutronInelastic)	Bulk	1.6775e-01	1
1605	neutron	1.053e-03	0	1	2	1	6.0902e+00	b(neutronInelastic)	Sensitive	0	1
1605	Si28	1.053e-03	14	28	3	1	2.3035e-01	b(neutronInelastic)	Sensitive	1.2189e-01	1
1605	gamma	1.053e-03	0	0	4	1	1.7730e+00	b(neutronInelastic)	Sensitive	0	1
1984	neutron	1.055e-03	0	1	2	1	6.0284e+00	b(neutronInelastic)	Sensitive	0	1
1984	Si28	1.055e-03	14	28	3	1	2.0772e-01	b(neutronInelastic)	Sensitive	1.6477e-01	1
1984	gamma	1.055e-03	0	0	4	1	1.7703e+00	b(neutronInelastic)	Sensitive	0	1
1993	Si28	1.054e-03	14	28	3	1	3.6548e-01	b(neutronInelastic)	Bulk	1.9489e-01	1
1993	gamma	1.054e-03	0	0	4	1	3.2000e+00	b(neutronInelastic)	Bulk	0	1
1993	gamma	1.054e-03	[illegible]	[illegible]	[illegible]	[illegible]	1.7790e+00	b(neutronInelastic)	Bulk	0	1
1993	g(gamma)	nan	[illegible]	[illegible]	[illegible]	[illegible]	nan	b(neutronInelastic)	Bulk	0	1
2044	Si28	1.072e-03	[illegible]	[illegible]	[illegible]	[illegible]	7.3092e-02	b(hadElastic)	Bulk	0	1
2176	proton	1.066e-03	1	1	2	1	3.3008e+00	b(neutronInelastic)	Sensitive	4.8202e-03	1
2176	Al28	1.066e-03	13	28	3	1	7.5380e-01	b(neutronInelastic)	Sensitive	4.1540e-02	1
2176	g(gamma)	nan	0	0	-1	nan	nan	b(neutronInelastic)	Sensitive	0	1
2559	proton	1.063e-03	1	1	2	1	2.6926e+00	b(neutronInelastic)	Sensitive	2.4314e-03	1
2559	Al28	1.063e-03	13	28	3	1	3.8967e-01	b(neutronInelastic)	Sensitive	8.7722e-02	1
2559	gamma	1.063e-03	0	0	4	1	9.8268e-01	b(neutronInelastic)	Sensitive	0	1
2559	g(e-)	nan	0	0	-1	nan	nan	hIoni	Sensitive	3.9645e-03	3
2559	g(gamma)	nan	0	0	-2	nan	nan	b(neutronInelastic)	Sensitive	0	1

$n + {}^{28}Si \Rightarrow {}^{25}Mg + \alpha\ (+\ 5e^-)$

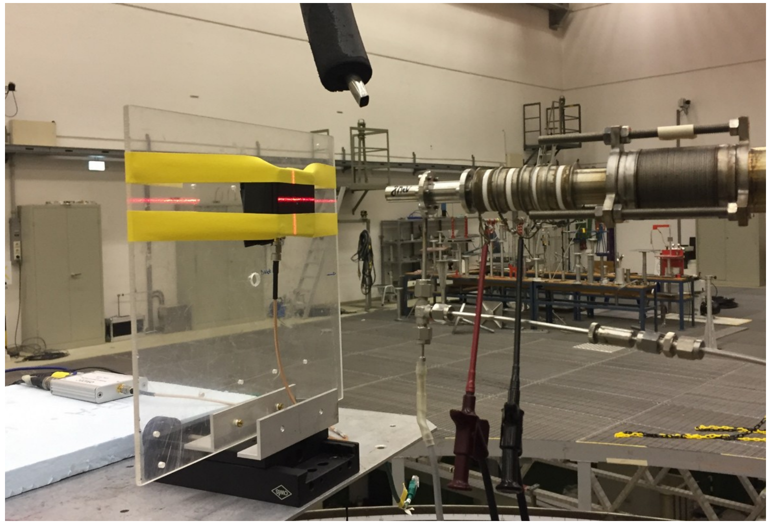
$n + {}^{28}Si \Rightarrow {}^{28}Al + p\ (+\ \gamma)$

- Mono-energetic fast neutrons impacting a Si component producing various secondary particle species.
- The 'Hits_tN.out' detailed scoring output file containing information of individual particles (and in this case groups of e^-, e^+ and γ particles) scored inside the sensitive volume.
- Implementation of new scoring is ongoing to avoid such large data files and post-processing

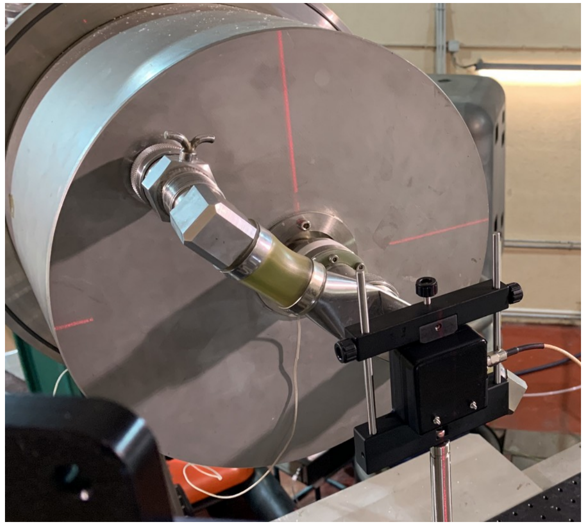
Validation of G4SEE with neutrons [1]



Silicon diode detector (2cm × 2cm × 300 μm)



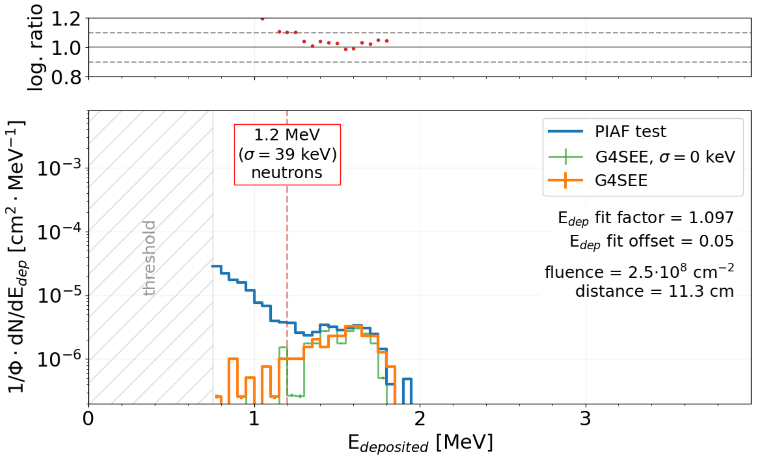
Diode setup irradiated at PTB Ion Accelerator Facility (PIAF)



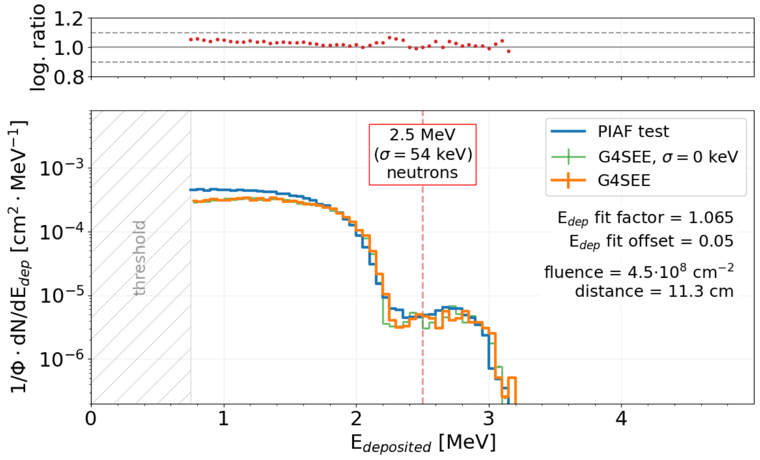
Diode setup irradiated at Frascati Neutron Generator (FNG)

Facility, Reaction	E_n (MeV)	σ_E (keV)	d (cm)	$\langle\varphi\rangle$ (cm^{-2}/s)	Φ (cm^{-2})
PIAF, ^{3}H(d,n)	17	154	11.3	$1.18\cdot10^5$	$1.11\cdot10^8$
FNG, ^{3}H(d,n)	14.8	276	7.6	$9.01\cdot10^6$	$2.74\cdot10^9$
PIAF, ^{2}H(d,n)	8	85	12.4	$7.41\cdot10^5$	$3.61\cdot10^8$
PIAF, ^{2}H(d,n)	5	85	12.4	$1.73\cdot10^5$	$2.65\cdot10^8$
PIAF, ^{3}H(p,n)	2.5	54	11.3	$4.12\cdot10^5$	$4.51\cdot10^8$
PIAF, ^{3}H(p,n)	1.2	39	11.3	$3.44\cdot10^5$	$2.48\cdot10^8$

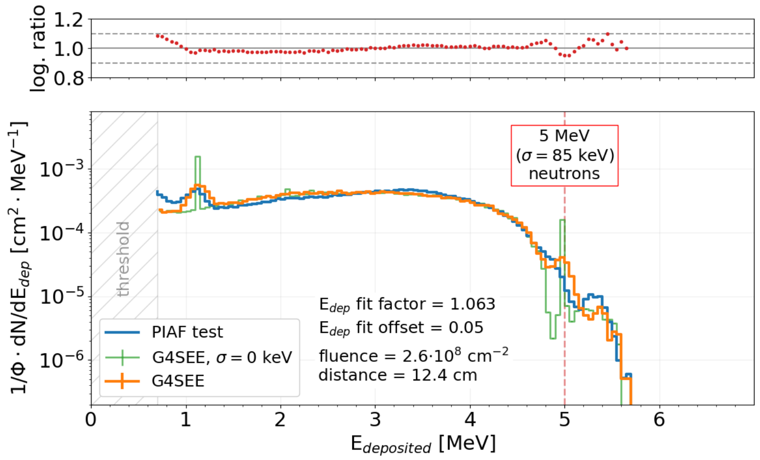
Validation of G4SEE with neutrons [1]



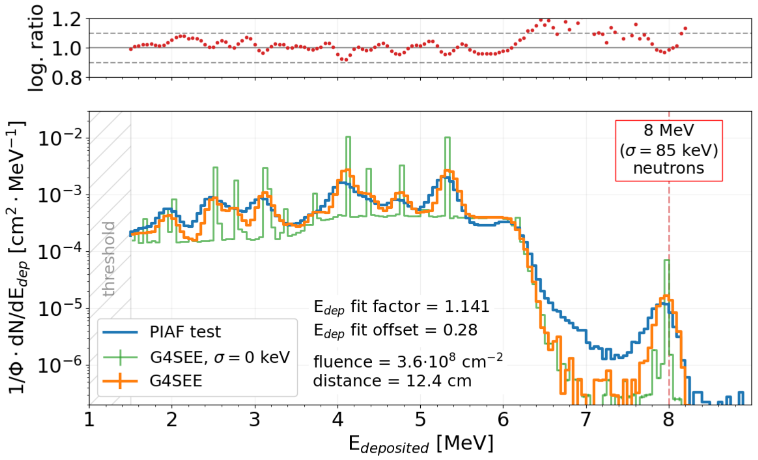
1.2 MeV



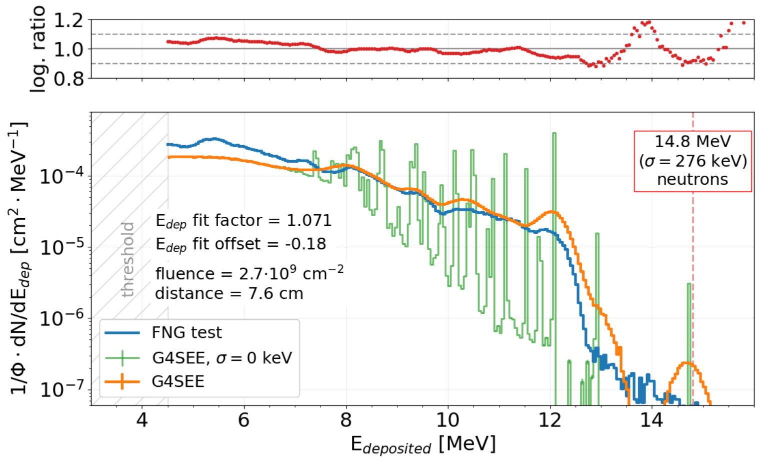
2.5 MeV



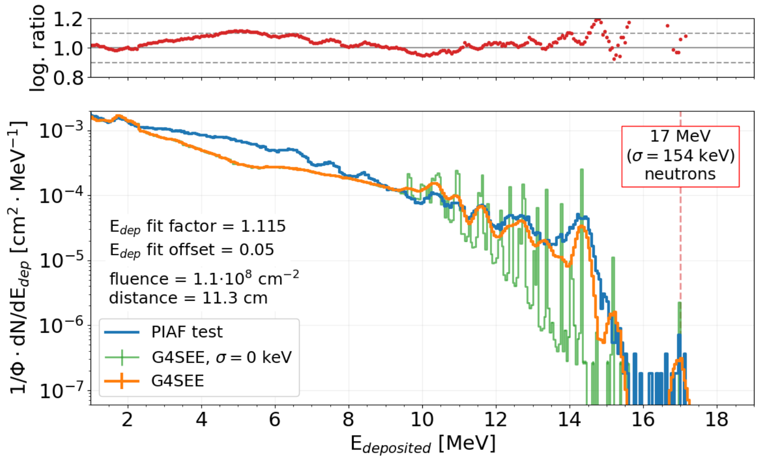
5 MeV



8 MeV

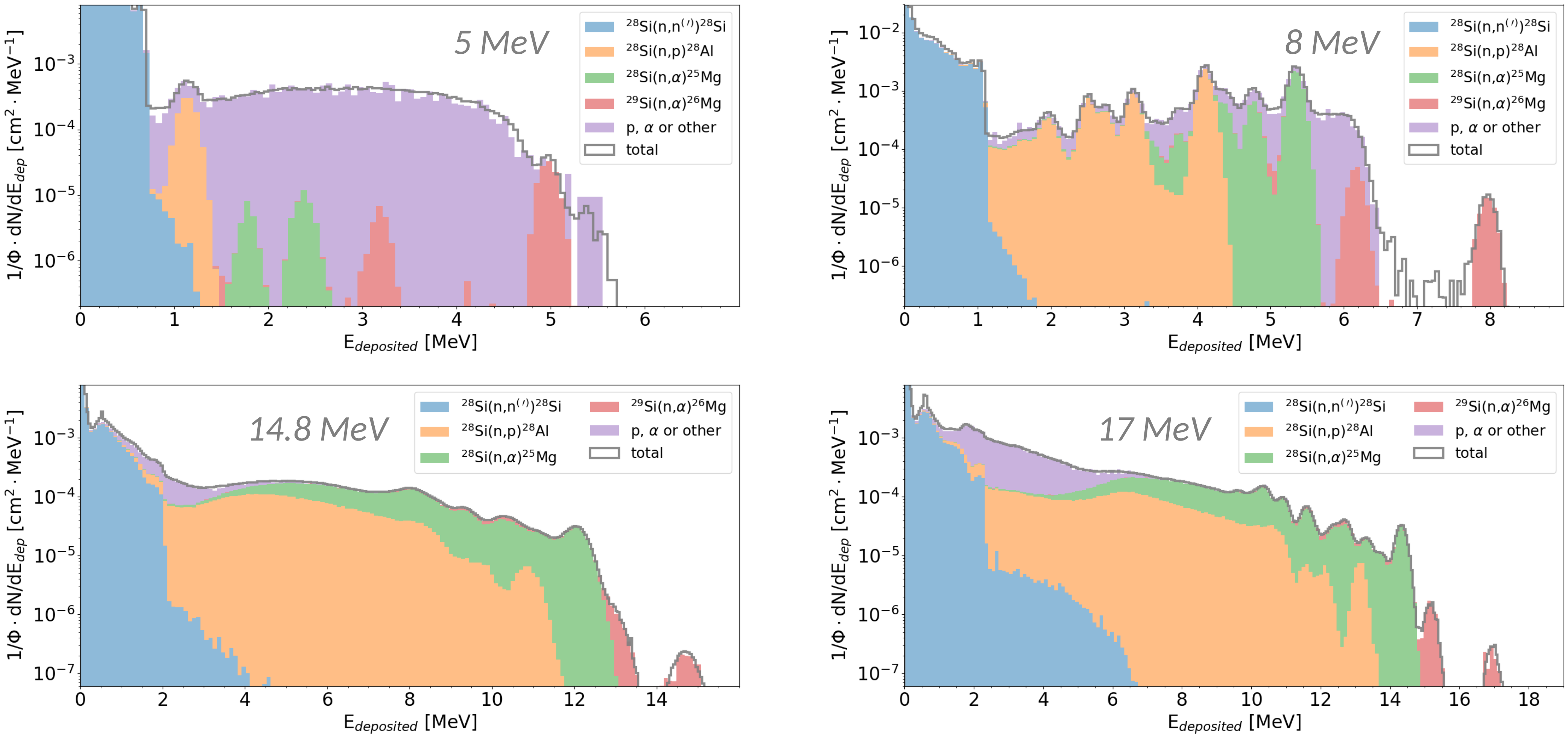


14.8 MeV



17 MeV

Validation of G4SEE with neutrons [1]



Contribution of the most frequent nuclear reactions to energy deposition distributions of mono-energetic neutrons in Silicon diode detector

Summary

- We went through tutorials how to run Monte Carlo simulations of Single Event Effects in SRAM cells using the Geant4-based G4SEE toolkit
- Free and open-source toolkit for the whole radiation effects community
- The demonstrated features will be integrated soon into FLUKA.CERN 5, and more new SEE scoring features will be added as well, so stay tuned!
- Until then, development is ongoing, so always checkout/pull the latest release of G4SEE (upcoming release v0.6)!

Thank you for your attention!

Questions?

If you have further questions, need more help, or you are interested in contributing to the G4SEE toolkit, please let us know!

g4see.toolkit@cern.ch