SERESSA 2022

5^{th} to 9^{th} of December at CERN, Geneva

Part 2

Introduction to G4SEE:

a toolkit for simulating radiation effects in electronics

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G4SEE CERN

Agenda (part 2)

- Hands-on tutorial #2:
  - The simulation case: Neutron interactions in Silicon (ISSI SRAM)
  - 2.1) Geometry, Primaries, Scoring and Physics
  - 2.2) Biasing (non-analog MC)
  - 2.3) Detailed Scoring
- Validation of the G4SEE toolkit with monoenergetic neutrons

Get the latest G4SEE release!

- See lecture preparation slides on SERESSA Indico page
- Options to run G4SEE toolkit on your computer:

  A) Cloning CERN GitLab repos & building from source *(not recommended now)*

  — OR —

  B) Using Docker ***(recommended, see lecture preparation slides)***

  - After Docker installation, pull the latest, **G4SEE v0.5.1** Docker image
  - Run a Docker container based on **G4SEE v0.5.1** image (with shared folder)
  - Download 'tutorial_2' folder from CERNbox

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

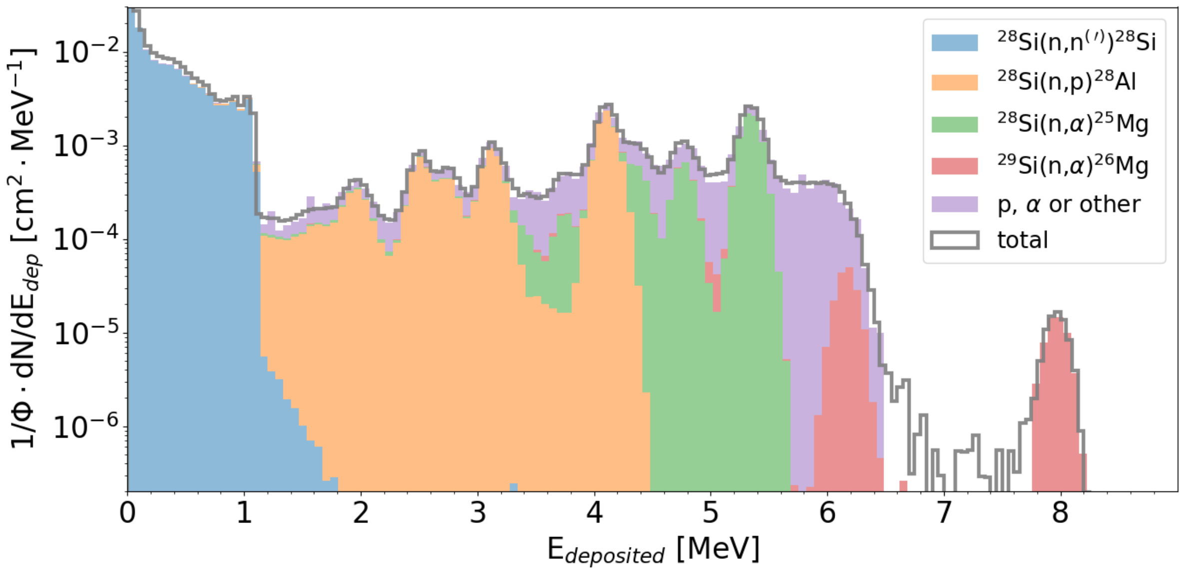
```
$ cp -r tutorial_2 /host/path/to/shared_folder
$ docker pull gitlab-registry.cern.ch/g4see/g4see:v0.5.1_G4-11.0.3
$
$ docker run -it -h g4see -v /host/path/to/shared_folder:/home \
        gitlab-registry.cern.ch/g4see/g4see:v0.5.1_G4-11.0.3
root@g4see:/home#
```

Download or copy 'tutorial_2' folder to the shared folder of your host computer, so you can access it in Docker container!

Share a folder between host and Docker container!

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

- **DUT:** Si diode det., 40-nm ISSI SRAM
- **Facilities:** PTB (PIAF)
- **Primaries:** 8 MeV neutrons
- **Physics:** nuclear reactions
- **Scoring:** standard, detailed
- **For SEU calc.:** Q_{crit}=0.72 fC (≈16.2 keV)
- Tutorial files can be viewed in GitLab



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

References (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)

[2] 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)

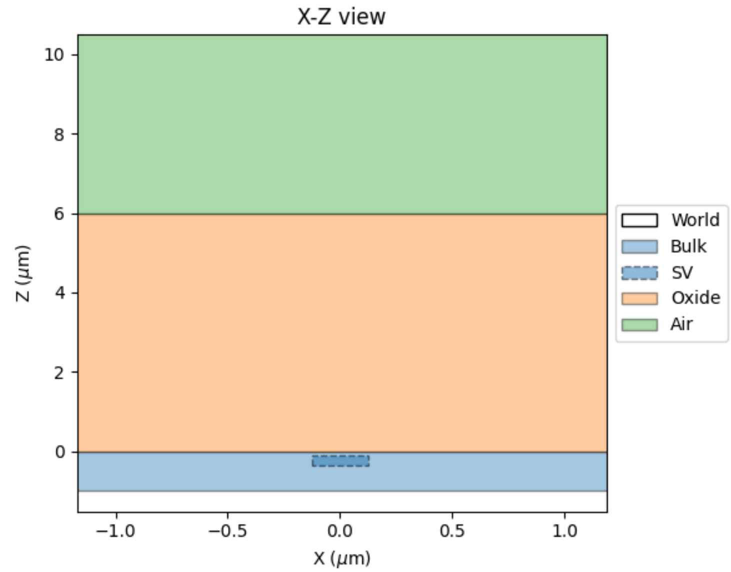
See lecture by Matteo Cecchetto (Thursday, 10h10)!

Tutorial 2.1 – Geometry, Primaries, Scoring

- 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 files in GitLab]
[Tutorial files in CERNbox]

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 files in GitLab
Tutorial files in CERNbox

Tutorial 2.2 – Biasing

- 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
```

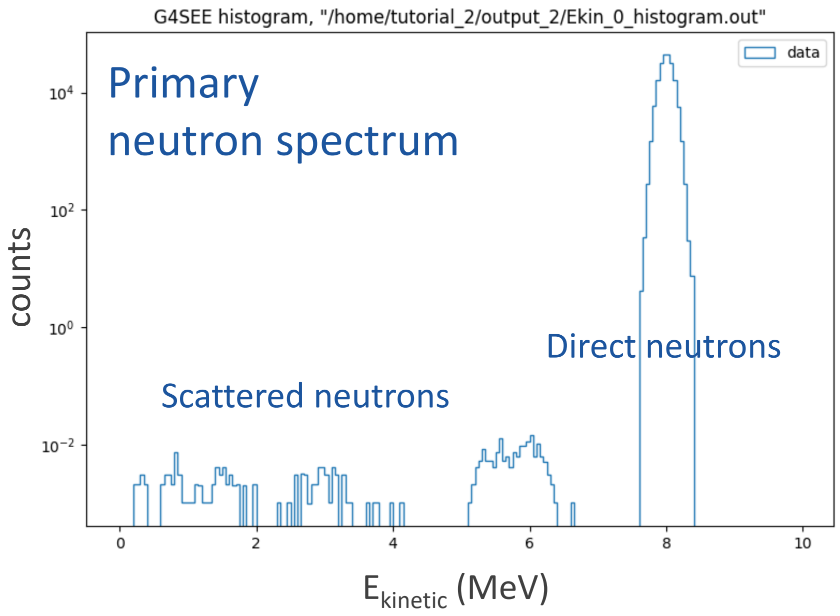
Don't forget to enable biasing for the volumes here!

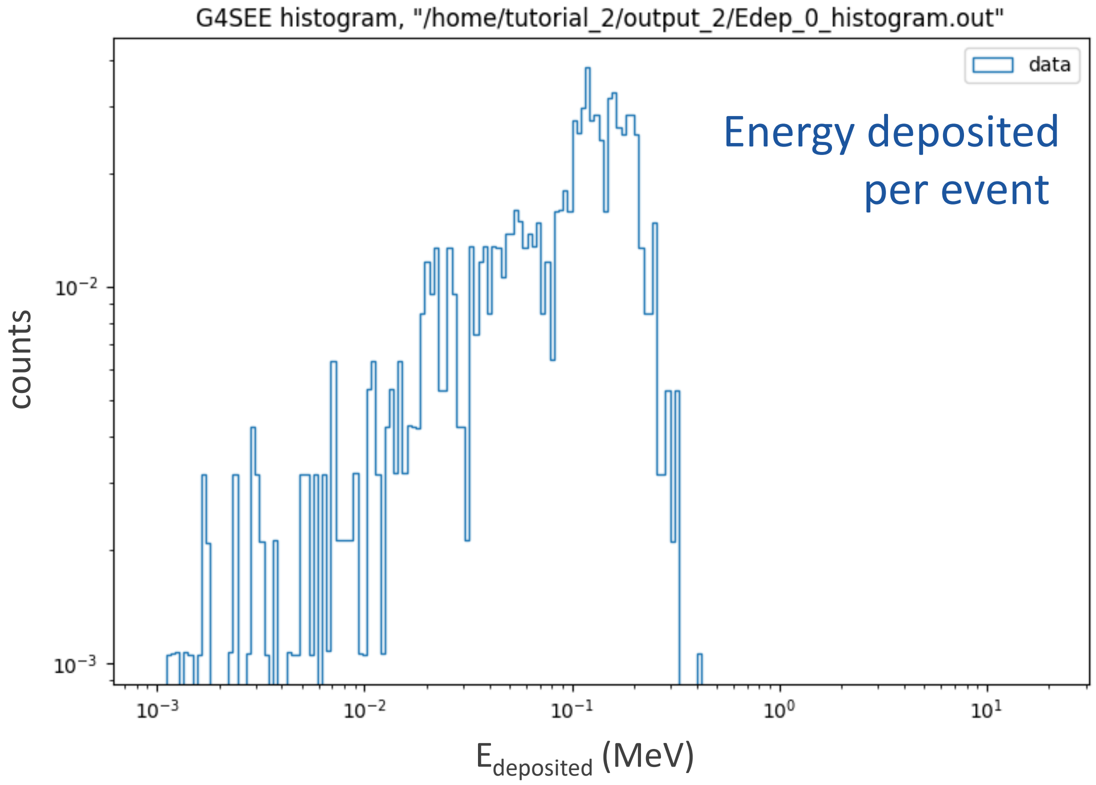
Use biasing cautiously, since it is very easy to over-bias a simulation, producing non-valid results!
To avoid this, run at least once without any biasing (with high pp number) for validation

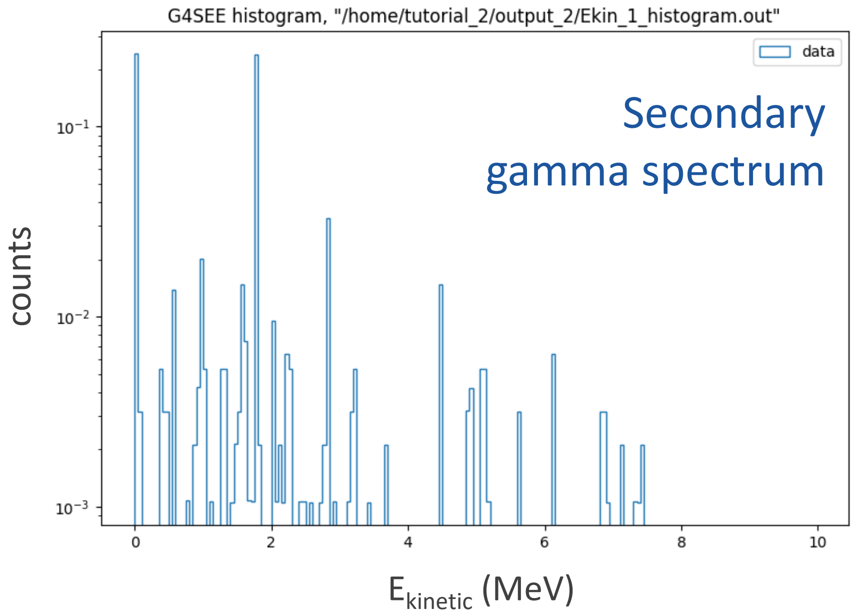
Tutorial files in GitLab
Tutorial files in CERNbox

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
```

Tutorial files in GitLab
Tutorial files in CERNbox

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

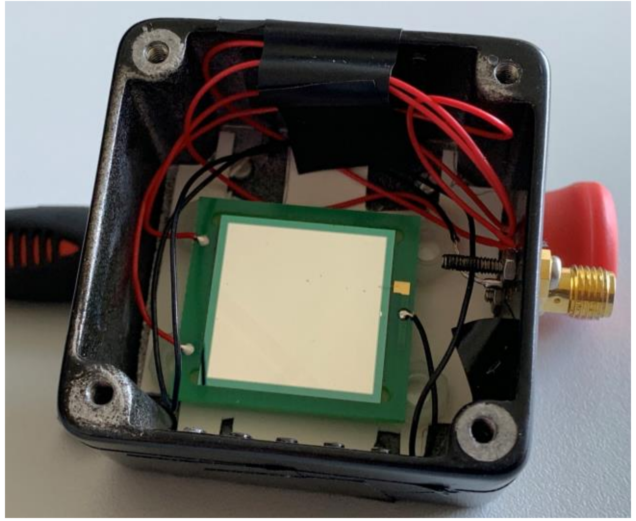
event	particle	weight	Z	A	track	parent	E_kin	process	volume	E_dep	counts
377	alpha	1.055e-03	2	4	2	1	3.8826e+00	b(neutronInelastic)	Sensitive	2.5712e-02	1
377	Mg25	1.055e-03	12	25	3	1	1.5530e+00	b(neutronInelastic)	Sensitive	2.4899e-02	1
377	g(e-)	nan	0	0	-1	nan	nan	ionIoni	Sensitive	5.4009e-03	5
490	neutron	1.053e-03	0	1	2	1	5.9415e+00	b(neutronInelastic)	Sensitive	0	1
490	Si28	1.053e-03	14	28	3	1	3.4732e-01	b(neutronInelastic)	Sensitive	1.2955e-01	1
490	gamma	1.053e-03	0	0	4	1	1.7778e+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	0	0	5	1	1.7790e+00	b(neutronInelastic)	Bulk	0	1
1993	g(gamma)	nan	0	0	-1	nan	nan	b(neutronInelastic)	Bulk	0	1
2044	Si28	1.072e-03	14	28	2	1	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

- 'Hits_tN.out' detailed scoring output file containing information of individual particles (or particle groups if grouped, in case of e^-, e^+ and γ)
- Further processing and analysis needed (such a post-processing python script to be added to a future G4SEE release)

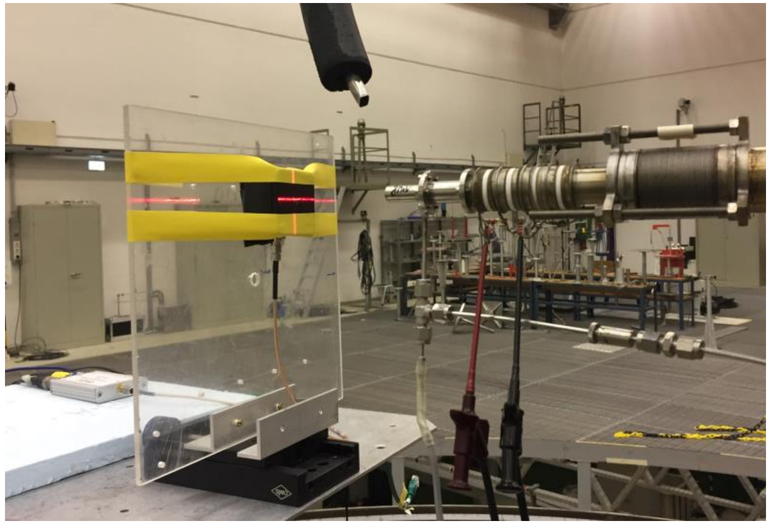
Tutorial files in GitLab

Tutorial files in CERNbox

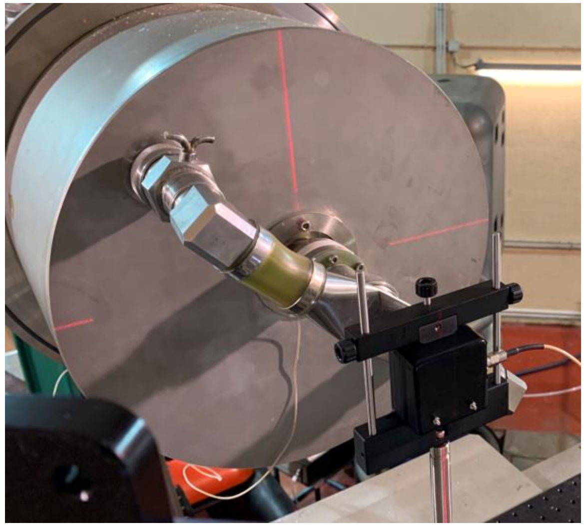
Validation of G4SEE with neutrons [1]



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



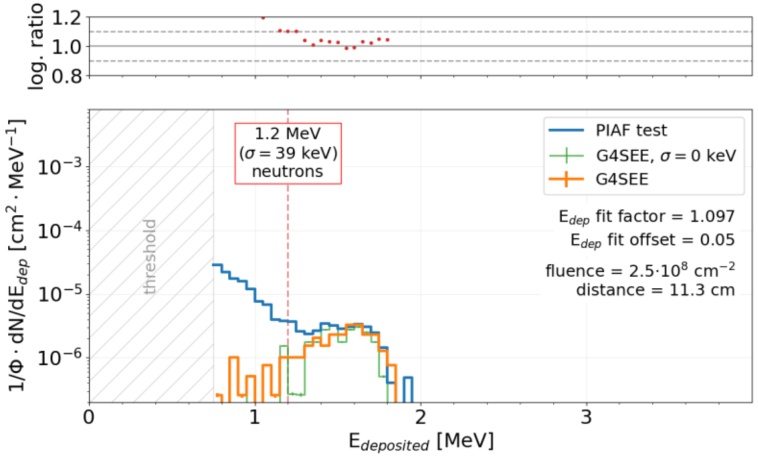
Diode setup irradiated at
PTB Ion Accelerator Facility (PIAF)



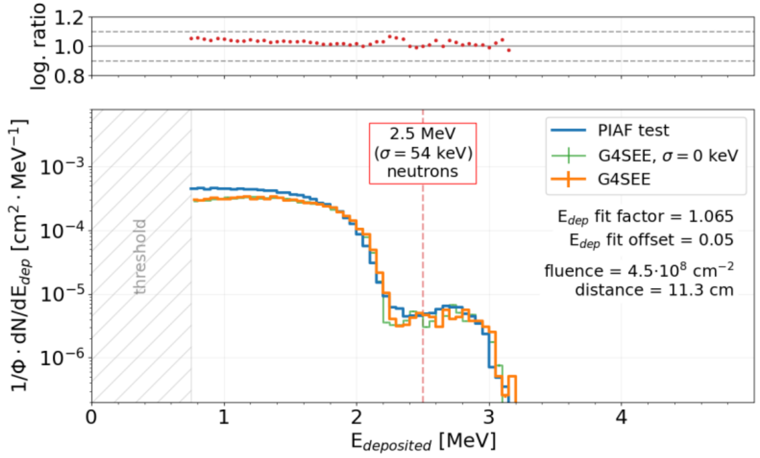
Diode setup irradiated at
Frascati Neutron Generator (FNG)

Facility, Reaction	E_n (MeV)	σ_E (keV)	d (cm)	$\langle\varphi\rangle$ (cm^{-2}/s)	Φ (cm^{-2})
PIAF, $^3H(d,n)$	17	154	11.3	$1.18 \cdot 10^5$	$1.11 \cdot 10^8$
FNG, $^3H(d,n)$	14.8	276	7.6	$9.01 \cdot 10^6$	$2.74 \cdot 10^9$
PIAF, $^2H(d,n)$	8	85	12.4	$7.41 \cdot 10^5$	$3.61 \cdot 10^8$
PIAF, $^2H(d,n)$	5	85	12.4	$1.73 \cdot 10^5$	$2.65 \cdot 10^8$
PIAF, $^3H(p,n)$	2.5	54	11.3	$4.12 \cdot 10^5$	$4.51 \cdot 10^8$
PIAF, $^3H(p,n)$	1.2	39	11.3	$3.44 \cdot 10^5$	$2.48 \cdot 10^8$

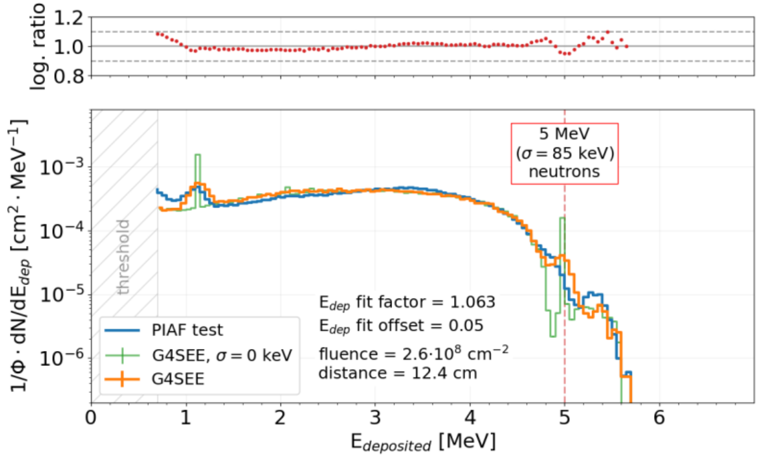
Validation of G4SEE with neutrons [1]



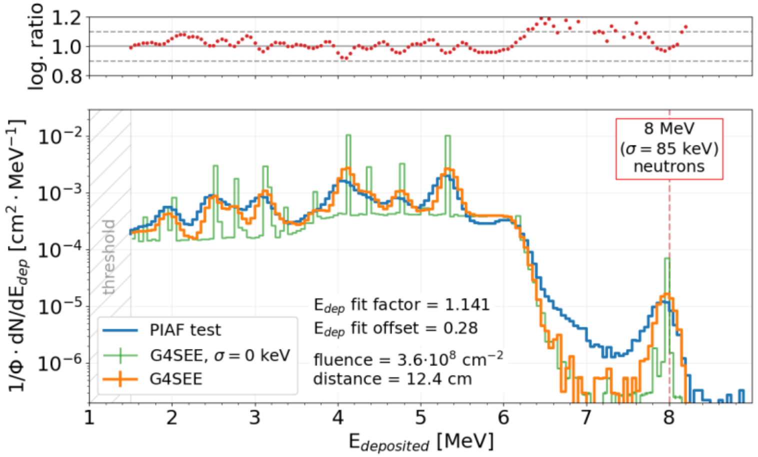
1.2 MeV



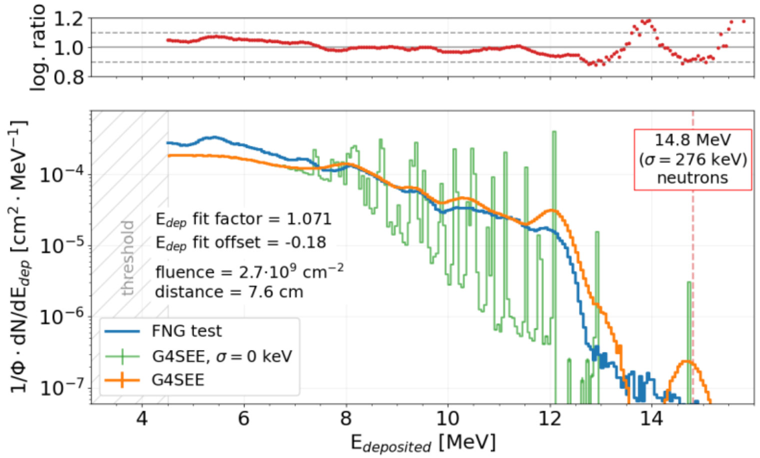
2.5 MeV



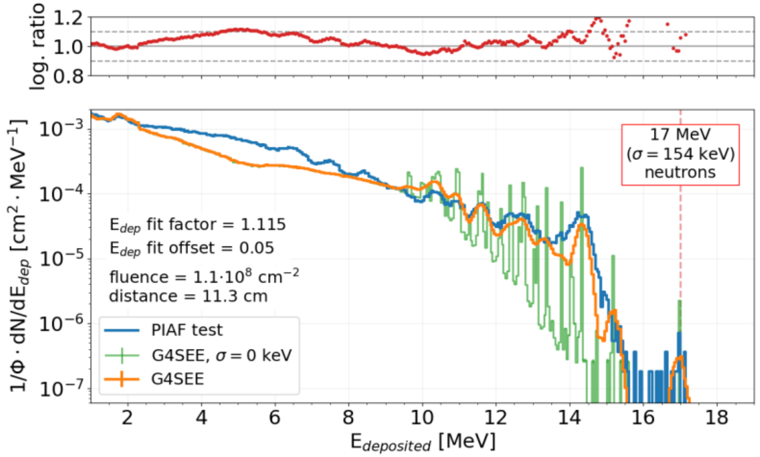
5 MeV



8 MeV

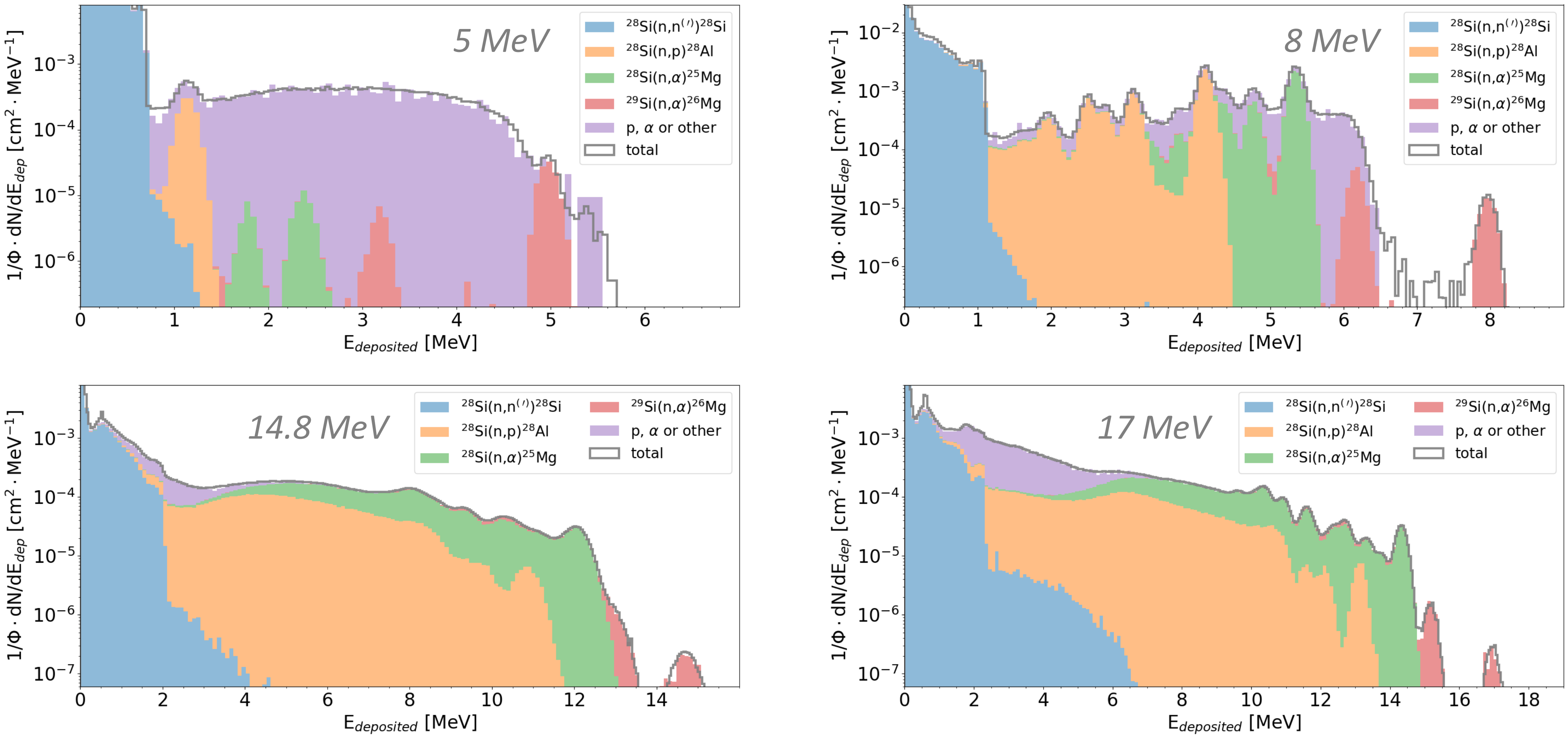


14.8 MeV



17 MeV

Validation of G4SEE with neutrons [1]



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

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