GSEAT

Geant4-based Single Event Analysis Tool

Version 1.0.0

User's Guide:

cogenda Pte Ltd

This documentation was typed in DocBook XML format, and typeset with the ConTEXt program. We sincerely thank the contributors of the two projects, for their excellent work as well as their generoisty.

Contents

Introduction

The Geant4-based Single Event Analysis Tool (GSEAT) is a computer code to be used to study single event effect (SEE) of microelectronics with space radiation environment. GSEAT is based on **Geant4**, a Monte Carlo code for the simulation of the passage of particles through matter.

For SEE simulation, the detailed 3D structure of microelectronic device is required. GSEAT can load the microelectronic device structure generated by the GDS2MESH tool in the Geometry Description Markup Language (**GDML**) format.

GSEAT support simulation of SEE caused by various particles including alpha, heavy ion, proton and neutron in a wide energy range. Realistic physical models for above particles have been implemented. User needn't have a pre-knowledge about nuclear physics.

The total energy deposit of the radiation event can be exported in both plane text file and xml file. The energy deposit can be further used with TCAD tool GENIUS to predicate SEE of the microelectronic device.

Installation

GSEAT is offered by Cogenda Pte. Ltd. as an add-on of VisualTCAD package and licensed separately. Before the installation, please make sure the VisualTCAD is already installed. GSEAT can be download from cogenda's website.

Usage

GSEAT has both GUI based application for convenient and command line code for batch execution. The input of GSEAT including the GDML file which contains geometry and material information of microelectronic device, the information of particle including particle kind, track and energy, and some control arguments.

Command Line Usage

The command line code has a input syntax as:

```
gseat -i <gdml_file> [-b macro_file] [-v schema_path]
      [-o xml_file] [-p out_path]
      [-t energy_threshold] [-m material_filter]
      [-c cut_value] [-l step_limit]
      [-s random_seed]
      [-fn neutron_enhance_factor]
      [-fp proton_enhance_factor]
      [-fion ion_inelastic_enhance_factor]
      [-r]
```

The options are:

Parameter	**Type**	**Description**	**Default**	**Unit**
`-i`	string	The GDML file which contains geometry and material information of microelectronic device.	none	none
`-b`	string	Geant4 macro file for batch mode simulation.	none	none
`-v`	string	Path to schema file for GDML validation.	none	none
`-o`	string	The name of output file which contains detailed information of each event with its energy deposite greater than given threshold. This file can be loaded by GUI for post process.	result.gse	none
`-p`	string	The path for files with energy deposite data. The default is none, which means no saving. When a valid path is given, each event with its energy deposite greater than threshold will be recorded to an individual file as `event<id>.dat`. This file can be loaded by Cogenda's 3D device simulator GENIUS for SEE simulation.	none	none
`-t`	numerical	Only save event with energy exceeds this threshold.	0.0	MeV
`-m`	string	Only save particle track in the region with given material.	none	none
`-c`	numerical	Cut value in range	0.1	Micron
`-l`	numerical	Step limit to heavy ion trace	0.25	Micron

Parameter	Type	Description	Default	Unit
`-s`	integer	Seed for random number generator. The same seed value gives identical Monte Carlo simulation result.	none	none
`-fn`	numerical	Enhance factor for neutron reaction.	1.0	none
`-fp`	numerical	Enhance factor for proton reaction.	1.0	none
`-fion`	numerical	Enhance factor for ion nuclear reaction.	1.0	none
`-r`	bool	Recover the factor of reaction enhancement after first particle step.	false	none

A Geant4 macro file must be offered by user which specified the information of incident particle. This file can be specified at command line by `-b` option or executed in the interactive mode by Geant4 `/control/execute` command.

A typical Geant4 macro file for GSEAT is show as follow. In this file, neutron with 18 MeV energy and momentum direction (0,0,-1) will be generated at space location (-0.5 um, 0, 2 um). Total 1000 neutron events will be simulated.

```
# set particle, can be proton, neutron, alpha, ion...
#/gun/particle proton
#/gun/energy 1 GeV

/gun/particle neutron
/gun/energy 18 MeV

#/gun/particle alpha
#/gun/energy 6.1 MeV

# Fe+
#/gun/particle ion
#/gun/ion 26 56 1
#/gun/energy 100 MeV

# trace information
/gun/position -0.5 0 2 um
/gun/direction 0.0 0.0 -1.0

# run 1000 events
/run/beamOn 1000
```

Here we only list the commands in the macro file.

The line begin with '#' is comment.

The `gun` command defines all the informations of the incident particle.

- `/gun/particle` [particle_name]

Set particle to be generated.
particle_name can be proton, neutron, alpha, ion and all the particles supported by Geant4. When particle name is ion, the `/gun/ion` command must be given for the detailed information of the ion.

- `/gun/ion [Z] [A] [Q] [E]`
  `Set properties of ion to be generated.`
  `Z:(int) AtomicNumber`
  `A:(int) AtomicMass`
  `Q:(int) Charge of Ion (in unit of e)`
  `E:(double) Excitation energy (in keV), default is 0`
- `/gun/energy` [energy] [unit]
  Set kinetic energy.
  The default unit of energy is GeV. Supported unit: eV keV MeV GeV TeV PeV
- `/gun/position [X] [Y] [Z] [unit]`
  `Set starting position of the particle.`
  `The default unit is cm. Supported unit: m cm mm um nm angstrom fm`
- `/gun/direction [Px] [Py] [Pz]`
  `Set momentum direction. Direction needs not to be a unit vector.`

The `run` command start a run of Geant4 simulation.

- `/run/beamOn [numberOfEvent]`
  `Start a Run.`
  `The default value of event is 1.`

With above `gun` and `run` command, user can use full features of GSEAT. However, there are other useful commands such as `control` for run time control and `visualization` for post process. The detailed syntax of each command of the macro file can be found at the **user's guide** of Geant4.

GUI Usage

Cogenda offers easy to use GUI VisualParticle to beginners. This GUI helps user to view the device structure, set incident particles and run time parameters and do post process of GSEAT simulation.

Lantch VisualParticle

VisualPartical GUI for GSEAT Simulation can be executed by typing "`VisualPartical`" in Linux platform or select corresponding shortcut in Windows platform. The main window of VisualPartical is shown in **Figure 1**, **p. 6**.

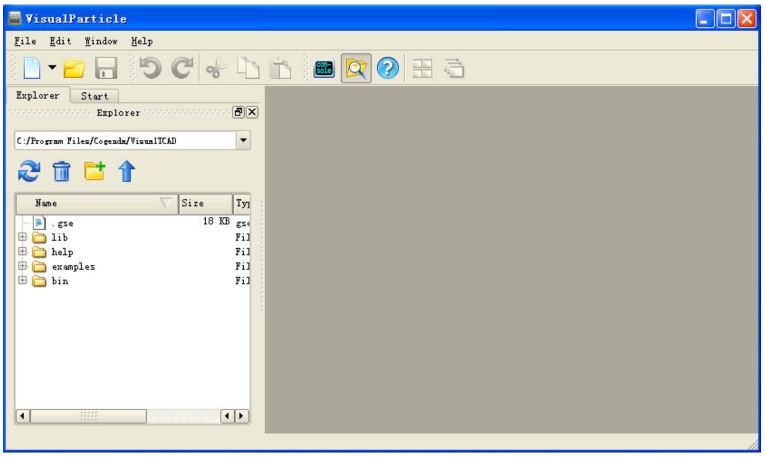

Figure 1 begin Window

After lantch the main window, click in the menu File ▷ New Radiation to open a new Radiation window, it is shown in **Figure 2**, **p. 6**.

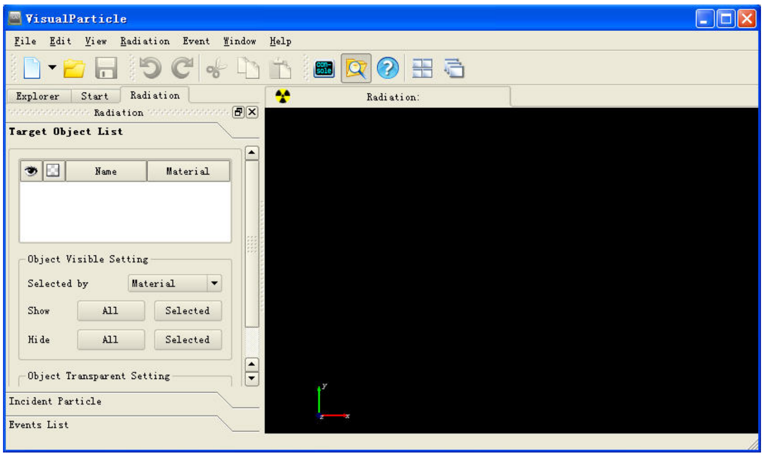

Figure 2 New Radiation Window

Load GDML File

Click in the menu Radiation ▷ Load GDML File to load the device structure file `sparse.gdml`, it is shown in **Figure 3, p. 7**.

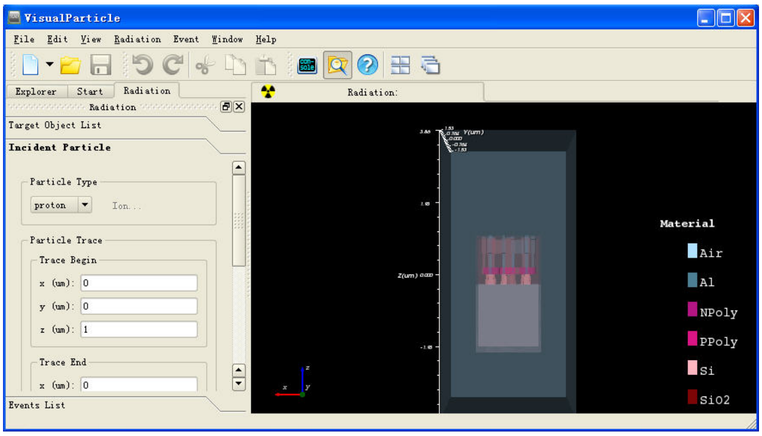

Figure 3 Load GDML File Window

The file `sparse.gdml` which contains 3D geometry and material infomation of target device can be generated 1) by Cogenda's GDS2MESH tool, 2) from other 3D device modeling file.

The most converinent way for generateing GDML structure is using GDS2MESH tool, user can select `.gdml` as output file format. The export structure file is shown in **Figure 4, p. 8**

When usr has their own device model with other file format, such as TIF3D format, DF-ISE format from Synopsys Sentaurus or STR format from Silvaco, it is possible to use Genius to transform them to `.gdml` file. The following deck for transformation is listed as below:

Program listing of the Genius input deck for GDML file.

```
GLOBAL resistivemetal=true
# import device structure as TIF3D
IMPORT TIF3D="npn_20_20.tif3d"
# import device from DF-ISE
#IMPORT ISE="SentaurusMsh"
# import device from silvaco str file
#IMPORT Silvaco="SilvacoMesh.str"

# export device with GDML format
EXPORT GDML.Surface=sparse.gdml
```

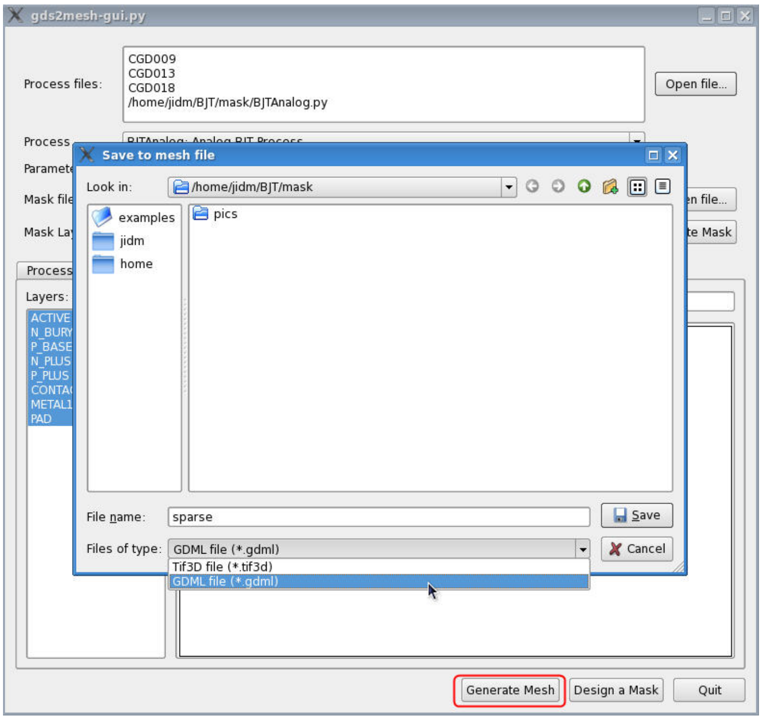

Figure 4 Export GDML File Window

Set Particle

Click in the menu Radiation ▷ Set Incident Particle to edit the incident particle. User need to select particle type, set start and end position of the partial trace, set kinetic energy of particle and choose the beam numbers. The dialog is shown in **Figure 5**, **p. 9**. Here alpha partial with18 MeV kinetic energy is selected as the incident partial. The partial trace is vertical from the surface of the device to the device. The total beam number here is 10, which means GSEAT will simulate 10 alpha particle events.

If proton or neutron is selected for particle simulation, more beam numbers may be needed. For example, user may need 1e6 beams for a naive simulation to get several useful events. Hence some trick to reduce the beam number should be used here. For more details, please refer to "**Bias Cross-Section of Reaction**", **p. 23**

Set Runtime Parameters

Click in the menu Radiation ▷ Set Run Control to set output file path, it is shown in **Figure 6**, **p. 9**. Also, it is possible to set the seed value of pseudo random number generator. Different seed value gives different simulation result.

VisualParticle provides Advanced Settings for proton and neutron. The recom-

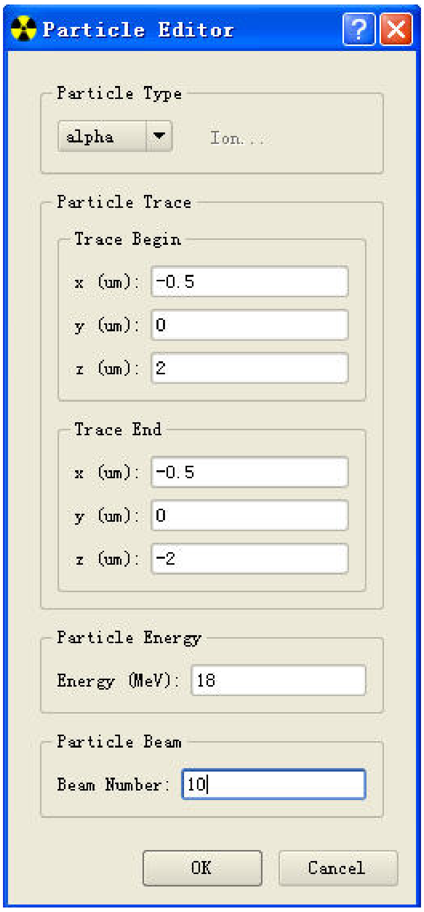

Figure 5 The Particle Editor Window

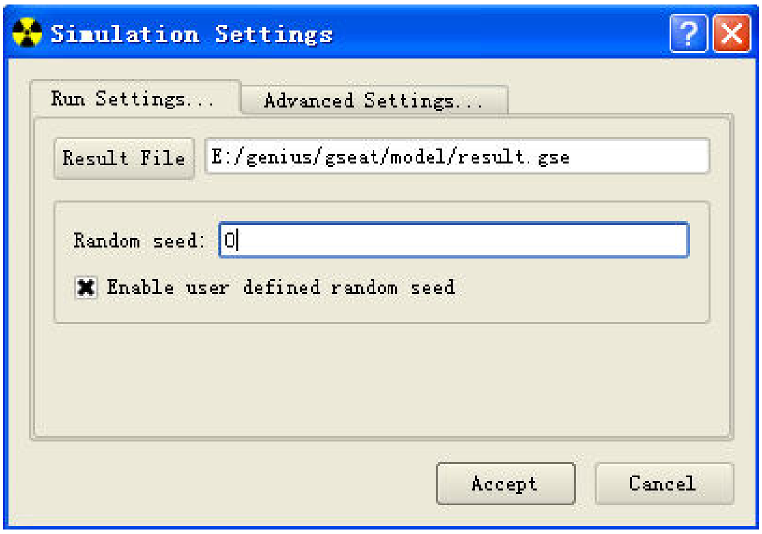

Figure 6 The output file path

mend value of Threshold Energy for proton is 0.01 MeV. This value can filter most proton events with very little energy deposite. The proton Advanced setting is shown in **Figure 7**, **p. 10**. And the neutron Advanced setting is shown in **Figure 8**, **p. 10**. For the reaction enhancement factor, please refer to “**Bias Cross-Section of Reaction**”, **p. 23**

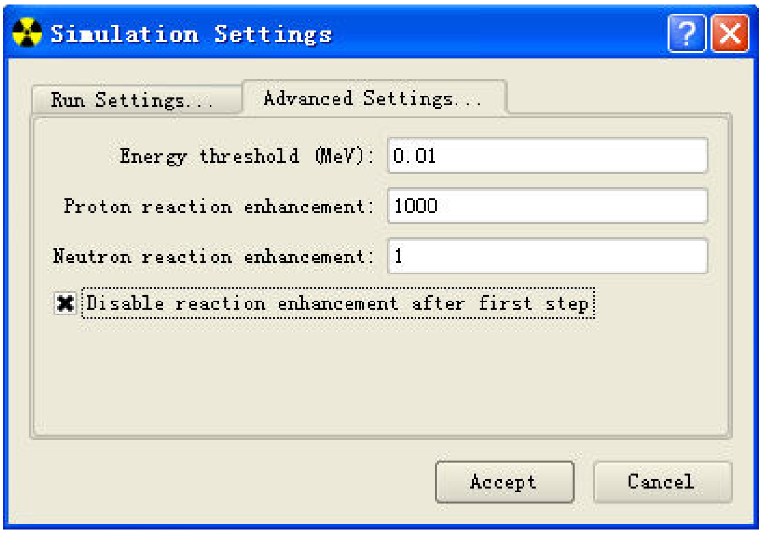

Figure 7 The proton particle advanced setting

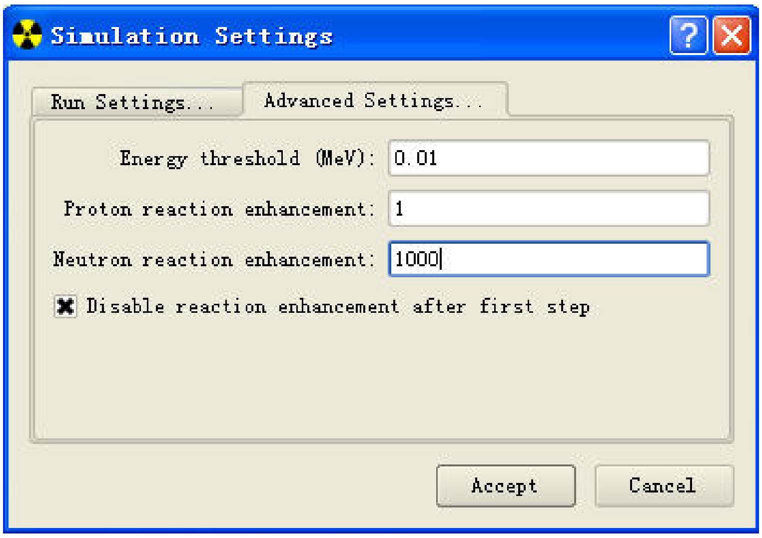

Figure 8 The neutron particle advanced setting

Run Simulation

When finishing above setting, Click in the menu Radiation ▷ Set Run Control to run the particle simulation, the simulation console is shown in **Figure 9**, **p. 11**.

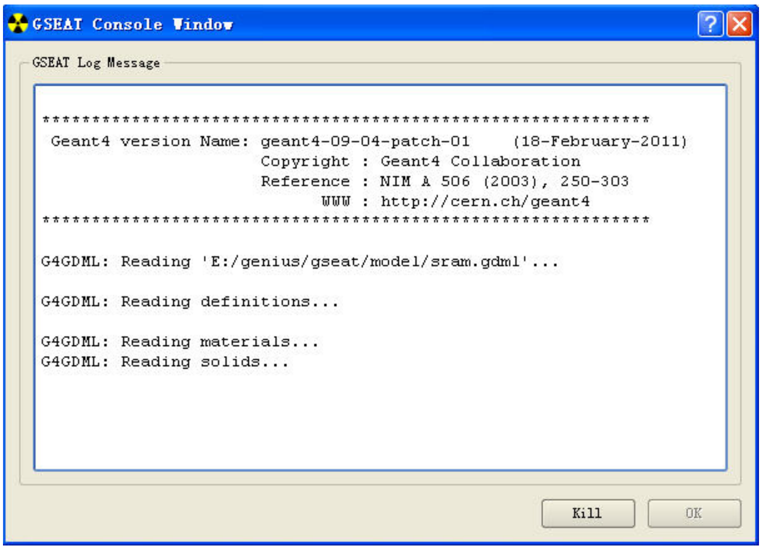

Figure 9 The simulation console Window

View Event and Export Energy Deposite

When the simulation finished, the events are loaded into VisualParticle automatically as shown in **Figure 10**, **p. 11**, user can show all or individual events.

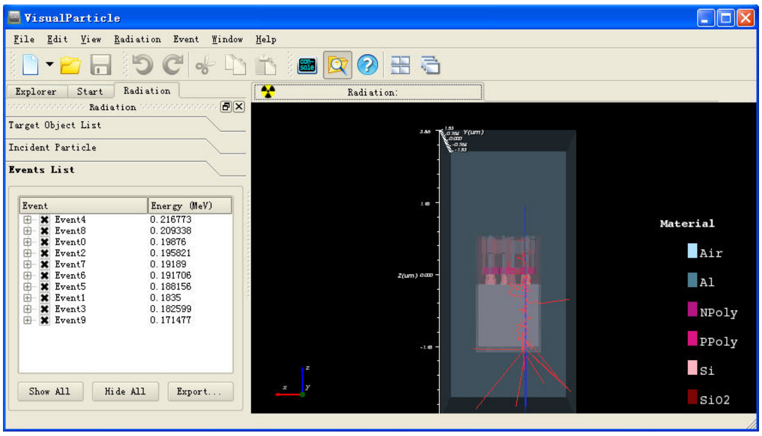

Figure 10 The Event Trace

The missive particle Trace is shown in **Figure 11**, **p. 12**. User can highlight the chosen trace.

Finally, user can click the Export button to export the event data. It is shown in **Figure 12**, **p. 12**. Here the alpha particle simulation finished.

The output event file data is listed as below:

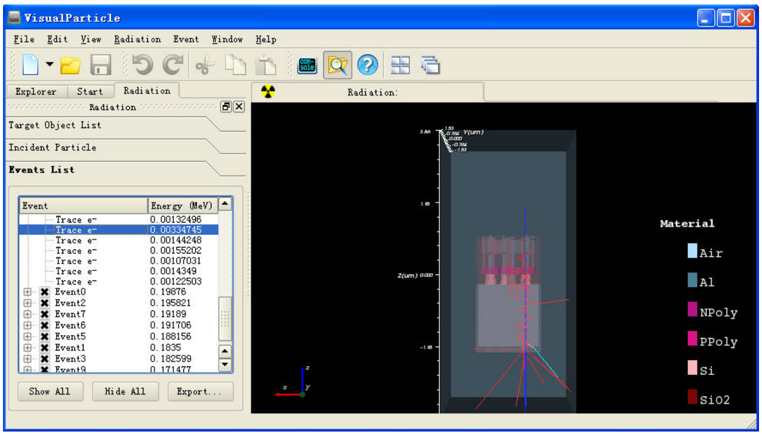

Figure 11 The electronics Trace

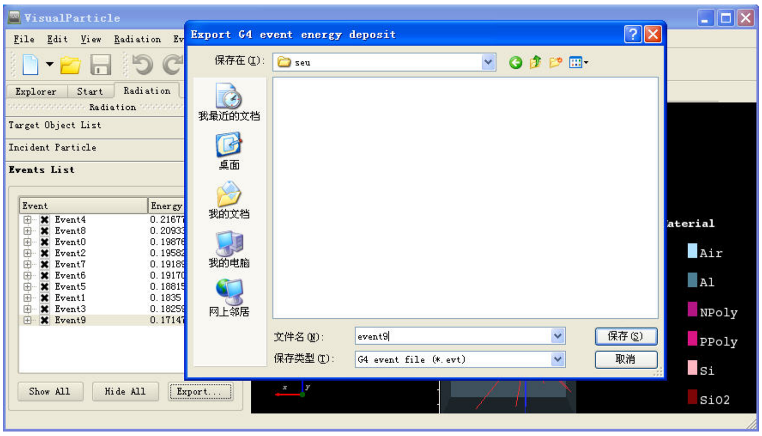

Figure 12 Export event data file

```
#Data file for energy
#device_info
#{
# name = GeniusToGeant4
#}
#event_info
#{
# eventid = 8
# tracks = 214
# total_energy = 1.98125MeV
#}
T 0 0 2 0 0 1.66127 0.0169979
T 0 0 1.66127 4.99358e-05 1.01828e-05 1.62147 0.00249687
T 4.99358e-05 1.01828e-05 1.62147 5.81009e-05 1.32237e-05 1.6136
0.000128777
T 5.81009e-05 1.32237e-05 1.6136 0.000156247 5.33847e-05 1.51402
0.00399031
T 0.000156247 5.33847e-05 1.51402 0.000171452 6.07151e-05 1.502
0.000828062
T 0.000171452 6.07151e-05 1.502 0.000227292 8.42656e-05 1.45987
0.00151206
T 0.000227292 8.42656e-05 1.45987 0.000280307 0.000131192 1.40693
0.00303379
T 0.000280307 0.000131192 1.40693 0.000298462 0.000153189 1.39097
0.0012539
T 0.000298462 0.000153189 1.39097 0.000455208 0.0003324 1.26505
0.0057886
```

The event file which contains the energy deposite can be loaded into Cogenda's TCAD tool Genius as the source of particle effect.

Physics List

For a simulation of high energy particle reaction, the selection of **physics processes** is a key issue to the reliability and accurate of the result. GSEAT contains the best-guess selection of electromagnetic and hadronic physics processes required to run simulations of micro-electronics applications in a space environment.

Boson Physics

The boson physics defines the four possible gamma reaction:

- gamma
  - Gamma converts to e+ e- pairs
  - Compton scattering of gamma
  - Gamma-electric effect
  - Gamma-nuclear process
    - ⋆ hadronic models:
      - ▷ Gamma nuclear reaction : 0 - 3.5 GeV
      - ▷ Quark-gluon String with Precompound : 3.0 GeV - 100 TeV

Note: Two hadronic models are required to describe photon interactions with nuclei and nucleons. These hadronic models are discussed further in Hadron Physics.

Lepton Physics

The lepton physics defines physical processes for electrons, muons and taus along with their corresponding neutrinos. The following processes are assigned to each particle:

- electron
  - multiple scattering
  - electron ionization
  - electron bremsstrahlung
  - electron-nuclear process
    - ⋆ hadronic model:
      - ▷ electro-nuclear reaction : all energies

- positron
  - multiple scattering
  - electron ionization
  - electron bremsstrahlung
  - positron annihilation
  - positron-nuclear process
    - ⋆ hadronic model:
      - ▷ positron-nuclear reaction : all energies

- mu-
  - multiple scattering
  - muon ionization
  - muon bremsstrahlung
  - e+ e- pair production by muon
  - muon capture at rest

- mu+
  - multiple scattering
  - muon ionization
  - muon bremsstrahlung
  - e+ e- pair production by muon

- tau-
  - multiple scattering
  - hadron ionization

- tau+
  - multiple scattering
  - hadron ionization

Note: One hadronic model is required to describe electron- and positron-induced nuclear reactions. The electro-nuclear reaction model relies on the method of equivalent photons to calculate a virtual photon spectrum, which in turn is interacted with the nucleus and nucleons using a photo-nuclear model similar to that in Boson Physics.

Hadron Physics

The hadron physics defines all stable and long-lived baryons, except for the neutron, and all long-lived mesons. These are the particles that Geant4 can track and therefore require processes to be assigned. Short-lived particles are not tracked, but they appear in some hadronic models, so a large list of resonances, quarks and diquarks is also defined.

- pi+
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Bertini cascade : 0 - 9.9 GeV
      - ▷ Low Energy Parameterized : 9.5 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV

- pi-
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Bertini cascade : 0 - 9.9 GeV
      - ▷ Low Energy Parameterized : 9.5 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV
  - absorption at rest

- K+
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV

- K-
  - multiple scattering

  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV
  - absorption at rest

- K0L
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV

- K0S
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV

- proton
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Bertini cascade : 0 - 9.9 GeV
      - ▷ Low Energy Parameterized : 9.5 - 25 GeV
      - ▷ Quark-gluon String with Precompound : 15 GeV - 100 TeV

- anti-proton
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies

- hadron inelastic scattering
  - ⋆ hadronic models:
    - ▷ Low Energy Parameterized : 0 - 25 GeV
    - ▷ High Energy Parameterized : 20 GeV - 10 TeV
- annihilation at rest

- anti-neutron
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ High Energy Parameterized : 20 GeV - 10 TeV
  - annihilation at rest

- lambda, anti-lambda, xi0, anti-xi0
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ High Energy Parameterized : 20 GeV - 10 TeV

- sigma-, anti-sigma-, sigma+, anti-sigma+, xi-, anti-xi-, omega–, anti-omega–
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ LElastic : all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Low Energy Parameterized : 0 - 25 GeV
      - ▷ High Energy Parameterized : 20 GeV - 10 TeV

Neutron Physics

The neutron physics defines the neutron and its associated models, processes and cross sections. G4NDL3.7 neutron data library is used for high-precision neutron models.

- hadron elastic scattering
  - high precision neutron elastic : 0 - 20 MeV
  - Elastic: above 20 MeV

- hadron inelastic scattering
  - high precision neutron inelastic: 0 - 20 MeV
  - Bertini cascade : 20 MeV - 9.9 GeV
  - Low Energy Parameterized : 9.5 - 25 GeV
  - Quark-gluon String with Precompound : 15 GeV - 100 TeV

- neutron induced fission
  - high precision neutron fission: 0 - 20 MeV
  - Low Energy Fission : 20MeV - 20 TeV

- neutron capture
  - high precision neutron capture: 0 - 20 MeV
  - Low Energy Capture : 20MeV - 20 TeV

Ion Physics

The ion physics constructor defines deuterons, tritons, 3He and alphas, as well as a generic ion. The processes and models assigned to the deuteron, triton, and alpha are essentially identical. Also, all three particles are covered by the same set of inelastic cross sections.

3He and generic ions are treated differently. There are currently no elastic hadronic processes or models for these particles. However, the inelastic reaction can be handled. The cross section data sets are the same as those for deuteron, triton and alpha, with the exception that the Tripathi light ion cross section must not be used for ions heavier than alphas.

- deuteron, triton, alpha, 3He
  - multiple scattering
  - hadron ionization
  - hadron elastic scattering
    - ⋆ hadronic model:
      - ▷ all energies
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ Binary Light Ion Reaction : 0 - 10 GeV
    - ⋆ cross sections:
      - ▷ Sihver ion cross section
      - ▷ Shen ion cross section
      - ▷ Tripathi ion cross section
      - ▷ Tripathi light ion cross section (only for light materials)

- Generic ion
  - nuclear recoil
  - ion ionization
    - ⋆ Parametrised Loss Model
  - hadron inelastic scattering
    - ⋆ hadronic models:
      - ▷ QMD Reaction : 0 - 10 GeV
    - ⋆ cross sections:
      - ▷ Sihver ion cross section
      - ▷ Shen ion cross section
      - ▷ Tripathi ion cross section

Note: The Binary Light Ion Reaction model has been applied to light ions. For generic ion, the QMC reaction model is used.

Decay Physics

The decay physics handles the decay channels for all unstable particles defined in the physics list. The same process is assigned to all unstable particles.

Bias Cross-Section of Reaction

For a Geant4 simulation with all the particle reactions are determined according to the real cross-sections, this approach of course will lead to reliable simulation results. However, this method may be time consuming when the dominated reaction has a small cross section. For example, for investigate the SEE of microelectronic device caused by neutron-nuclear interaction or proton-nuclear interaction, usually 10k incident neutrons or protons can generate only one useful case. Here GSEAT offers "**biasing**" mechanism to speed up the simulation.

The principle of biasing mechanism is artificially enhance/reduce the interaction cross-section of certain process. For each step, when the biased process is being selected, the weights of current track and the secondaries are changed to

$$w' = \frac{1 - \exp\left(-\frac{s}{x}\right)}{1 - \exp\left(-\frac{f \cdot s}{x}\right)} w \tag{1}$$

If the process is not being selected, the weight of the current track is changed to

$$w' = \left(1 - \exp\left(-\frac{f \cdot s}{x}\right)\right) w \tag{2}$$

Here

- w: the original parent particle weight
- s: the step length
- x: the unbiased current interaction length of the particle
- f: the enhancement factor

When neutron/proton path though 1um thick silicon, the probability of nuclear interaction is around 1.0×10^{-5}.

There are two strategies for biasing. One is setting the bias factor in the range of 100-1000. For this situation, the probability is enhanced to 1.0×10^{-2}. This is an acceptable but still small value. User can simulate thousands of incident events to get enough cases. Further more, the secondary particle has little chance to cause another interaction. It is not necessary to remove the secondary particle. Another way is setting the bias factor to a very large value, i.e. 1.0×10^{8}. In this situation, the probability of nuclear interaction is very close to 1.0, which means nuclear interaction will be happened at the very location the particle be generated. Thus, user can specify the location of interaction by this method. However, the bias factor should be reset to 1.0 after the first particle step or it is very likely to cause another interaction near the former location, which can be done by setting the -r flag from command line.