High Performance Monte-Carlo Radiation Simulations workshop

-

Use cases and effects requiring GRAS/GEANT4 simulations to identify limitations and bottlenecks within the first trimester of Hi-MoCaRT

B. Jeanty-Ruard[1], L. Artola[2], B. Tezenas du Montcel[1], A. Trouche[1], J. Forest [1]

(1) Artenum
(2) ONERA

ruard@artenum.com

March 2026

Agenda

- ESA activity context
- Space-Suite context
  - Presentation of tools using GEANT4 and GRAS simulation results
    - EDGE for GDML definition
    - MoORa for GRAS simulation
    - SPIS-IC using GRAS simulation results
    - SEE-U using GRAS simulation results
    - Spacecraft specific risk forecast service using previous tools
  - Presentation of some use cases and effects computed for Space applications
    - Total Ionizing Dose (TID),
    - Total Non-Ionizing Dose (TNID),
    - Internal Charging (IC),
    - Single Event Upset (SEU)
- Identify limitations/bottlenecks in GRAS/GEANT4 for this different use cases

Context

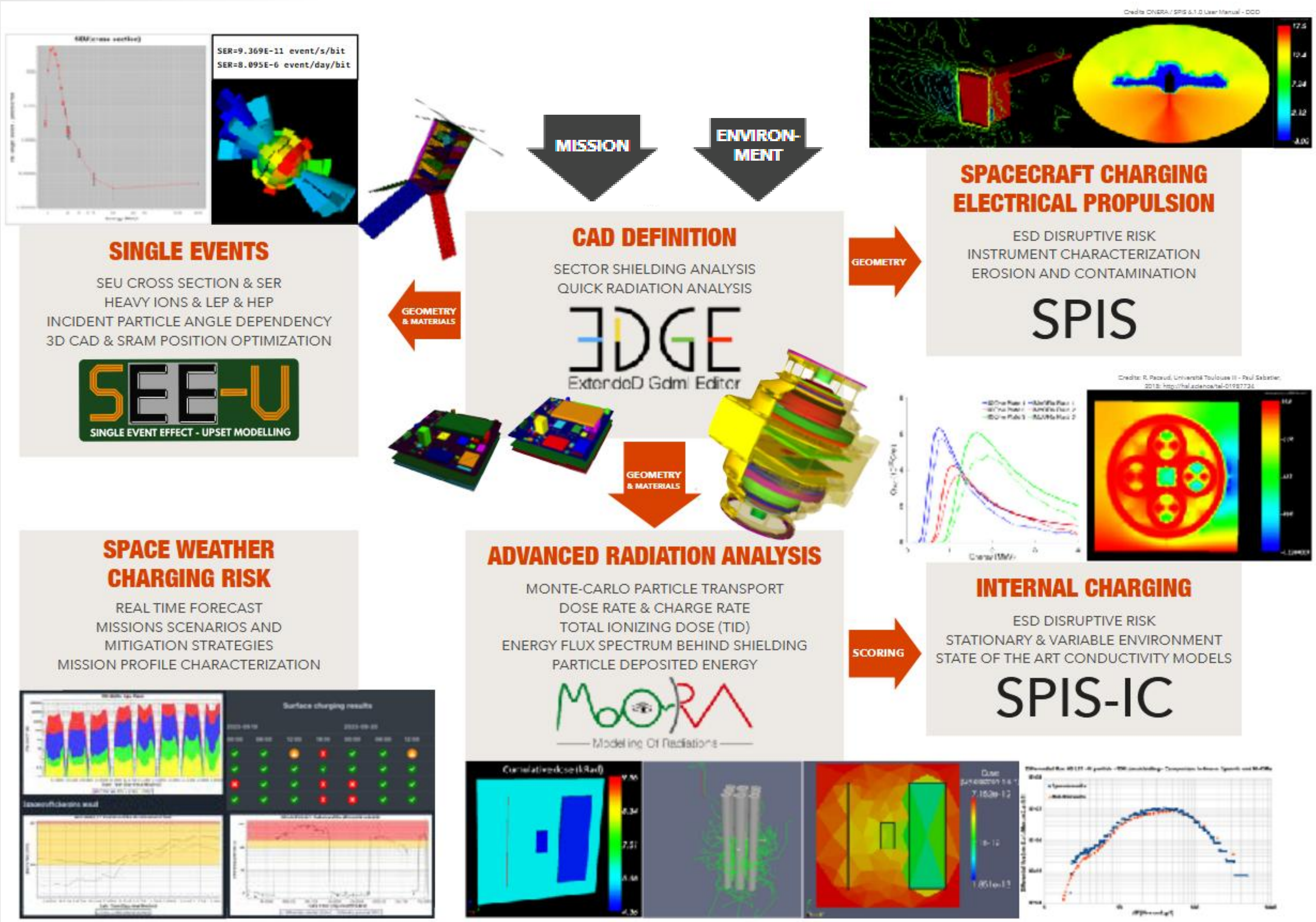
- ESA AO/1-12759/25/NL/CRS: HIGH-PERFORMANCE MONTE CARLO RADIATION TRANSPORT AND EFFECTS MODELLING
  - Consortium
    - IASA - prime
    - ONERA
    - Artenum
  - WP100: State-of-the-Art review
    - Artenum participates to task “Identify limitations/bottlenecks in GRAS/GEANT4”

Institute of Accelerating Systems and Applications

Context – Space-Suite

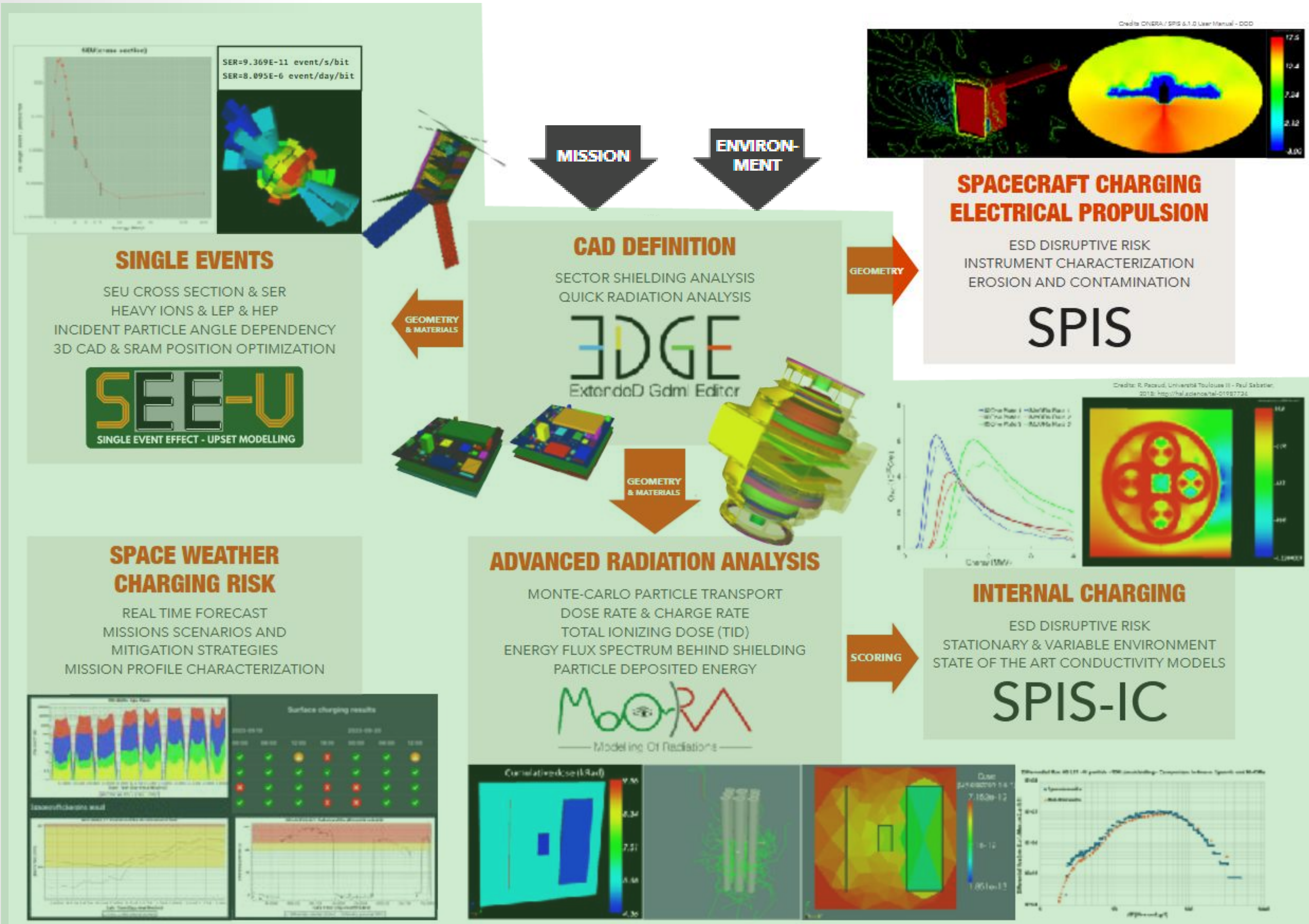
Reference answer from European experts: Space-Suite offer

- Model several effects of space environment www.space-suite.eu



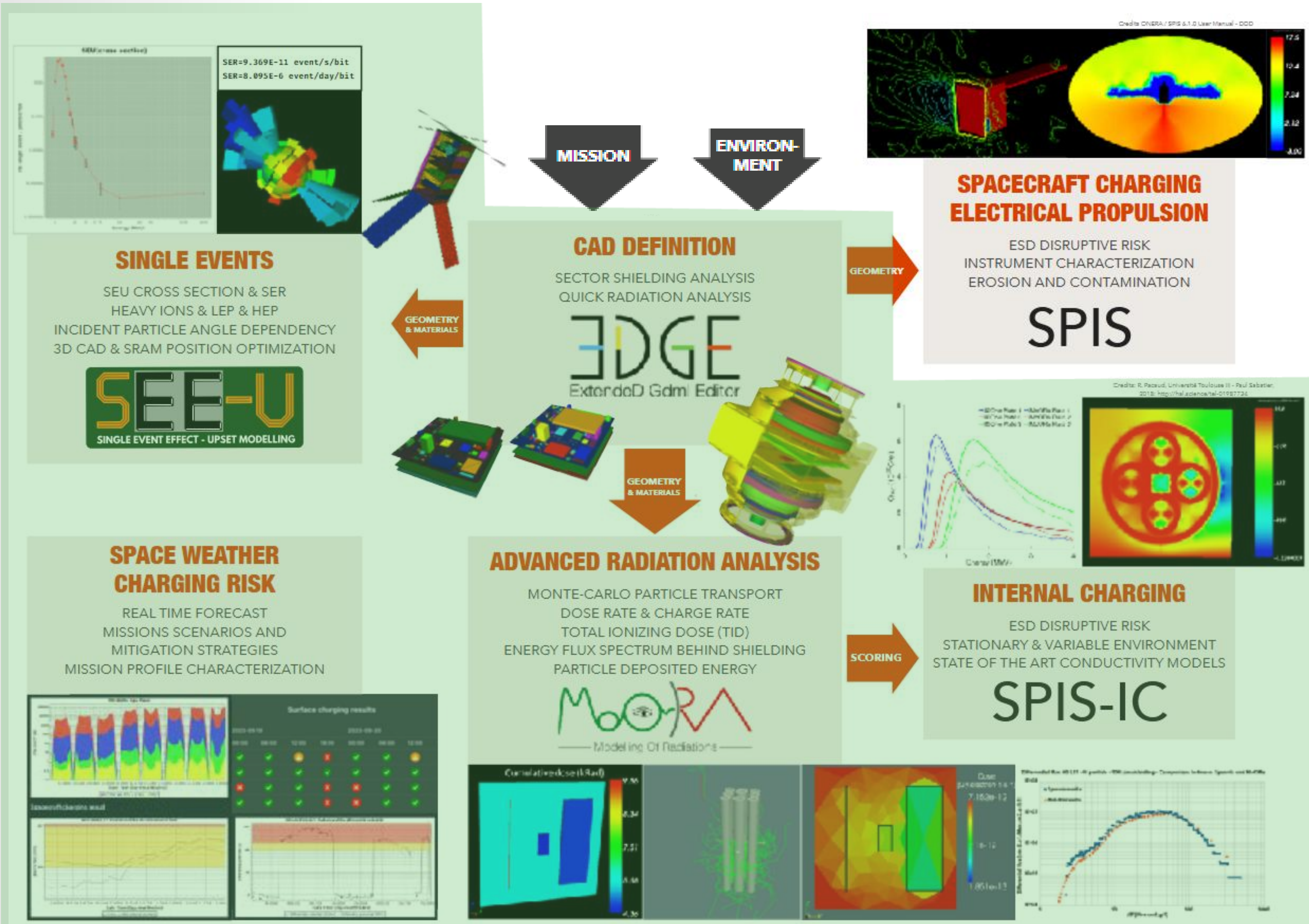
Context – Space-Suite

Several Space-Suite tools use directly or indirectly Geant4 and GRAS



Context – Space-Suite

Our participation to identify some limitations/bottlenecks in GRAS/GEANT4 is based on the use of these tools

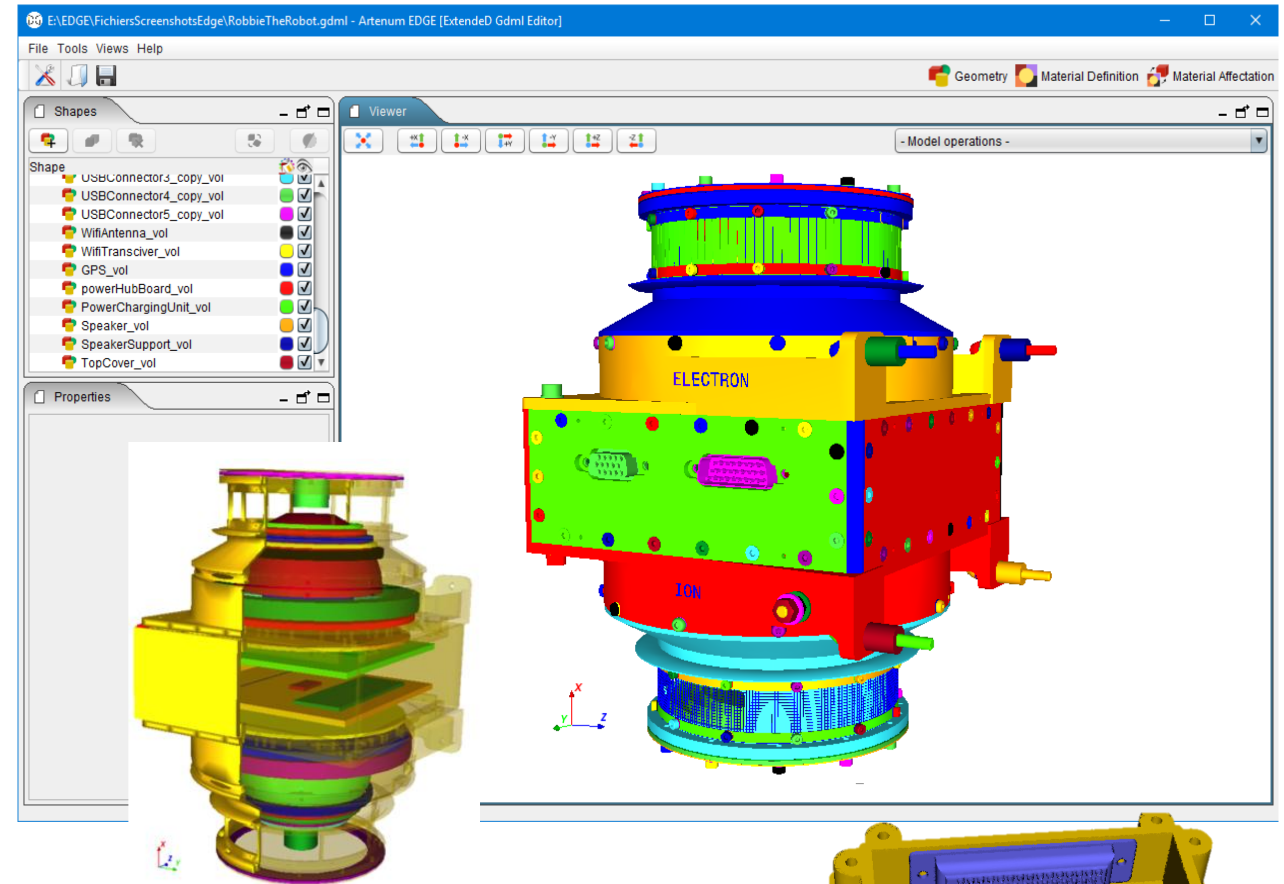


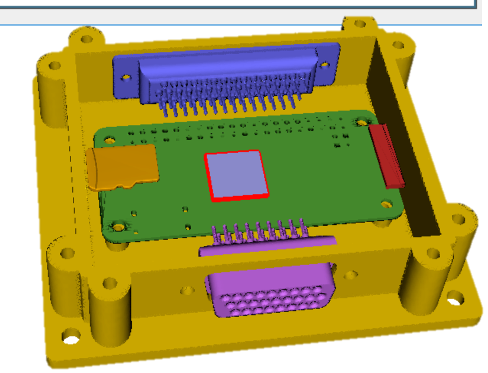
Artenum, Paris
Science & Groupware

Context – Space-Suite

EDGE – ExtendeD Gdml Editor

- Geometry creation / edition
  - GDML shape oriented
  - Geometry simplification function
- Geometric operations
  - Validate GDML using xsd
  - Overlap detection
  - Compute surface and volume
  - Compute geometric hierarchy
- GDML materials edition
  - Creation, edition and assignment
  - Import / export of materials from / to GDML files
  - Multi-attribution
- Import / export capabilities
  - GDML
  - STEP-AP 203/214
  - GMSH
  - MCNP



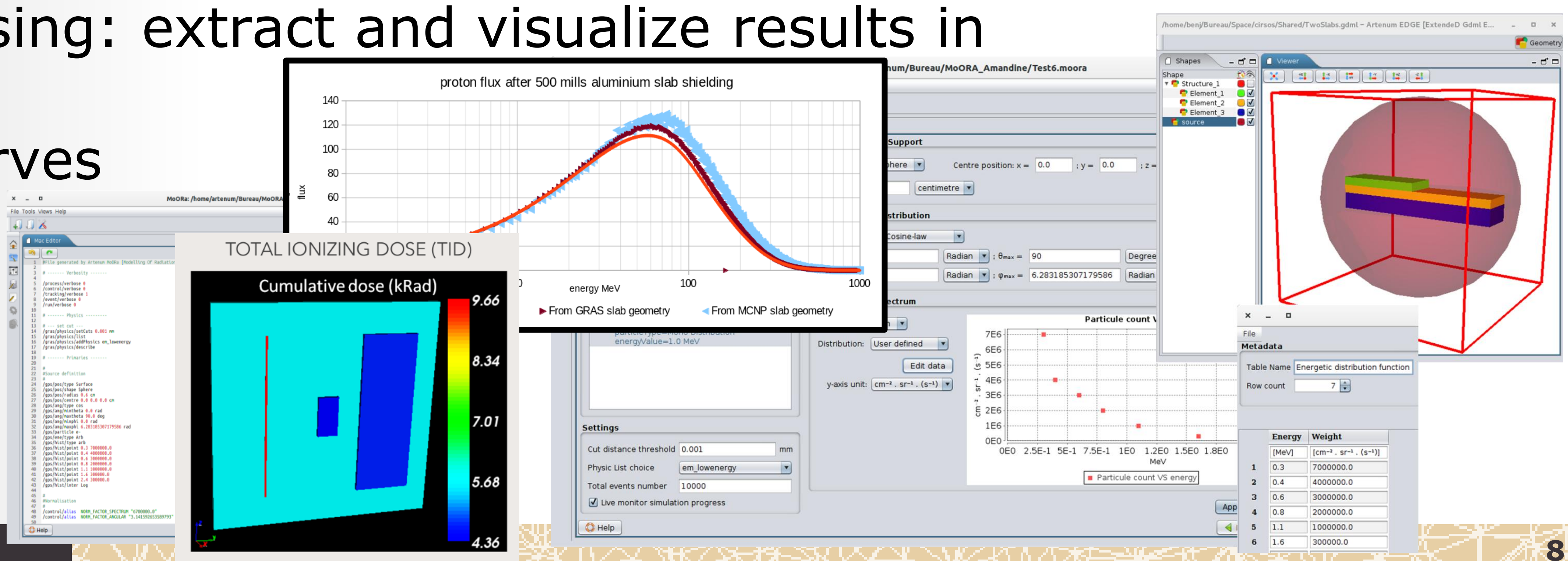


EDGE
ExtendeD Gdml Editor

Context – Space-Suite

MoORa – Modelling Of Radiation

- Modelling chain for GEANT4 simulation => compliant with GRAS
- Pre-processing
  - GDML file import
  - Source definition: geometry, angular distribution, particle type and spectrum, 3D visualization, …
  - Physic parameters: event count, physic list, CPU parallelism, …
  - Choose what result to compute: TID, energy spectrum behind shielding, deposited dose / charge on Gmsh or GEANT4 mesh, …
- Live monitoring: monitor the simulation progress
- Post-processing: extract and visualize results in
  - Text files
  - y=f(x) curves
  - 3D

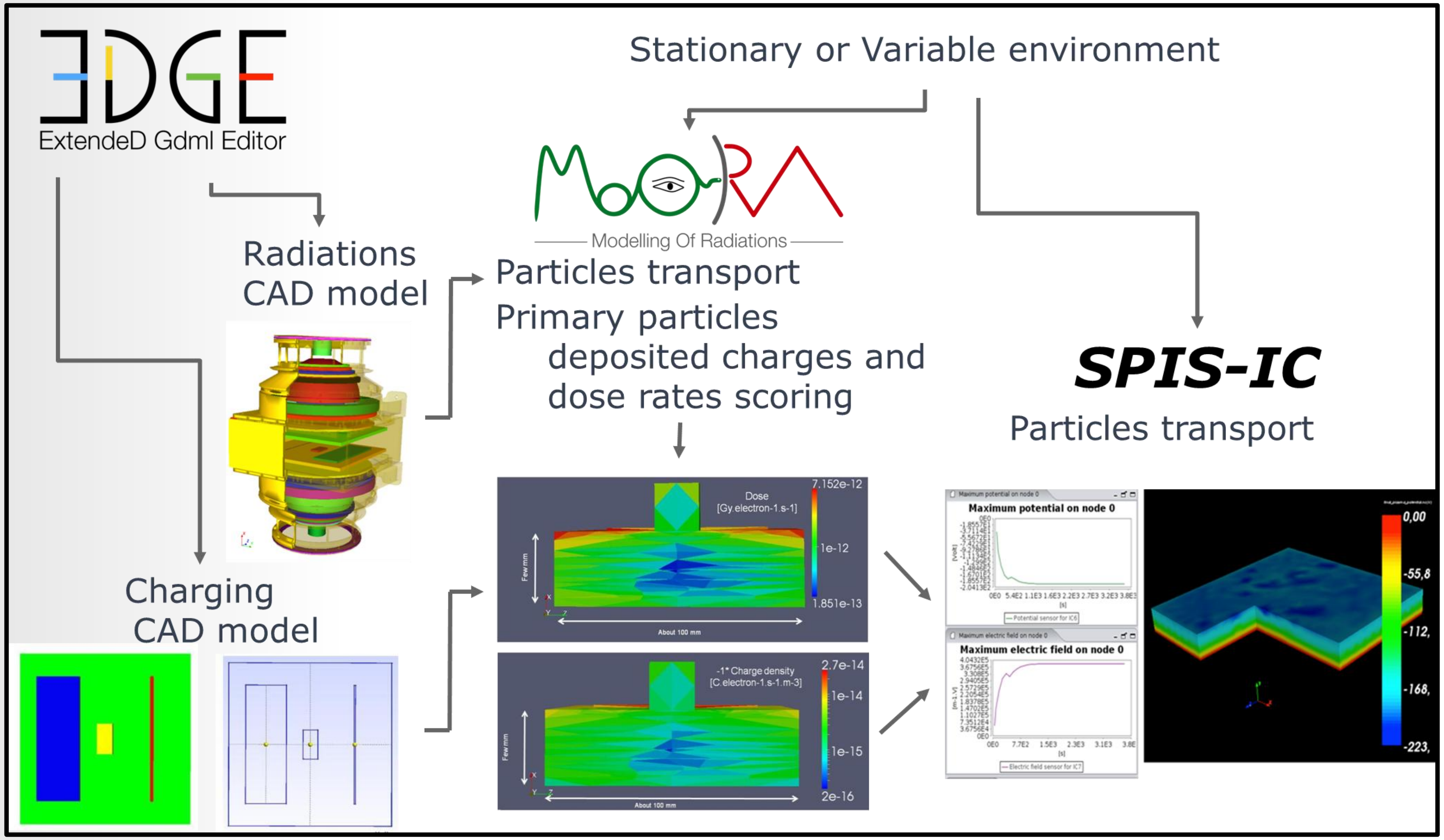


Modelling Of Radiations

Context – Space-Suite

SPIS-IC – Spacecraft Plasma Interaction Software - internal charging

- Model the electrical field evolution inside dielectric over the time
- Needs results from GRAS as inputs:
  - Deposited dose rate => conductivity material property in SPIS
  - Deposited charge rate => compute the charge transport in SPIS



Context – Space-Suite

SEE-U – Single Event Effect - Upset modelling

- Cosmic Rays Effects on MicroElectronics

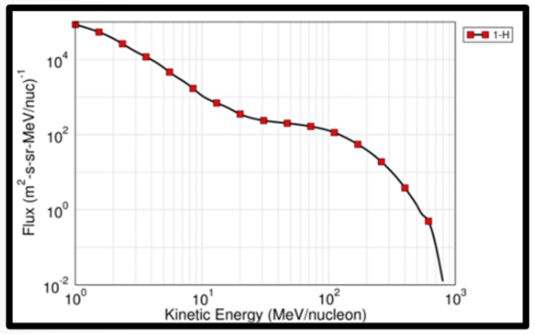
SEE-U
SINGLE EVENT EFFECT - UPSET MODELLING

Orbit

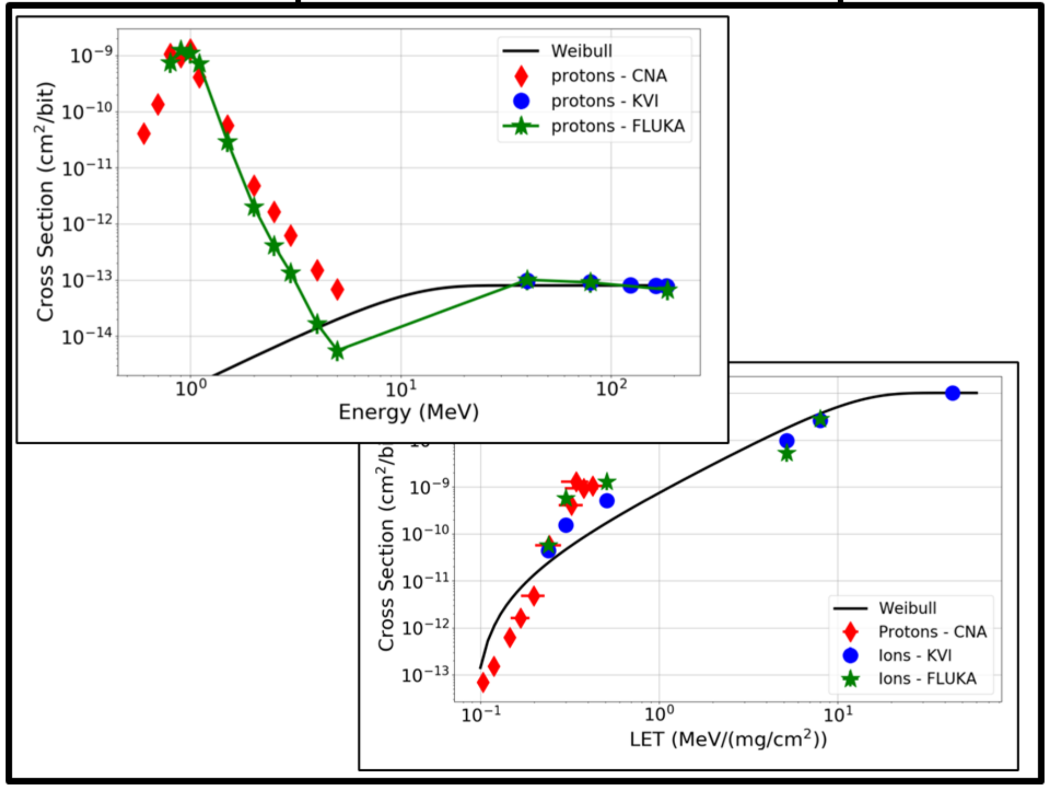
Environmental flux

Transport through Shielding

Flux behind shielding



Credits: *A. Coronetti et al. [1]*



Single Event Upset (SEU) Cross section

Software Error Rate (SER)

Context – Space-Suite

SEE-U – Single Event Effect - Upset modelling

- Use MoORa for some parts
  - Compute deposited energy close to transistor
  - Compute flux behind shielding

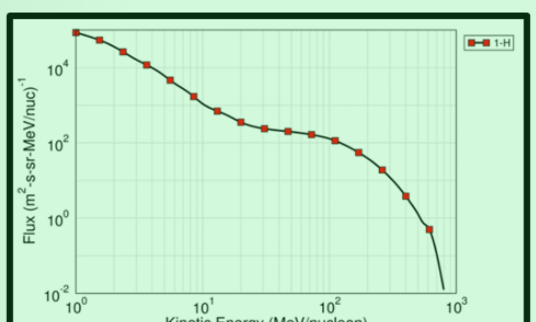
SEE-U
SINGLE EVENT EFFECT - UPSET MODELLING

Orbit

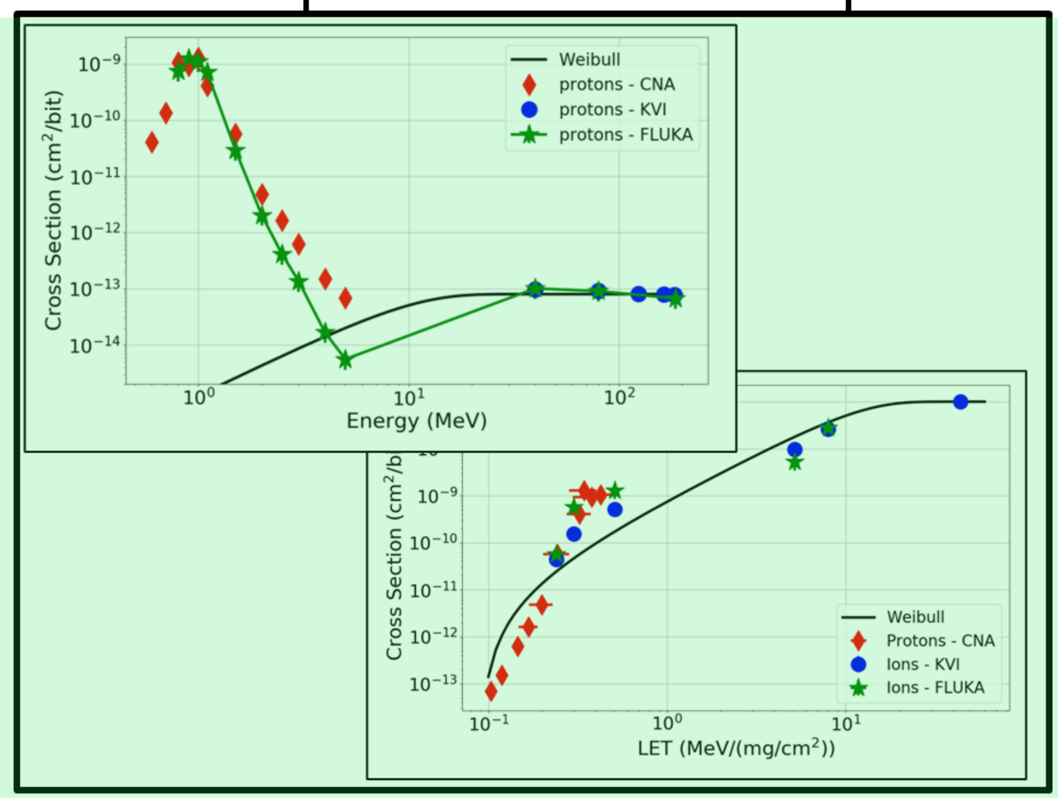
Environmental flux

Transport through Shielding

Flux behind shielding



Credits: *A. Coronetti et al. [1]*



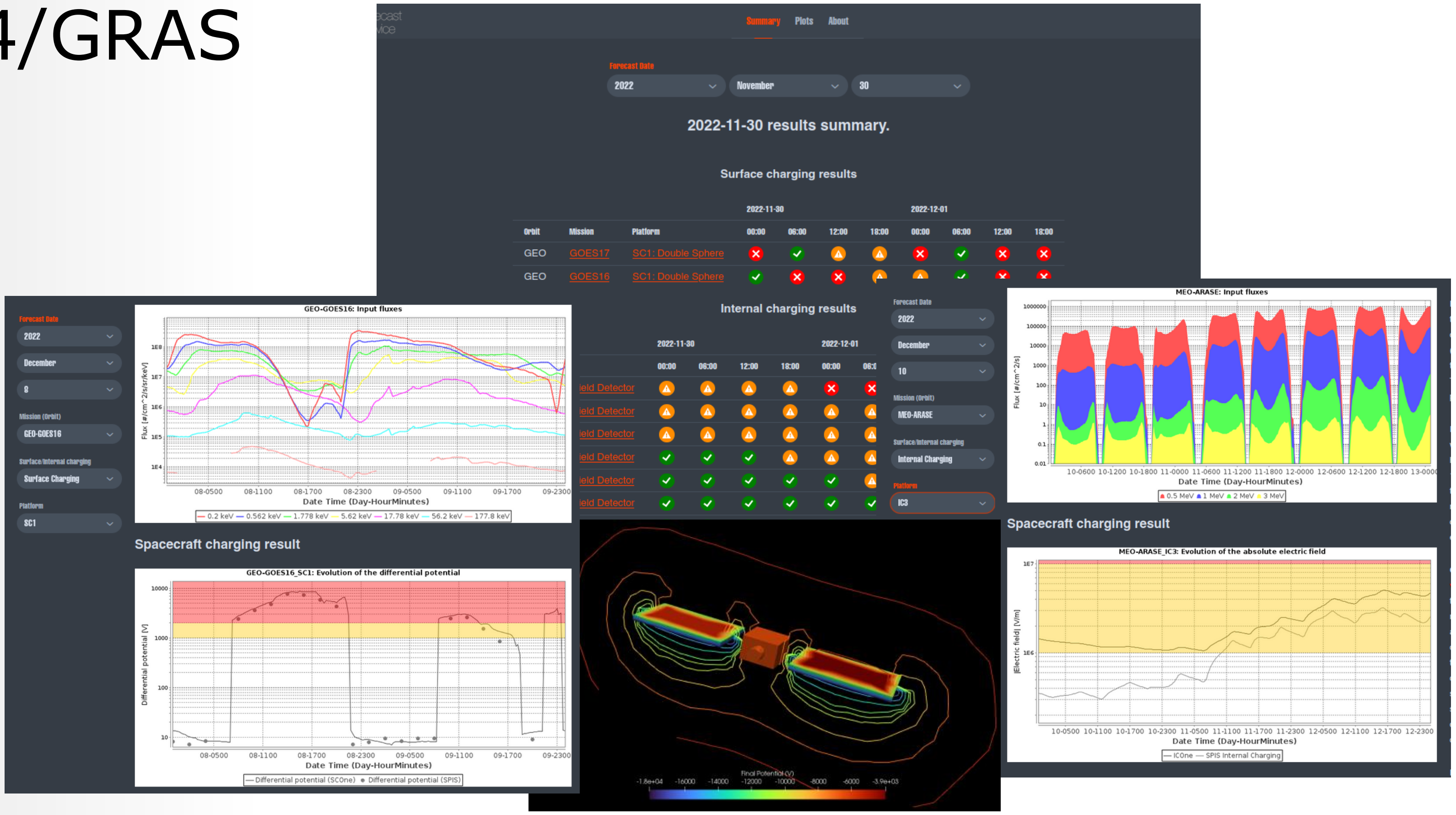
Single Event Upset (SEU) Cross section

Software Error Rate (SER)

Context – Space-Suite

Forecast effects service

- Forecast energy spectrum for dedicated orbit provided by a partner
- Connect this spectrum to our Space-Suite tools
  - Forecast risks for several effects:
    - Surface charging => not connexion with GEANT4/GRAS
    - Internal charging => use results from GEANT4/GRAS
    - TID (experimental) => computed with GEANT4/GRAS
    - Software Error Rate (experimental) => use results from GEANT4/GRAS



Identify limitations/bottlenecks in GRAS/GEANT4

1. TID

- Need accuracy in deposited energy in a shape and shape volume precision with multi-scale
- Geometry
  - Complex spacecraft geometries and shielding configurations
  - Few centimetres
- Particle type: electrons and protons
- Energy: from few keV to 500 MeV
- Physic list usually used: emstandard_opt4

2. TNID

- Similar to TID
- Geometry: idem TID
- Particle type: electrons, protons and neutrons (lunar ground)
- Energy: from few 100 keV to 500 MeV
- Physic list usually used: emstandard_opt4 and QGSP_BIC_HP

Identify limitations/bottlenecks in GRAS/GEANT4

3. Internal Charging

- Need accuracy in deposited energy and deposited charge in a volume mesh
- Geometry: Cables, connectors, electronic boards, multilayer dielectric structures
- Particle type: electrons
- Energy: from low energies up to approximately 2 MeV
- Physic list usually used: emstandard_opt4

4. Single Event Upset

- Need accuracy in deposited energy of a G4track in specific volume
- Geometry: micrometre scale: volume in semiconductor devices
- Particle type: protons, heavy ions
- Energy: 1 MeV/nucleon up to several GeV/nucleon
- Physic list usually used:
  - emstandard_opt4 and QGSP_BIC to model
    - Direct ionization processes
    - Elastic and inelastic nuclear interactions
    - Secondary particle production

Artenum, Paris
Science & Groupware

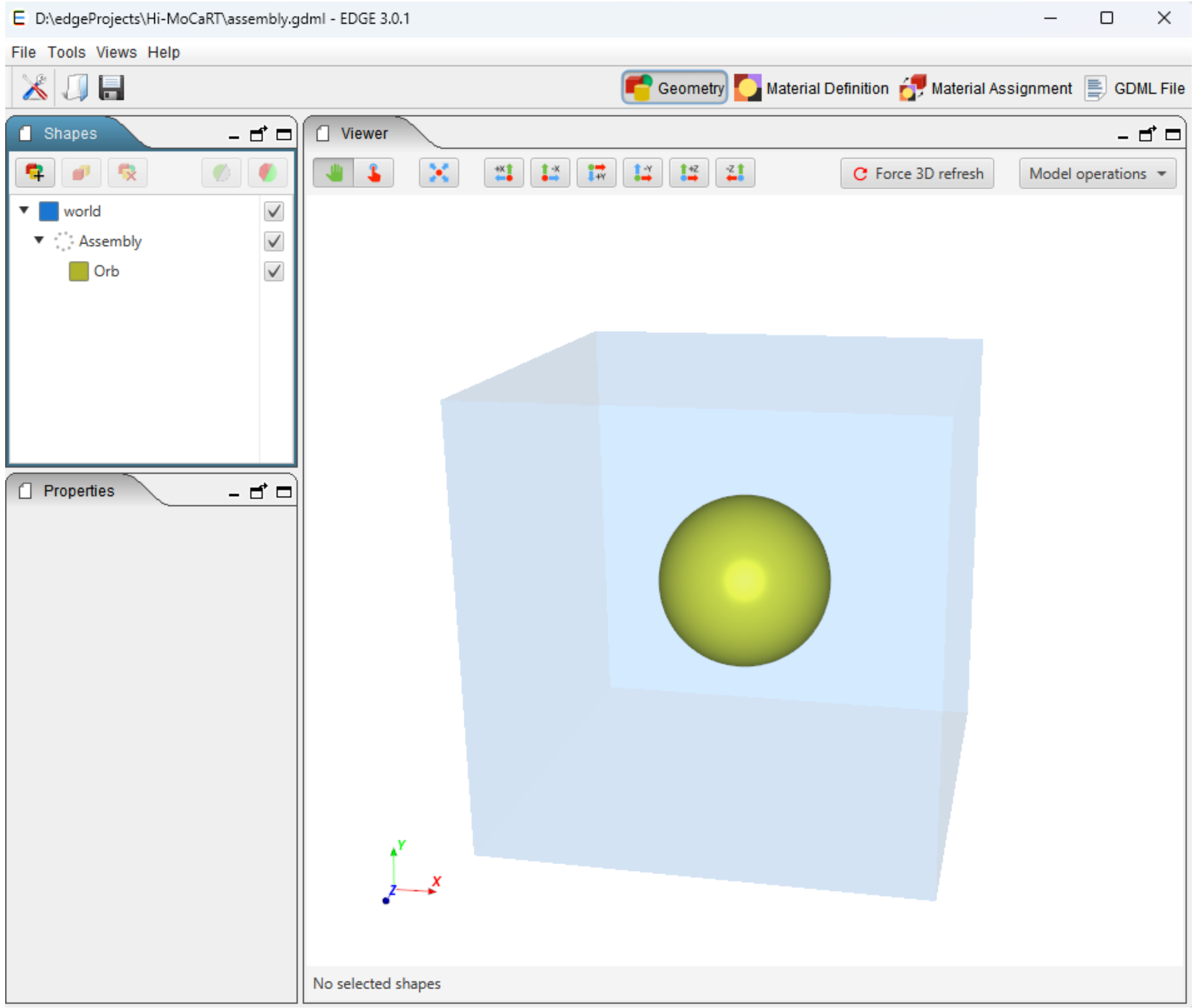
Identify limitations/bottlenecks in GRAS/GEANT4

1. TID: Details for dose using GDML file with shape inside assembly

- Simple CAD geometry defined with EDGE
  - Orb inside Assembly inside World
- In GRAS macro script:
  - Example:

/gras/analysis/dose/addModule dose1
/gras/analysis/dose/dose1/addVolume Orb

  - Accepted values are:
    - World_PV
    - Av_1_impr_1_Orb_logic_pv_0



- Issue
  - Volume names automatically generated and difficult to anticipate
  - Exact volume name is required in GRAS macro scripts
  - This complicates usage from a user perspective

Identify limitations/bottlenecks in GRAS/GEANT4

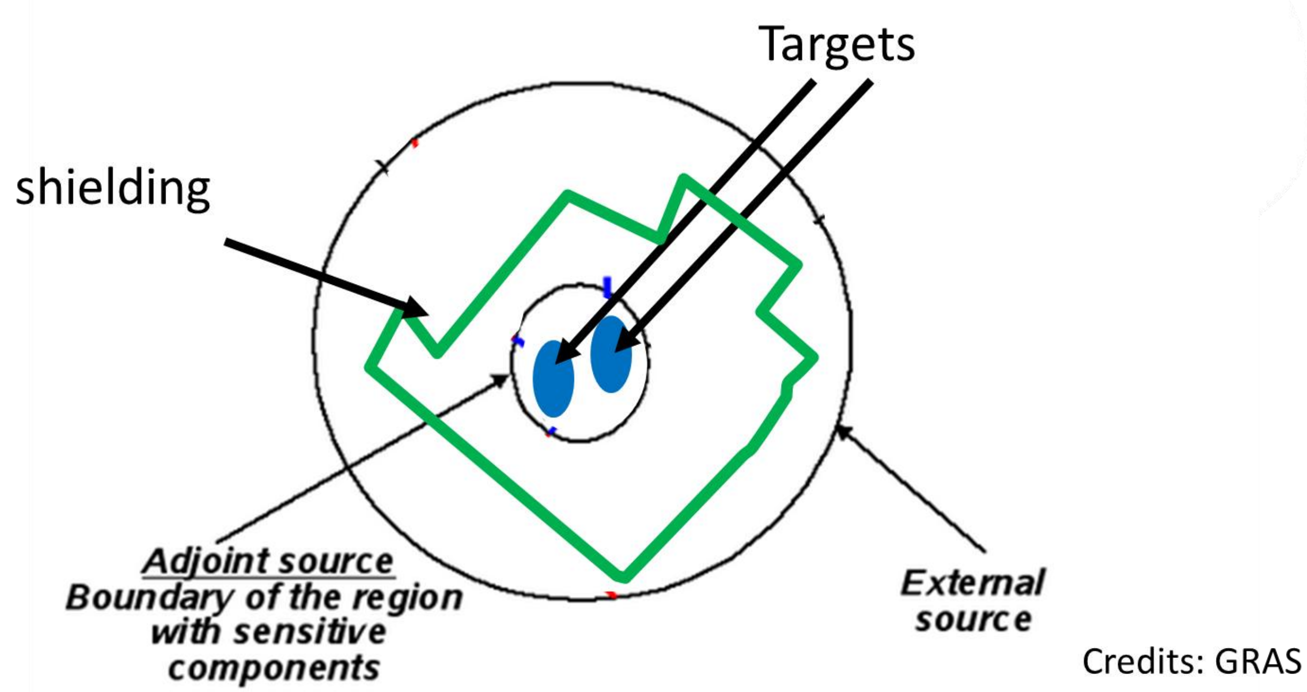
1. TID: Monte-Carlo use in space community

Monte-Carlo not the only method used for TID in space applications

- Sector shielding analysis is also an option
  - Launch rays from the target position
  - Compute material thickness encountered along each ray path
  - Convert to an equivalent thickness of a reference material (alu)
  - Convolve the equivalent thickness with dose–thickness curve

  ⇒Works well for some particles such as protons or heavy ions

  ⇒Not good for electrons
- Adjoint Monte-Carlo is an option with GRAS => reduce a lot the total CPU time



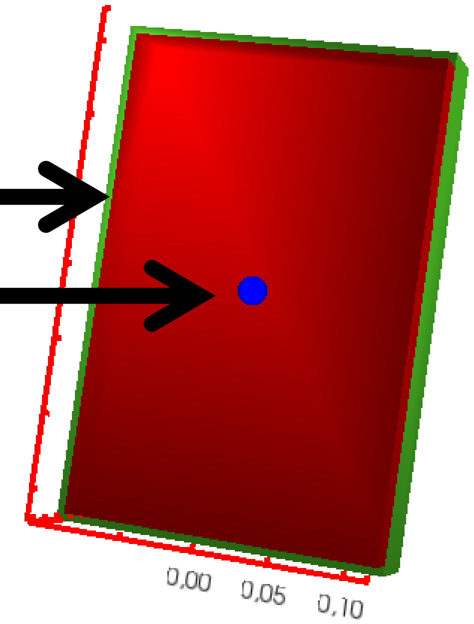
Credits: GRAS user manual

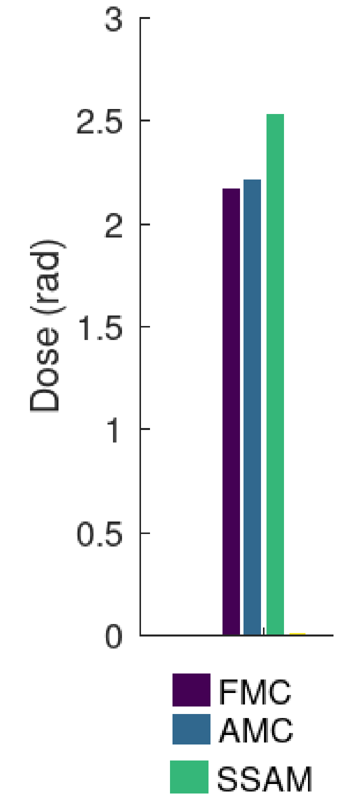
Identify limitations/bottlenecks in GRAS/GEANT4

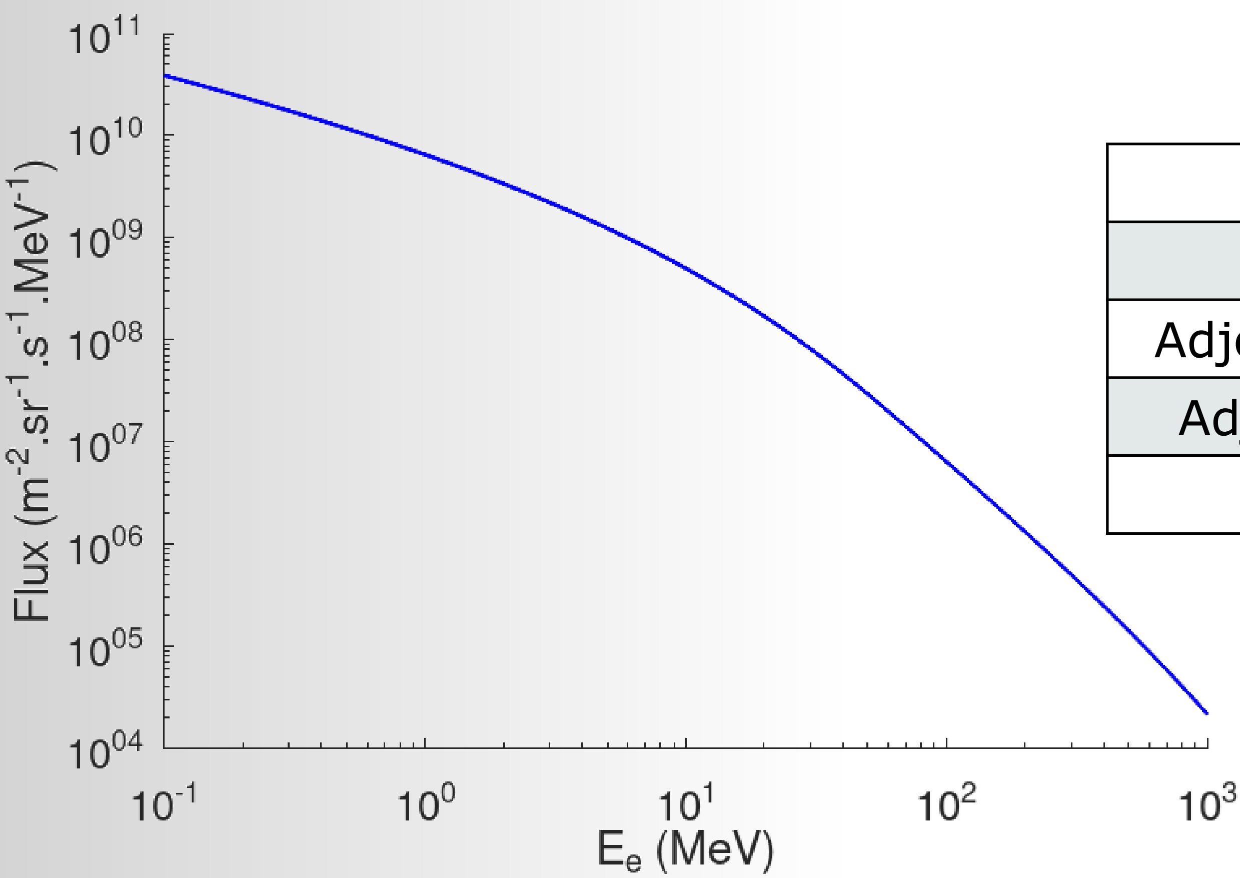
1. TID: Monte-Carlo use in space community
Use case 1 with protons

Shielding box: 20 cm * 40 cm * 5 cm

Sphere target radius = 2mm







Method	CPU time
Forward Monte-Carlo	28 days
Adjoint Monte-Carlo (0,5% precision)	8 hours
Adjoint Monte-Carlo (5% precision)	5 minutes
Sector shielding analysis	Less than 10 seconds

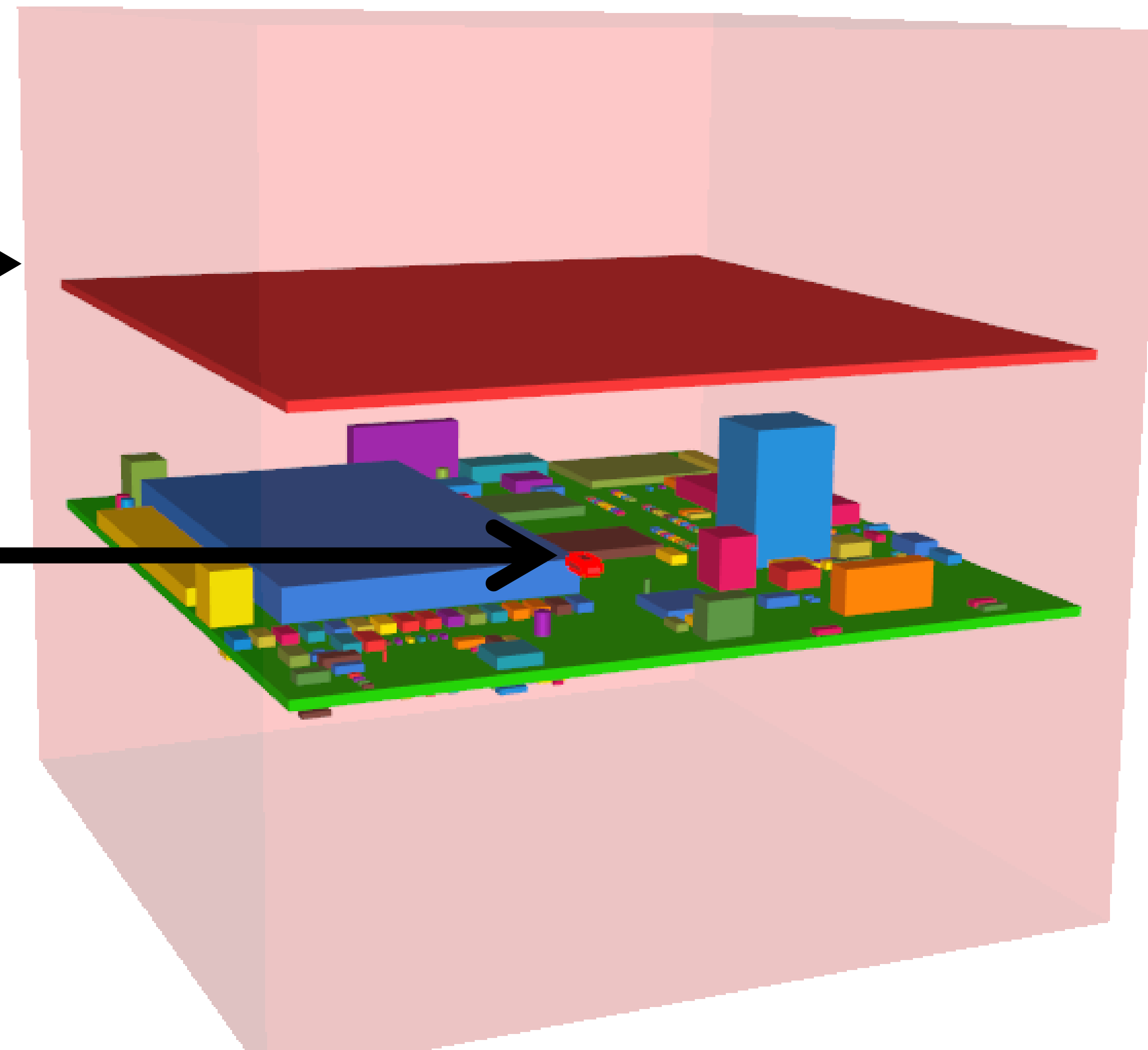
Identify limitations/bottlenecks in GRAS/GEANT4

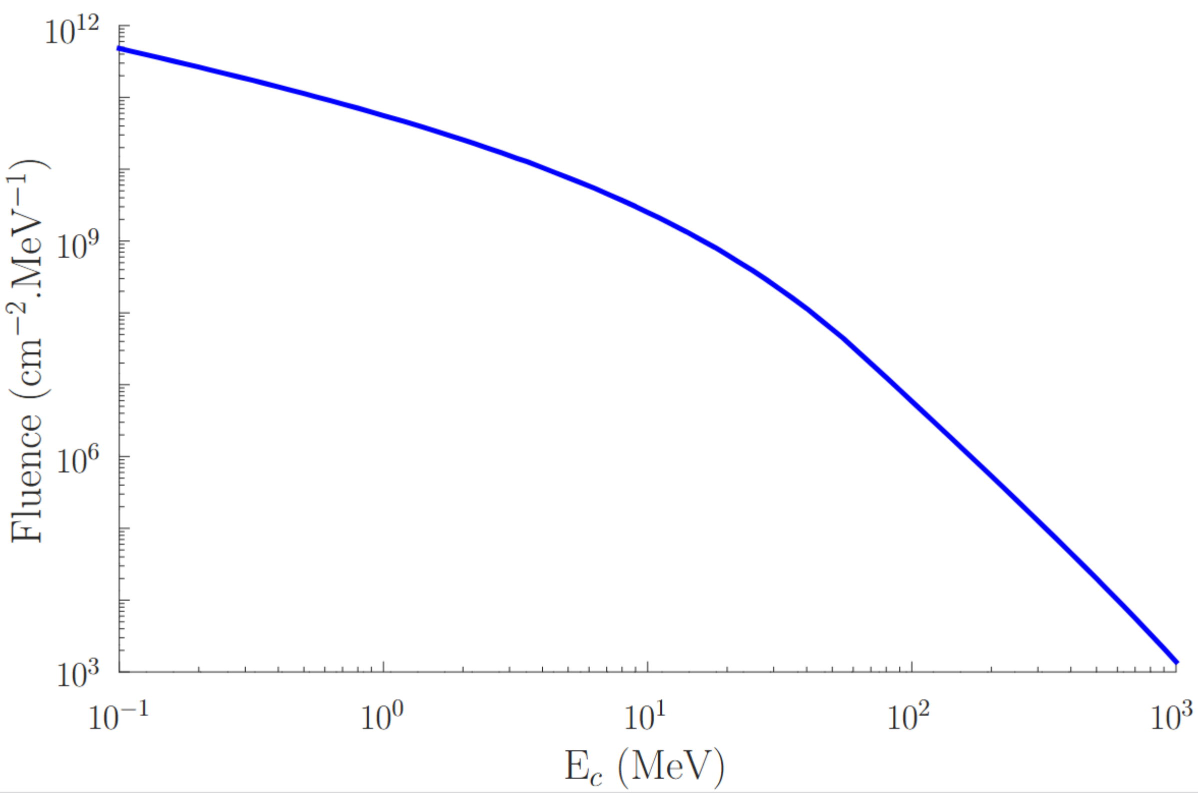
1. TID: Monte-Carlo use in space community

Use case 2 with electrons

Shielding box: 10*10*10cm

Target radius = 2*1*4mm





Method	CPU time
Adjoint Monte-Carlo (1% precision)	5 minutes
Sector shielding analysis	Less than 10 seconds

Identify limitations/bottlenecks in GRAS/GEANT4

1. TID: Monte-Carlo use in space community

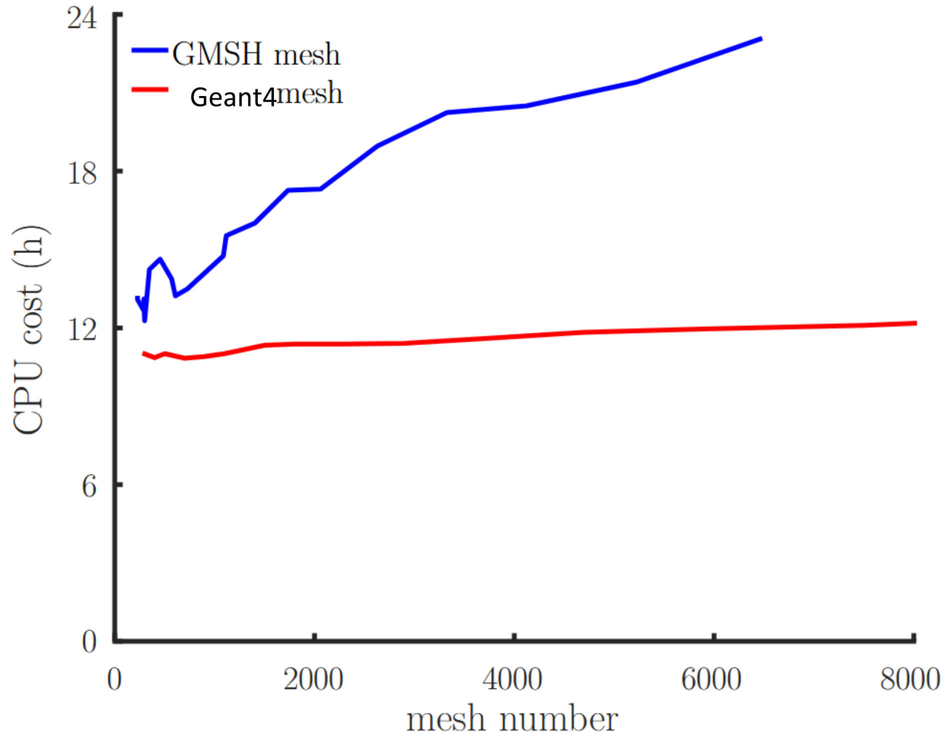
- 1 physic list available today for AMC, other possible?
- Possibility to use GRAS macro file for simple and fast physic list every where but close to the target with a more accurate one?
- Several AMC sources for the same AMC simulation possible?
- Precision depends on the final use case => which factor gain using other methods (GP/GPU, Machine learning, G4Biasing, other)?

Identify limitations/bottlenecks in GRAS/GEANT4

3. Internal charging

- CPU time differs significantly for calculation of deposited dose and charge in a volume mesh for the same number of mesh elements
  - GEANT4 structured volume mesh scoring

  Versus
  - GRAS Gmsh (unstructured tetrahedron volume mesh) scoring



  - What is the difference between the Gmsh and GEANT4 mesh scoring implementations?
  - Is it possible to expect the same performance?

Identify limitations/bottlenecks in GRAS/GEANT4

3. Internal charging

- Adjoint Monte-Carlo available in GRAS 7 for Gmsh mesh scoring
- Is it validated for
  - Electrons particle type?
  - From low energies up to approximately 2 MeV?
  - Using emstandard_opt4 physic list?

Identify limitations/bottlenecks in GRAS/GEANT4

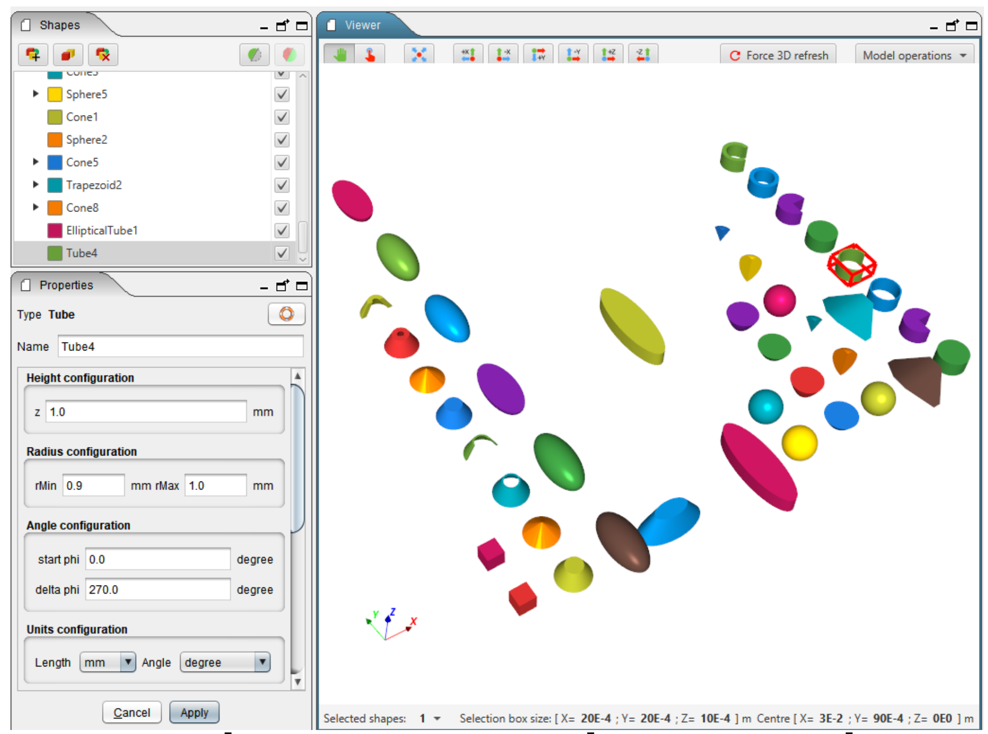
4. Single Event Effect

- Nuclear physic reaction happen with low probability
- Consequences:
  - Need to run simulation with a lot of events
  - Need biasing to increase a chosen physic reaction
  - Available from GRAS macro command
- use case with SEU
  - compute SEU cross section with SEE-U
  - for protons at 200 MeV (true for proton energy > 40-50 MeV)
  - 5E9 events are necessary to see SEU cross section value
  - In comparison: 1E7 is necessary for 1MeV (direct Ionization)
- G4Biasing is available in GRAS 7
  - ⇒Validity for which energy domains?
  - ⇒Which particle types and physical reactions?
  - ⇒Which error bars?
  - ⇒Known limitations?

Identify limitations/bottlenecks in GRAS/GEANT4

GEANT4/GRAS has been successfully used in lot of other use cases without any bottleneck nor limitations, such as

- Compute the volume of geometry => less than 2% error for results between Geant4 and EDGE for different GEANT4 shapes
  - Box
  - Cone family
  - Ellipse family
  - Sphere family
  - Paraboloid family
  - Trapezoid
  - Tesselated shapes
  - Boolean operations
  - Hierarchy volumes: one shape inside another shape



- Compute the deposited energy to qualify and validate instrument signal answer => GEANT4/GRAS used to compute the number and position of electron/holes pair in the instrument detector
- **Thanks to both GEANT4 and GRAS communities for these quality tools!**

Conclusion

- Artenum participates to identify some limitations and bottlenecks in GRAS and Geant4 using Space-Suite tools for space applications:
  - Total Ionizing Dose (TID),
  - Total Non-Ionizing Dose (TNID),
  - Internal Charging (IC),
  - Single Event Upset (SEU)
- Each application domains has its own specificity to consider:
  - Geometry
  - Particle types, energy, physic list, …
- If identified bottlenecks not addressed
  - Limit for large geometry spacecraft modelling
  - Limit for full mission Monte-Carlo campaigns
  - Limit for industrial deployment scalability
  - Probably use other tools than the ESA reference tools
- Software optimization is good but not enough for industrialization
  - Use complexity (macro file versus user interface modelling chain)
  - Installation and deployment complexity
  - Hardware resources limitation

Questions?