FASTRAD
3D RADIATION SIMULATION

3D modelling software for
radiation shielding analysis
in **space environments**

TECHNICAL DESCRIPTION

Software developed by
TRAD Tests & radiations

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Version 5.0

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FEATURES

INTERFACE & MODELING

- Graphical User Interface
- Advanced CAD Toolkit
- Import/export of CAD geometries (including STEP and GDML formats)
- Material and component database: access and modification
- Extended modelling interface
- Environment input portfolio, mission specific
- Invalid shapes management
- Overlap detection and repair

SECTOR ANALYSIS

- Sector analysis for Total Ionizing Dose (TID), Total Non-Ionizing Dose (TNID), current density, or any other custom quantity
- Multi-environments calculation
- Calculation at defined points (detectors) or across surfaces/volumes (mappings)
- Creation of a Six Faces representing the satellite shielding
- Mapping post-processing tools
- Shielding optimization post-processing tool
- Line of site analysis

MONTE CARLO CALCULATION CAPABILITIES & SCRIPTING MODULE

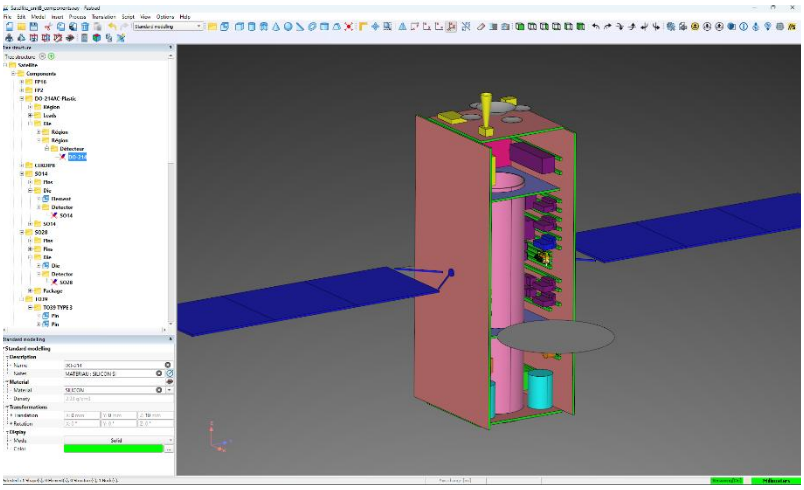
- TID and TNID calculation
- Depth Curve calculation
- Radiation Protection for crewed missions
- Internal Charging
- Post-processing of the particle transport: display and operations on mappings
- Scripting module

INTERFACE AND MODELING –

Create 3D radiation models, import, export and modify entire STEP models!

Graphical User Interface

- Framework: menus, toolbar buttons, property dialog boxes, hierarchy tree
- 2D/3D viewer and easy object handling (*rotation, translation, etc.)*
- Insertion of simple shapes (*box, cylinder, cake, sphere, …)*
- Hollow out and merge operations on all shapes (*including STEP*) for creating complex shapes
- Material definition interface with a database



CAD Toolkit

GENERAL

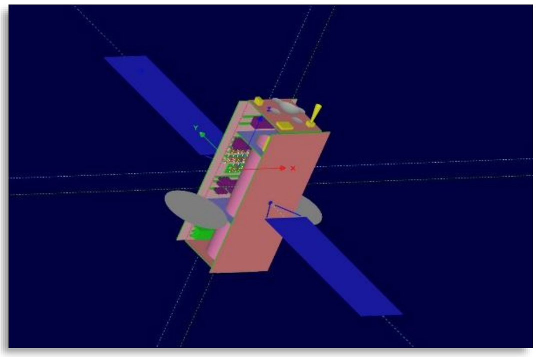
- Keyword search engine
- Print & copy view functions
- Clipping plane view
- Black & White photo view

GEOMETRY

- Detection of overlaps
- 3D measuring tool
- 2D/3D move
- 2D grid

RADIATION ANALYSIS TOOLS

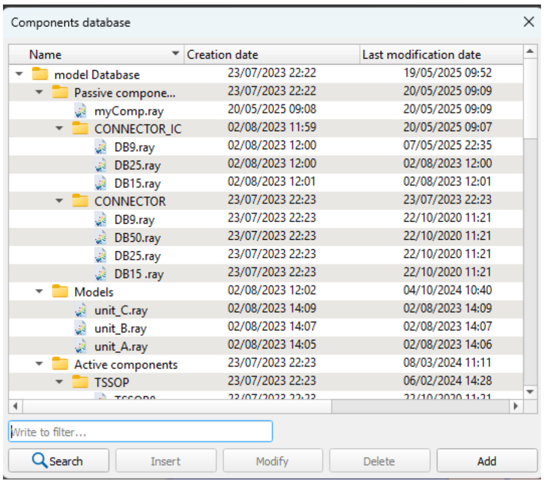
- Invalid shapes detection and repair
- Overlap detection and repair
- Mass calculation
- Material tool (*display specific material, replacement, drop-down list cleaner*)
- Detector handling tool
- Material & Detector list exchange: export/import



Database Interface

A dedicated interface allows to manage the FASTRAD® component database. FASTRAD® is delivered with a component package database (*flatpack, TO, etc.*). The user is invited to complement this database.

Through this interface, a new component model can be saved or any existing component model can be inserted in a FASTRAD® model. The database can be shared between FASTRAD® users.

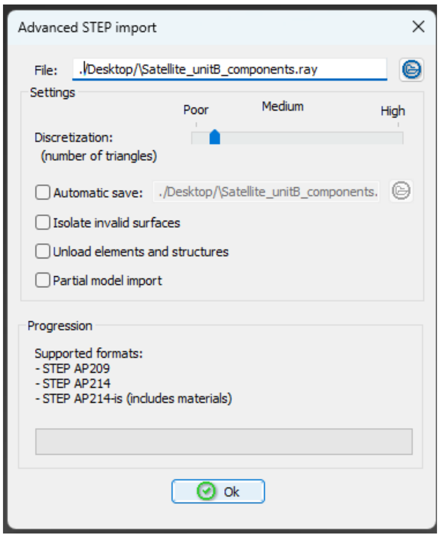


Advanced STEP import

Import models written in STEP format (*AP209, AP214, AP214_is, partially AP203*). Compatible STEP files can be generated by CAD tools.

Different options are available:

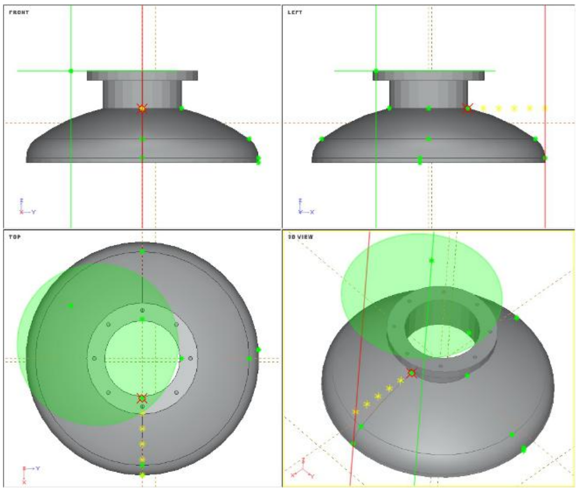
- Import the full model or only a part of it
- Upload the model progressively as it is imported (allows a heavy model to be imported on a computer with a limited RAM)
- Information on the material can be retrieved from the AP214_is format.



Extended Modelling

Points, lines and planes can be created by using the surfaces and edges of existing solids. It is possible to apply different transformations (*projections, spaces, etc.*) on the entities, to create points, lines and planes anywhere in the 3D scene.

Specific shape definition interfaces allow to create FASTRAD® solids by directly selecting the points of the 3D graph. Transformation tools allow to define geometrical transformations that could be repetitively applied on any part of the model in order to create geometrical patterns.

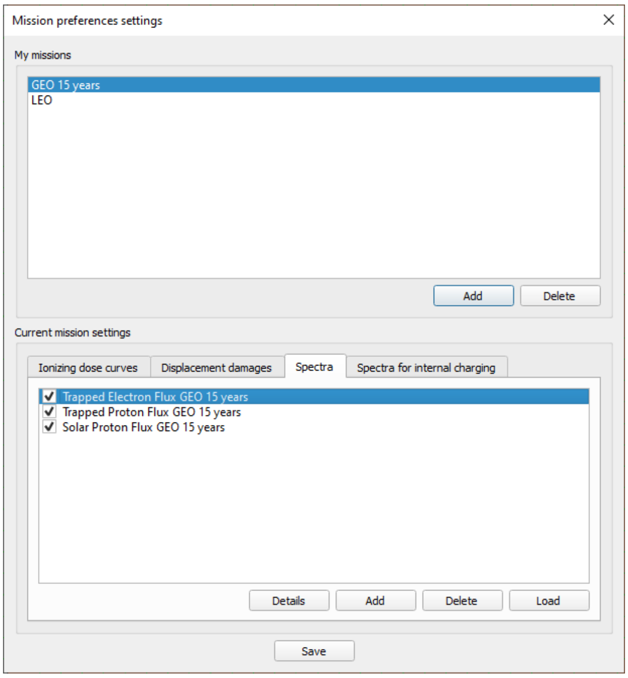


Mission Preferences

A dedicated dialog box allows users to define, modify and save input environment files.

These files can then be loaded into the corresponding calculation modules:

- TID and TNID depth curves for sector analysis
- Spectra for Reverse Monte Carlo
- Short term (peak) electron spectrum for Internal Charging (Internal Charging Module)



SECTOR ANALYSIS

— —

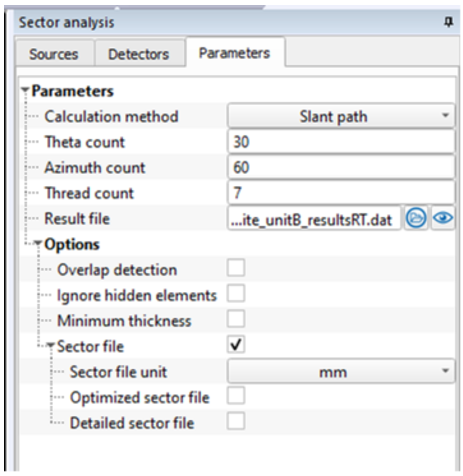
Perform essential calculations by sector analysis (ray-tracing), calculate six face equivalent thickness, post-process results to optimize shielding!

Sector analysis (*ray-tracing*)

Calculation by sector analysis can be performed on any FASTRAD® model containing simple and complex shapes.

Ray-tracing calculation tool capabilities include:

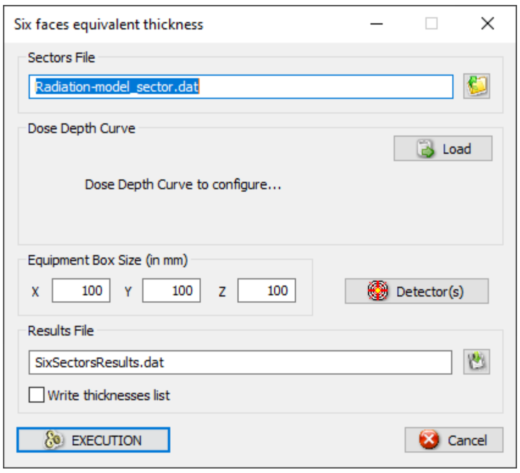
- Single or multi-environments definition
- Estimation of various quantities : TID, TNID, current, custom
- Isolated detectors or 2D/3D mappings
- Two calculation methods : slant path or minimum path
- Multi-threading option
- Optimized and/or detailed post-processing file



Six faces equivalent thickness

The 6 faces equivalent thickness dialog box allows to calculate the dose-equivalent thickness provided to any detector in each of the 6 directions (*+/-X, +/-Y, +/-Z*).

The user can set the size of the shielding box that simulates the equivalent shielding.



Sector analysis post-processing

The crossed thicknesses calculated by sector analysis can be displayed thanks to color-coded rays indicating the most critical locations in terms of radiation shielding (Figure 1).

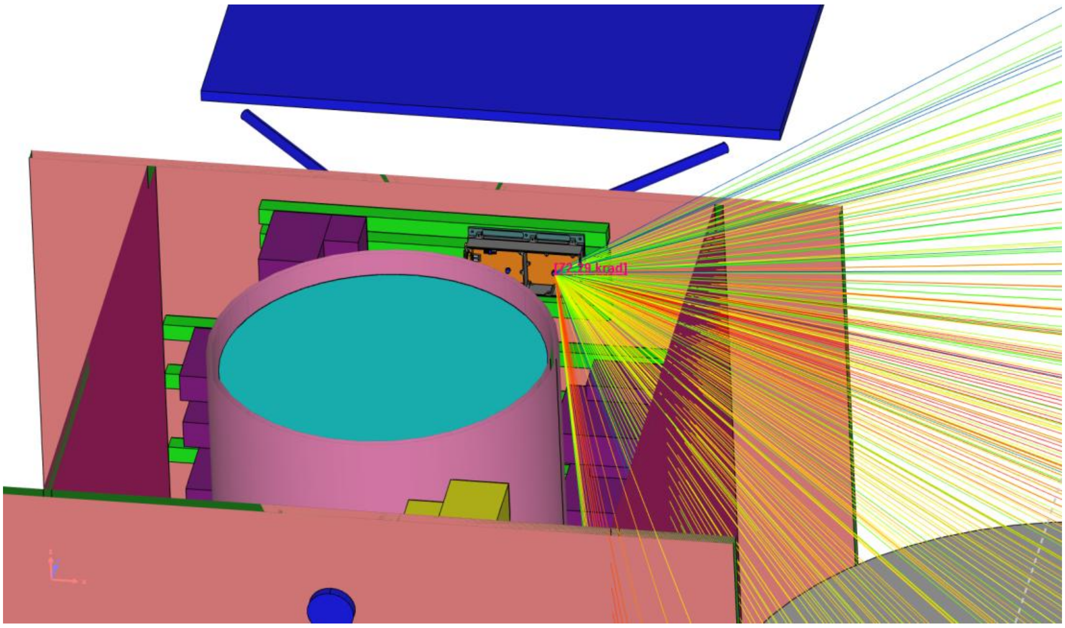


Figure 1 – Display of the smallest crossed thicknesses.

The rays can be projected on a box allowing the creation of spot shielding (Figure 2).

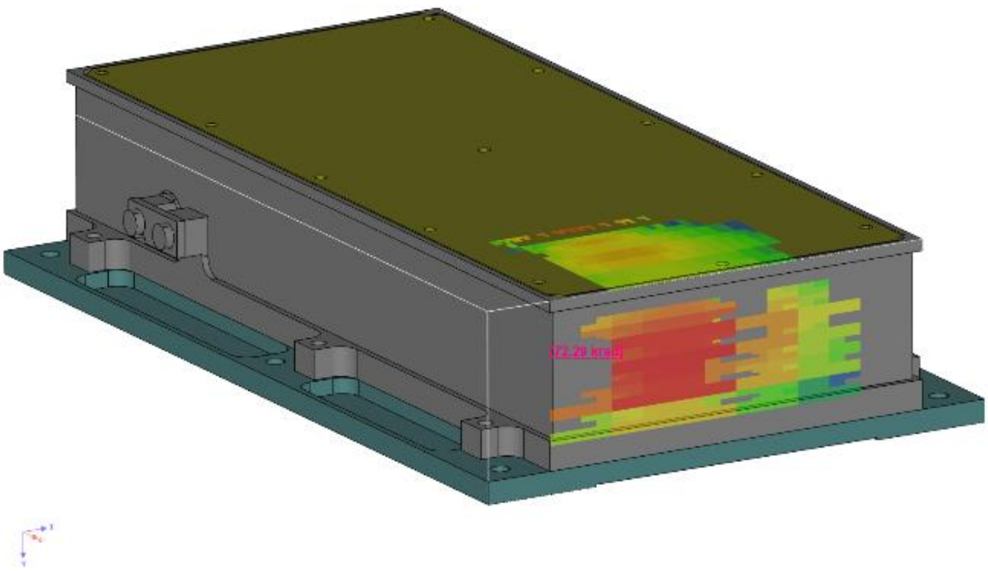


Figure 2 – Projection of crossed thicknesses on the unit to build a optimize shielding i.e. spot shielding.

2D/3D mappings calculated with Ray-tracing can be displayed on the model.

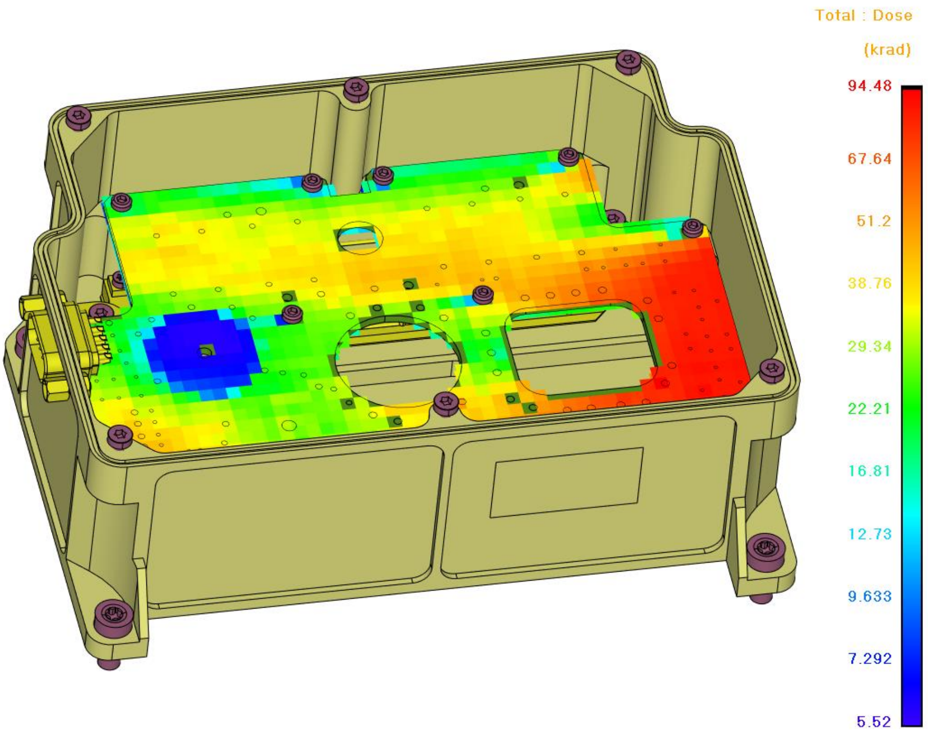


Figure 3: display of a 2D mapping on the surface of a PCB

MONTE CARLO CALCULATION & SCRIPTING

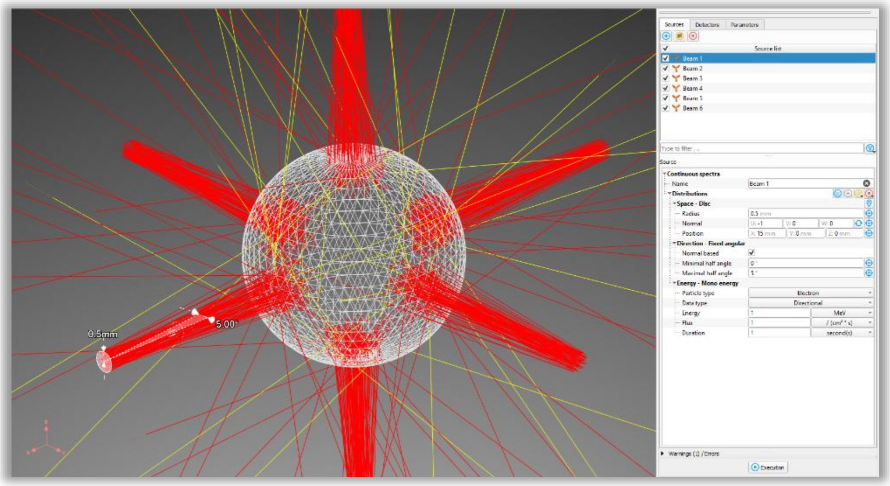
Perform precise calculations using the Forward and Reverse Monte Carlo particle transport methods!

The Monte Carlo particle transport is based on the tracking of particle interactions with matter, based on the interaction cross sections. It considers material composition and particle behavior, allowing to get a higher level of accuracy. Calculation can be run on several threads (*parallelization*) to increase calculation speed.

The precision of the Forward Monte-Carlo tool can also be increased by adding the hadronic physics add-on. This allows for a better precision for the tracking of high energy protons and is compulsory for the tracking of heavy ions.

The scripting module allows to customize and optimize the use of FASTRAD® by interacting with the main FASTRAD® entities through scripts.

3D Forward Monte Carlo transport



This module allows to perform calculations using a Forward Monte Carlo algorithm. Primary electrons, protons and photons as well as secondary electrons, positrons and photons can be considered with the standard tool. When the hadronic physics add-on in installed, other particles (heavy ions, neutrons, …) are also tracked.

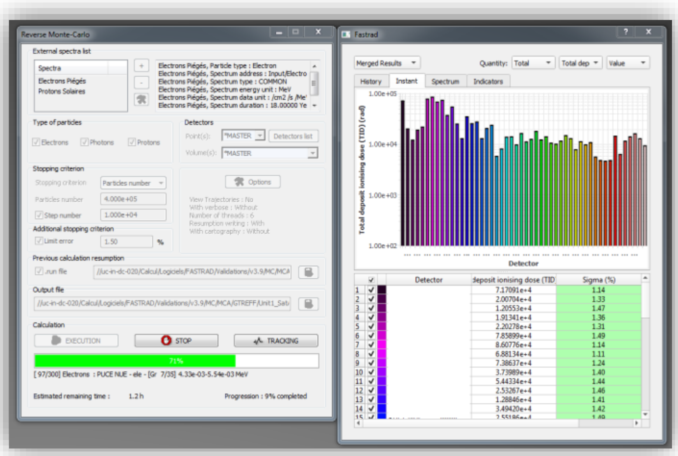
Several sources of particles can be defined at the same time. A wide range of source geometries can be defined, based on the model geometry or from virtual shapes.

Mono-energetic fluxes or continuous energy spectra can be used for the calculation. (*No limitation in the number of sources.*)

Several sensitive volumes can be selected in the 3D model. The results are:

- The deposited energy
- The dose depending on the material of the target
- The particle fluence for each particle type

A tracking window displays up-to-date results (*dose, spectra, statistical errors*) during calculation.



Particle trajectories can be visualized and interaction properties are displayed when a track is selected (Figure 4).

The 3D mapping module allows calculation of deposited energies, transmitted integral flux and associated errors in sensitive zones previously specified. With this tool, critical zones can easily be identified (Figure 5).

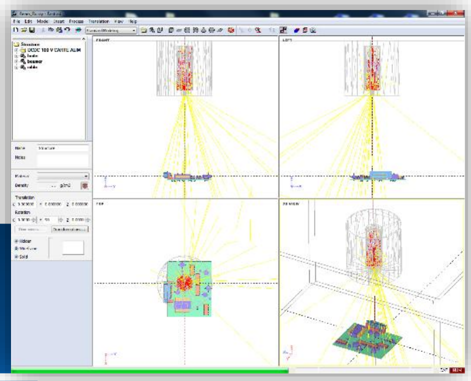


Figure 4

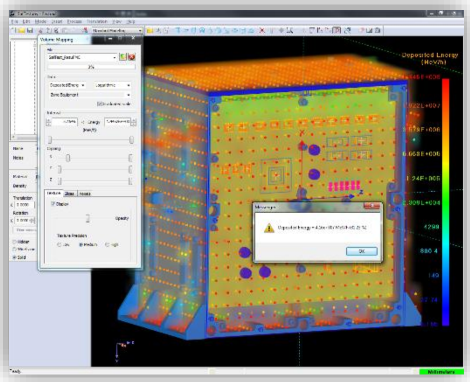


Figure 5

3D Reverse Monte Carlo transport

TID and TNID can be estimated by using the Reverse Monte Carlo particle transport method for incident electrons and protons.

For complex 3D models, including different geometrical scales, the particle transport calculation becomes very time-consuming with the standard (*Forward*) Monte Carlo approach. The Reverse Monte Carlo approach gives a powerful solution for faster accurate calculations.

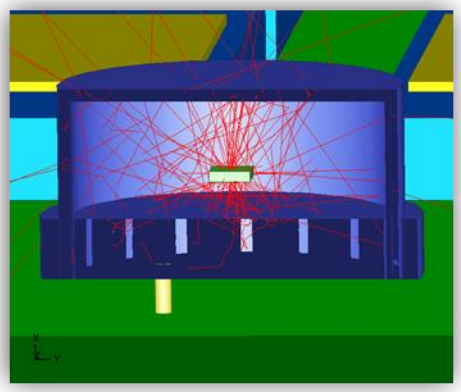
Primary and secondary electrons, primary protons and secondary photons (*Bremsstrahlung*) are considered. Point detectors and sensitive volumes can be considered to obtain:

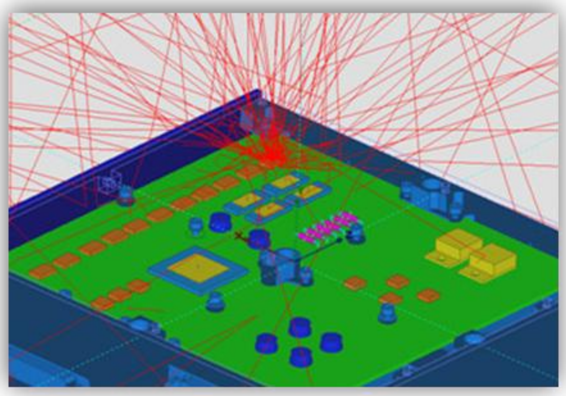
- The ionizing dose: total and also per particle type
- The total non-ionizing dose (*using NIEL tables*)
- The transmitted fluence per particle type

The radiation environment is defined by several spectra of electrons and protons (*no limit*).

The particle transport simulation is performed according to the materials assigned to the point or volume targets. Note that the Reverse Monte Carlo method is dedicated to an isotropic environment.

A tracking window displays up-to-date results (*dose, spectra, statistical errors*) during calculation.





As for the Forward method, the Reverse Monte Carlo method allows to display particle trajectories and interaction properties by double-clicking on one step of the particle path. The 3D mapping module allows to display deposited energies, charge deposition rate in dielectrics, transmitted flux and associated errors in sensitive volumes. The Reverse Monte Carlo tool is able to produce one mapping file for all detectors and sensitive volumes or a merged mapping file including all the selected detectors.

Depth curve

This tool allows for the calculation of depth curves, i.e. radiation-related quantities as a function of shielding thickness. The environment and a few calculation parameters (including a list of thicknesses and the shielding material) are the needed inputs and the calculation is then run with successive Monte-Carlo calculations, one per thickness.

Four quantities can be calculated: Total Ionizing Dose (TID), Displacement Damage Equivalent Fluence (DDEF), current density and fluence.

The depth curve calculation can be done for four different types of geometry:

- Solid sphere with a point detector at its center

- Shell sphere with a point detector at its center
- Shell sphere with a point detector on the inner surface of the shell
- Shell sphere with a volume detector at its center (for both RMC and FMC methods)

Any material can be defined for the shielding and the detector. By default, the shielding is made of aluminum and the detector of silicon.

As a result, a summary file is created that can then be used as the input for the sector analysis.

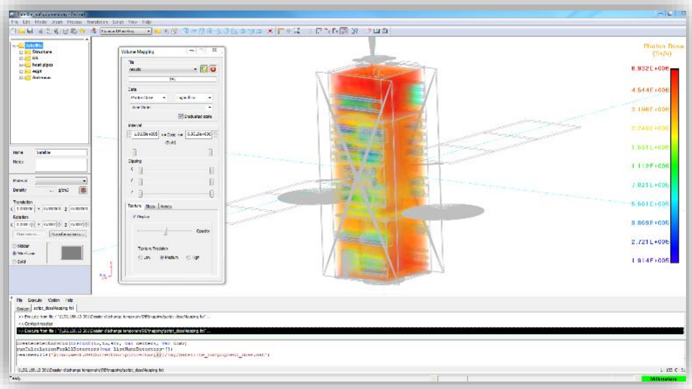
Scripting module

A script language has been integrated into FASTRAD®. It allows to interact with the main FASTRAD® entities. It also allows to perform parameterized tasks, to deal with custom file formats, etc.

A Script Integrated Development Interface allows to write a new script. A complete documentation (*Doxygen*) is provided to describe the scripting API and to give application examples.

A Script Portfolio is available in order to store the script files and execute them quickly.

The possibilities offered by the script are limitless!



INTERNAL CHARGING

Assess electrostatic discharge risks with the internal charging analysis!

By using FASTRAD®, the same geometry used for the dose analysis can be used for the internal charging analysis. The Reverse Monte Carlo method allows to consider the real geometry of the spacecraft while maintaining a reasonable calculation time.

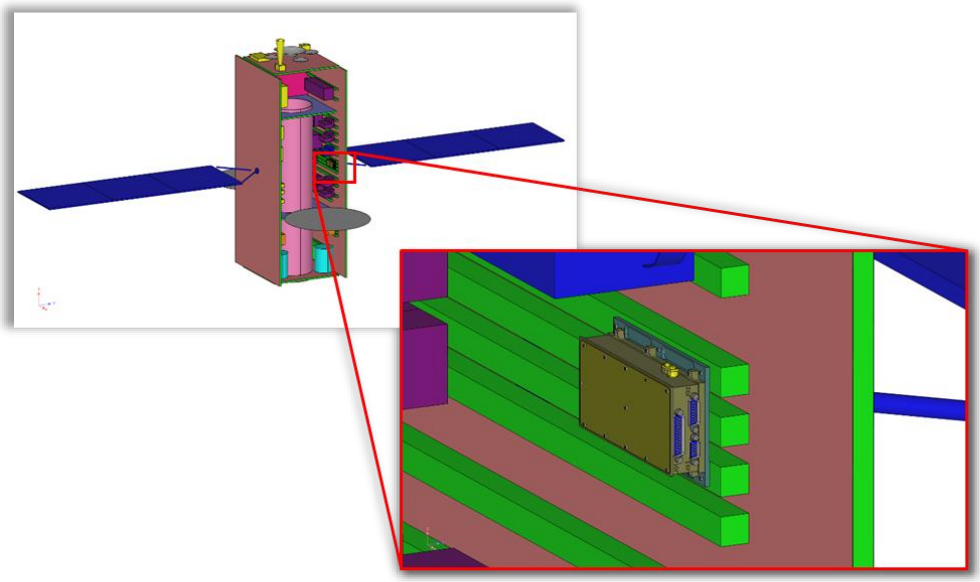


Figure 6 – Spacecraft model with an electronic unit and connectors.

The 3D internal charging analysis in FASTRAD® relies on two types of simulation: Monte Carlo particle transport (Table 1), for current density and charge deposition calculation and Finite Element Analysis (FEA) (Table 2), for potential and electric field calculation. For the latter, the two methods need to be coupled. In that case, the charge and dose deposition rates computed in a 3D mapping are the inputs of the quasi-electrostatic calculation to get the potential and the electric field.

MONTE CARLO PARTICLE TRANSPORT				
	Point detector	**Sensitive element**	**Volume mapping**	**Surface mapping**
Incident current density (pA/cm²)	Available with Reverse Monte Carlo only.	Averaged over the whole surface of the sensitive element.	N/A	Averaged over each elementary surface of the mapping.
Net current density (pA/cm²)	Available with Reverse Monte Carlo only.	N/A	N/A	N/A
Charge deposition rate (C/m³/s)	N/A	Averaged over the volume of the sensitive element.	Averaged over each elementary volume of the mapping.	N/A

Table 1 – Quantities available for internal charging analysis from Monte Carlo particle transport simulations.

FINITE ELEMENT ANALYSIS	
	Volume mapping
Potential (V)	Calculated on nodes of a tetrahedral mesh.
Electric field (V/m)	Calculated on nodes of a tetrahedral mesh.

Table 2 – Quantities available for internal charging analysis from Finite Element Analysis simulations.

Incident current density

The calculation of the incident current density, by using the Reverse Monte Carlo method, allows to rapidly identify an element potentially sensitive to electrostatic discharge, like coaxial cables, PCB or connectors, among several units (Figure 7).

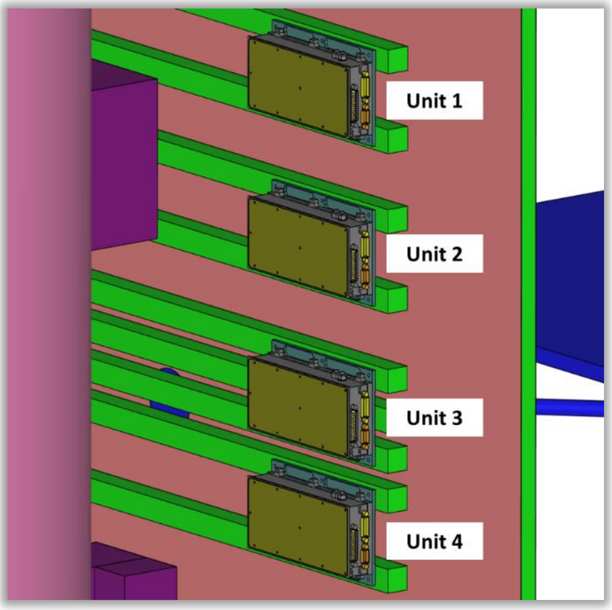


Figure 7 - Identification of the most critical components among several units in the spacecraft.

A surface mapping can be used to get the incident current density on a surface (Figure 8). The surface mapping can be an unstructured triangle mesh based on the surface of an element (Figure 9a) or a structured rectangular mesh that can be placed anywhere (Figure 9b).

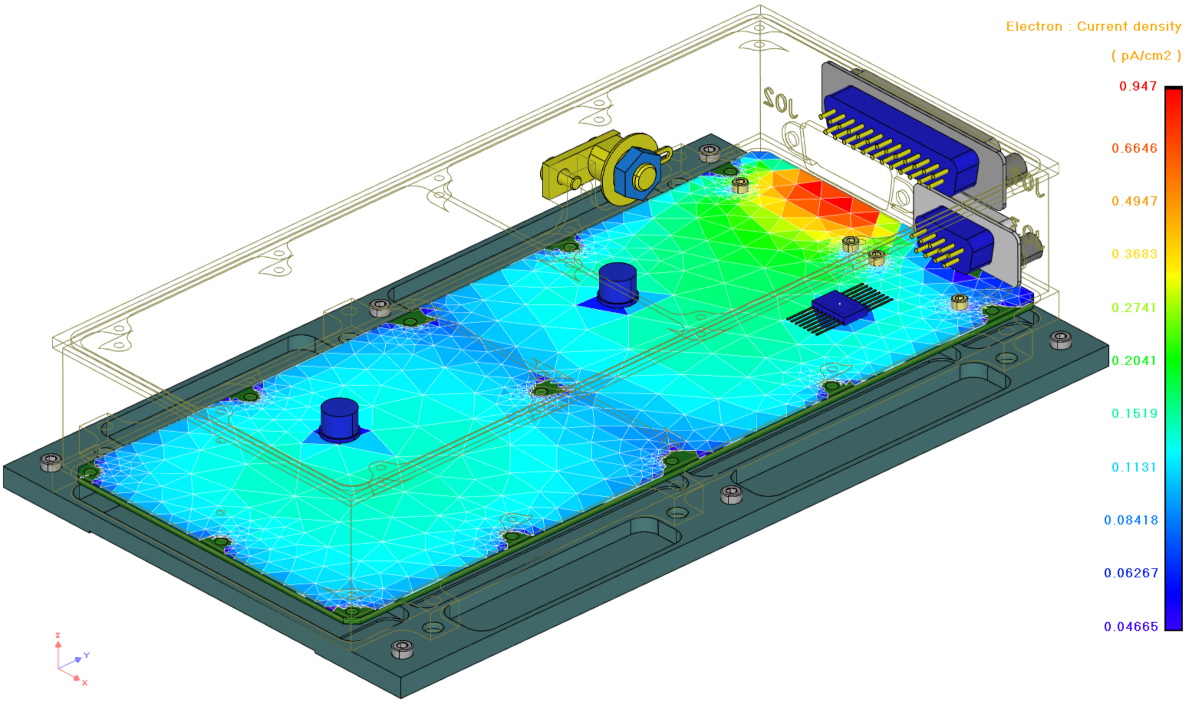


Figure 8 - Incident current density on the PCB displayed by using a surface mapping.

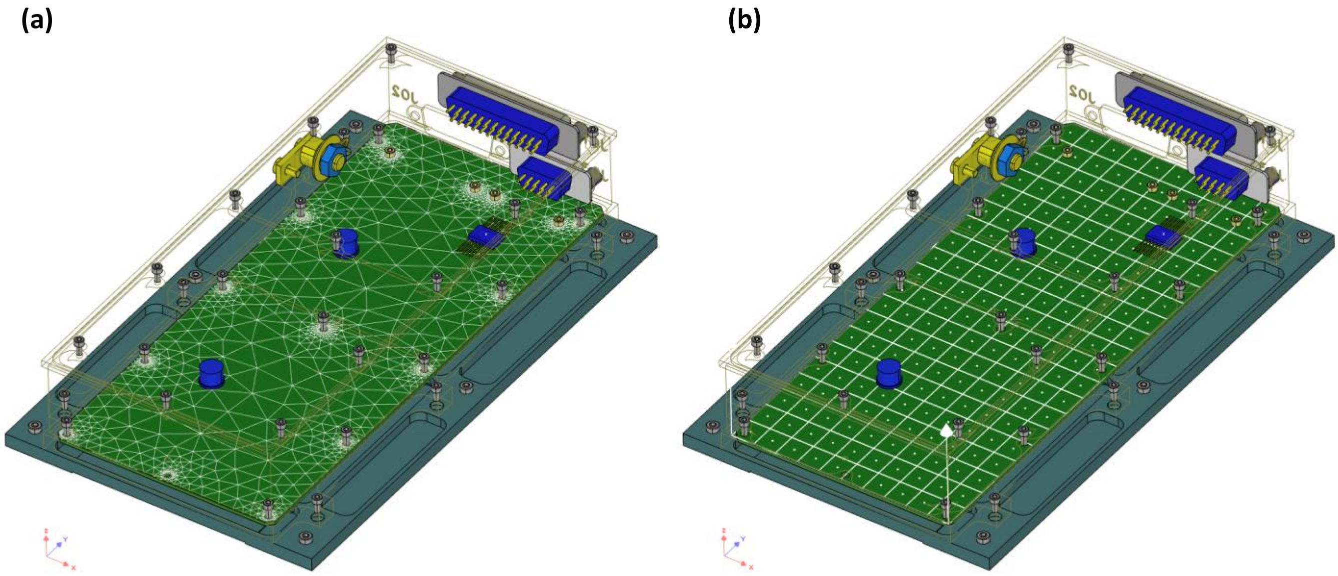


Figure 9 – Two types of surface mapping can be used. (a) Triangular mesh. (b) Rectangular mesh.

Point detectors can be used to get the incident current density at specific locations (Figure 10). The current density is estimated for a field of view of 180° on the external face on which the point detector is placed. This is only available by using the Reverse Monte Carlo method.

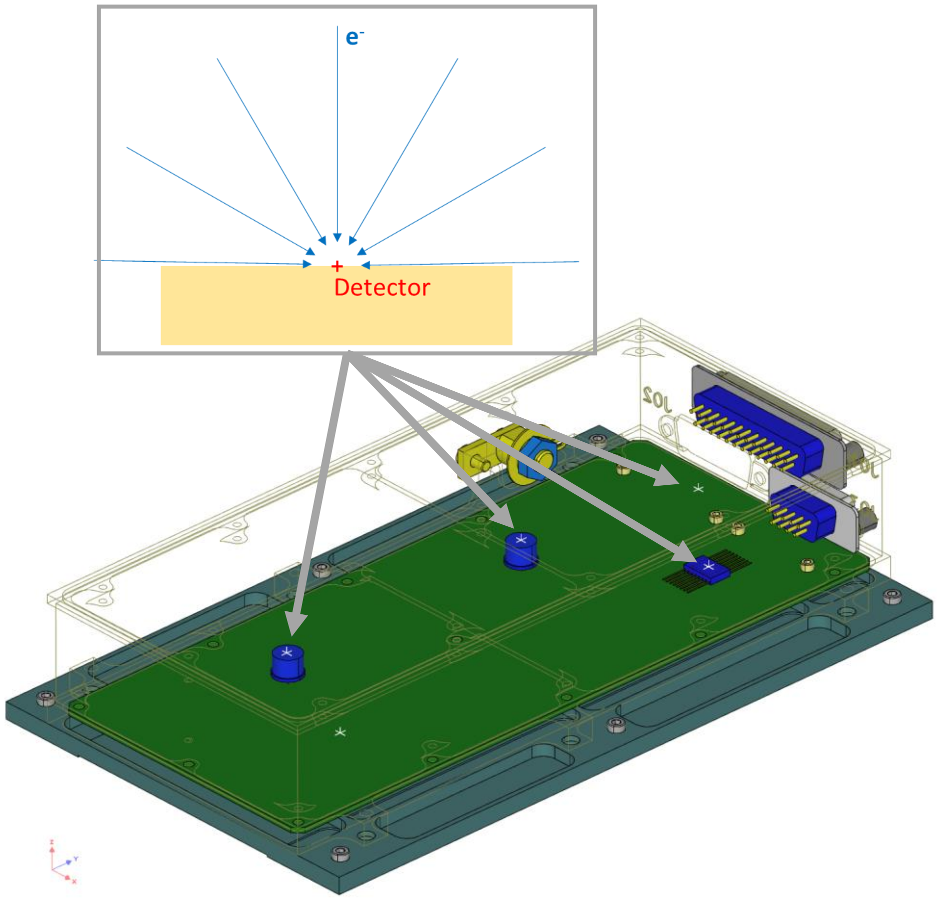


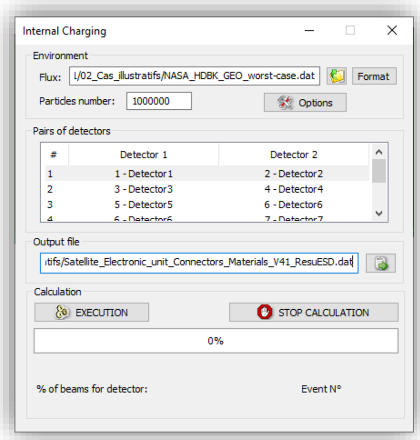
Figure 10 - Several point detectors are located on components and on the PCB (white cross) to get incident current density at these positions.

Net current density

A simple internal charging tool is available to calculate the net current densities (*in pA/cm²*) between two points in a dielectric volume of a 3D model.

These calculations are based on the Reverse Monte Carlo algorithm. A Monte Carlo calculation estimates the incoming and outgoing electron current for selected detector pairs.

The difference between the incoming and outgoing electron current gives the electric current density trapped in the dielectric volume (Figure 11).



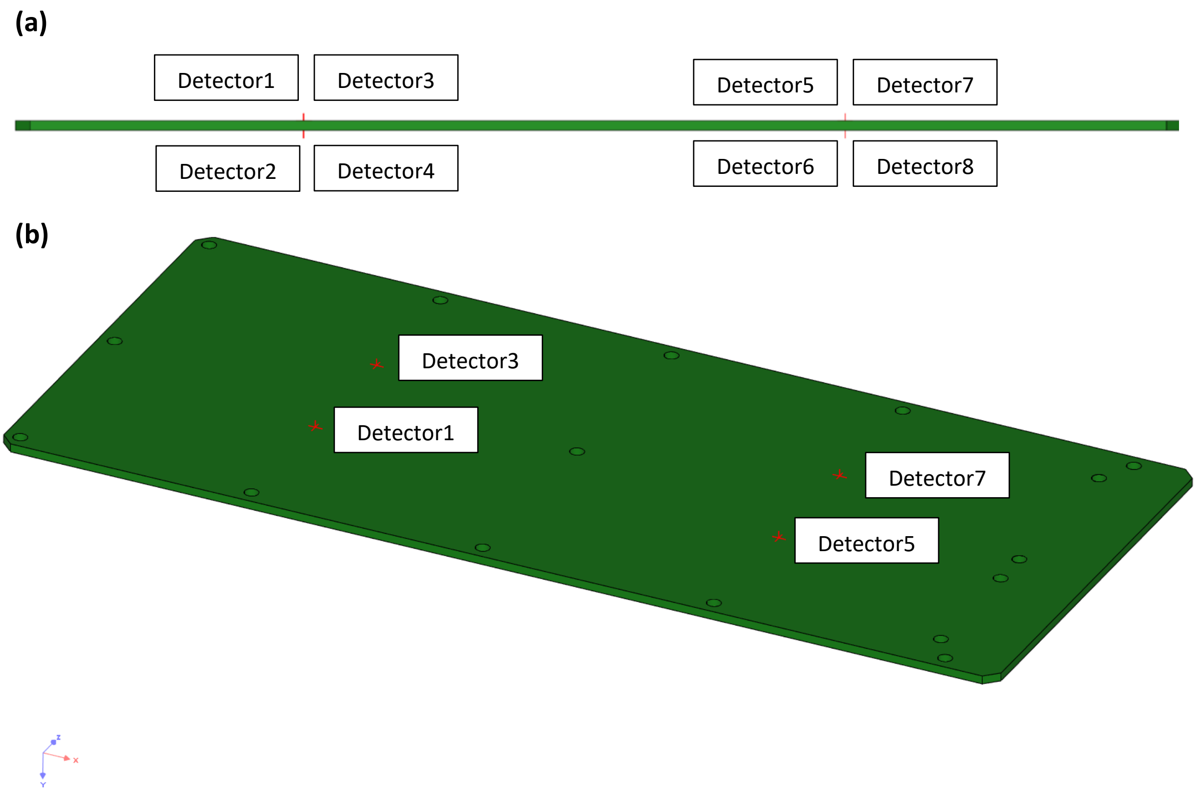


Figure 11 – Example of point detectors placed on the top and bottom face of a PCB. (a) Side view and (b) top view.

Charge and dose deposition rates

The charge and dose deposition rates are needed to get the potential and electric field generated by internal charging. They can be provided from uniform values or from a mapping.

Uniform

The charge and dose rates can be manually set by the user (Figure 12). These values will be applied to every node of the mesh for the electrostatic calculation.

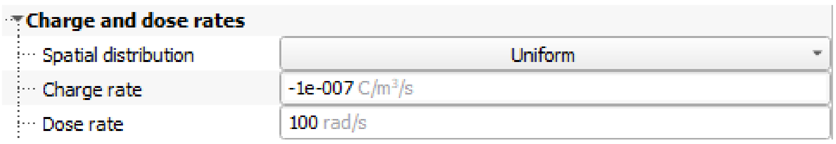


Figure 12 – Setting of the charge and dose rates with a uniform spatial distribution.

Mapping

The charge and dose rates can be provided to the electrostatic calculation from a Monte Carlo particle transport calculation by using a 3D mapping (Figure 13).

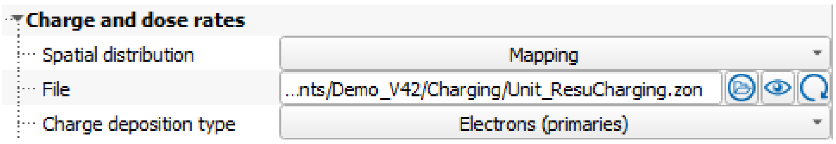


Figure 13 – Setting of the charge and dose rates with a spatial distribution coming from a mapping.

The Monte Carlo results can be scored in three different types of mesh: cartesian (Figure 14), cylindrical (Figure 15) and tetrahedral (Figure 16).

Cartesian mesh

- Fits any cubic geometry.

- Overlaps of materials at curved boundaries can exist, the mesh resolution can be increased to improve this.
- Fast particle tracking in structured mesh.

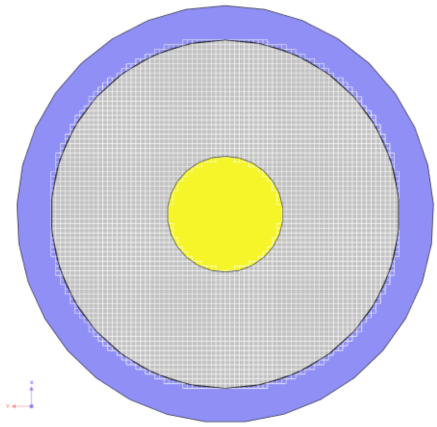


Figure 14 – Cartesian mesh.

Cylindrical mesh

- Perfectly adapted for cables.
- Only cylindrical geometries.
- Fast particle tracking in structured mesh.

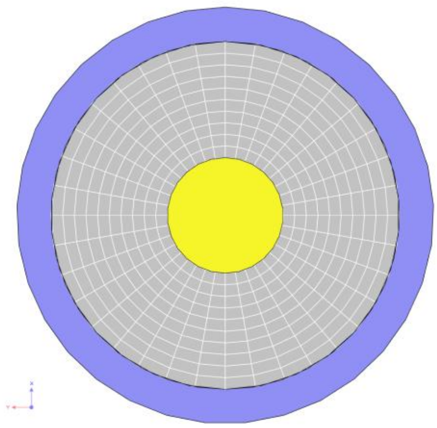


Figure 15 – Cylindrical mesh.

Tetrahedral mesh

- Adapted for any geometry.
- Time-consuming particle tracking due to the unstructured mesh.
- A trade off can be found between the number of tetrahedrons and the calculation time.

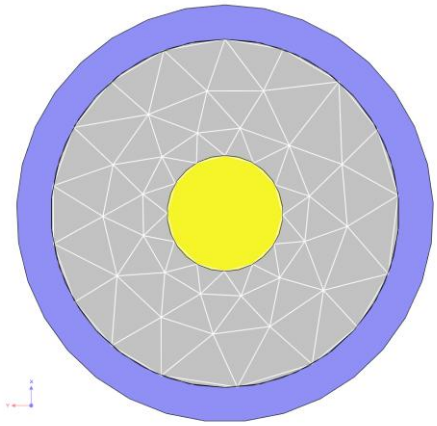


Figure 16 – Tetrahedral mesh.

An example of using the 3D mapping features on a specific element like a connector is displayed in Figure 17. The charge and dose deposition rates are scored in a tetrahedral mesh by using the Reverse Monte Carlo method.

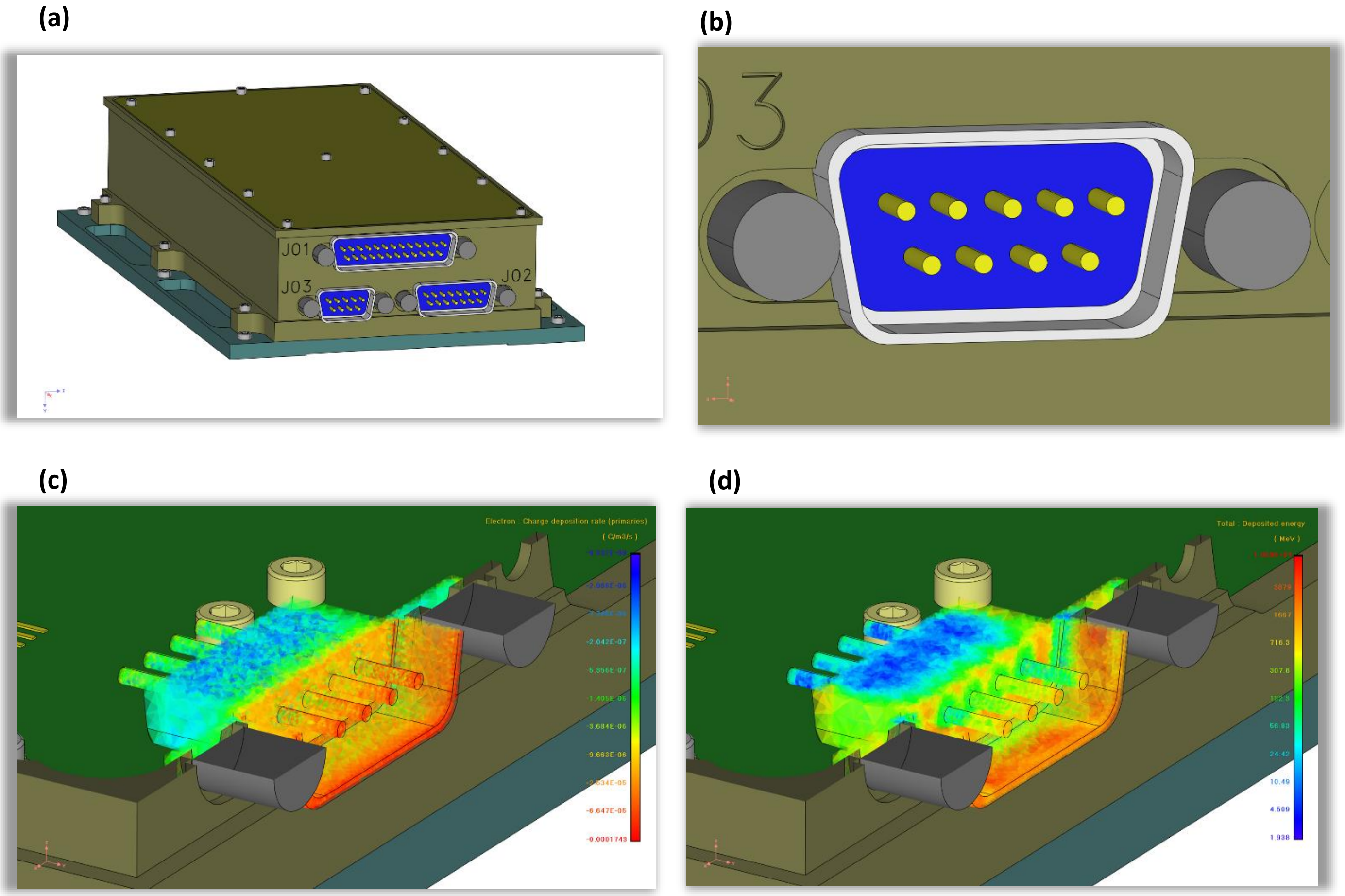


Figure 17 – (a) Electronic unit with connectors. (b) Zoom on the J03 connector. (c) and (d) Charge and dose deposition rates inside the connector obtained from a Reverse Monte Carlo particle transport.

Mesh coupling between Monte Carlo and Finite Element Analysis

The electrostatic calculation is done by FEA in a tetrahedral mesh. Therefore, the source terms coming from the Monte Carlo volume mesh must be assigned to each node of the FEA tetrahedral mesh (Figure 18).

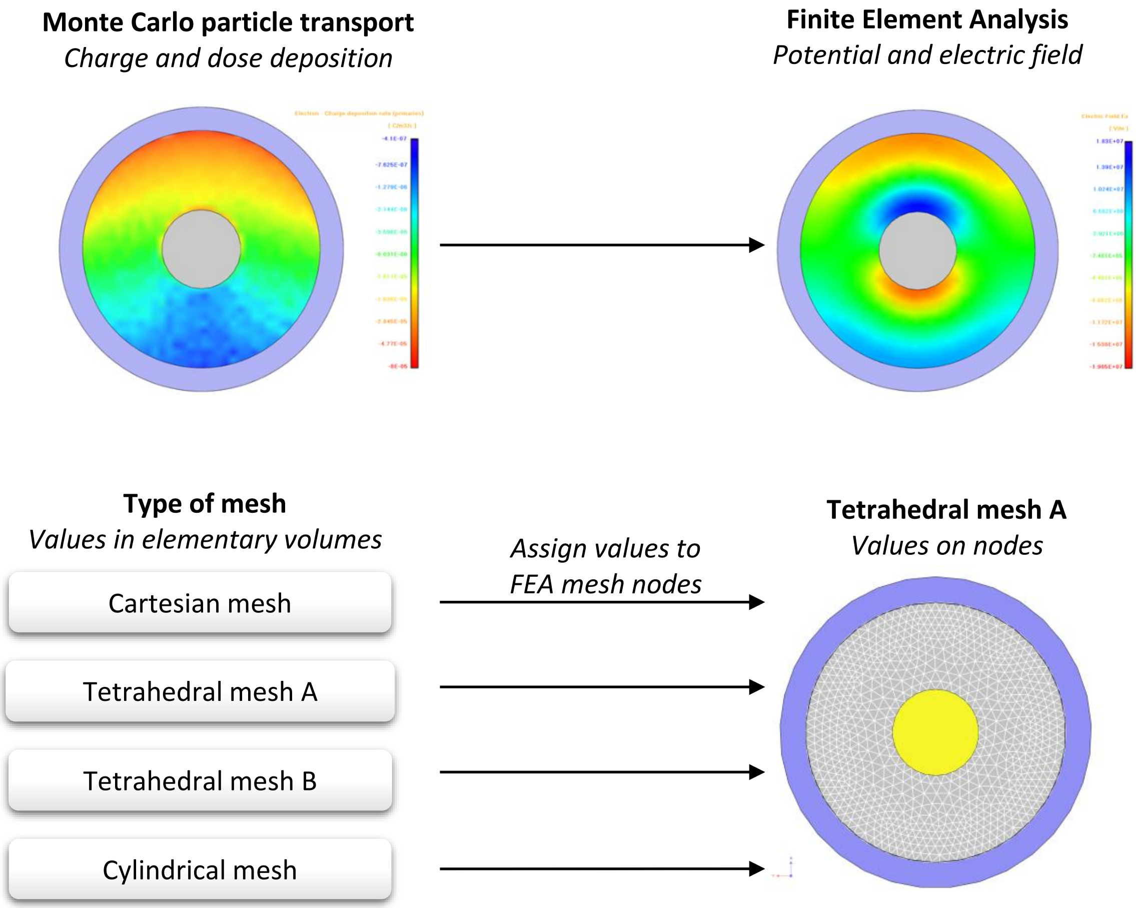


Figure 18 – Mesh coupling between Monte Carlo and Finite Element Analysis.

Constant

Constant charge and dose rates are applied to each node of the FEA mesh. Meaning that the same values are applied whether they come from a uniform spatial distribution (Figure 19a) or from a mapping (Figure 19b). This is the default setting, for the internal charging rate to be applied for the duration of the electrostatic calculation until reach of the steady state.

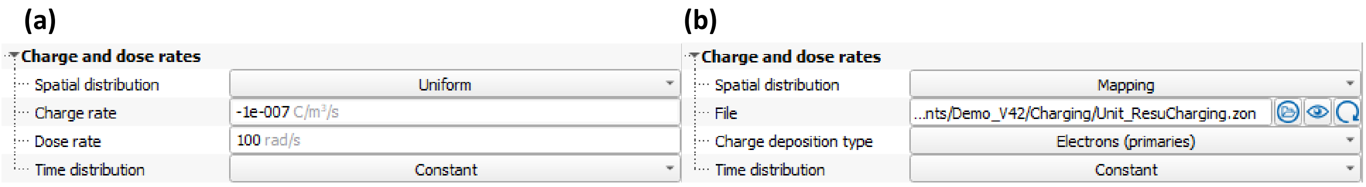


Figure 19 – Constant time distribution for (a) uniform and (b) mapping, spatial distributions.

Time-dependent factor

A factor ranging from 0 to 1 can be applied to the magnitude of the charge and dose rates. This factor must be given with respect to the time of the electrostatic simulation. It can be used for charge and dose rates that come from a uniform spatial distribution (Figure 20) or from a mapping (Figure 20b). It allows the user to modulate the magnitude of the charge and dose rates.

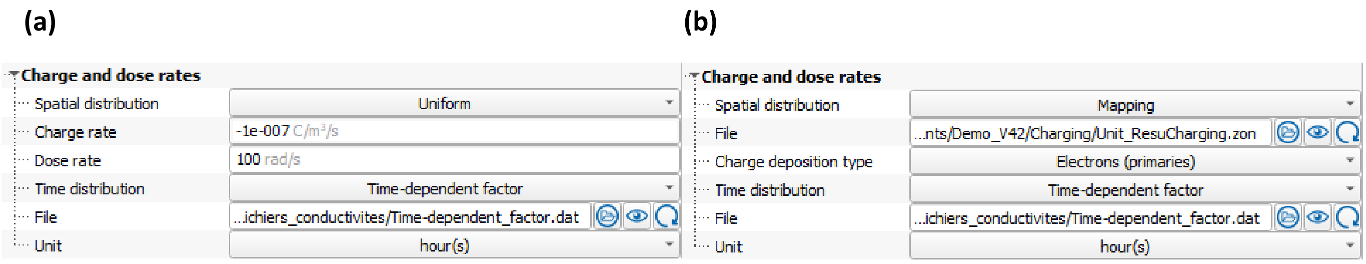


Figure 20 – Time-dependent factor applied to charge and dose rates for (a) uniform and (b) mapping, spatial distributions.

The 3D time-dependent electric field generated by charged particles inside dielectrics or on floating conductors can be calculated and displayed in FASTRAD® (Figure 21).

The electrical potential and electric field are computed in 3D using the finite element method. This method requires a volume mesh that is created in FASTRAD®. The charge deposition rate calculated by a Reverse or Forward Monte Carlo particle transport is the source term for the calculation of the electric field. The potential and the electric field can be displayed in 3D to assess the risk of electrostatic discharge.

The first step, prior to obtain the potential and electric field, is to compute the charge deposition rate given in $C/m^3/s$ in 3D. This charge deposition rate corresponds to charged particles that have lost all their energy in the dielectric and are trapped. The deposited energy is also computed in order to be used for the radiation induced conductivity. To obtain these quantities in 3D, a mapping is used as displayed in the previous section (Figure 17).

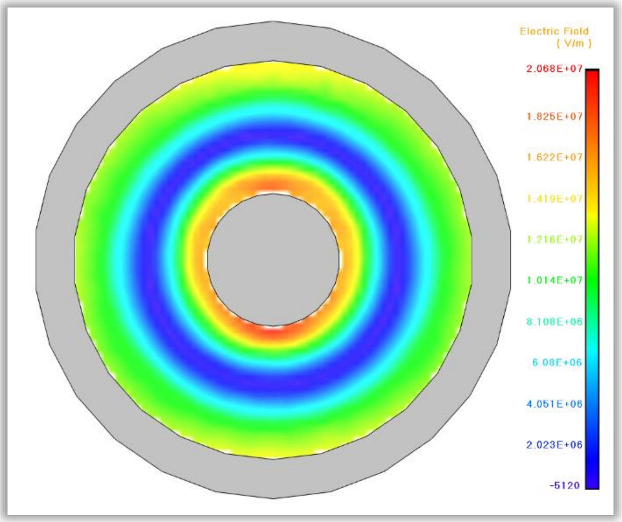


Figure 21 – Example of the electric field distribution in a coaxial cable.

The volume mesh is calculated in FASTRAD (Figure 22). An unstructured tetrahedral mesh is used. Several pre-defined mesh resolutions are provided but the user can use the advance settings to create the mesh. The mesh is displayed in the 3D view. It can be refined, saved and loaded from a previous mesh calculation.

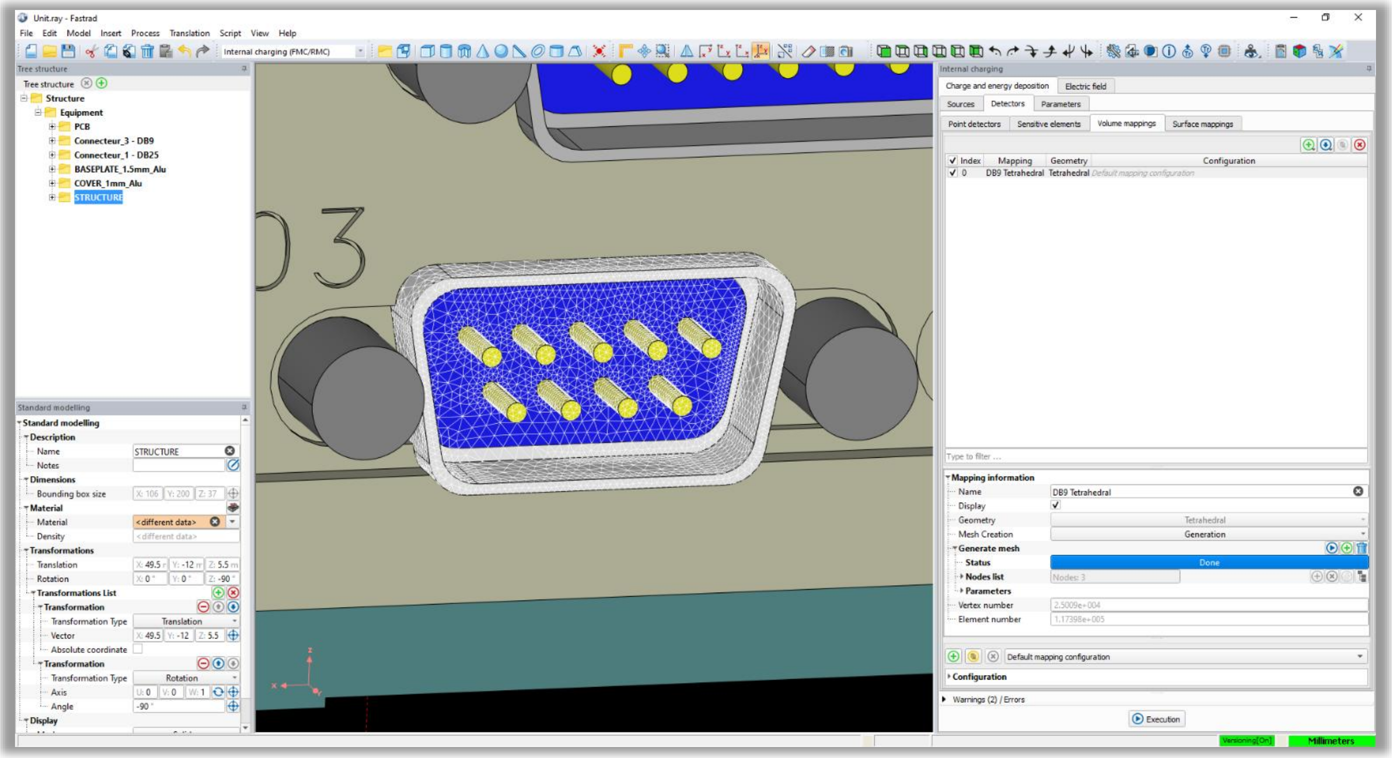


Figure 22 – Example of a meshed connector. Only the surface mesh is displayed but the whole volume is meshed.

The electric field is calculated by solving the potential in 3D. The numerical method can be iterative or direct. The simulation can be transient or steady-state (Figure 23a). Boundary conditions for the potential must be assigned (Figure 23b). When a conductor has no boundary conditions and is electrically isolated, it is considered as floating and can be charged.

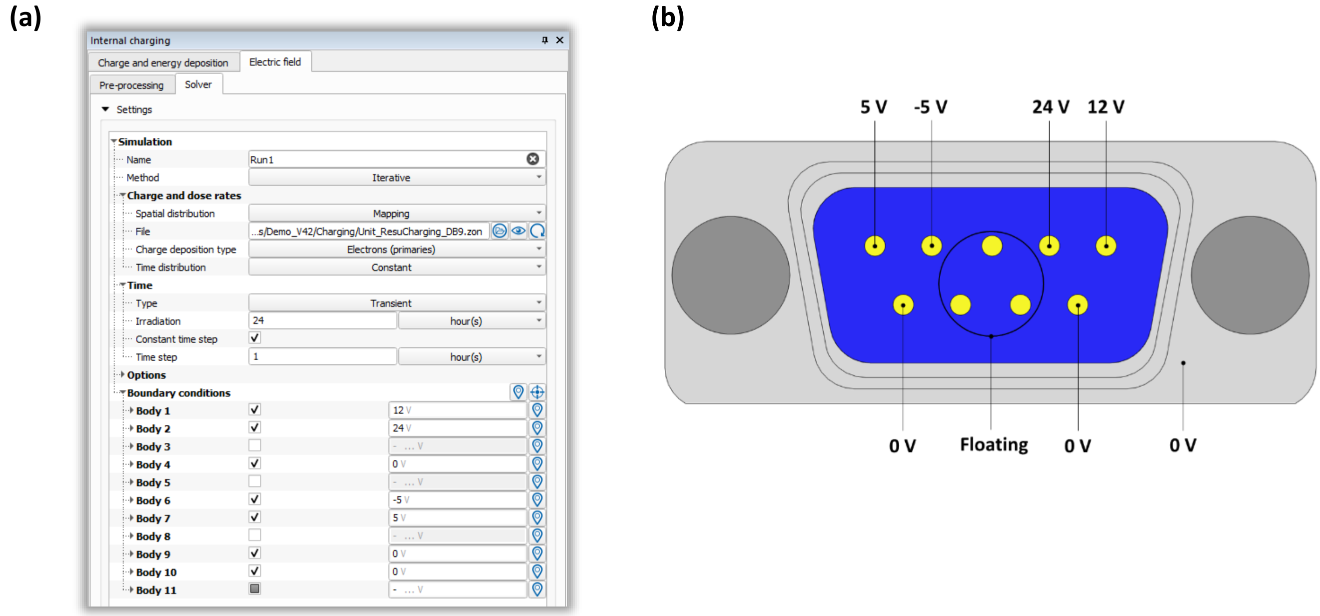


Figure 23 – (a) Solver settings. (b) Example of assigned boundary conditions for electrical potential.

Before running the FEA calculation, the method for the conductivity must be selected (Figure 25). Several methods are available for the conductivity:

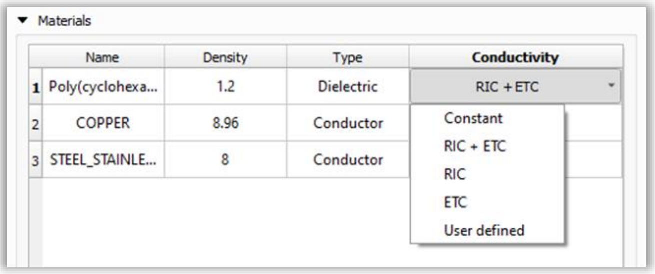


Figure 24 – Selection of the method for the conductivity.

a. Constant conductivity.
b. Radiation Induced Conductivity + Electric field and Temperature dependent Conductivity.
c. Radiation Induced Conductivity only.
d. Electric field and Temperature dependent Conductivity only.
e. User defined conductivity (time-dependent or electric field-dependent conductivity).

The properties of the materials used in the simulation will be used depending on the selected conductivity model. Several features are available for setting the temperature and the conductivity of dielectrics. These material properties are described in the next section.

FASTRAD® then calculates the potential and electric field and allows to post-processes them in 3D (Figure 25). If a transient simulation is selected, the evolution of the electric field can be displayed at each time step. The maximum potential and electric field values are gathered in a result file. The maximum reached values can also be found directly in the 3D results by using the mapping features.

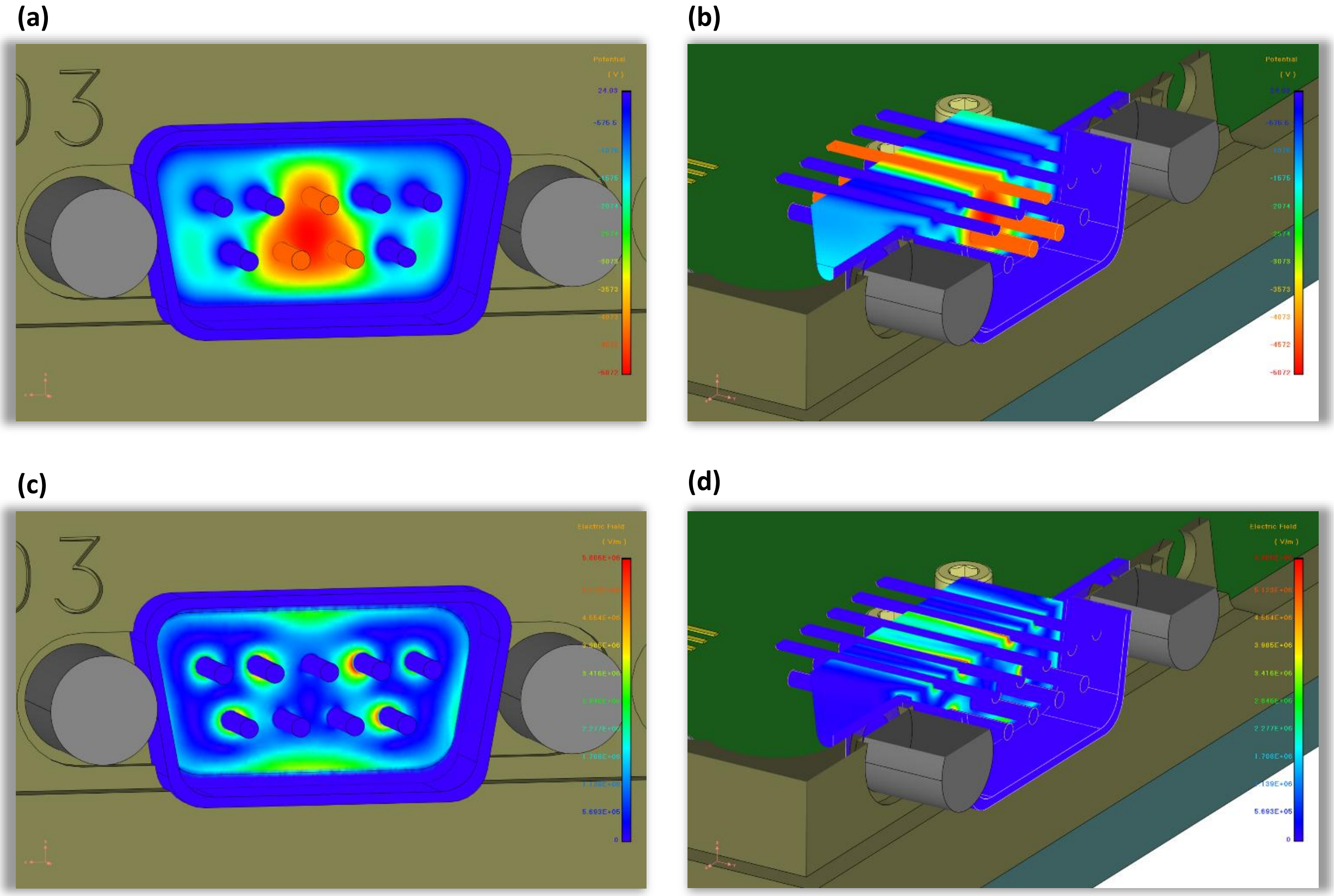


Figure 25 – (a) and (b) Potential distribution at steady-state. (c) and (d) Electric field distribution at steady-state.

The electrical properties of materials for internal charging analysis are managed in the general material edition tool, in a dedicated tab named *Electrical* (Figure 26). All the properties can be saved. Depending on the selected method for the conductivity, FASTRAD® will use the required properties.

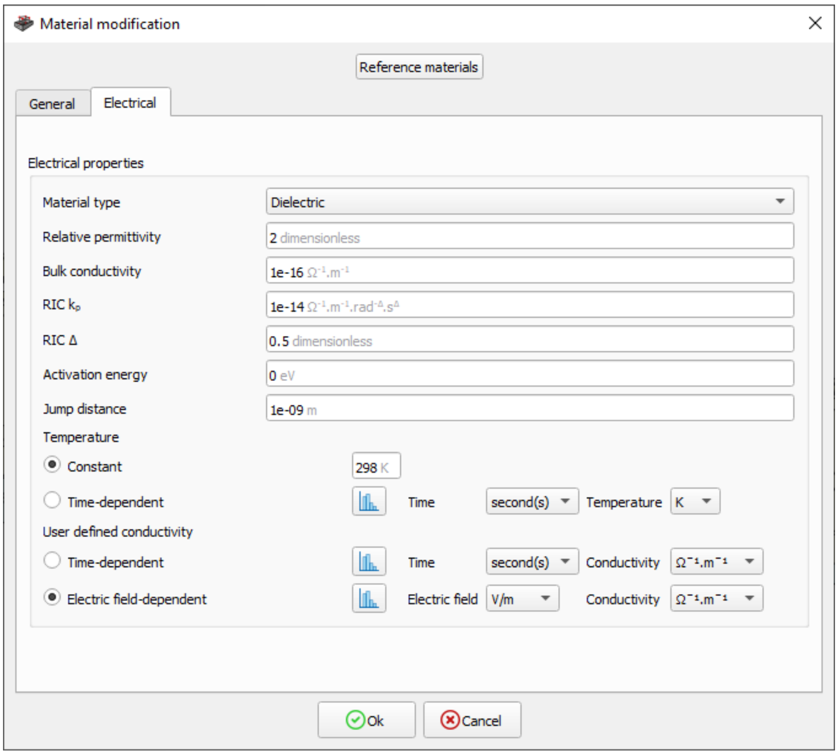


Figure 26 – Edition of electrical properties of a material.

Constant and time-dependent temperature

In addition to the constant mode, a time-dependent temperature of the dielectric can be set (Figure 27) and it will be used in the conductivity model that requires a temperature (Figure 28).

Figure 27 – Time-dependent temperature setting.

This new feature can be helpful if only the temperature of the dielectric is known, the conductivity will then be computed by FASTRAD®.

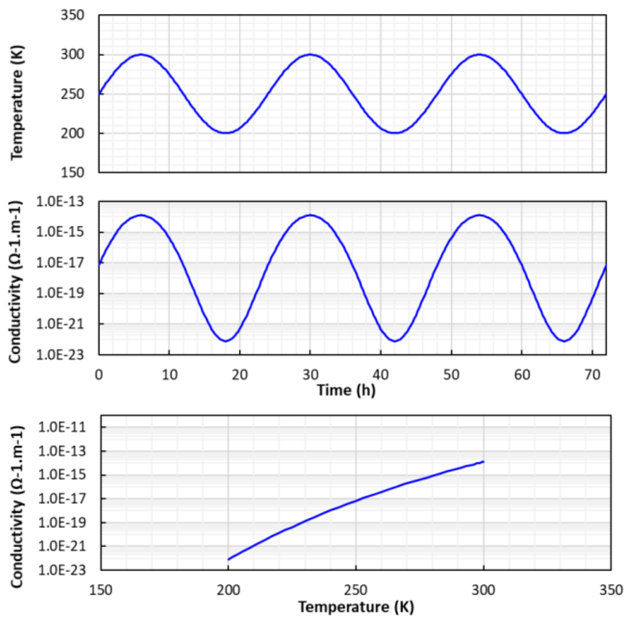


Figure 28 – Example of time-dependent temperature and the associated conductivity computed by FASTRAD®.

User-defined conductivity: time-dependent

A two-column file containing the time-dependent conductivity of a material can be directly set (Figure 29).

Figure 29 – User-defined time-dependent conductivity setting.

This feature can be used to consider for temperature variation in space during a mission. An example of the effect of conductivity on the potential is displayed in Figure 30, by using two constant conductivities and one time-dependent conductivity.

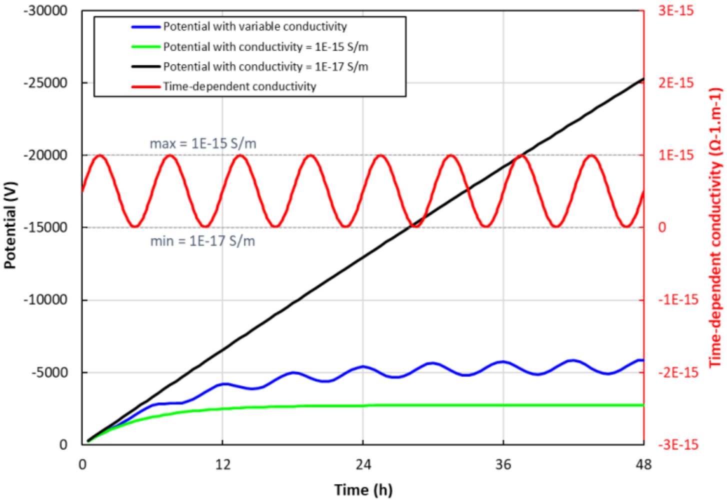


Figure 30 – Variations of potential for a conductivity of 10^{-15} S/m (green), 10^{-17} S/m (black) and for a time-dependent conductivity (blue).

User-defined conductivity: electric field-dependent

A two-column file containing the electric field-dependent conductivity of a material can be directly set (Figure 26).

Figure 31 – User-defined electric field-dependent conductivity.

This feature can be used when the user has measurements of conductivity as function of the applied electric field.

Export

The conductivity used in the electrostatic calculation can be exported and post-processed in 3D (Figure 32).

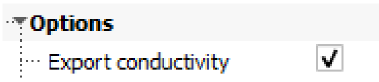


Figure 32 – Export the conductivity used in the calculation.

Capacitance

In the options, the calculation of the capacitance of a dielectric at the last time-step or at steady-state is available (Figure 33).

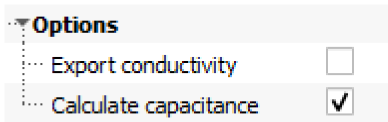


Figure 33 – Calculated the total capacitance of a dielectric at steady-state or the last time-step.

RADIATION PROTECTION

From low Earth orbit to space exploration missions, optimize shielding to ensure the health and security of crews!

Radiation Protection for Crewed Missions

FASTRAD® is able to compute radiological quantities used to calculate radiation levels received by the body, tissue or specific organs. Hence, the equivalent dose, effective dose and many other radiation quantities defined by the International Commission on Radiological Protection (ICRP) and by the International Commission on Radiation Units and measurements (ICRU) can be estimated with FASTRAD for any radiation environment in any geometric model.

Transport of energetic particles - proton, electron, photon, neutron, positron, ions, alphas, deuton and triton - is performed with the Forward Monte Carlo method in FASTRAD.

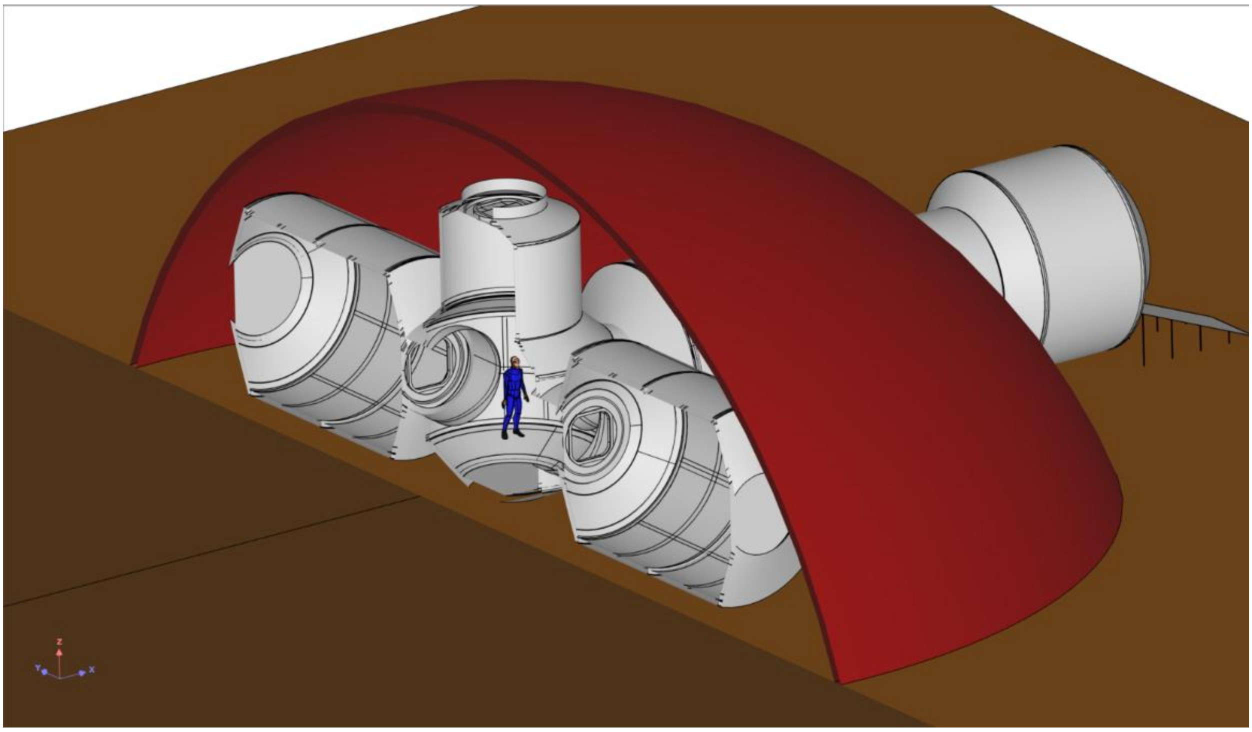


Figure 34 : Modeling of a human in a Martian habitat. In this cross section, the ground station is covered by a Martian regolith dome. FASTRAD is able to simulate the transport of energetic particles coming from Galactic Cosmic Rays (GCR) and Solar Energetic Particles.

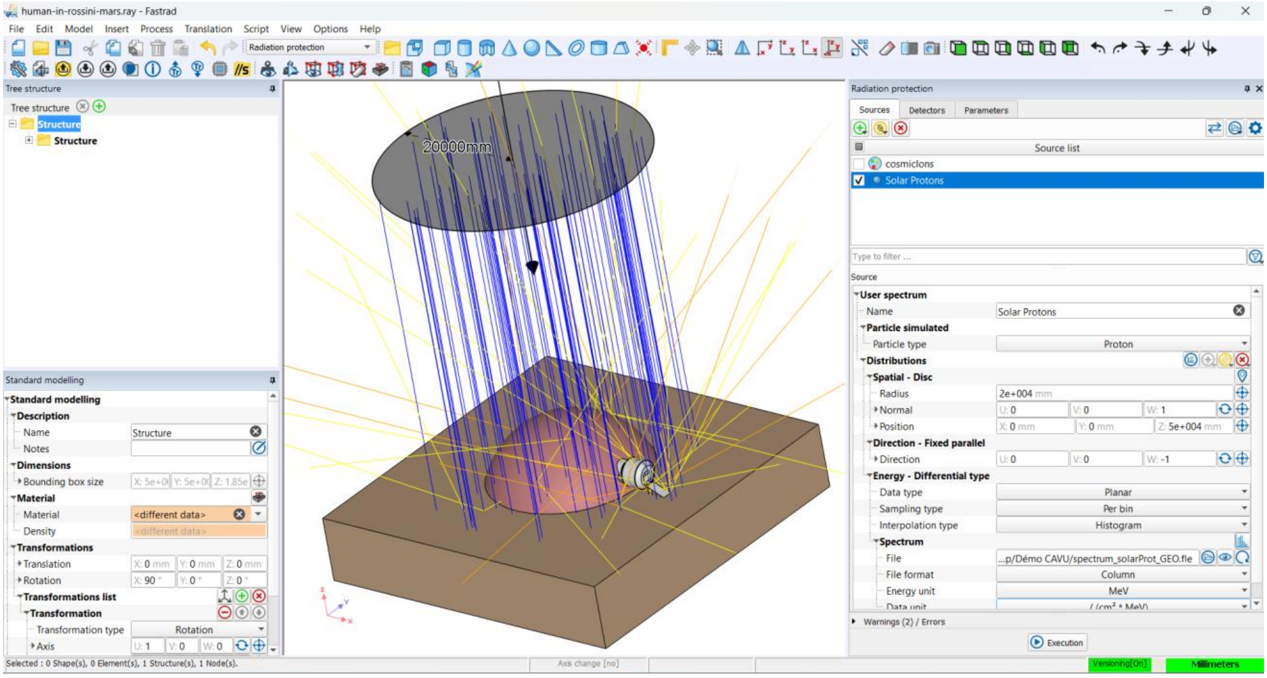


Figure 35 : FASTRAD simulates the irradiation of the Martian habitat by solar energetic protons. The blue lines correspond to the trajectory of primary protons, the orange and yellow lines correspond to secondary neutrons and photons respectively.

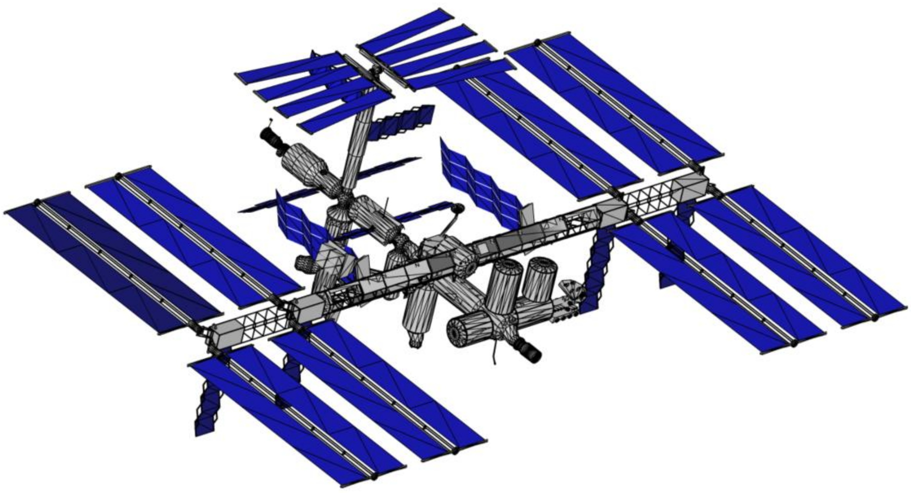


Figure 36: Modeling of the International Space Station, low Earth orbit mission. FASTRAD is able to model the transport of energetic particles (trapped particles, GCR, solar particles) through the shielding of the space station and estimate the dose received by the crew.

The table hereunder summarizes the radiological quantities that can be computed with FASTRAD® 5.0:

Type of detectors	Biological, radiation and physical quantities
Sensitive elements	Equivalent dose: H*(10), H'(0.07, 0°), H'(3.0, 0°), H'(10.0, 0°), Hp(10), Hp(3)
Volume mappings	Effective dose: E(AP), E(ISO) Kerma : air and water Effective dose equivalent Total absorbed dose (total, primaries and secondaries) Total deposited energy (total, primaries and secondaries) Fluence
Surface mappings	Current of particles: in, out, net and total

The user can define different source types:

- **Single spectrum**: it shares common features with other computation modules of FASTRAD. The user inputs its spectrum (for example a solar proton spectrum for this application) with its units, duration etc…

- **Multi-ion source**: this is a new feature specifically developed for the radiation protection module. In the case of space exploration, Galactic Cosmic Rays need to be considered for the radiation risk estimation. The multi-ions source allows to input a single file for all the ion species. FASTRAD can model ions from hydrogen to roentgenium.

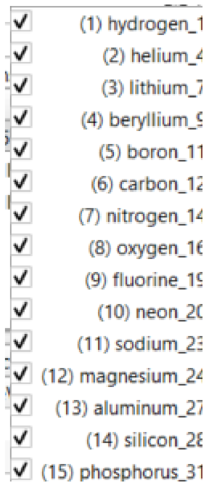


Figure 37: Extract of the list of ions that can be simulated by FASTRAD. The user can edit the list.

Computations can be performed in a specific part of the model (considered as the sensitive volume), but the elements can also be mapped. The contribution of the different particle sources can be followed in real-time during the simulation:

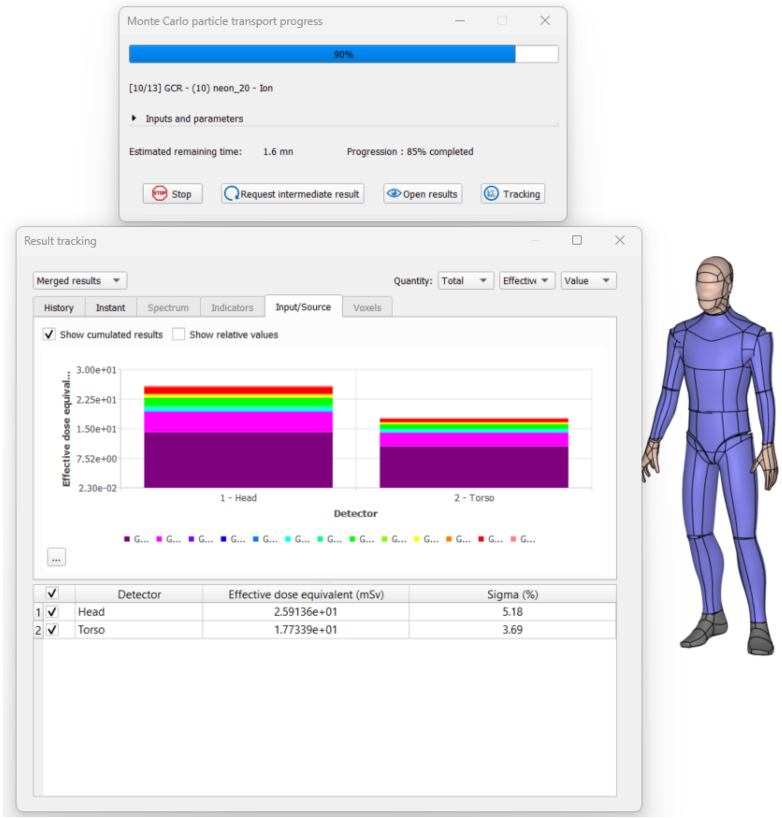


Figure 38 : Tracking results during the simulation. Each color corresponds to a specific ion from the Galactic Cosmic Rays source. The sensitive volumes are the head and the torso of the crew member. Effective dose and equivalent dose can be estimated for each part of the body of the crew member.

The goal of this functionality is to eventually optimize shielding to manage the risk of radiation on crews. The lifetime of a crewed mission can be designed to respect the ALARA approach (As Low As Reasonably Achievable).

As an example, a Martian habitat has been mapped to estimate the effective equivalent dose received at different locations in the station.

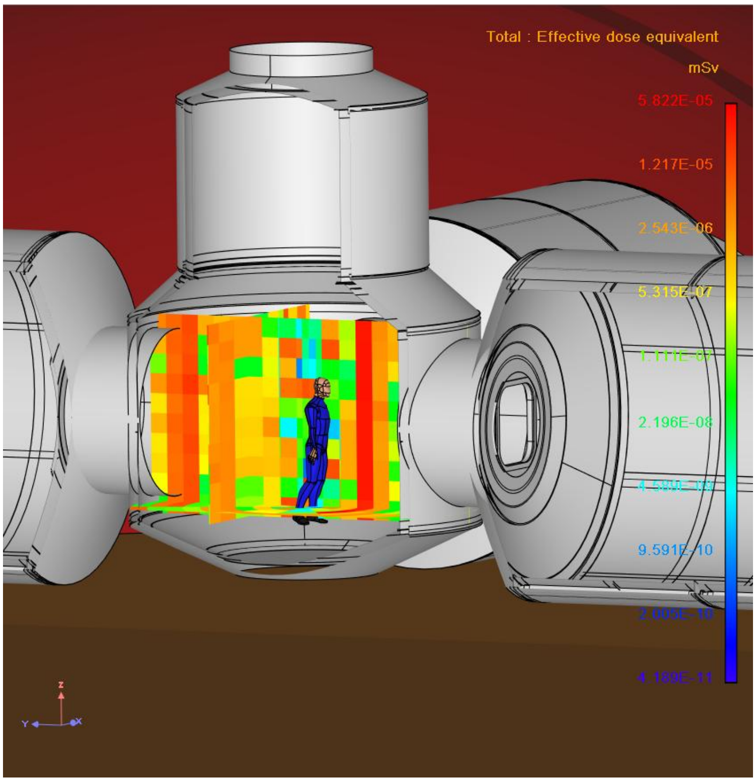


Figure 39 : Mapping of the central module of the Martian habitat. Mappings allow to identify critical areas in terms of radiation related