Using SPENVIS to evaluate the Space Environment

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ECSS-E-ST-10-04C
Trapped Rad. Belts Fluxes

Earth Orbit:

1. Long term average fluxes:
   a. AE-8 and AP-8 models
   b. IGE-2006 for GEO (+/- 500 km),
      "upper" model for "conservative" analyses
   c. ONERA MEOv2 for electrons in GPS orbits (20000km circular +/- 500 km altitude), "upper" model for conservative analyses
2. Worst Case for Internal Charging:
   a. FLUMIC v3 model
   b. NASA worst case model for GEO
   c. Can also be used for short term analyses (1 day → 1 month) of worst case cumulative radiation effects
3. Worst Case trapped proton fluxes:
   a. No provision in the current standard

Solar Particles: ESP model, confidence level is a project decision.

Effects Requirements

1. Dose (TID/TNID) ← total mission fluences
2. Solar cell degradation: ← total mission fluences
3. Internal charging ← peak daily fluences
4. Single event effects:
    a. long term (destructive): ← total mission fluence, probabilities
    b. Short term (SEU, Transients): ← peak fluxes, probabilities
5. Instrument background/noise:
    a. Maximum noise levels: ← peak fluxes,
    b. Loss of "science" ← duration of "events"
       ← frequency of "events".
6. Material Degradation ← total mission fluences
   ← low energies required (~ keV).

Confidence levels/Risk, uncertainty and errors → Margin policy

Outline

1. Introduction to SPENVIS – getting started
2. Generate a mission trajectory
3. Overview of available radiation environment models
4. The various simple effects tools
    a. SHIELDOSE
    b. EQFLUX/MC-SCREAM
    c. Single Event Effects
5. The Geant4 tools (Mulassis, SSAT, GRAS, GEMAT)
6. Advice, Exporting results & other useful features.

Registration

https://www.spenvis.oma.be/registration.php

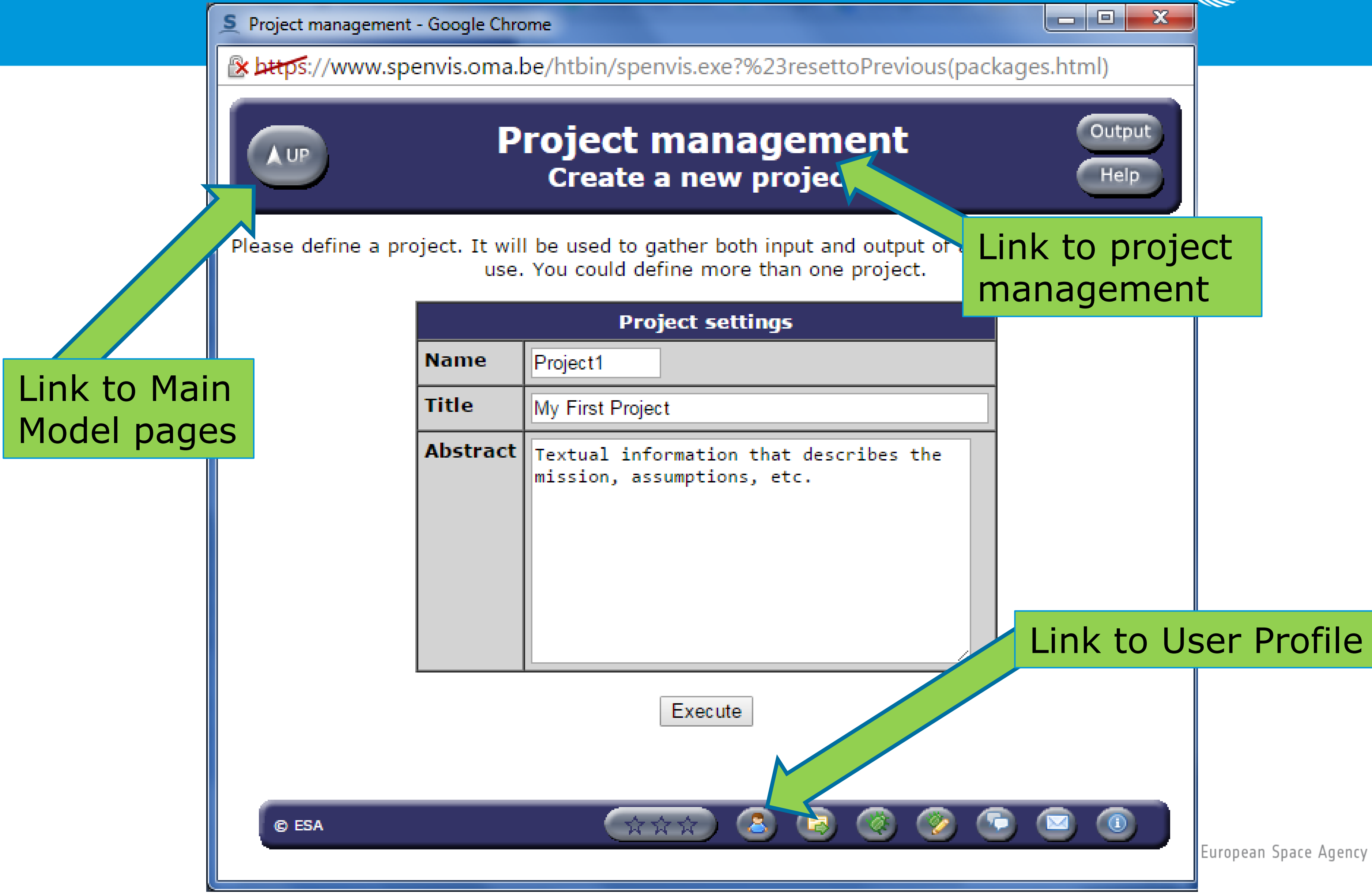
Temporary Accounts available:

juice_1
juice_2
…
juice_70

Password for each is:

Lulea-2016

Create a Project



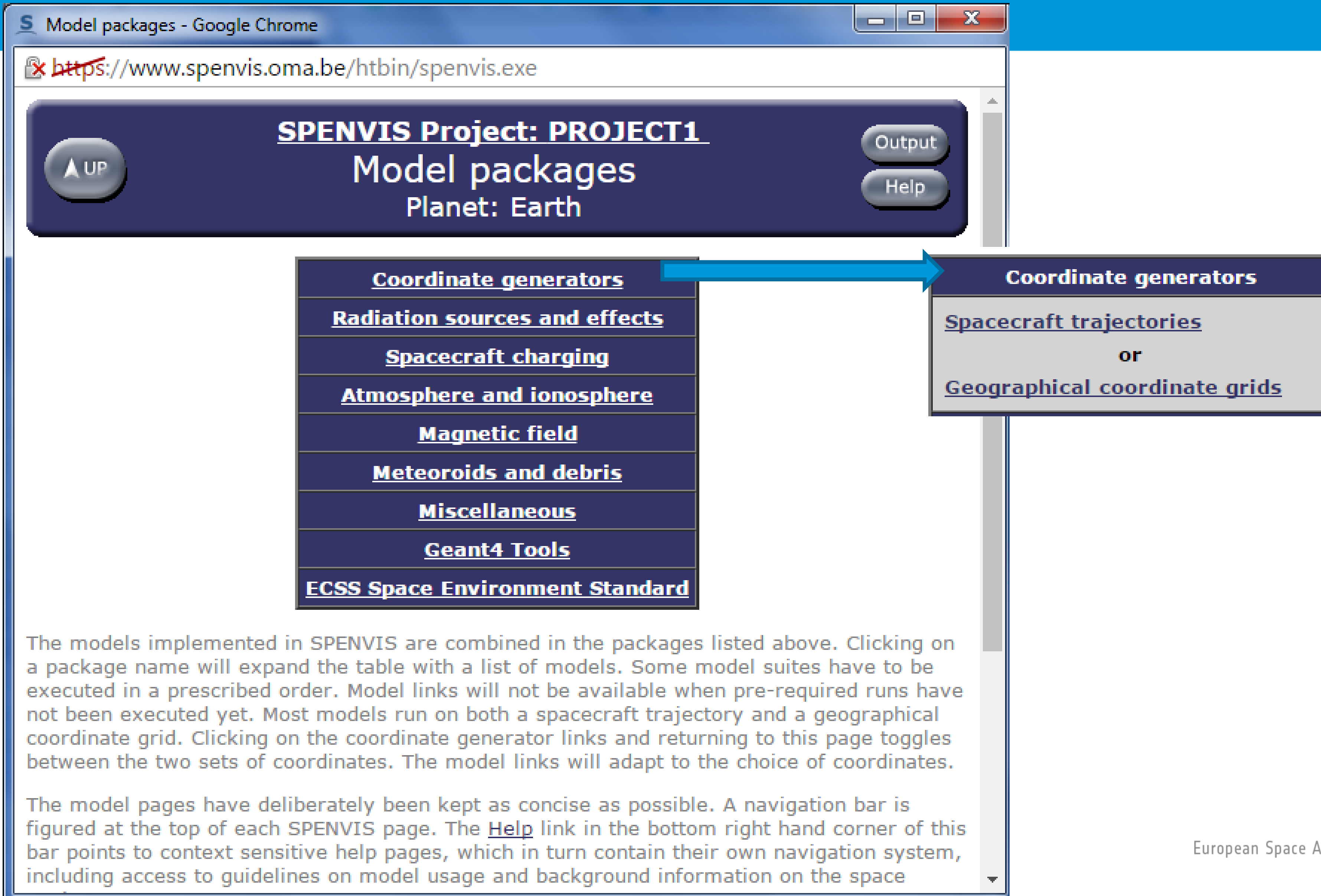
A Mission Trajectory is required

Three means of specifying the trajectory:

- **<u>Orbit Generator</u>**
- Upload trajectory file (SPENVIS format - Advanced)
- Upload CCSDS OEM trajectory file (JOREM extension)

- Orbit generator uses ephemera and propagates the orbit
  - General
    - Semi-major axis/eccentricity
    - Apogee/perigee
    - Circular
  - Hyperbolic (for fly-by missions)
  - Geostationary
  - Helio-synchronous (SSO)
  - Near Earth Interplanetary

Model Home Page



Traditional GEO

Trajectory generation:	use orbit generator
Number of mission segments:	1
Mission end:	total mission duration
Mission duration:	1.0 years
Account for solar radiation pressure:	no
Account for atmospheric drag:	no

Segment title: GTO Phase

Orbit type:	general
Orbit start:	calendar date
	01 Jan 2020 00 : 00 : 00
Representative	number of orbits : 2
Altitude specification:	perigee and apogee altitudes
Perigee altitude [km]:	300
Apogee altitude [km]:	36000
Inclination [deg]:	0.0
R. asc. of asc. node [deg w.r.t. gamma50]:	0
Argument of perigee [deg]:	0
True anomaly [deg]:	0

<< Back Next >>

Segment title:

Orbit type:	geostationary
Orbit start:	calendar date
	02 Jan 2020 00 : 00 : 00
Representative	trajectory duration [days]: 1
Longitude [deg]:	0

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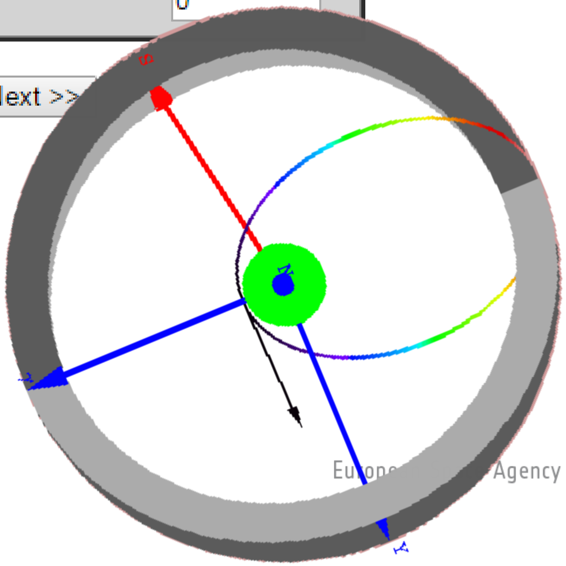
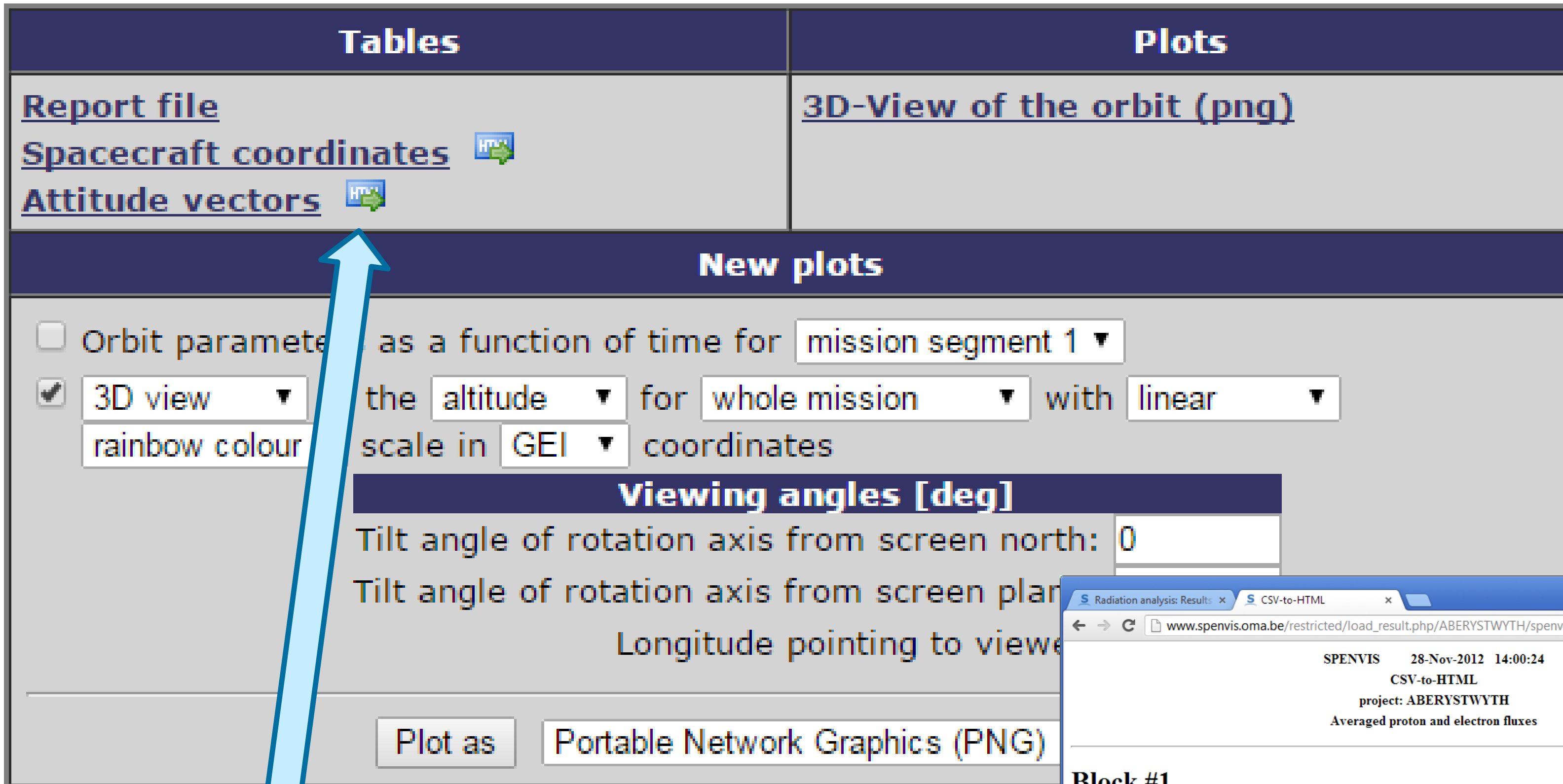
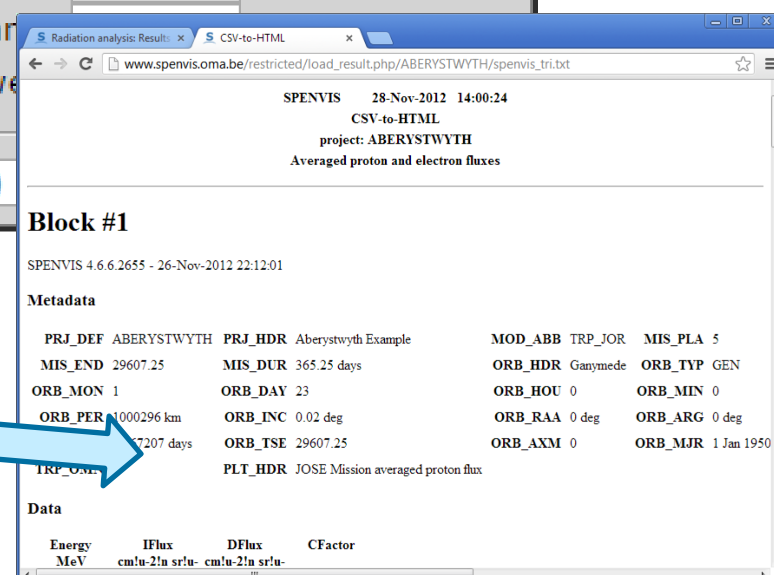


Output Pages





Link that can be used by Excel
to download CSV formatted data
as HTML tables

CSV Format defined in help pages

Radiation Models

Radiation sources include:

- Trapped radiation belts (AP8, AE8, IGE-2000, etc.)
- Solar protons (long, short term)
- Galactic cosmic rays

Models for all three sources in:

"Radiation Sources and Effects"

In most cases, the default parameters should follow ECSS-E-ST-10-04C

Coordinate generators

Radiation sources and effects

Radiation sources

Trapped proton and electron fluxes

Trapped proton flux anisotropy

Short-term solar particle fluxes (only for SEU)

Long-term solar particle fluences

Galactic cosmic ray fluxes

Shielded flux

Solar cell radiation damage

Damage equivalent fluences for solar cells (EQFLUX)

NIEL based damage equivalent fluences for solar cells (MC-SCREAM)

Long-term radiation doses

Ionizing dose for simple geometries

Non-ionizing energy loss for simple geometries

Effective dose and ambient dose equivalent

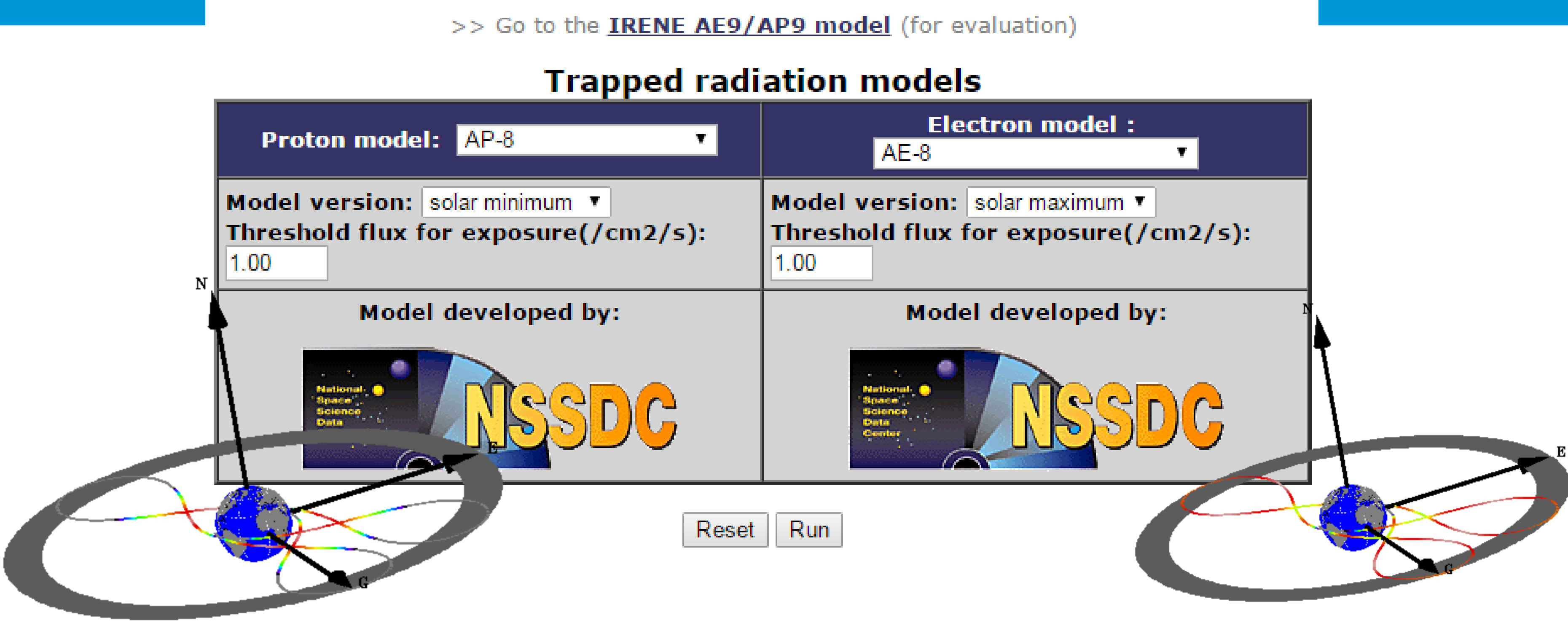
Single event effects

Short-term SEU rates and LET spectra

Long-term SEU rates and LET spectra

Spacecraft charging

Radiation Belt Models



AP-8 and AE-8 come in two flavours: Solar minimum and Maximum

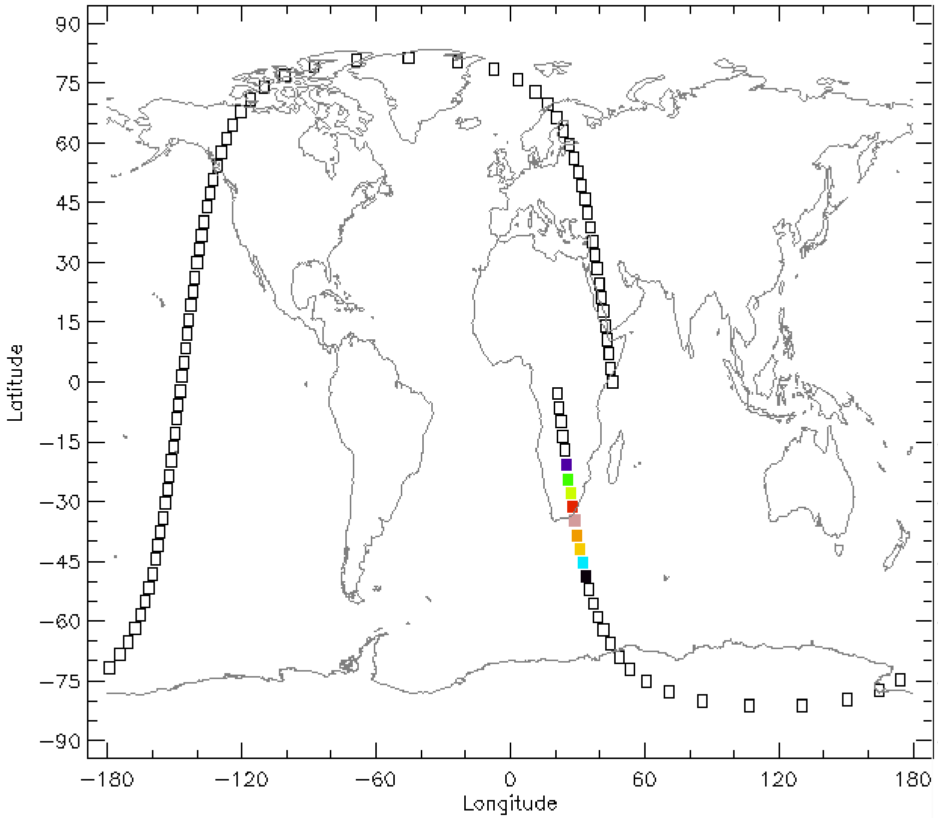
Slight anomaly: the IGE-2006 model is only available if a single mission segment is selected and “Geostationary orbit” type selected.

Plotting of fluxes around orbit as world map, 3D, or time series possible.

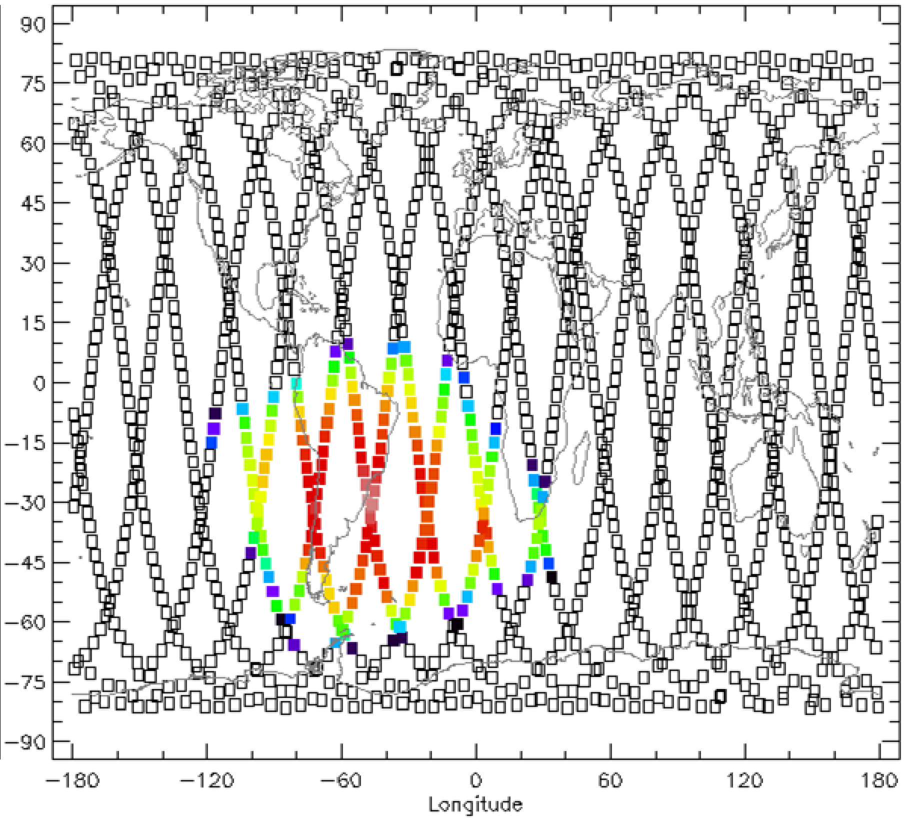
USE THIS TO CHECK YOU HAVE ADEQUATELY COVERED THE MISSION.

Number of representative orbits

Sun Synch. 800 km; 1 orbit



Sun Synch. 800 km; 1 day

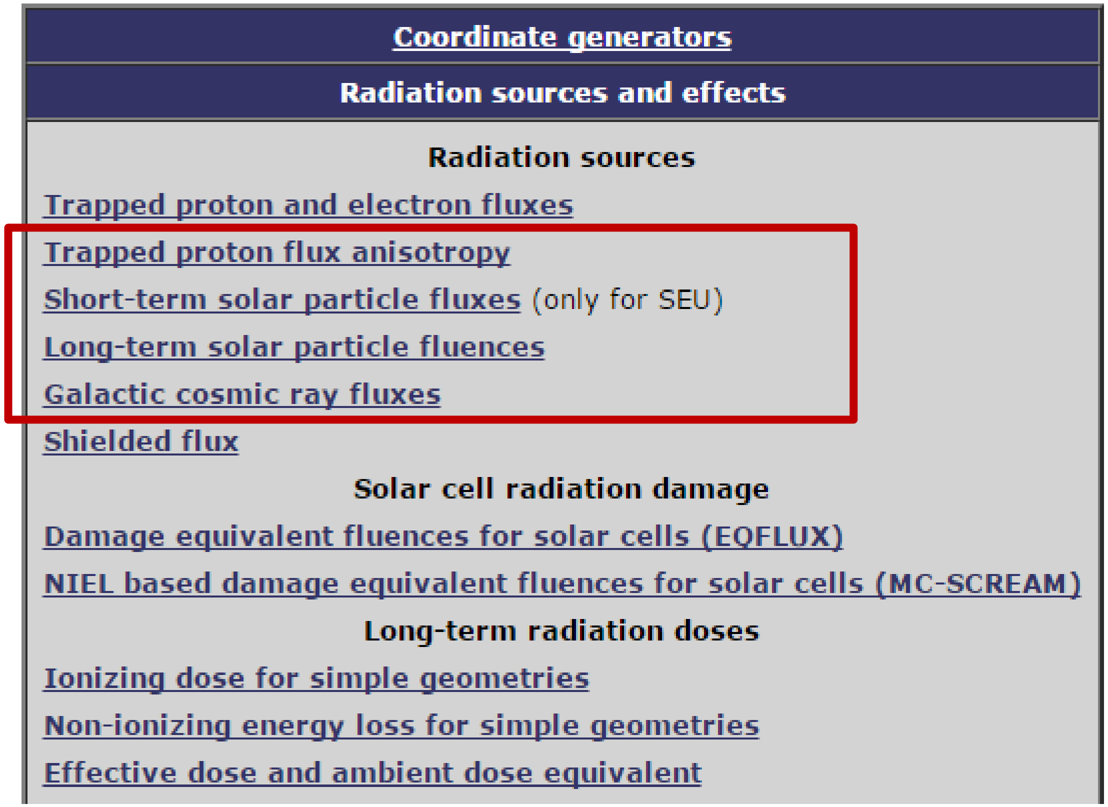


Also run for Solar particles & GCR

Once the trapped proton spectra model is run, the option to run the anisotropy model is available (relevant for low Earth orbits).

Also run the short and long term solar particle flux models* and GCR model.

Then move on to the effects tools



*For the Solar particle models, select a confidence level reasonable for the mission.

Radiation Effects Tools

1. SHIELDOSE-2	Dose as function of shielding thickness (p+, e-)
2. Non-Ionising dose	NID as function of shielding thickness (p+, e-) (Opto-electronic degradation)
3. EQFLUX/MC-SCREAM	Solar cell degradation models (p+, e-)
4. CREME models	SEU rate predictions (GCR, p+)
5. Geant4	
a. Mulassis	Simple geometries (slab, sphere)
b. GRAS	Complex 3D geometries (GDML)
c. SSAT	Ray tracing/Sector Shielding (GDML)
d. GEMAT	SEU effects in components
Generating GDML files	

Dose/Non-Ionising Dose Calculation

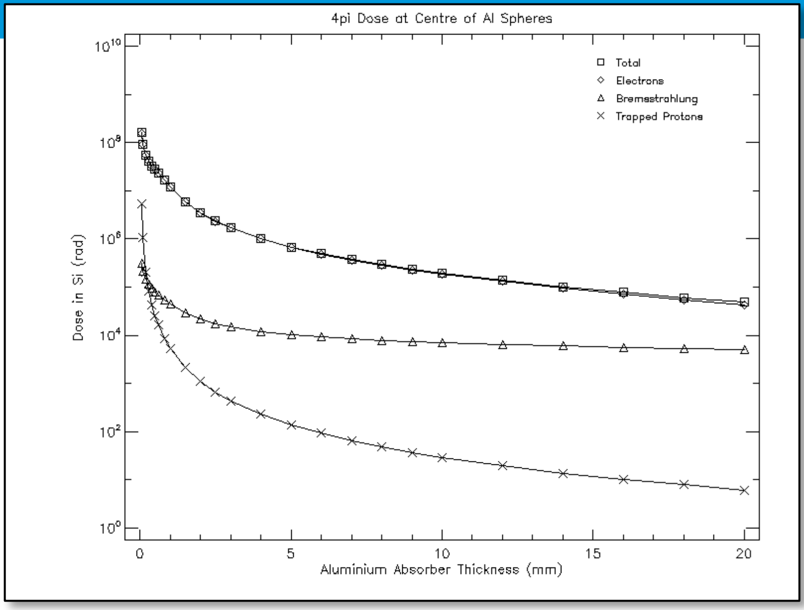
- Components are rated to a dose limit, beyond which they may fail or fade. This is typically in the range of <100 krad(Si). COTS components are closer to 1-15 krad(Si).
- The ionising dose limit is commonly established by testing using a Cobalt-60 source – Gamma ray dose (very penetrating). The non-ionising dose limit is determined with proton beam tests.
- The radiation dose from the space environment is mixed (protons, electrons, cosmic rays), each with varying levels of shielding effectiveness. This rich environment is simplified into a single metric, e.g. TID, TNID, etc.
- Non-Ionising dose mostly affects Opto-Electronics and Bipolar devices.
- It is often necessary to establish how much dose will be received by a component in the environment given the shielding available:
  - Simple shielding geometries (**solid sphere**, slab, spherical shell, etc).
  - Realistic shielding geometry:
    - Sector shielding analysis
    - Full physics simulations (Geant4, Fluka, etc.)

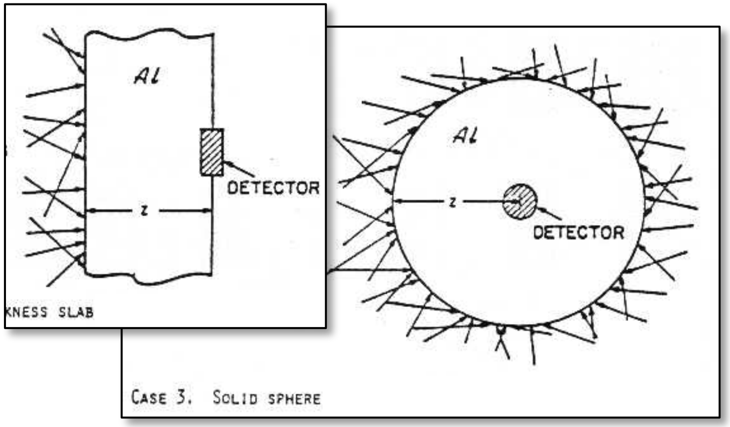
Simple Dose Effects Tools

SHIELDOSE(2,2-Q) provides dose-depth curves for simple geometries. Similarly, the NIEL model provides non-ionising doses .

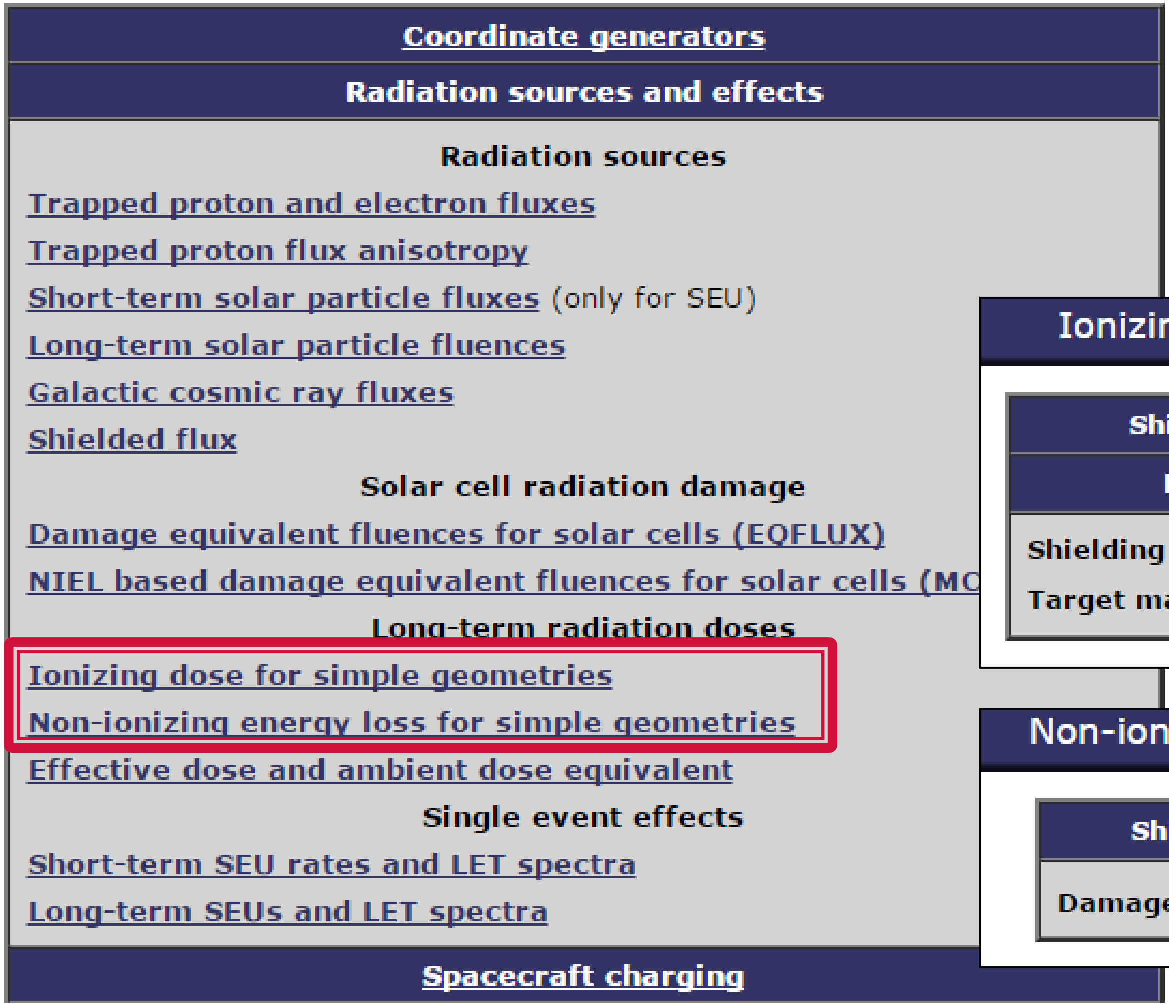
This is the simplest, and most conservative approach to RHA of a component.

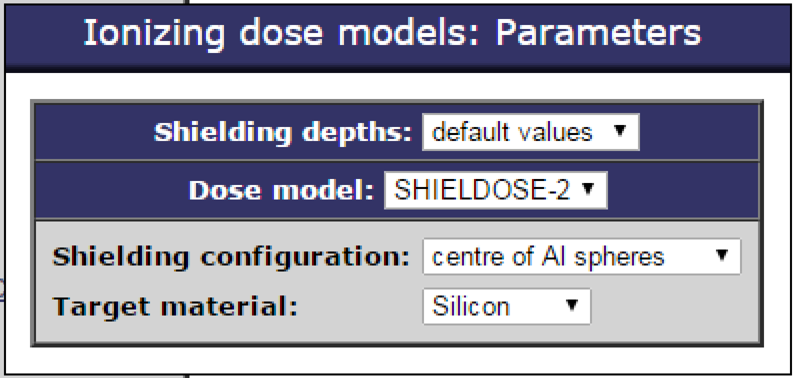
Generally, the **solid sphere geometry** is used and can serve as an input to the sector shielding approach (SSAT, FASTRAD, DOSRAD, etc.)

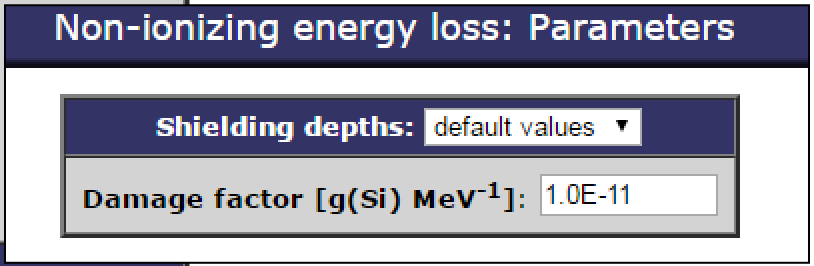




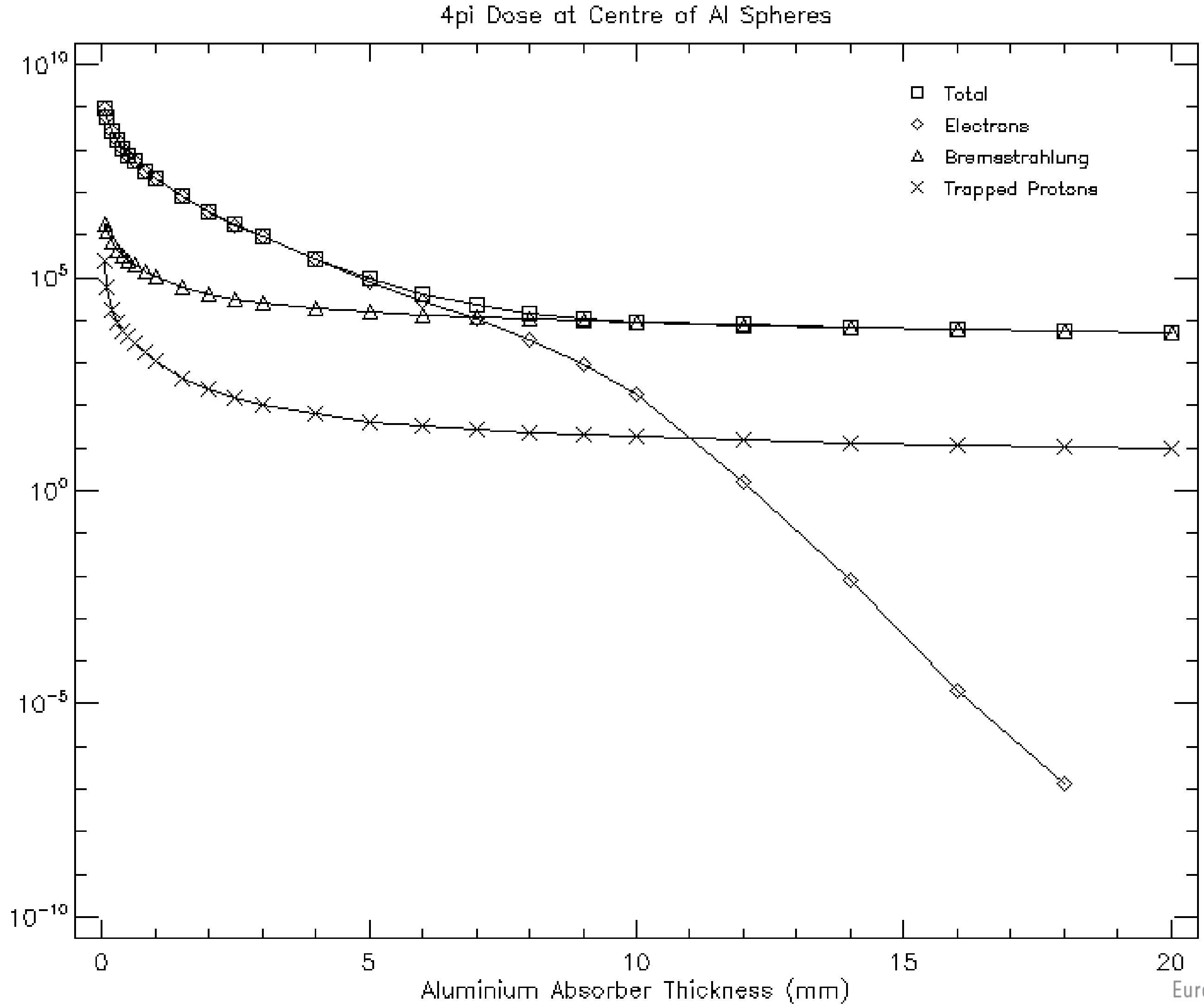
Simple Effects tools – SHIELDOSE-2







Dose-Depth Curve



Solar Cell Degradation

Two Methods:

Older JPL “EQFLUX” method

(MC) SCREAM method

Older method relies on extensive test data related to equivalent 1 MeV electron fluxes and conversion of proton and electron spectra to an equivalent 1 MeV electron fluence

MC-SCREAM method converts the environmental spectra to Non-Ionising Dose and combines with solar cell test data based on NID to determine degradation.

The MC-SCREAM method is preferred.

Solar Cell Degradation

In the lab, assume the use of Azur 3G28 solar cells.

In the report file, the damage for the cells will be provided, as will the relative degradation of the cells during the mission:

Cell definition

Cell type: Azur 3G28

Cover glass thickness [µm **]:** 150.0

Radiation environment

Particle selection

Trapped protons **Trapped electrons** **Solar protons**

Reset | Create Macro only | Create Macro & Run

Param set	Total Damage	Total Error	Proton Damage	Proton Error	Electron Damage	Electron Error	Degradation (P(d)/P0)
Ipmax	8.96e+08	5.46e+07	8.76e+08	5.46e+07	1.98e+07	2.12e+06	0.98956
Isc	8.97e+08	5.46e+07	8.76e+08	5.46e+07	2.11e+07	2.25e+06	0.9913
Pmax	8.90e+08	5.46e+07	8.76e+08	5.46e+07	1.44e+07	1.53e+06	0.95511
Voc	8.90e+08	5.46e+07	8.76e+08	5.46e+07	1.37e+07	1.46e+06	0.96547
Vpmax	8.85e+08	5.46e+07	8.76e+08	5.46e+07	8.72e+06	9.31e+05	0.95453

Upset Calculation - Theory

SEE are caused by **GCRs** and **protons**

SEE can be:

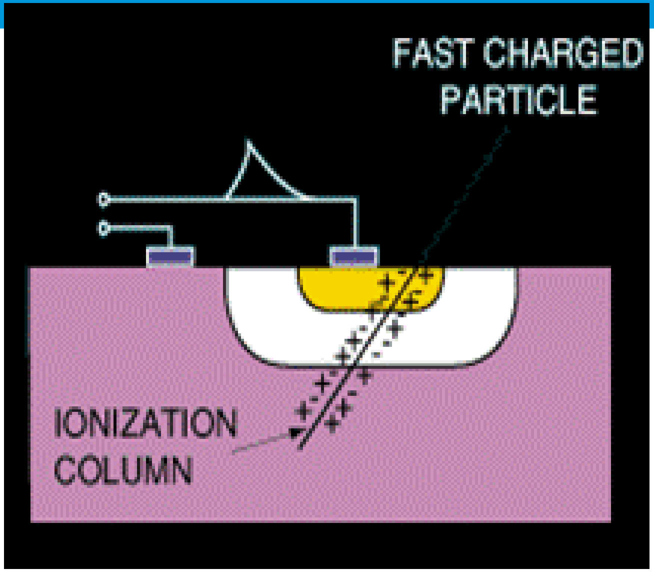
destructive, e.g. Latch-up, or

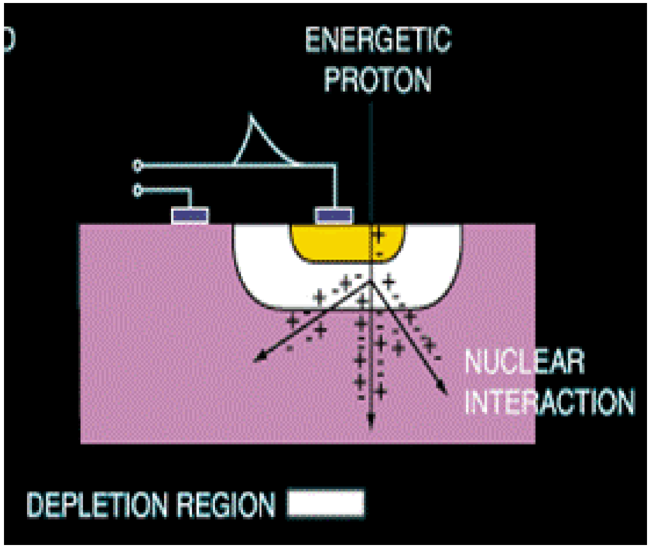
temporary, e.g. Single event upset/bit flip

Mechanism is species dependent:

- **Ions**: cause upsets via ionization; this depends on the length of the ionization column in the sensitive volume of the component.
- **Protons**: cause upsets via a nuclear interaction leading to an ionization column (LET_{th} < 15 MeV cm²/mg).

Evaluating SEE requires knowledge of component → Test data
(some component data included in SPENVIS)



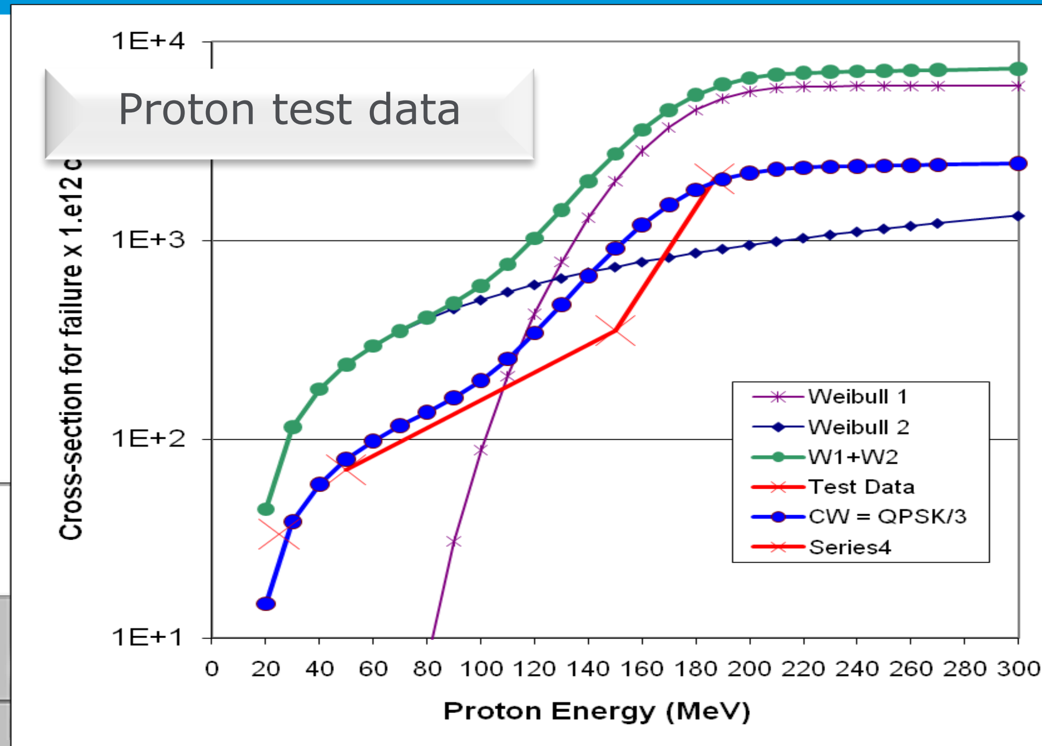


Device Test Data

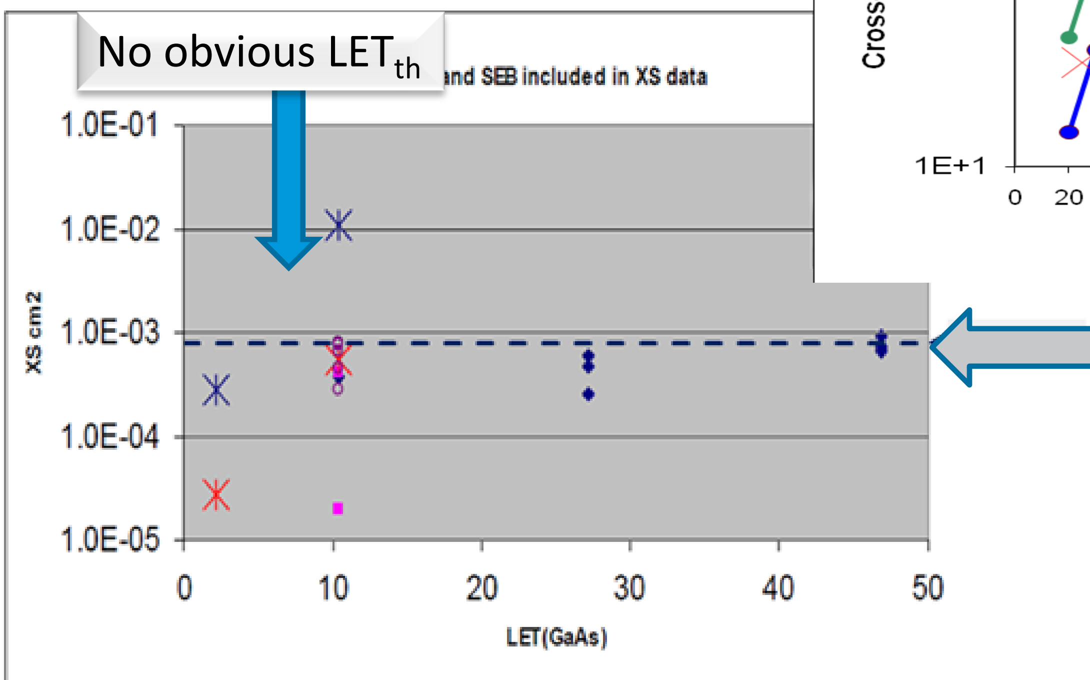
Aim is to have a cross section curve as a function of incident particle LET or proton energy.

The data is typically fit to a Weibull or Bendel function

Proton test data



No obvious LET_{th}



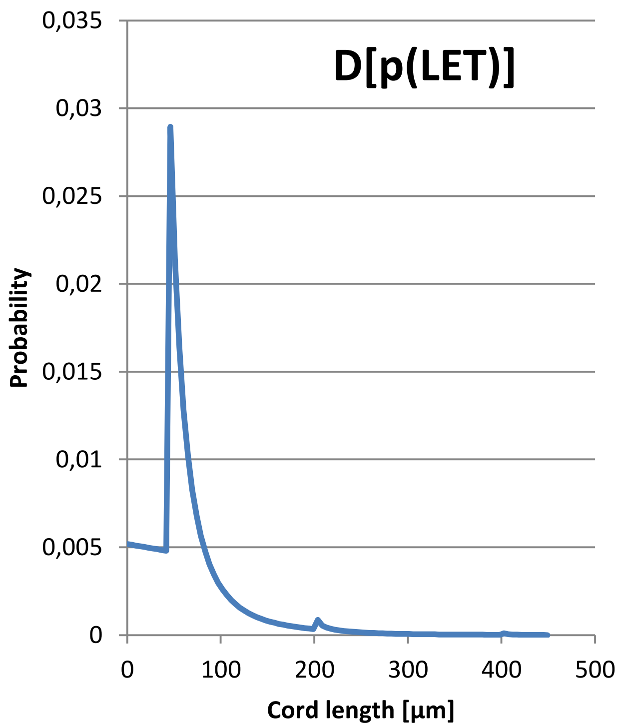
Test saturation cross section matches the visual inspection

Heavy Ion test data

Upset Calculation - Ions

CREME Rectangular parallelepiped (RPP):

- **Device Dimensions** (l×w×h) → RPP path length distribution. These dimensions are derived from actual device dimension measurements OR guessed from the cross section test data and device thickness.
- **D[p(LET)]** is the diff. path length distribution with $p(L)=(X/e)Q_c/L$ – the length over which a ion of LET L will produce a charge Q_c.
- **Critical Charge** (Q_c) – proportional to LET_{th}.
- **Cross section (σ)**: is from the device test data.
- **F(LET)** is the integral LET spectrum



$$SEUrate(\#/bit-s)=22.5\pi\sigma Q_{crit}\int_{22.5Q_{cri}/p_{max}}^{LET_{max}}\frac{D[p(LET)]F(LET)}{LET^2}\,dLET$$

N.B.: 22.5 is for Silicon, for GaAs this becomes 30.0

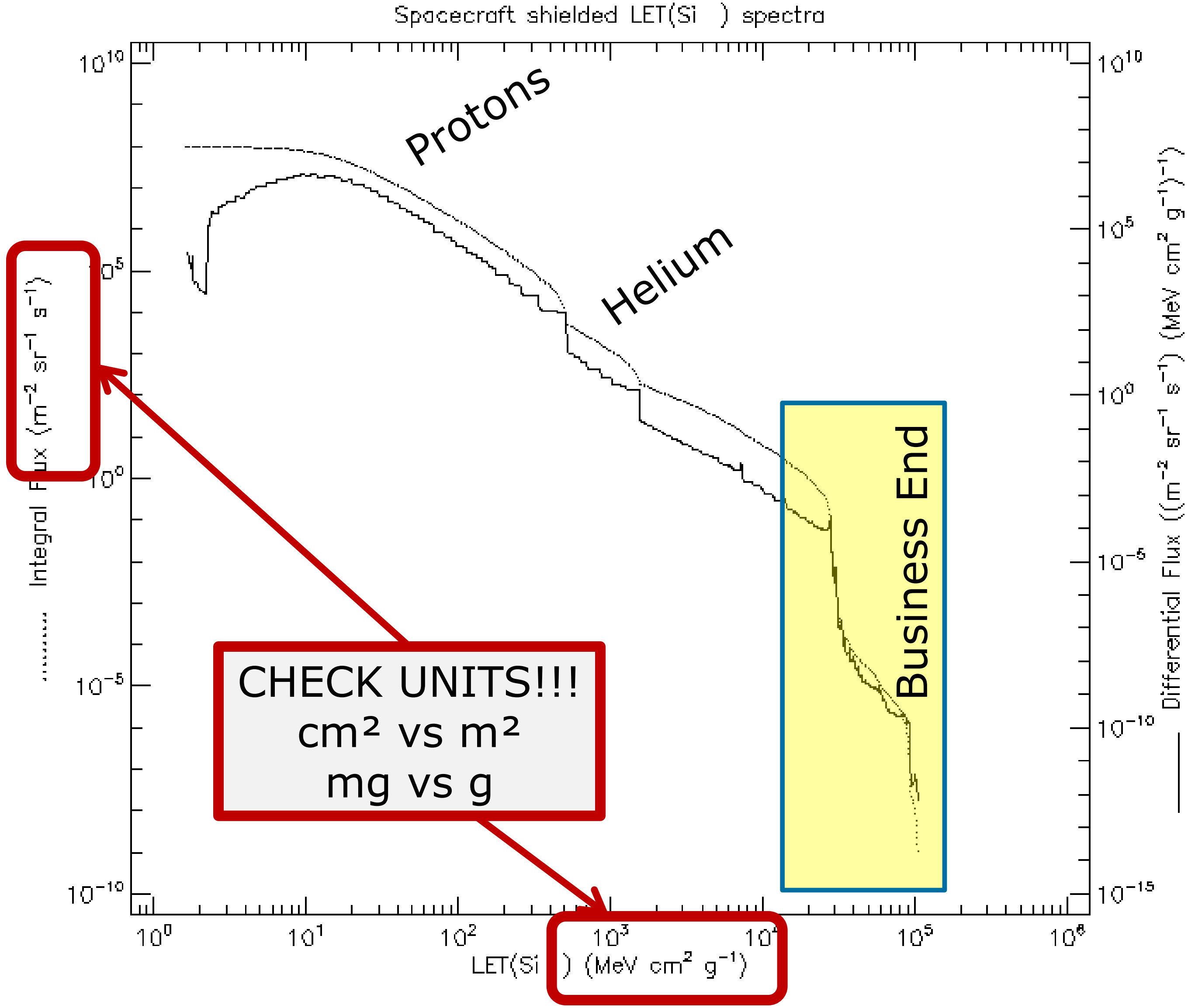
Upset Calculation - Protons

Protons: CREME 86/96 method:

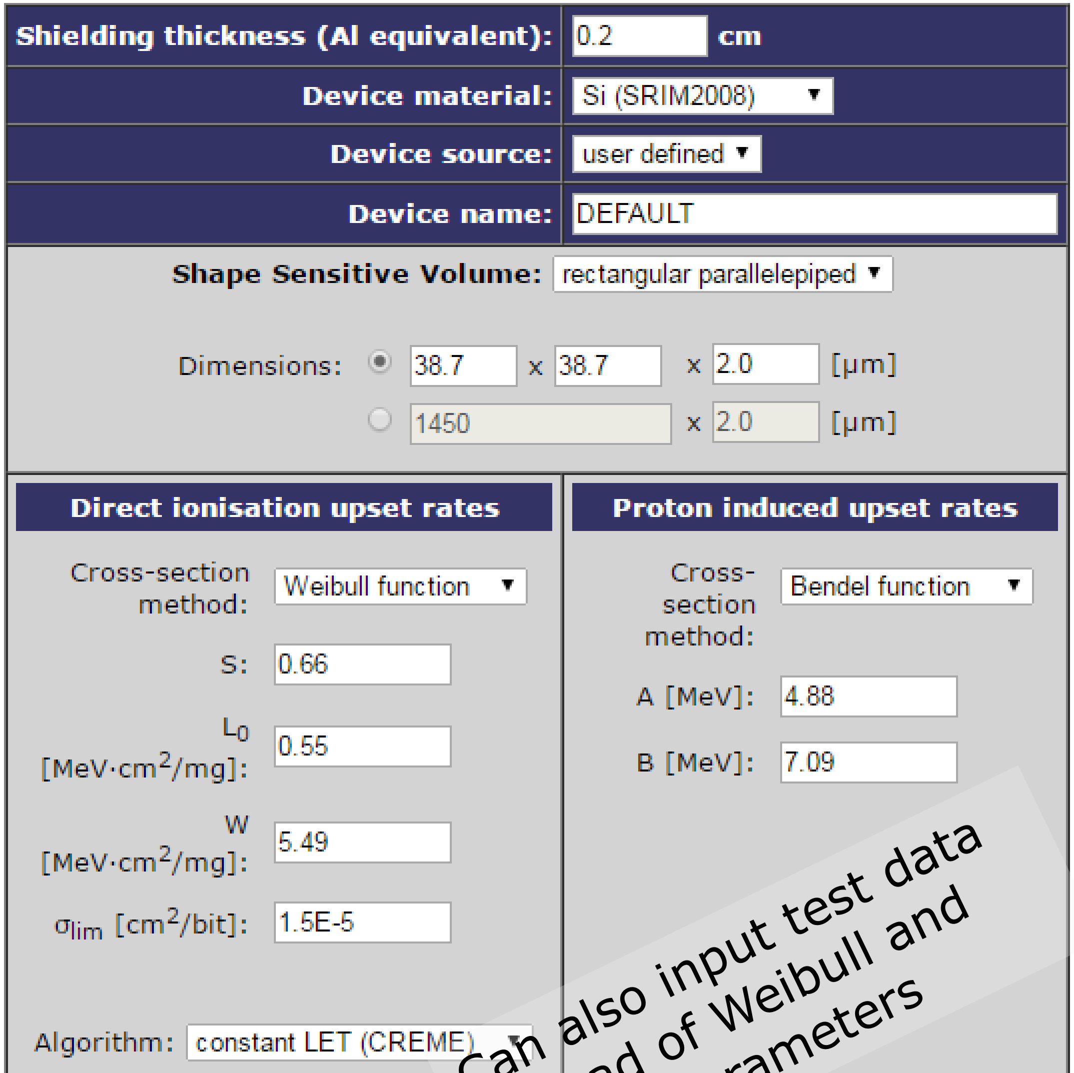
- Cross-section data (Bendel, Weibull, Profit)
  - Profit is a tool for estimating the cross section from heavy ion test data.
- In principle, there are no angular effects to consider.
- Components with an LET_{th} < 15 MeV cm²/mg are considered susceptible. (Look up Si in Si Stopping power maximum value).

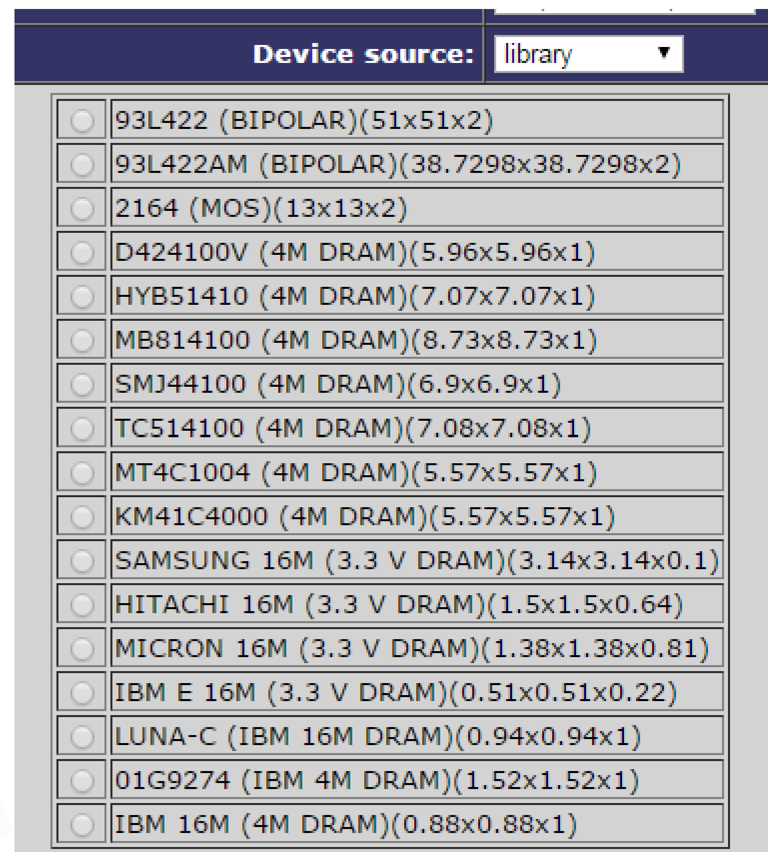
$$SEErate = \int f(E)\sigma(E)dE$$

LET Spectrum



SEE in SPENVIS





Can also input test data instead of Weibull and Bendel parameters

Geant4 Models

Geant4 tools have similar inputs

- Source particle definitions
- Physics lists
- Material lists
- Geometry (GRAS, SSAT)

- Mulassis & GEMAT have their own geometry definitions.

Geant4 input files (macros & GDML) available for download to permit local runs.

Coordinate generators

Radiation sources and effects

Spacecraft charging

Atmosphere and ionosphere

Magnetic field

Meteoroids and debris

Miscellaneous

Geant4 Tools

General models

Multi-Layered Shielding Simulation (MULASSIS)

Geant4 Radiation Analysis for Space (GRAS)

Geant4-based Microdosimetry Analysis Tool (GEMAT)

Sector Shielding Analysis Tool (SSAT)

Planet specific models

Magnetocosmics

Planetocosmics

Common settings

Definition of source particles

User defined materials

Geometry definition tool

ECSS Space Environment Standard

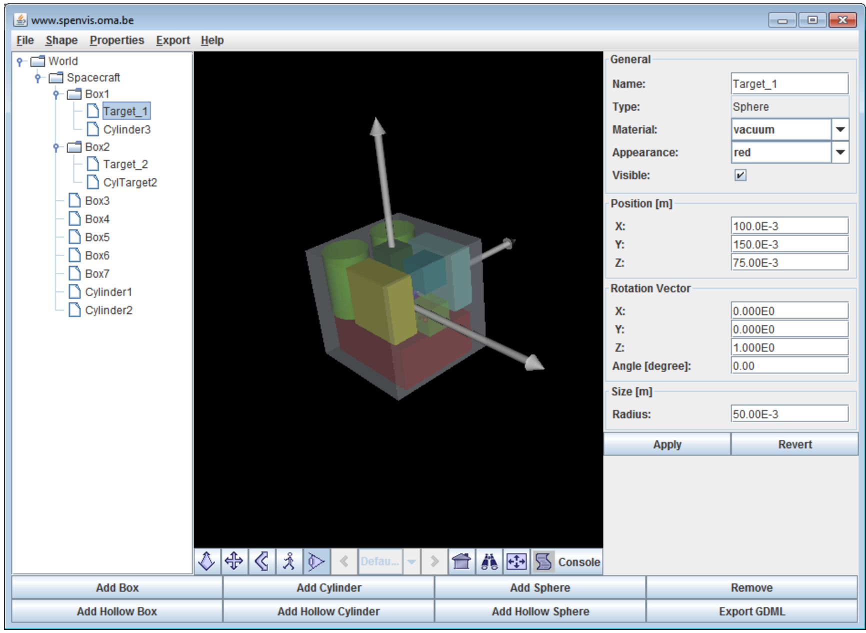
Geometry Definition (GDML)

Two tools available to generate simple GDML geometries:

- HTML based Geometry Definition tool
    - Series of HTML pages to specify a geometry with up to 10 elements using CSG (sphere, box, cylinder)
    - Visualisation available at each step using VRML (need plug in, such as Cortona (http://www.cortona3d.com/)

- Java Geometry Generation Tool
    - Downloaded Java application
    - Interactive visualisation

- Upload GDML file from CAD tool, e.g. FASTRAD.



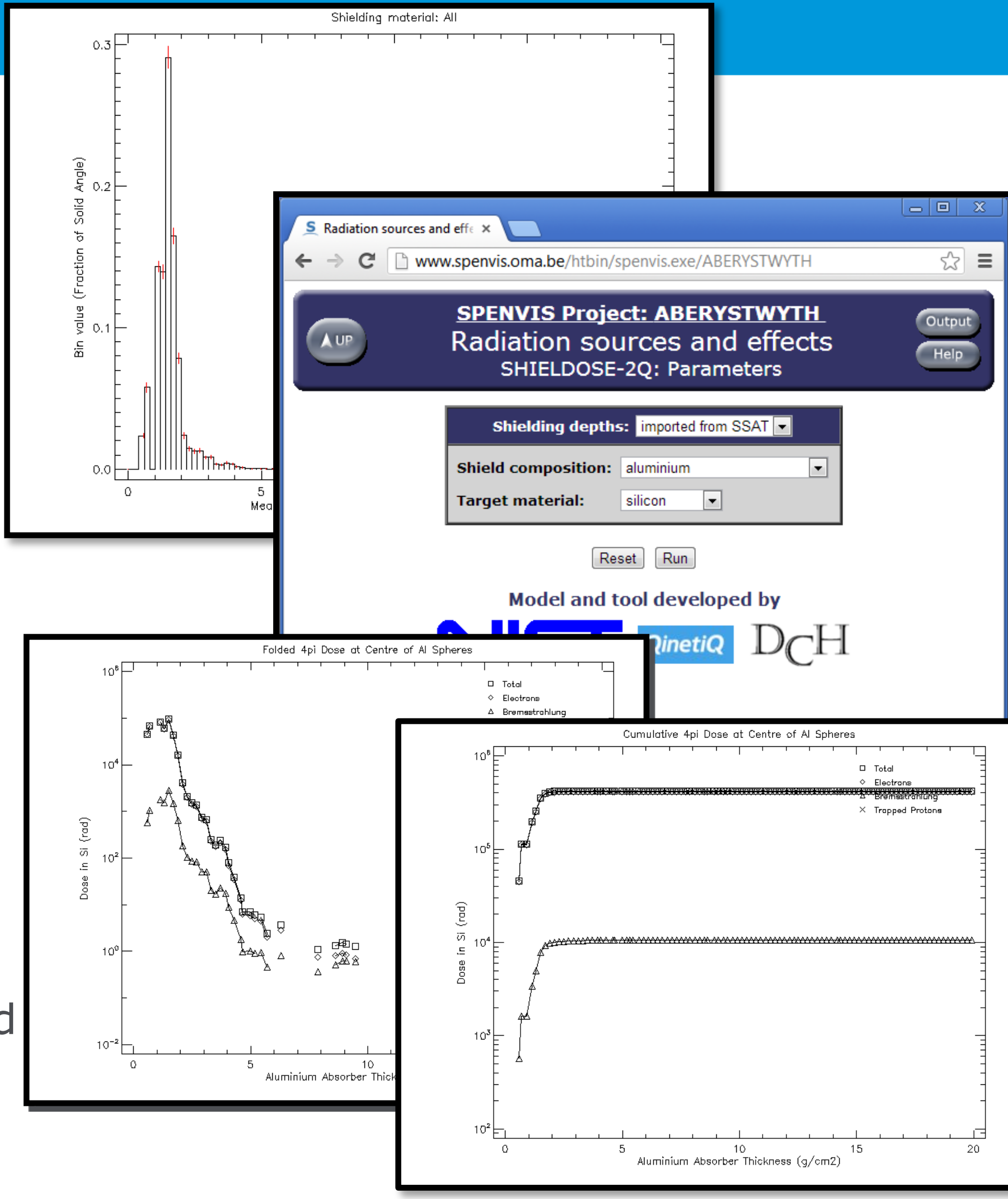
Sector Shielding Doses (SSAT)

Run SSAT to derive shielding distribution curve

Use SHIELDOSE-2 or SHIELDOSE-2Q and import shielding depths from SSAT.

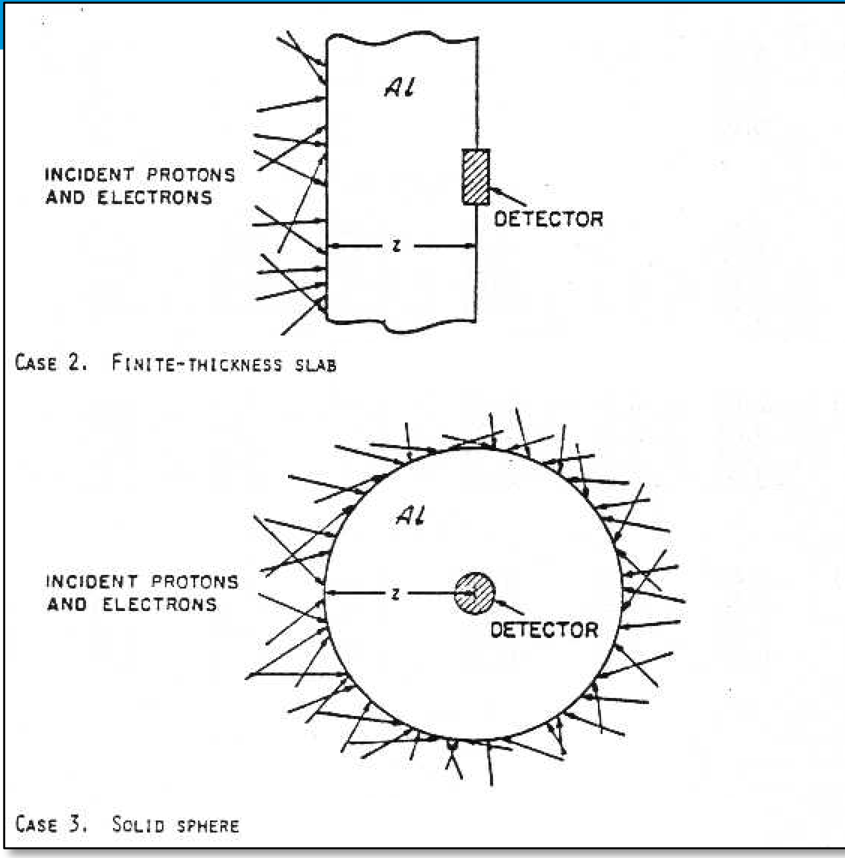
Running SD2(Q) will fold Shielding distribution curve with the Dose-depth curve to provide Dose contribution for each shielding thickness for the geometry. The cumulative curve gives the dose in the target.

Look in SSAT GDML file analysis to find location of target (not obvious)



Mulassis

1. Simple geometries, like Shieldose:
    a. Slab
    b. Spherical shells (solid sphere)
2. Can be used to investigate graded, or exotic shields and targets.
3. Outputs include:
    a. Shielded flux spectra
    b. Total Ionising dose
    c. Non-Ionising dose
    d. Pulse height spectrum
    e. Dose Equivalent (Human effects)



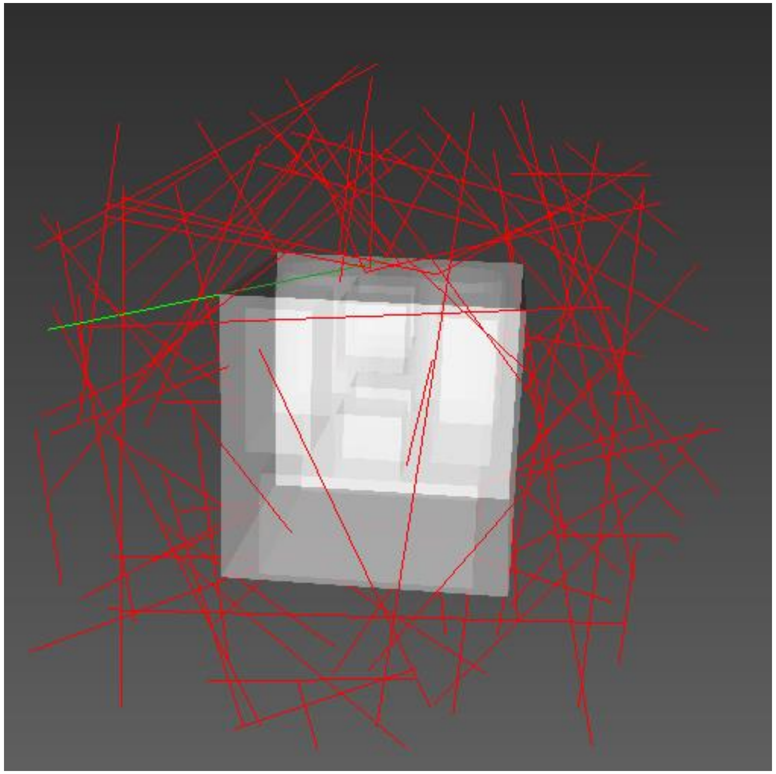
Recommend using slab geometries, as statistics are better. Although for solid sphere equivalent, an good approximation (~10%) is to use a spherical shell with a vacuum "core" that's 1/10th the thickness of shield.

GRAS

Complex 3D analysis module

Geometry defined by GDML file

Targets selected from GDML file

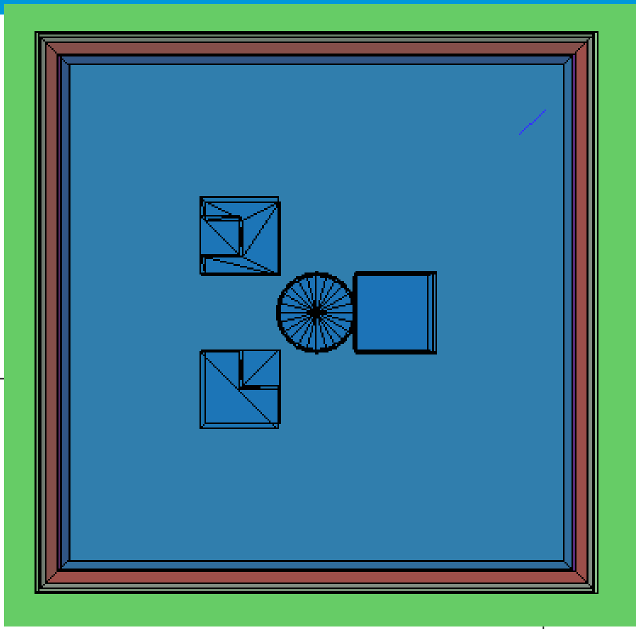


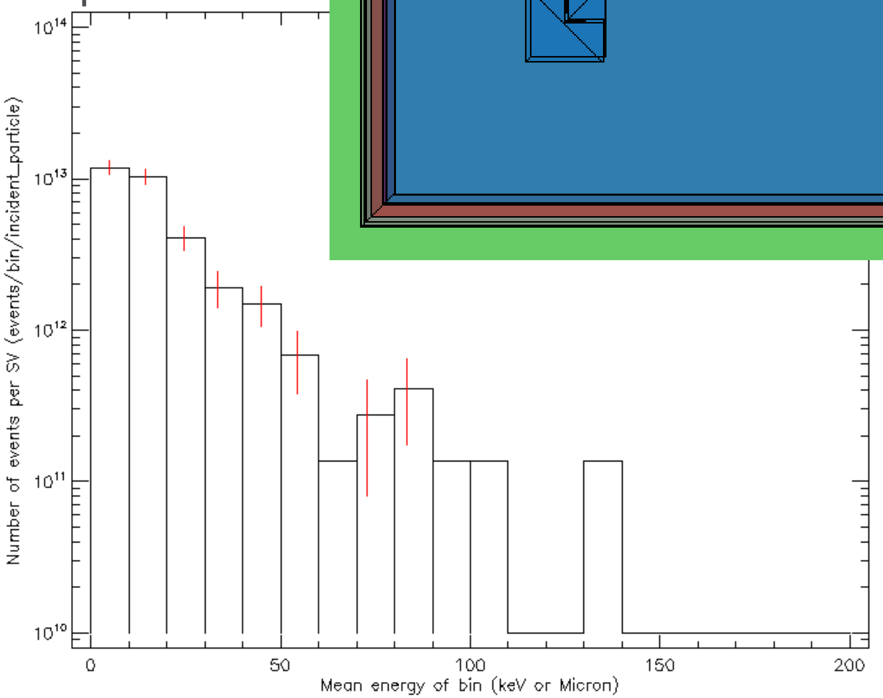
Can use the SPENVIS system to set up a **basic** run, download the input files and run more detailed analysis locally.

SPENVIS limits model runs to 600s, Which can often be insufficient for a complex geometry to be analysed with adequate statistics.

GEMAT

1. Used to study the effects of radiation on micro-electronics (Single Event Effects).
2. A geometry is defined for a component in terms of layers. Using common shapes cylinder, box, "L" and "U" shapes
3. Analysis of
    a. incident flux
    b. Pulse height
4. Allows analysis of more complex geometries than provided by CREME.





Other Useful(?) Information

1. The SPENVIS system, being an on-line system, limits model runs to only 600 CPU seconds. Some models can take a significant time to run – sample an orbit of interest or use a single relevant orbit.
2. Resources:
    a. SPENVIS BACKGROUND & HELP pages are extensive!
    b. Normally only 2 projects are provided to users, this can be increased by request to the SPENVIS team
    c. Similarly, CPU limits and disk usage can be extended beyond the default on request.
    d. Forums are available for assistance.
    e. **It is possible to ZIP and download the entire project**
3. ECSS Standards:
    a. ECSS-E-ST-10-04C: Environment specification
    b. ECSS-E-ST-10-12C: for determining radiation effects
    c. ECSS-Q-ST-60-15C: Radiation Hardness Assurance standard
4. **For RHA – a margin of a factor of 2 should suffice in most cases**

Determining Margins

- The trapped radiation belt models are stated to be accurate to within a factor of 2-3, but this will vary considerably over the magnetosphere.
  - In Geostationary orbit, AE-8 is known to be overestimating the fluxes.
  - At GNSS/Galileo orbits, AE-8 is underestimating the fluxes…usually.
  - The trapped proton model appears to be underestimating above, say 1000 km altitude.
  - The dynamic range of the environment can be several orders of magnitude→ regression to the mean is important, long missions → lower margins (maybe).
- The solar proton models, while they have a statistical confidence level, suffer due to underlying data calibration uncertainties.
- It is necessary to balance the margin policy with the risk that can be assumed for the mission – over engineering is expensive, but getting it wrong is even more expensive.

Caveat Emptor!

CREME Stopping Powers