Geant4 Tools for Space

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  - REAT http://reat.space.qinetiq.com
  - SPENVIS http://www.spenvis.oma.be/spenvis/

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Section 1

Application of MC radiation transport to spacecraft: History & trends

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Previous applications of MC to space radiation studies

- Shielding studies based on Monte Carlo simulation applied in early 1960's (*e.g.* Hill *et al*, 1964)
- Calculations of atmospheric showers using HETC - Armstrong, Chandler and Barish (1973)
- Study of background rates in astrophysics gamma-ray missions by Dyer, Trombka, Seltzer *et al* (1975)
- Study of space-borne gamma-ray instrument performance using EGS by Dean, Lei and Knight (1989)

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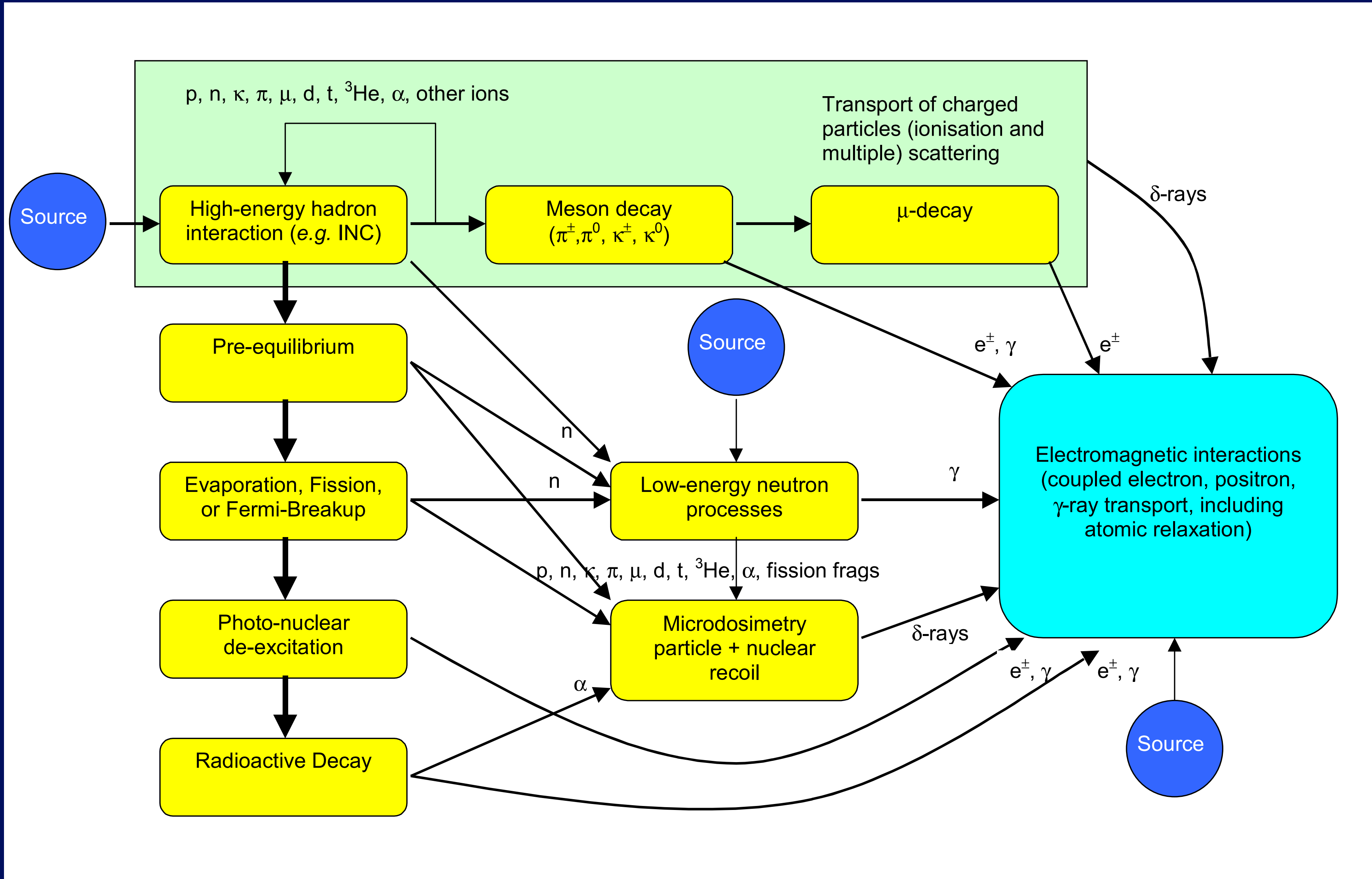
Trends in tools and analytical approach 1

- Previously codes tended to cover a limited range of physical processes (EM transport of leptons and photons, or high-energy hadronic simulation, *etc*)
- For some space radiation studies, vital to cover complete range of particles and physical processes
- Several codes integrated to form code suites to meet this requirement (*e.g.* GEANT3, GCALOR, MCNPX, HERMES and IRTS)
- Geant4 is really first code written from the outset to cover a wide range of physics without "bolting-together" old code

Space radiation interaction processes - a potted summary!



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Trends in tools and analytical approach 2

- Previously Monte Carlo radiation analysis tools were largely limited to scientific research
- Today, the availability of high-performance low-cost computers allows greater use of more complex simulation tools
- MC simulators can now be considered as engineering tools that may be regularly employed to aid spacecraft and space instrument design
- However, important to ensure ease of access and operation by someone who isn’t necessarily a space radiation effects or radiation transport expert

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Section 1

Trends in Systems, Missions & Technology

- Trends in missions:
  - mobile communications for higher, proton-intense orbits
  - GPS, including the proposed Galileo system, subject to the most intense radiation environment
  - increased processing power by using SOTA microelectronics and photonics
  - desire to use COTS to reduce component costs $\Rightarrow$ accurate calc. of shielding
  - spacecraft sizes from nanosats (10 kg) to ISS dimensions $\Rightarrow$ secondaries
- Microelectronics technology
  - rapidly decreasing feature size and increasing frequency bandwidth
  - microdose and SEE increasingly important (even terrestrially)
  - SiGe and InP in competition with GaAs. Displacement damage important
  - Use of GaAs and InP for solar cells requires accurate consideration of NIEL. Low energy populations and propagation important for cover glasses
  - power MOSFETs susceptible to SEB and SEGR (direct ionisation by ions, and ionisation by recoils following nuclear interactions of protons and neutrons).
  - total dose problems can arise in MEMS from charging of insulators near to micro-mechanical systems

Section 1

Trends in Systems, Missions & Technology

- Packaging and shielding
  - commercially available packages and coatings available for which dose reduction is claimed
  - graded shielding may afford factor of 3 improvement in shielding against electrons

Section 1

Areas for Tool Development

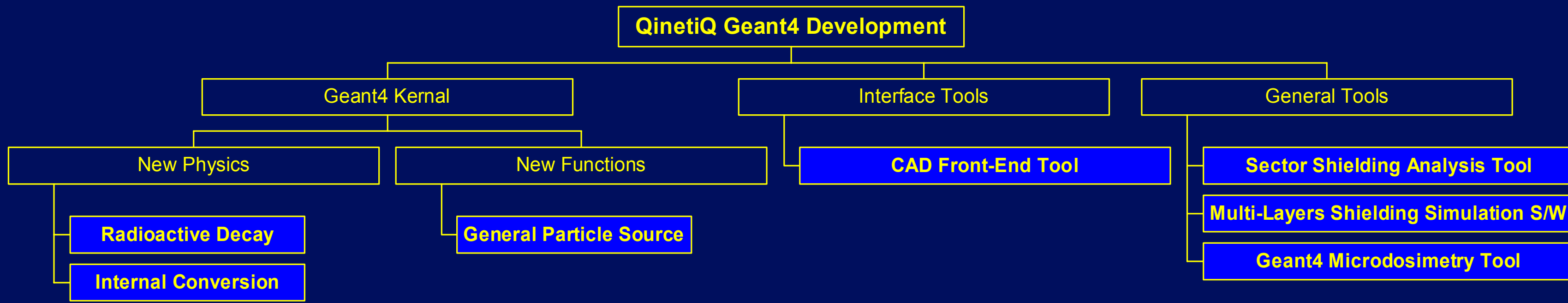
- Prediction of spacecraft secondaries and their spectra
  - More accurate assessment of material shielding distribution around a component/instrument
  - Generation of an engineering tool for quantifying secondaries
  - Effects of secondaries (including thermal neutrons) such as dose, damage, charge-deposition, SEE, radioactivity
  - Dose enhancement and graded shielding
- Prediction of microdosimetry effects
  - Propagation of heavy ions and secondary fragments
  - Microdosimetry down to 1 nm for SEE and biological effects
  - Consideration of track structure and influence on above
  - Correlations of energy depositions in sensitive regions for MBU and detector response

Section 2

Tools Developed

Section 2

Space Specific Geant4 Modules



- **Sector Shielding Analysis Tool:** *1st-order shielding assessment*
- **MULASSIS:** *1D shielding tool using full Geant4 physics*
- **Geant4 μdose Tool:** *3D simulation of microdosimetry*
- **Radioactive decay:** *induced background*
- **General Particle Source :** *specification of arbitrary source*
- **CAD Front-End Tool:** *specification of geometry and materials for G4 STEP interface with CAD file*

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Section 2

Sector Shielding Analysis Tool

- Objective & application:
  - To determine the physical distribution of shielding around a user-defined point in the geometry using Geant4 particle tracking facilities
  - *1st assessment of shielding as a function of position*
- Functionality:
  - Uses "geantino" to determine pathlengths between material boundaries
  - Histogram of fraction of solid angle with shielding within a given interval as a function of shielding interval (+ Poisson errors)
  - 2D Histogram of mean shielding level (in g/cm^2, cm or radiation lengths) as a function of (θ,ϕ) (+standard deviation of shielding)
  - Output as a function of material and/or element type, as well as overall shielding (irrespective of material)

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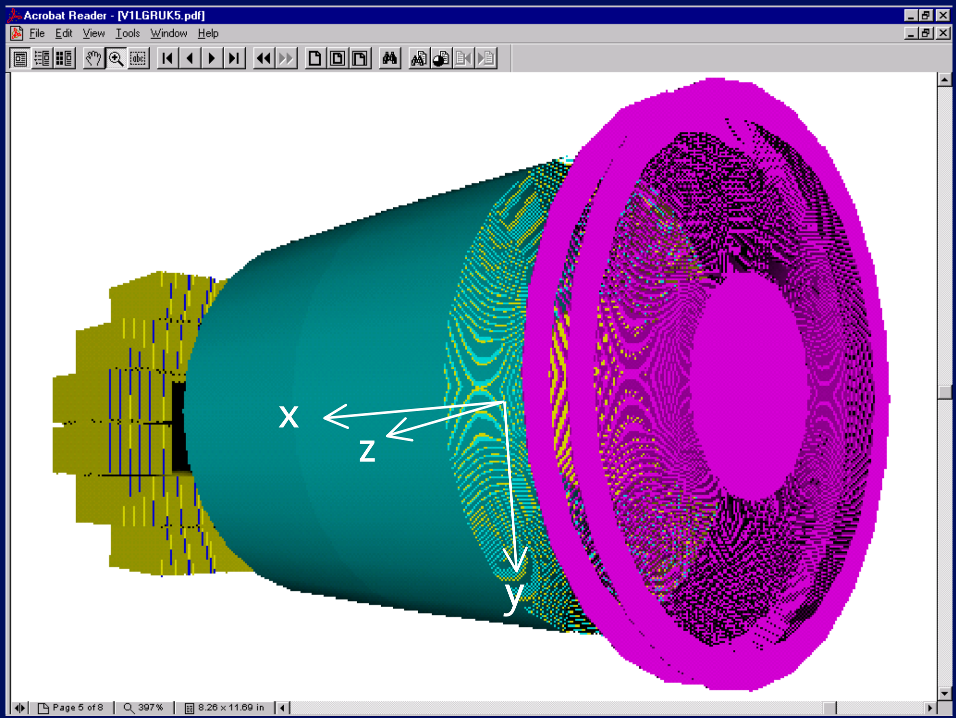
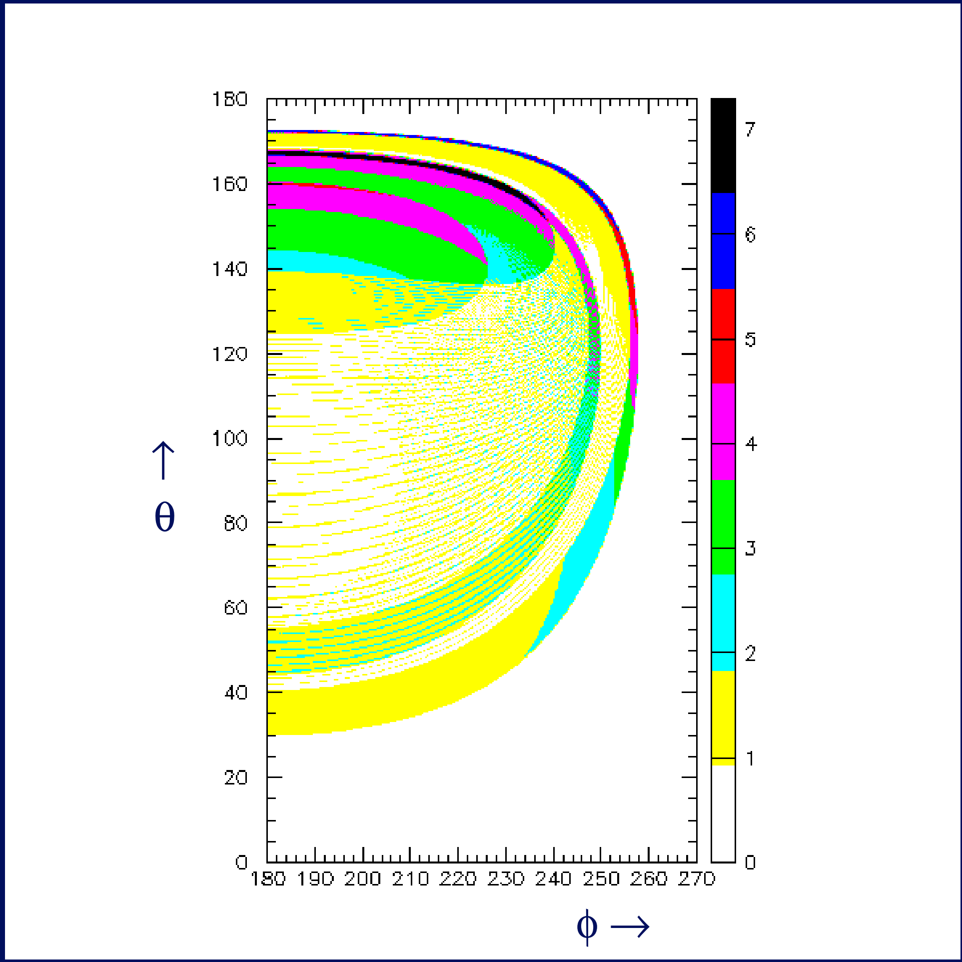
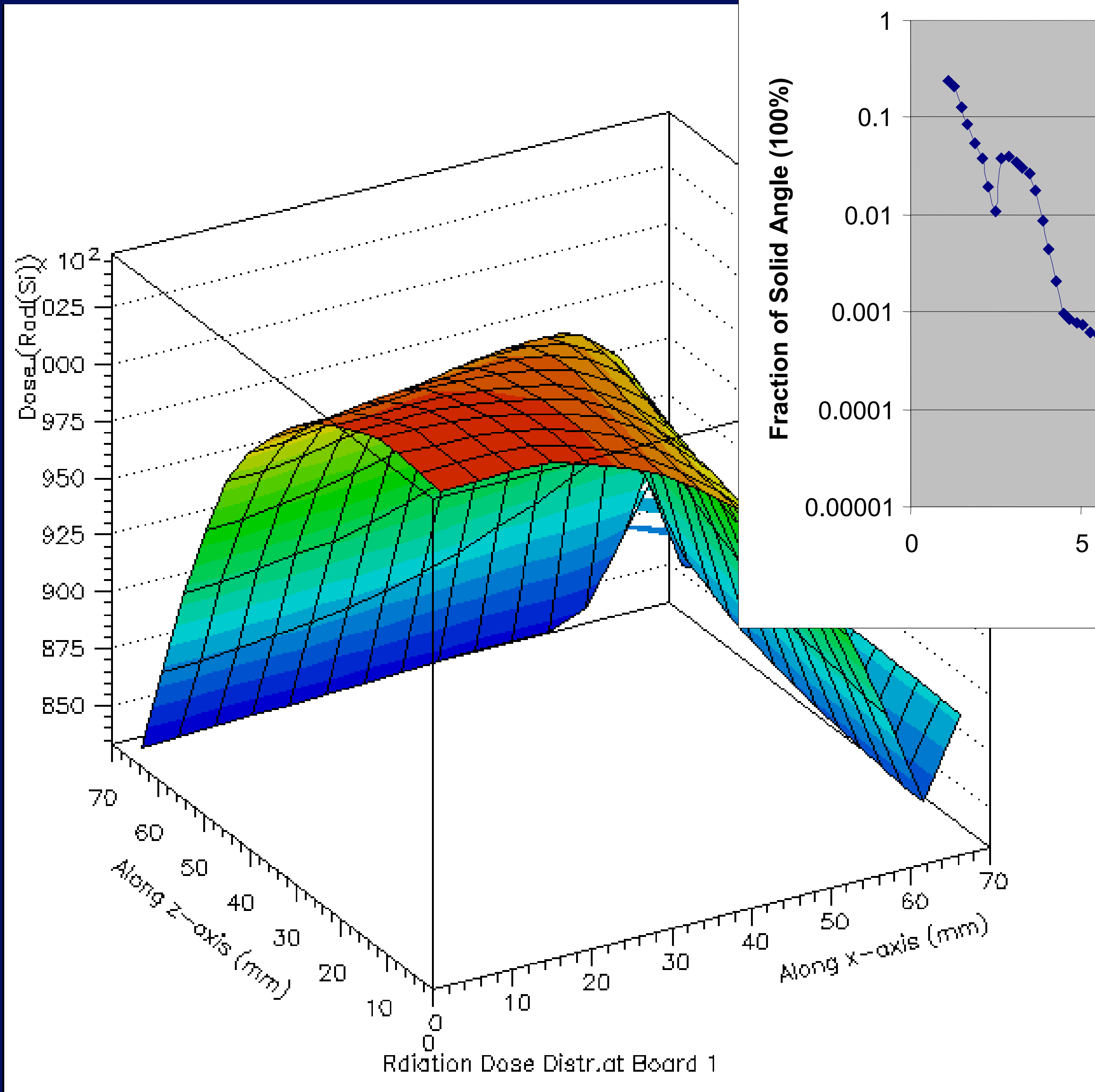
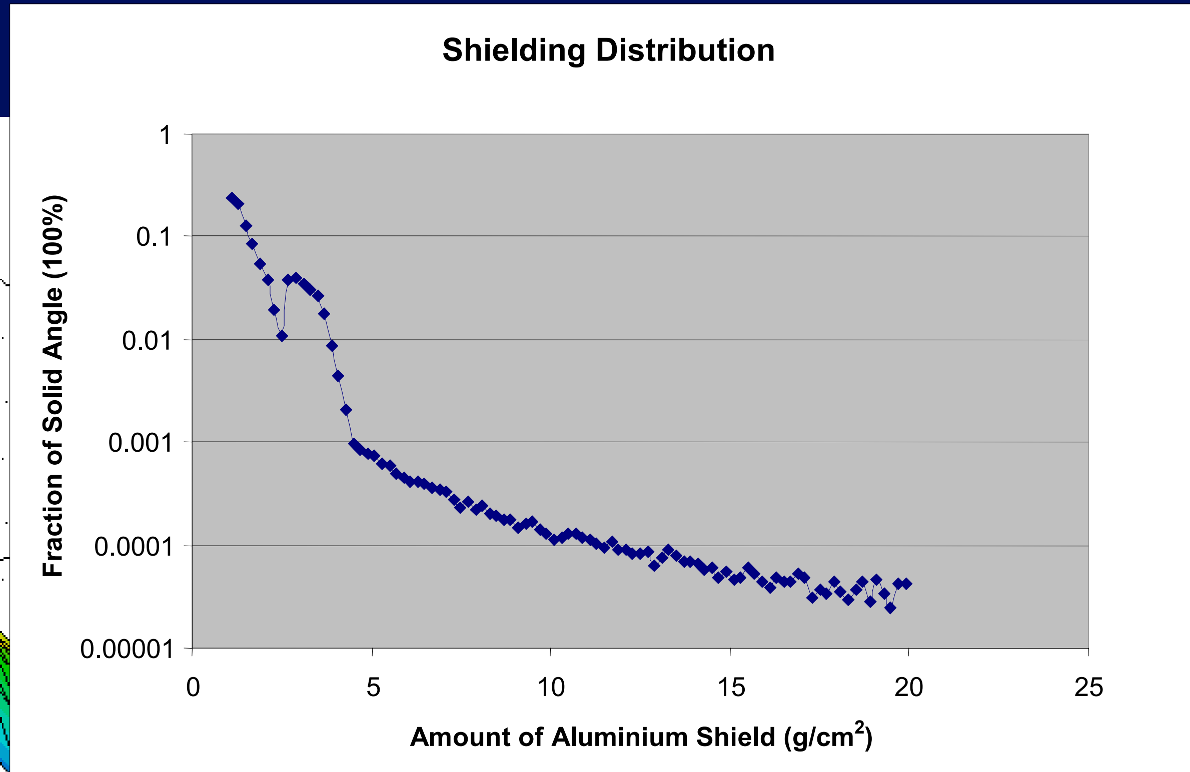
SSAT Analysis of XMM Baffle









Analysis of RF electronics subsystem

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Section 2

Multi-Layered Shielding Simulation S/W

- Objective & application:
  - 1D simulation of shielding effects (planar or spherical)
- Functionality:
  - Facilities to determine:
    - Fluence as a function of layer, particle type, energy and angle
    - Integrate existing NIEL coefficients over fluence
    - Energy deposition or dose calculation as a function of layer
    - Energy deposition spectra as a function of layer
  - Uses General Particle Source
  - Interactive operation with a local implementation of Geant4
  - Also can be operated over WWW under SPENVIS

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Section 2

General Particle Source

- Objective & application:
  - To permit definition of an arbitrary source distribution without coding
  - By default Geant4 only allows unidirectional, monoenergetic sources
  - *Definition of general source particle distributions*
- Functionality:
  - **Spatial** : point, area source (disc, ellipse, rectangle), or simple volume (sphere, cylinder, RPP)
  - **Angular** : unidirectional, isotropic, cosine-law, arbitrary
  - **Energy** : mono-energetic, linear, exponential, power-law, arbitrary spectrum
  - **Source particle biasing** : according to point of origin, first interaction, energy
- Status
  - Currently integrated into Geant4

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Section 2

General Particle Source

2D Surface sources	3D Surface sources	Volume sources	Angular distribution	Energy spectrum
• circle • ellipse • square • rectangle	• sphere • ellipsoid • cylinder • paralellapiped (incl. cube & cuboid)	• sphere • ellipsoid • cylinder • paralellapiped (incl. cube & cuboid)	• isotropic • cosine-law • user-defined (through histograms)	• mono-energetic • linear • exponential • power-law • bremsstrahlung • black-body • CR diffuse • user-defined (through histograms or point-wise data)

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Radiation models: Geometry definition for Multi-Layered Shielding Simulation - Microsoft Internet Explorer

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SPENVIS Project: SIGMUND

Radiation models

Multi-Layered Shielding Simulation: Geometry

Tables | Plots | Help

Mulassis allows the definition of a multi-layered, one-dimensional shield and incident particle source, and using the Geant4 toolkit simulates radiation transport through the geometry, treating electromagnetic and nuclear interactions.

Mulassis is a complex tool, so please consult the help page before using it. We would appreciate any feedback on the interface, please send your comments to B. Quaghebeur at B.Quaghebeur@oma.be.

Geometry: User defined

Shape: planar slab		Number of layers: 4	
Layer number	**Material** Edit	**Thickness (unit)**	**Visualisation colour**
Layer 1	Aluminium	1.5 cm	red
Layer 2	Tungsten	0.2 cm	dark grey
Layer 3	Aluminium	100 µm	red
Layer 4	Silicon	5.0 µm	white

include the particle tracks in the visualisation of the geometry in Encapsulated PostScript (EPS) format.

Reset | Next >>

Model developed by

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Done | Internet

Radiation models: Material definitions for Multi-Layered Shielding Simulation - Microsoft Internet Explorer

User defined materials			
Material id	**Name**	**Chemical formula**	**Density ($g\ cm^{-3}$)**
Material 1	Tungsten	W	1.930E+01

☐ Add predefined [Antimony ▾]

☐ Add new material:

Name: [bismuth germanate]

Chemical formula: [Be4-Ge3-O12]

Density: [7.13] ($g\ cm^{-3}$)

☐ Remove [Tungsten ▾]

[<< Back] [Reset] [Update]

Done | Internet

Radiation models: Source paricles for Multi-Layered Shielding Simulation - Microsoft Internet Explorer

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Radiation models

Multi-Layered Shielding Simulation: Source particles

Tables | Plots | Help

Source particle type and spectrum

Incident particle type:	proton
Number of primary particles to simulate:	10000
Incident energy spectrum:	trapped protons
Interpolation type:	linear
Angular distribution:	isotropic
Minimum angle:	0.0 degrees
Maximum angle:	90.0 degrees

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Radiation models: Physical models for Multi-Layered Shielding Simulation - Microsoft Internet Explorer

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Radiation models

Multi-Layered Shielding Simulation: Physical models

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Help

Physical models and material cut-offs

Simulation conditions: Hadron nuclear interactions

No low-energy neutrons

No lepton-gamma transport

Standard EM processes

Material/Particle cut-off lengths in: µm				
Material \ Particle	All	p^+	alpha	ion
All	1	1	1	1
Vacuum	1	1	1	1
Air	1	1	1	1
Aluminium	1	1	1	1
Silicon	1	1	1	1
Tungsten	0	1	1	1

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Internet

Application Scenario	Simulation conditions				Source									Models used											Particles										
	Hadron-nuclear interactions	Low-energy neutron	γ-$e^{\pm}$-$\mu^{\pm}$	LowE electromagnetics	Trapped protons	Solar protons and light ions	Cosmic ray protons	Mono-energetic protons	Reactor, fission, D-T, D-D neutron	Spallation neutron	Trapped electrons	Mono-energetic electrons	X-ray spectra	Parameterised "low-energy" hadron-nuclear	Precompound	Neutron_hp	Evaporation	Fermi break up	Fission	Photo-evaporation	Std EM interactions for hadrons/ions	Std EM interactions for leptons/photons	LowE EM interactions for hadrons/ions	LowE EM interactions for leptons/photons	Protons	Anti-protons	Neutrons	Anti-neutrons	K^+, K^-, K^0	π^+, π^-, π^0	Light ions	General ions/nuclei	γ, X-rays	e^+, e^-	μ^+, μ^-
1	✓				✓	✓	✓	✓	✓	✓				✓	✓		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓			
2	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓			
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4	✓	✓	✓		✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5	✓			✓	✓	✓	✓	✓	✓	✓				✓	✓		✓	✓	✓	✓			✓		✓	✓	✓	✓	✓	✓	✓	✓			
6	✓	✓		✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓			✓		✓	✓	✓	✓	✓	✓	✓	✓			
7	✓		✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
9			✓		✓	✓	✓	✓			✓	✓	✓									✓			✓	✓			✓	✓	✓	✓	✓	✓	✓
10			✓	✓	✓	✓	✓	✓			✓	✓	✓											✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
11					✓	✓	✓	✓													✓				✓	✓						✓			
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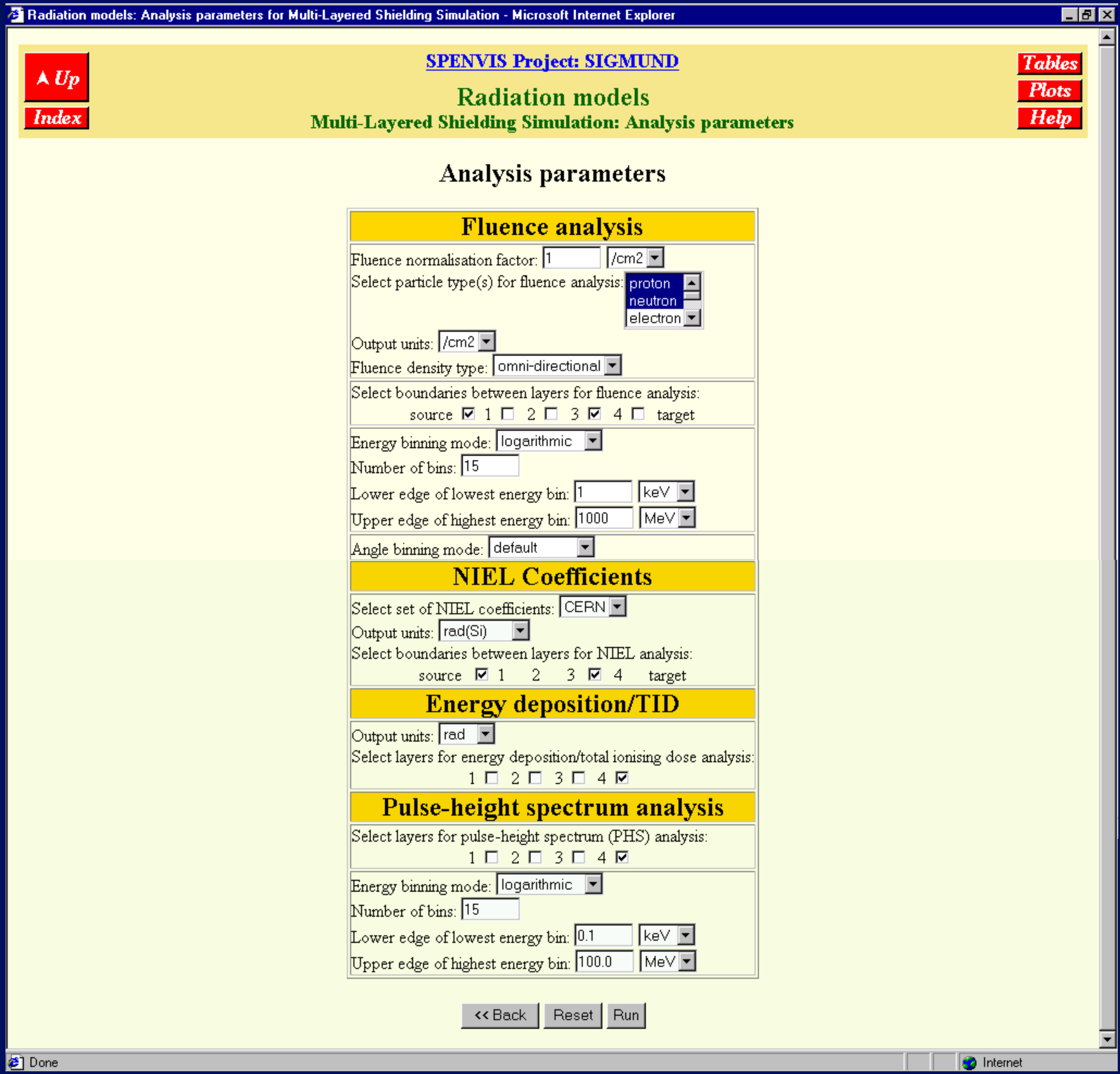
Radiation models: Analysis parameters for Multi-Layered Shielding Simulation - Microsoft Internet Explorer
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Radiation models
Multi-Layered Shielding Simulation: Analysis parameters
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Analysis parameters
Fluence analysis
Fluence normalisation factor: 1 /cm2
Select particle type(s) for fluence analysis: proton neutron electron
Output units: /cm2
Fluence density type: omni-directional
Select boundaries between layers for fluence analysis:
source (checked) 1 2 3 (checked) 4 target
Energy binning mode: logarithmic
Number of bins: 15
Lower edge of lowest energy bin: 1 keV
Upper edge of highest energy bin: 1000 MeV
Angle binning mode: default
NIEL Coefficients
Select set of NIEL coefficients: CERN
Output units: rad(Si)
Select boundaries between layers for NIEL analysis:
source (checked) 1 2 3 (checked) 4 target
Energy deposition/TID
Output units: rad
Select layers for energy deposition/total ionising dose analysis:
1 2 3 4 (checked)
Pulse-height spectrum analysis
Select layers for pulse-height spectrum (PHS) analysis:
1 2 3 4 (checked)
Energy binning mode: logarithmic
Number of bins: 15
Lower edge of lowest energy bin: 0.1 keV
Upper edge of highest energy bin: 100.0 MeV
<< Back
Reset
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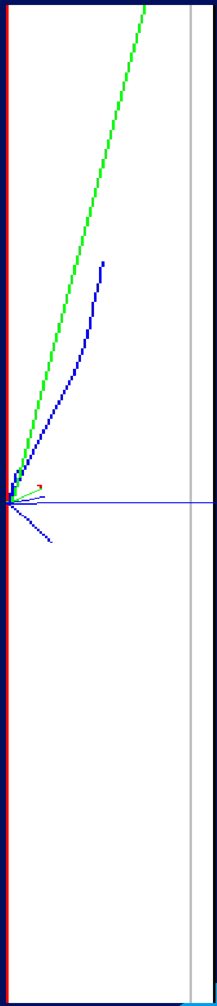
Done
Internet

```
# some comments
/geometry/layer/delete  0
/geometry/material/add Tungsten W    1.930E+01
/geometry/layer/shape slab
/geometry/layer/add  0 Aluminium   4    1.500E+00 cm
/geometry/layer/add  1 Tungsten   3    2.000E-01 cm
/geometry/layer/add  2 Aluminium   4    1.000E+02 mum
/geometry/layer/add  3 Silicon   1    5.000E+00 mum
/phys/scenario hadron-em-ln
/phys/cuts/material/setcut Tungsten              0.000E+00 mum
/analysis/normalise    1.000E+00 cm2
/analysis/fluence/particle/add proton
/analysis/fluence/particle/add neutron
/analysis/file spenvis
/analysis/fluence/unit cm2
/analysis/fluence/type OMNI
/analysis/fluence/add  1
/analysis/fluence/add  4
/analysis/fluence/energy/mode log
/analysis/fluence/energy/nbin  15
/analysis/fluence/energy/min    1.000E+00 keV
/analysis/fluence/energy/max    1.000E+03 MeV
/analysis/fluence/angle/default
/analysis/niel/add   1
/analysis/niel/add   4
/analysis/niel/function cern
/analysis/niel/unit rad
.........
```

SPENVIS generates a text macro file for Geant4/MULASSIS



Note actual aspect ratio of geometry is 100 and total number of particle histories followed is 100,000

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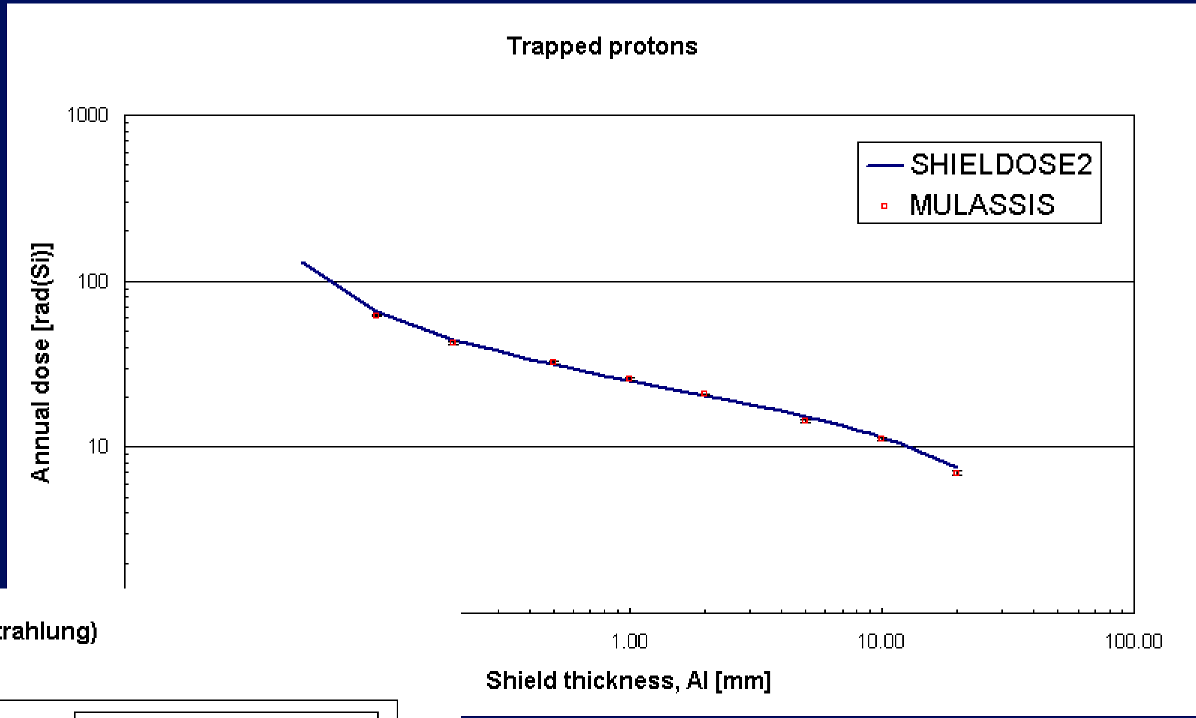
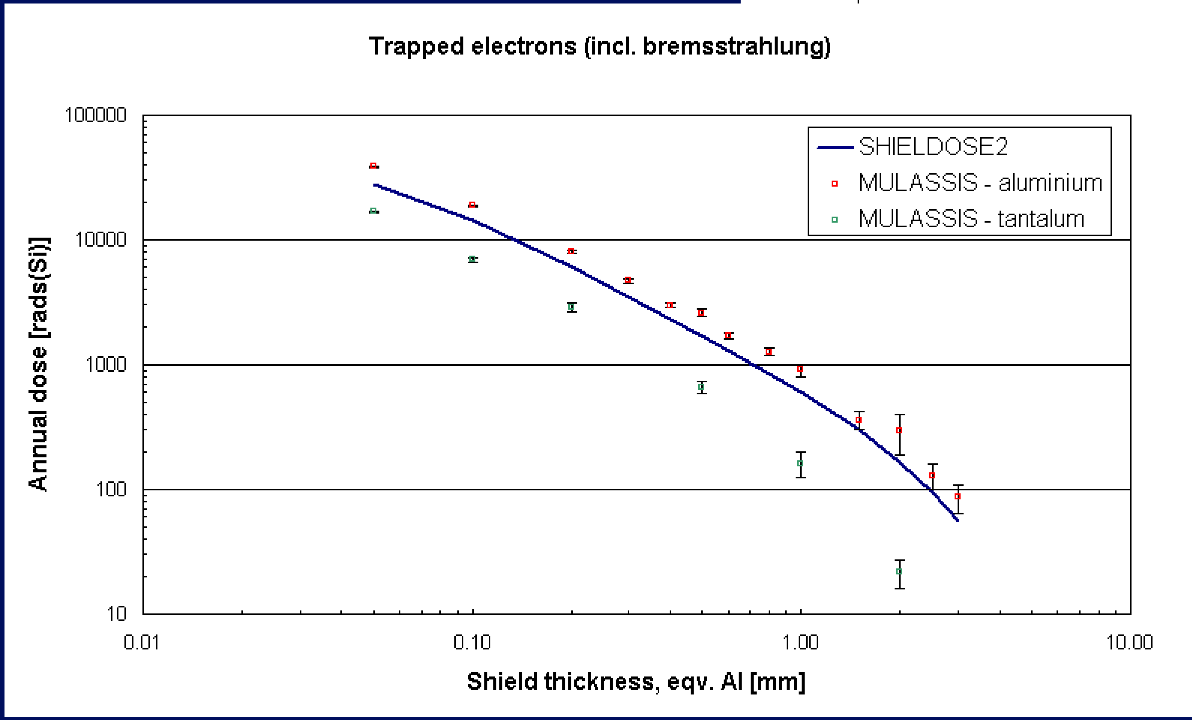
SHIELDOSE2 and MULASSIS results for 450km, 61.8° LEO





MULASSIS will predict shielding effects for any shield/device material, and perform better treatment of secondaries

Section 2

Geant4 Microdosimetry Tool (GEMAT)

- Objective & application:
  - 3D simulation of microdosimetry in parallelepiped and trapezoid geometries
- Functionality:
  - Facilities to determine:
    - Energy deposition spectra in depletion layer and funnel
    - Pathlength distribution function for complex micro-volumes may also be determined (for geantino particles)
    - Simultaneous energy deposition in different depletion regions (MBUs)
  - Uses General Particle Source
  - Intended for local and WWW operation (implemented under SPENVIS)
- Status
  - Interactive version implemented in prototype

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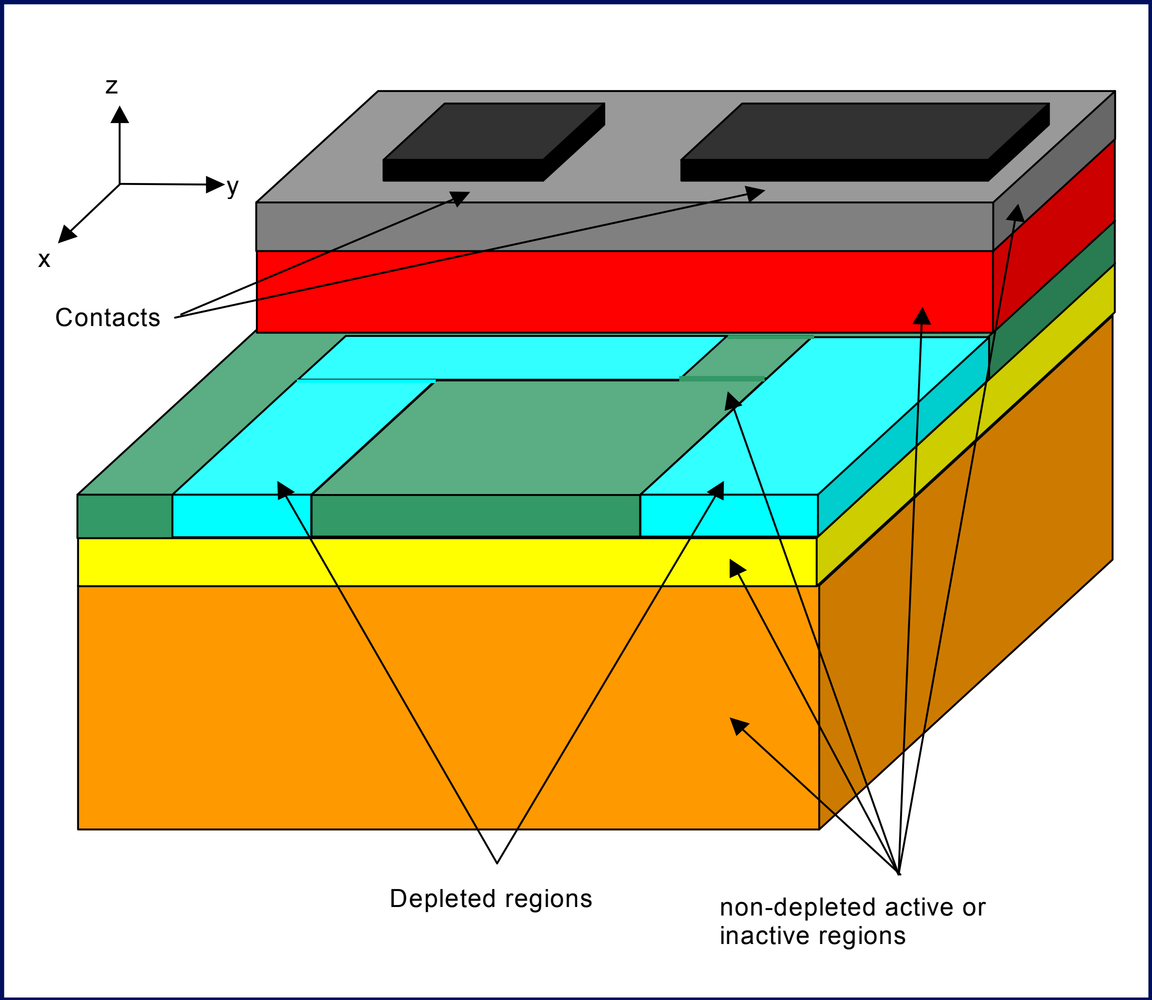
Section 2

Geant4 Microdosimetry Tool (GEMAT)



- Microdosimetry without restrictions to parallelepipeds
- Depleted regions can have “L” and “U” shapes with rectangular or trapezoidal cross-sections

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Section 3

Project SEPTIMESS

SEPTIMESS

Space Energetic Particle Transport and Interaction Modelling for ESA Science Studies

Geant4 Space User Forum, ESTEC/ESA

Fan Lei
Space Department, QinetiQ
20.01.2003

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Introduction

An ESA funded project (Contract No. 16339/02/NL/FM)

- ITT AO/1-3867/01/NL/FM " Energetic Particle Shielding and Interaction Software "
- QinetiQ as the prime contractor.
- Started at 01/09/02, and will last for 30 months.
- Five academic institutions, selected under a separated ESA ITT, are working in parallel, managed by QinetiQ.
- Activities will cover both Geant4 kernel developments and specific space applications

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Main Study Objectives:

- Review the potential energetic particle radiation effects on payloads of future ESA missions, science missions in particular.
- Identify radiation transport analysis requirements to quantify effects and thereby reduce risks for these missions.
- Develop Geant4 based applications for quantifying the specific radiation effects.

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Other Objectives:

- Support ESA and the European space science community through the provision of information and tools to quantify the risks to current and future missions from the natural radiation environment.
- Help expand the utilisation of Geant4 within the European space science community, and make Geant4 the preferred tool for space radiation effects analysis.
- To strengthen the collaboration between ESA and CERN, established in 1998, and between ESA and the Geant4 consortium.

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Major Activities:

- Review of radiation effects to future ESA science missions:
  - Radiation environment
  - Radiation as background noise and potential damage to the scientific instruments
  - Methods for quantifying such effects
- Investigating new requirements in Geant4 for space applications and identify areas for further developments
- Software developments in both Geant4 kernel and space applications.

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The List of Missions

- Mercury Orbiter
- Solar Orbiter
- INTEGRAL
- GAIA
- STEP
- LISA
- Eddington
- Darwin
- XEUS
- FIRST-Herschel
- Planck
- Rosetta
- NGST
- SMART-1
- Mars Express

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Geant4 Developments:

- Implementation Process Biasing
- Improvement of Geant4 CAD/STEP file interface
- Implementation of hadronic cross-section based simulation
- Improvement of Geant4 atomic relaxation process
- Development of Geant4 statistical testing system

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Possible Application Developments:

- Background study of the INTEGRAL mission
- Simulation of the proof-masses experiment on LISA
- Simulation of the proof-masses experiment on STEP
- Simulation of the MGS and MXS on BepiColumbo
- Simulation of the X-ray imaging spectrometer on SMART-1
- Analysis of low-energy electron and proton scattering in X-ray mirror shells, such as that of XEUS.

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Possible Application Developments (con.):

- Study of X-ray CCD background, such as XMM.
- Simulation of the SREM detector system via CAD/STEP interface.
- Cosmic ray trajectory tracing and rigidity cut-off calculation.
- Cosmic ray atmospheric penetration and secondary radiation production.

Parallel Activities:

- Four institutes selected from proposals to ESA AO/1-4051/01/NL/FM:
  - Imperial College (Prof. Tim Sumner)
  - University of Southampton (Prof. Tony Dean)
  - University of Geneva (Prof. Alain Blondel)
  - INFN(Genova)/CERN (Dr. Maria Grazia Pia, Dr. Andreas Pfeiffer)
- One from unsolicited proposals:
  - University of Bern (Prof. E. Fluckiger, Dr. L Desorgher)

Imperial College:

The transport of low-energy secondaries in experiments using proof-masses:

- Effects:
  - Charging
  - momentum transfer
  - thermal input
- Missions to be studied:
  - LISA
  - STEP

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University of Southampton:

- INTEGRAL Background Studies:
  - To develop a Geant4 based Mass Model
  - Understanding of the background noise in all detector systems
  - Induced radioactivity in the germanium detector
  - Solar Flare effects
- XEUS Radiation Studies:
  - Background sources and potential radiation damage
  - tools/methods to quantify the effects.

University of Geneva:

- Implementation of hadronic cross-sections in Geant4
  - To identify the shortcomings in Geant4, in studies of impact of hadronic showers on materials.
  - Compilation of c-s data: GSI,PSI, Los Alamos, former Soviet Union, and compare them with those collected in AMS and HARP
  - Code development in Geant4: projectile energy range of 0.1 to 10 GeV.
  - Validation and benchmarking.

INFN(Genova)/CERN:

- Design and development of a "standard" analysis toolkit/library based on the AIDA standard, to be used by all Geant4 applications within the SEPTIMESS project, including an example on its usage.
- Elicitation, specification and analysis of User Requirements for a general purpose tool for test and validation of Geant4 electromagnetic physics processes; object oriented analysis and design, development and testing.
- Refinement of Geant4 atomic relaxation package, including design iteration, implementation and test.

University of Bern:

Geant4 cosmic ray applications:

- Propagation of cosmic rays through the Earth's magnetosphere:
  - Dynamic internal and external magnetospheric magnetic field models (IGRF/DGRF + Tsyganenko).
  - Improved tracking algorithm in magnetic fields
- Propagation of cosmic rays through the Earth's atmosphere.

Section 4

Summary

Section 4

Summary

- Geant4 provides an environment to enable comprehensive simulation in 3D of radiation interaction processes from PeV to keV energies (and below for thermal neutrons, and EM processes)
- Several physics enhancements required for space as well as HEP have or are being addressed
- There is also a need to permit easy access to space radiation effects *engineering* tools based on detailed MC

Section 4
Summary

- SSAT, MULASSIS and GEMAT are a significant improvement over conventional engineering tools used in space radiation effects simulation
- The availability of MULASSIS over WWW increases general accessibility (user doesn’t have to download Geant4), although the interactive version is available if required for user-dedicated application
- There is now an ongoing programme (SEPTIMESS) to help develop applications for Geant4 in space science missions

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