Geant4 Radiation Analysis for Space

GRAS

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Outline

- Motivation
- Description of the tool structure and functionalities
- GRAS as
  - framework for Monte Carlo analyses
  - Monte Carlo engine for external packages (e.g. SPENVIS)
- Present status, expectations, conclusions

Simulations of the Space Radiation Environment

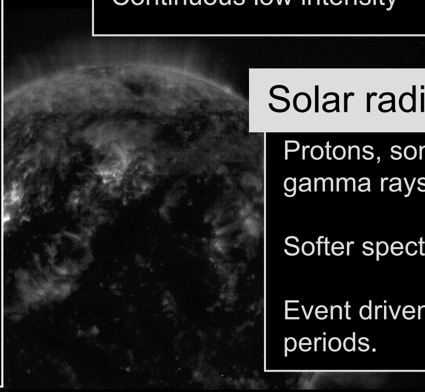
Sources

(Extra) Galactic and anomalous Cosmic Rays

Protons and Ions

$\langle E \rangle \sim 1$ GeV, $E_{max} > 10^{21}$ eV

Continuous low intensity



Solar radiation

Protons, some ions, electrons, neutrons, gamma rays, X-rays…

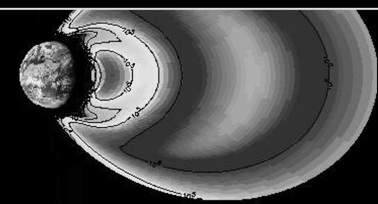
Softer spectrum

Event driven – occasional high fluxes over short periods.

Trapped radiation

Electrons ~< 10 MeV

Protons ~< 10^2 MeV



Goals

Mission design

Ground tests

Extrapolation to real life in space

Cheaper than accelerator tests

Science analyses

Particle signal extraction

Background

Degradation

Environment models

Simulation of the emission and the propagation of radiation in space

Effects

Effects in components

Single Event Effects

(SE Upset, SE Latchup, …)

Degradation

(Ionisation, displacement,…)

Effects to science detectors

Background

(Spurious signals, Detector overload,…)

Charging

(internal, interferences, …)

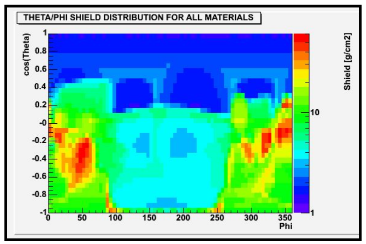
Threats to life

Dose (dose equivalent) and dose rate in manned space flights

Radiobiological effects

Commonly used Ready to Use **Simulation Tools**

3D



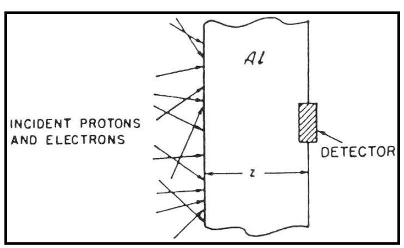
Ray-Tracing

Look-Up Table

(e.g. ESABASE, SSAT)

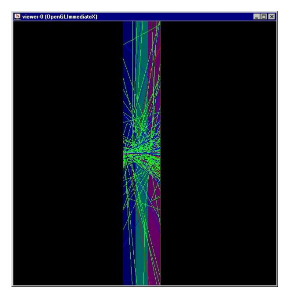
Good physics 3D

1D



CSDA appr.

(e.g. SHIELDOSE-2)



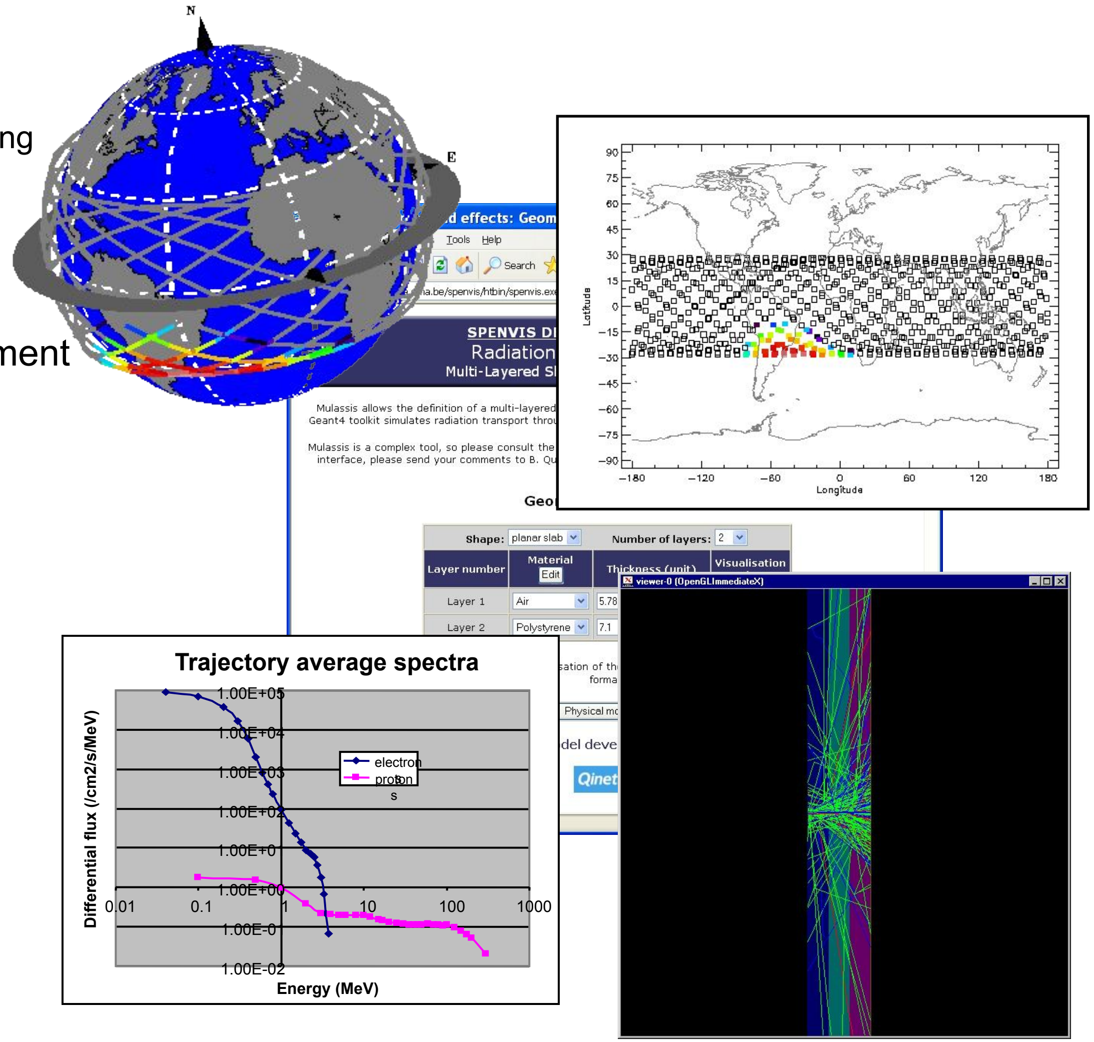
Good Physics

(e.g. MULASSIS)

Physics

The example of MULASSIS

- Geant4-based tool
  - Geant4 is a “Toolkit”
  - Flexible, powerful, extendable,…
  - But intentionally “not a tool” ready for use
- MULASSIS Features
  - 1D Layered geometry via scripting
  - Geant4-based
  - Predefined physics lists
  - Materials by chemical formula
- Interfaced to the Space Environment spectra inside the Web-based SPENVIS framework
  - User success
- Raised the level of radiation shielding analysis in the space community
- Limitations
  - 1D geometry
  - Extensibility



GRAS
Geant4 Radiation Analysis for Space

Geometry
GDML,
C++,
CAD (on-going)

Physics
EM,
Hadronics,
Ions

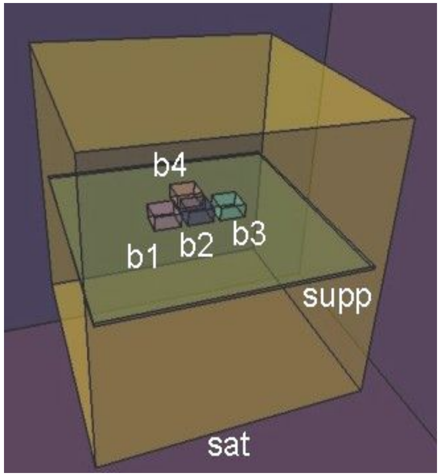
Radiation environment
SPENVIS,
CREME96

- Analysis types
  - 3D
  - Dose, Fluence, NIEL, activation… for support to engineering and scientific design
  - Dose Equivalent, Equivalent Dose,… for ESA exploration initiative
  - SEE: PHS, LET, SEU models
- Analysis independent from geometry input format
  - GDML, CAD, or existing C++ class, …
- Pluggable physics lists
- Different analyses without re-compilation
- Modular / extendable design
  - Publicly accessible

Histogramming
AIDA,
ROOT,
CSV

GRAS components

1



Geometry

- GDML (Geometry Description Markup Language)
  - ASCII file, looks similar to HTML
  - Adopted as exchange format by SPENVIS
- C++ model
- Future CAD interface

```
/gras/geometry/type gdml
/gdml/file geometry/see1.gdml
```

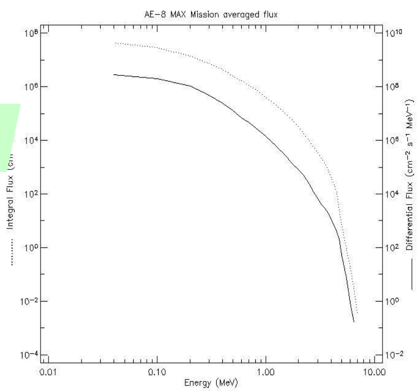
```
<materials>
  <material name="SiO2"> <D value="2.200"/> ...
...
<solids>
  <box name="solid_World" x="50.0" y="50.0" z="50.0"/>
...
<volume name="World">
  <materialref ref="Vacuum"/>
  <solidref ref="solid_World"/>
  <physvol> <volumeref ref="satellite"/> <positionrefref="center"/> ...
...
```

GRAS components

2

Source

RADIATION ENVIRONMENT




```
/gps/pos/type Surface
/gps/pos/shape Sphere
...
/gps/ang/type cos
/gps/particle e-

/gps/ene/type Arb
/gps/hist/type arb
/gps/hist/point    4.000E-02   2.245E+08
...
/gps/hist/point    7.000E+00   0.000E+00
/gps/hist/inter Lin
```

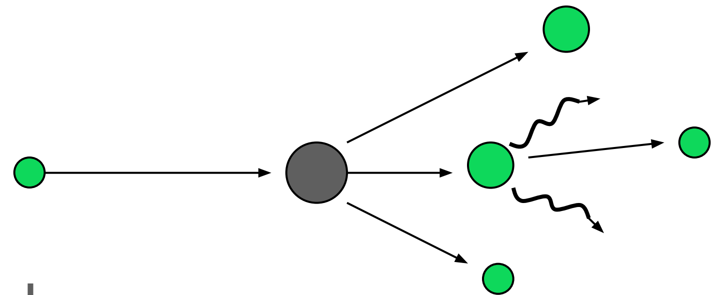
- G4 General Particle Source

GRAS components

3

Physics

All the Geant4 physics models are available through script commands



```
/gras/phys/addPhysics standard
/gras/phys/addPhysics binary
/gras/phys/addPhysics binary_ion
/gras/phys/addPhysics gamma_nuc
/gras/phys/addPhysics lowe_neutron


/gras/phys/setCuts 0.1 mm
/gras/phys/region/setRegionCut detectorRegion default 0.01
mm
/gras/phys/stepMax 1.0 mm
/gras/phys/regionStepMax detectorRegion 0.01 mm
```

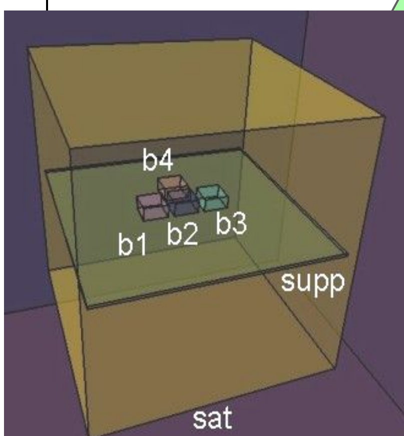
User can use a private C++ Physics List

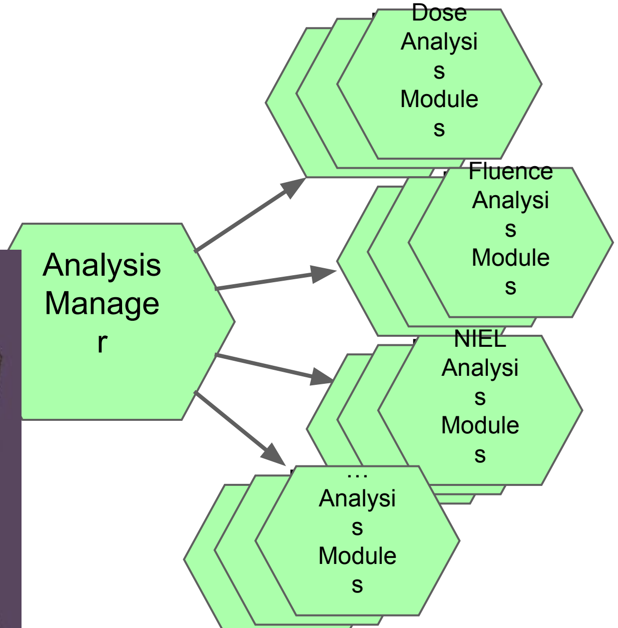
GRAS components

4

Analysis

RADIATION EFFECTS





- At present:
  - Dose
  - Fluence
  - NIEL
  - Deposited charge
  - Dose equivalent
  - Equivalent dose
  - Path length
  - SEE
  - Pulse Spectrum
  - Charge deposit
  - Source monitoring

Component degradation, background

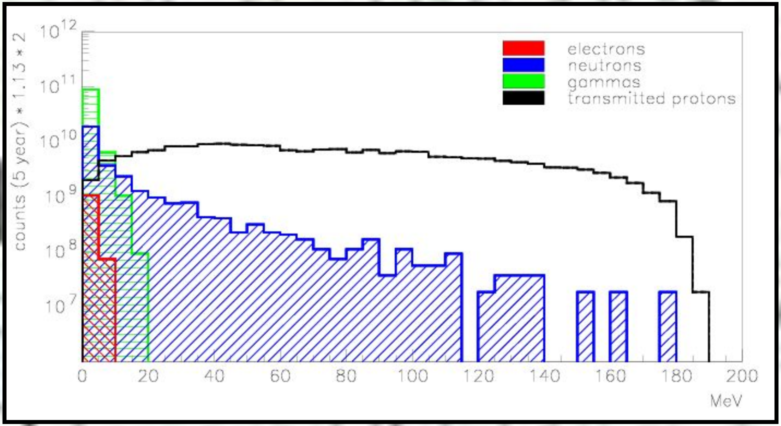
Human exploration initiatives

Components SEE

```
/gras/analysis/dose/addModule doseB12
/gras/analysis/dose/doseB12/addVolumeID b1
/gras/analysis/dose/doseB12/addVolumeID b2
/gras/analysis/dose/doseB12/setUnit MeV
```

- Analysis independent from geometry input mode
  - GDML, or existing C++ class, …
  - Open to future geometry interfaces (CAD,…)

GRAS Analysis modules: Component degradation, Background



- Total Ionizing Dose
  - Also per **incoming particle type**, with user choice of interface
  - Gives event **Pulse Height** Spectrum
    - For analysis of induced signal
  - Units:
    - MeV, rad, Gy

- FLUENCE
  - Particle type, energy, direction, time
  - One/Both ways

- NIEL
  - MULASSIS implementation
  - Modular approach
  - Several curve sets available
    - CERN/ROSE (p, e-, n, pi)
    - SPENVIS/JPL (p)
    - Messenger Si (p, e-)
    - Messenger GaAs (p, e-)
  - Units:
    - 95MeVmb, MeVcm2/g MeVcm2/mg, keVcm2/g

GRAS Analysis modules:
Human Exploration Initiatives

- New user requirements include:
  - planetary models (e.g. scaling of SPE fluence to other planets, magnetic field description, crustal maps)
  - ion physics (electromagnetics / hadronics for HZE)
  - biological effects (macroscopic / microscopic models)

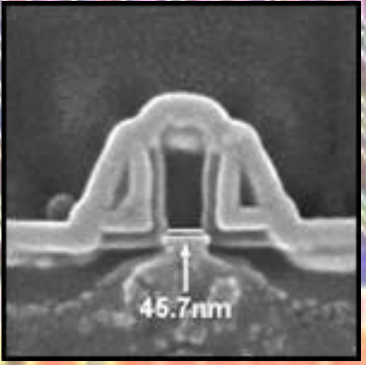
GRAS Biological effects modules

- **Dose equivalent**
  - ICRP-60 and ICRP-92 LET-based coefficients
  - Units:
  - MeV, Sv, mSv, Gy, rad
- **Equivalent Dose**
  - ICRP-60 weights
  - User choice of weight interface
  - Units:
  - MeV, Sv, mSv, Gy, rad

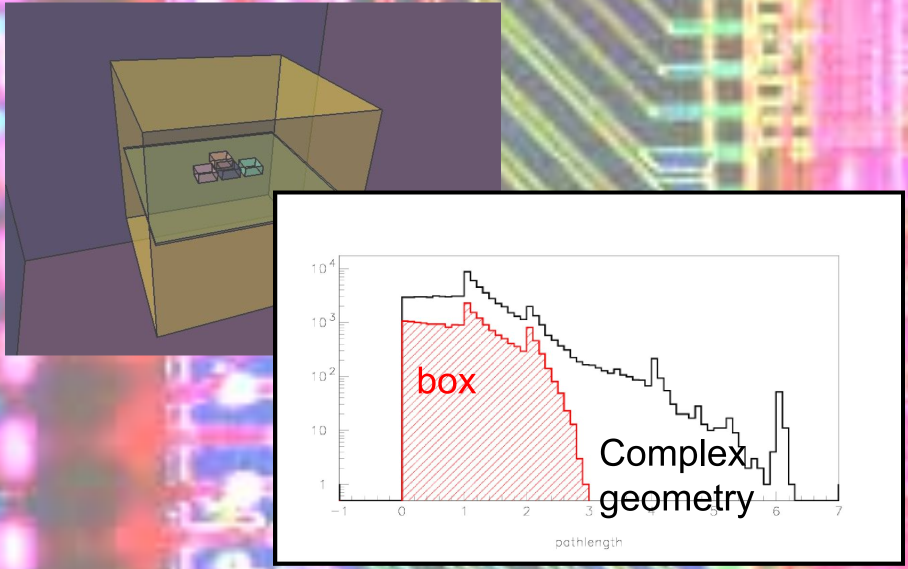
GRAS Analysis modules:

SEE in microelectronics

- Path length analysis
  - Event distribution of particle path length in a given set of volumes
  - If used with “geantinos”, it provides the geometrical contribution to the energy deposition pattern change
    - In a 3D model
    - W.r.t. a 1D planar irradiation model



Courtesy Sony/Toshiba

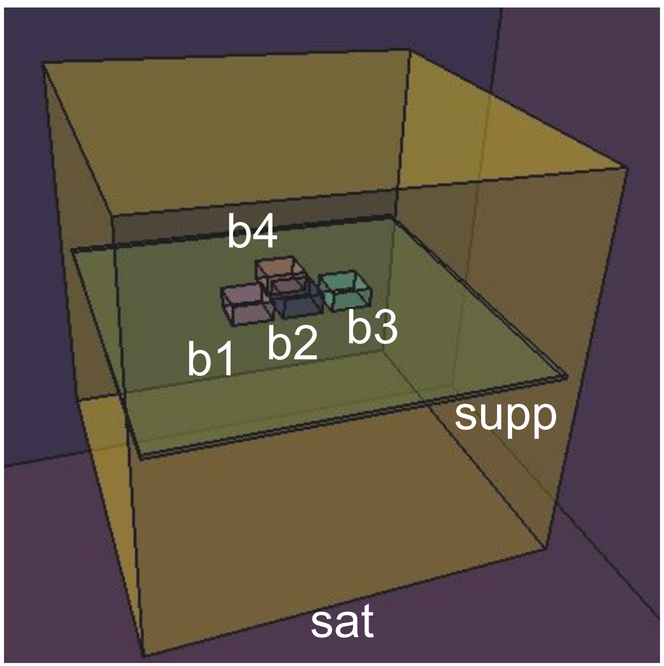


- SEE models
  - Threshold simple model implemented
  - Design open to more complex modeling
  - Coupling to TCAD will give device behavior
  - CAD import (on-going) will ease geometry modeling

Flexibility

- Volume
  - To identify a volume in the geometry tree
  - At present implemented as the couple (name, copy No)
- Volume Interface
  - To identify the boundary between two volumes
  - Couple of Volumes

- Each module can have
  - several Volumes and
  - several Volume Interfaces
- Different actions taken by various module types when "in volume" / "at interface"
- Result output units
  - User choice, module type dependent




```
/gras/analysis/dose/addModule doseB12
/gras/analysis/dose/doseB12/addVolumeID b1
/gras/analysis/dose/doseB12/addVolumeID b2
/gras/analysis/dose/doseB12/setUnit MeV
```

- Example:

  dose module "DoseB12"
  - Sensitive volumes:
    - b1 and b2
  - Interface (to tag particle type):
    - between (sat, world)
    - To detect secondaries created in the satellite structure

GRAS
Building blocks

- 1. Geometry
- 2. Primary generation
- 3. Physics
- 4. Modular analysis set via macros

+

Utility classes: UI for many useful tasks

- Regions
  - Create new region
  - Assign a volume to a region
- Cuts by region
  - Scripting examples
- Visualisation
  - Geometry vis. options
  - Colour definition
  - Volume colour / visibility / vis.options
- …

Output

- Interface to AIDA tools
  - Histograms, tuples
- ASCII output always available

Scripting

- All GRAS features are available via UI:
  - text macro files or
  - Interactive UI commands

Not satisfied…

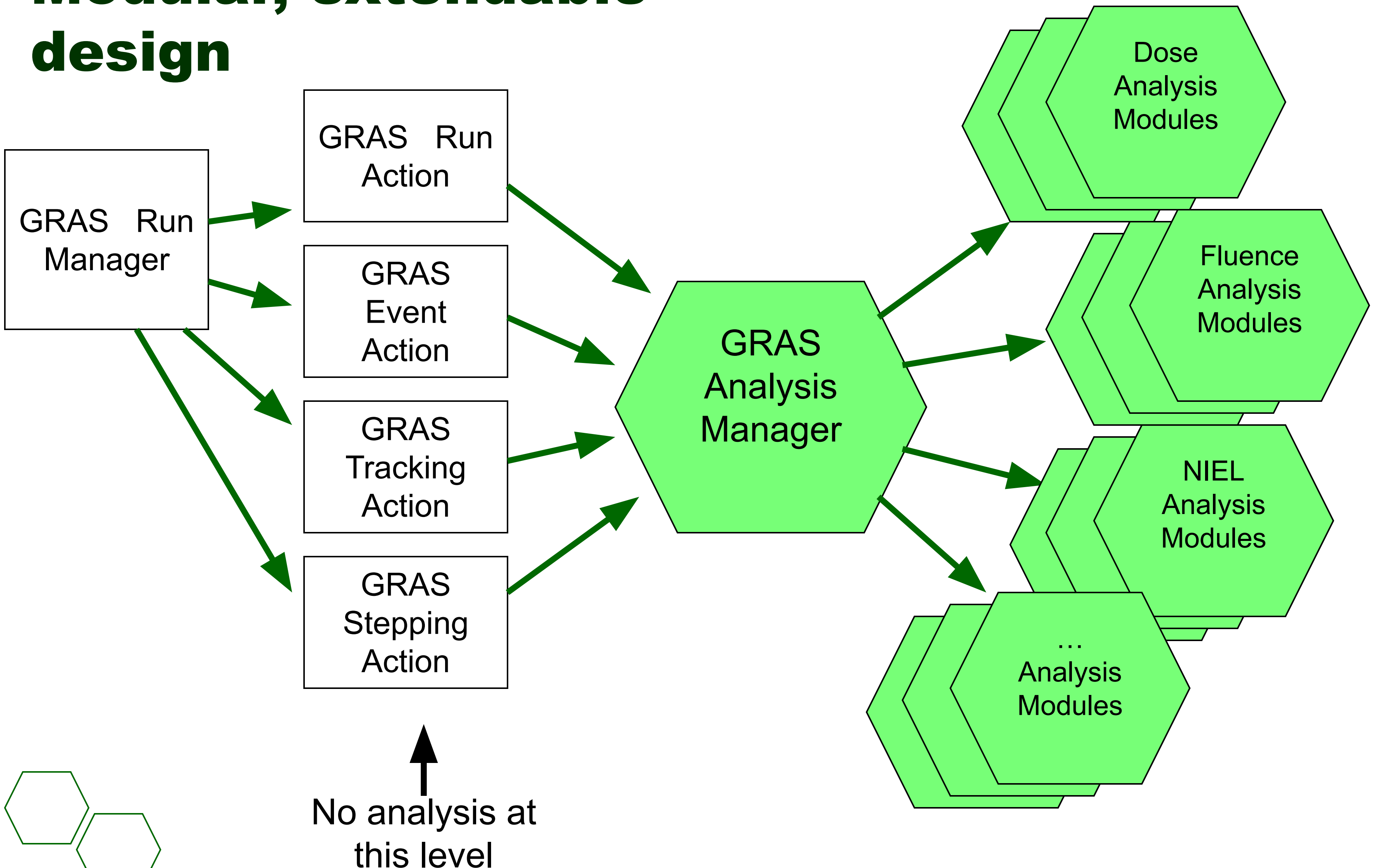
Satisfied

- MC analysis with no C++ coding
  - Geometry via GDML
  - Physics, Source, Analysis via scripts
  - Upgrades of models / interfaces

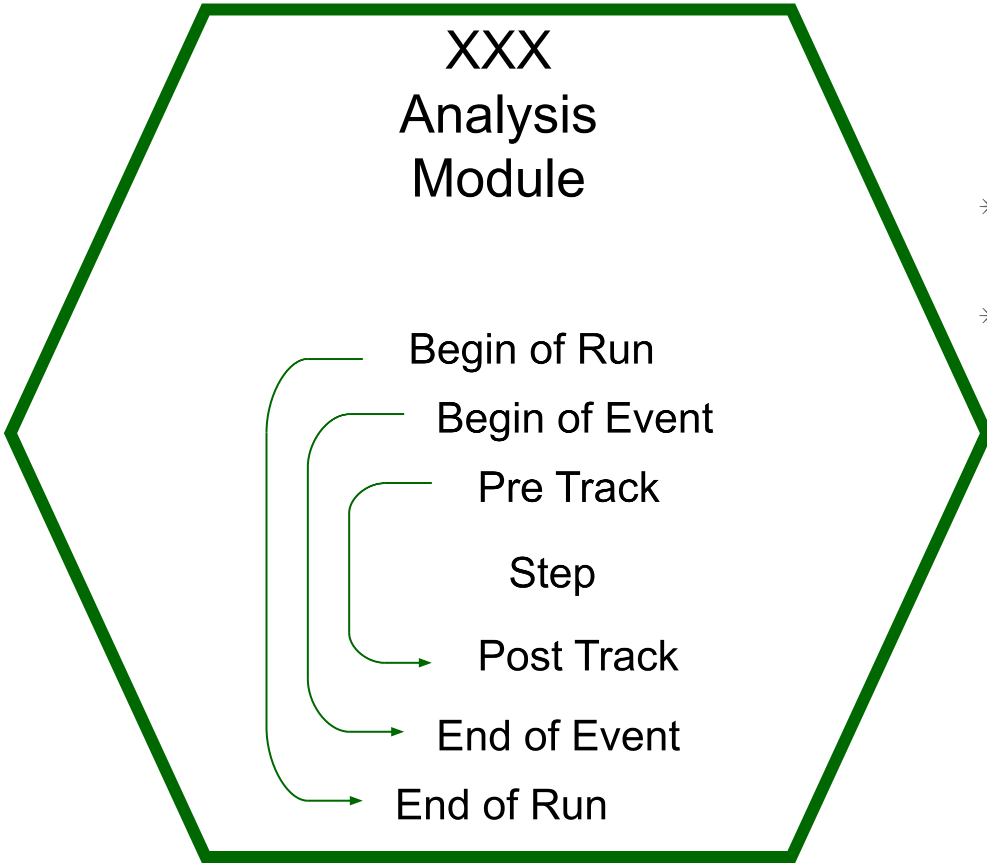
Not satisfied…

- Extend the tool
  - New analysis module
  - New interface
    (to geometry / post-processing)
  - …
- Open to collaborative development
  - http://geant4.esa.int

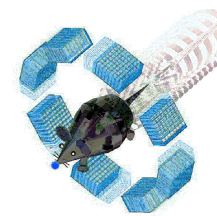
Modular, extendable design



Analysis Module



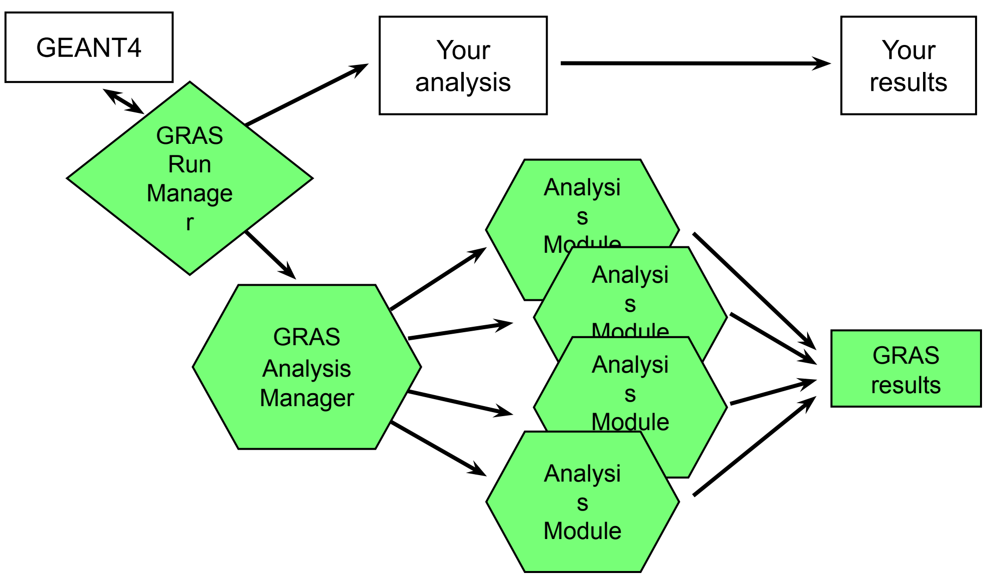
- Easy to implement:
  Self contained analysis element
  - Initialization, event processing, normalization, printout all inside
- Only one class to create/derive in case a new type of analysis is needed
  - No need to modify Run+Event+Tracking+Stepping actions
- AIDA histogramming “per module”
- G4 UI commands “per module”
  - Automatic module UI tree
  - *a la GATE*

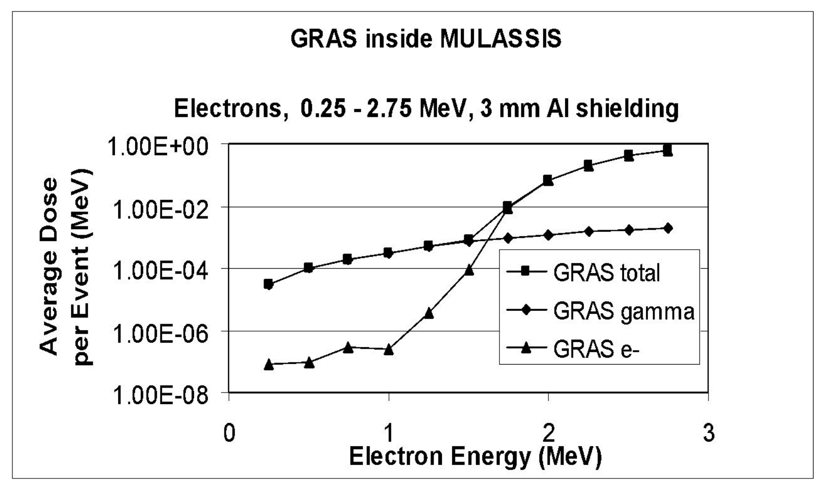


```
/gras/analysis/dose/addModule doseCrystal
/gras/analysis/dose/doseCrystal/setUnit MeV
```

GRAS and previous work

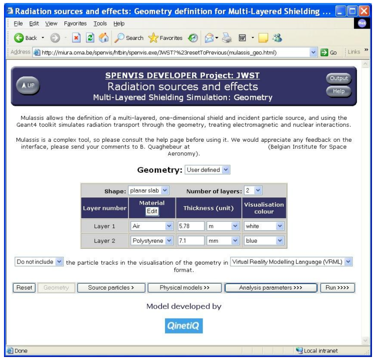
- 2 ways of obtaining GRAS output without discarding hours/days/months of work
  - A. Inserting C++ Geometry, Physics and/or Primary Generator classes inside GRAS
    - In the main gras.cc
  - B. Inserting GRAS into your existing applications
- Which way is the fastest depends on existing work



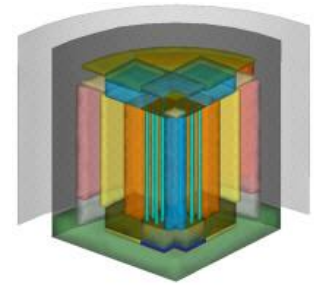


Ronnie Lindberg (ESA). See talk this session

Engineering tools:
GRAS as flexible Monte Carlo engine



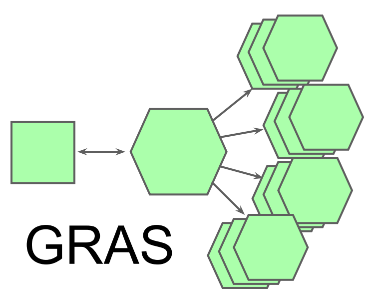
Tool GUI



Geometry modeling

Script instructions:
- Physics
- Radiation Environment
- Analysis type

Geometry exchange format
- GDML
- CAD / STEP
- …



User Requirements

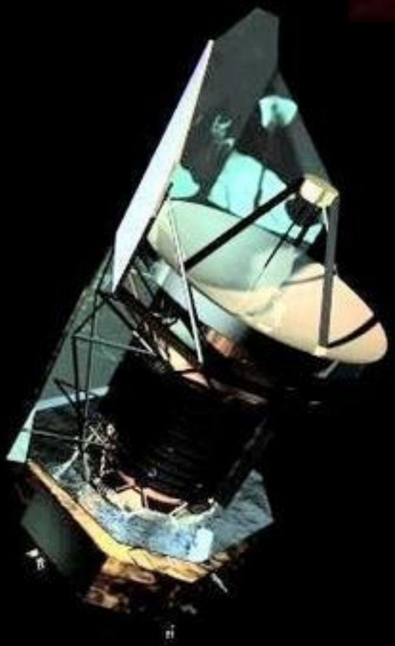
- Complete tool (Geometry, Physics, Source, Analysis) ✓
- Available as standalone executable
  - No need to download and compile Geant4 ✗
- Easy to integrate in existing applications ✓

- Analysis types
  - 3D ✓
  - Dose, Fluence, NIEL, activation… for support to engineering and scientific design ✓
  - Dose Equivalent, Equivalent Dose,… for ESA exploration initiative ✓
  - Transients: PHS, LET, SEU models ✓✗
- Analysis independent from geometry input mode
  - GDML, or existing C++ class, … ✓
- Different analyses set without re-compilation ✓
- Modular / extendable design ✓

- Source and Physics description adequate to space applications
  - Solar events ✓
  - Cosmic rays ✓✗

GRAS is being used for

- Herschel
  - Test beam detector study
  - Radiation effects to photoconductors and bolometers
- JWST
  - Dose
  - Background
- ConeXpress
  - See talk by Ronnie Lindberg
- Electronic components
  - Rad-hardness, local shielding, etc.

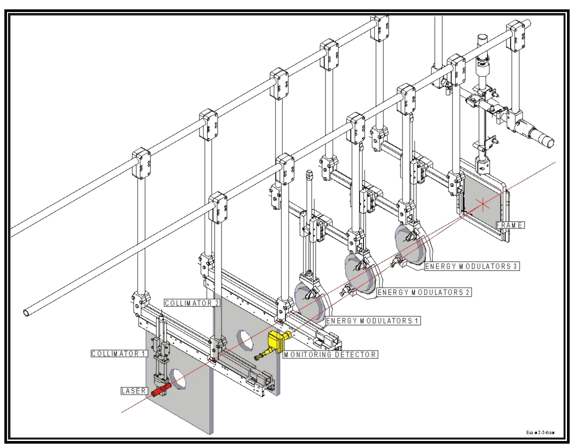


GRAS for HERSCHEL

- Herschel PACS Photoconductor instrument
  - Study and test of the detector to assess glitch rate
  - Impact on science objectives

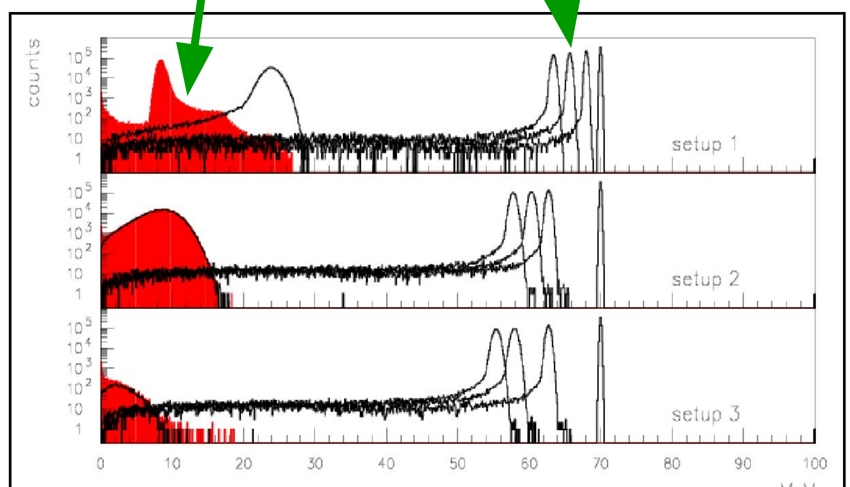
- Simulation of the proton irradiation at Leuven, Belgium

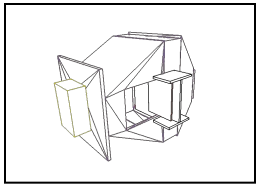
- Comparison with glitch data on-going
  - Need precise description of energy degraders and beam parameters
  - Extrapolation to detector behavior in space



GRAS Pulse Spectrum

GRAS Fluence

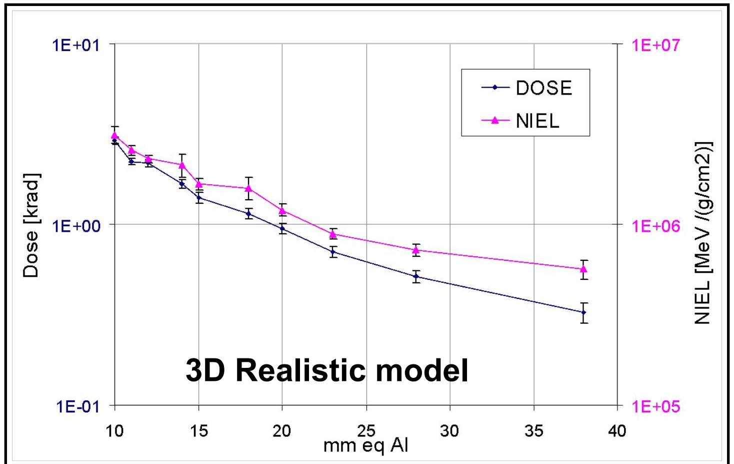




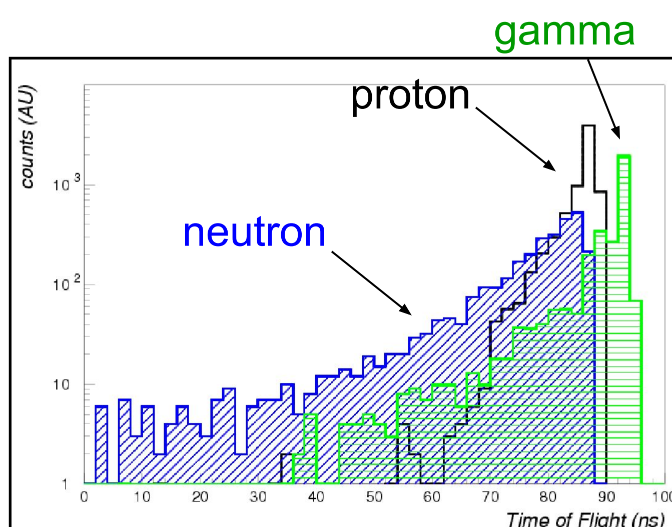
GRAS for JWST NIRSpec
Degradation

- Instrument design phase
  - Radiation shielding, material choice

Total Ionizing Dose		
Tool, Model	*Dose [krad] (11 mm eq. Al)*	*Dose [krad] (18 mm eq. Al)*
SHIELDOSE-2, Spherical Shell,	3.9	1.9
GRAS, Spherical shell	3.5 +/- 0.2	2.3 +/- 0.2
GRAS, Realistic model	2.2 +/- 0.1	1.1 +/- 0.1



- Secondary neutron production experiment
  - Beam test at PSI, Switzerland
  - GRAS simulation of the set-up
  - **Time of Flight (TOF)** based neutron spectrum

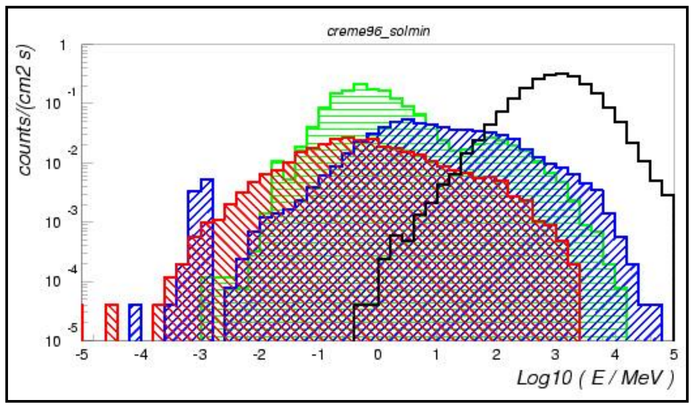


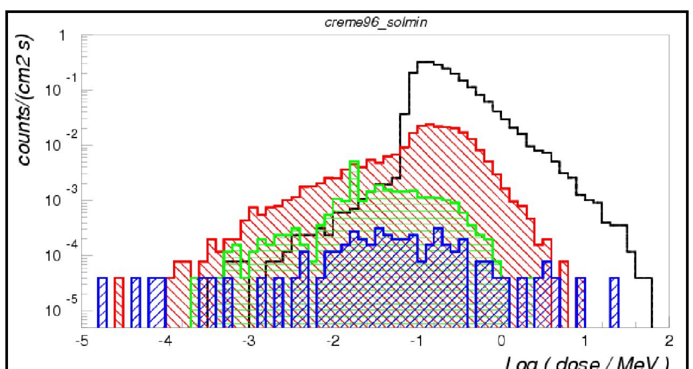
GRAS for JWST NIRSpec
Background

- Secondary particle production
  - Shielding effect on the particle flux on the detector

- Cosmic Ray background
  - CRÈME'96 Solar Minimum
  - Proton simulations

Results

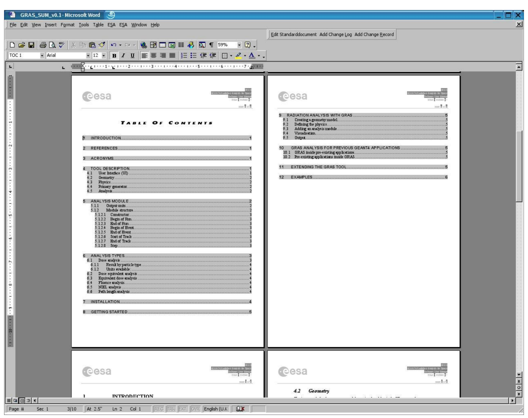




- Fluxes onto the detector
- Protons, Gammas, electrons neutrons
- Deposited energy
- per particle type

Status

- CVS repository online
  - http://geant4.esa.int
- Code
  - Latest stable tag works with
    - Geant4 7.1
    - GDML 2.3
- Documentation
  - Introduction
    - README file
  - Installation
    - INSTALL file
  - Detailed User Manual
    - In preparation



Perspectives

- New analysis types
  - Activation, LET/SEE
  - On-going collaboration with QinetiQ / REAT_MS contract
  - Open to new collaborations
- Minor improvements
  - Automatic normalization to real flux in space
- Interface to future G4 upgrades
  - Dose tallying in parallel geometry
- Geometrical biasing
  - To improve speed for local energy deposition
  - Analysis algorithms are ready for biasing
- Web Interface inside SPENVIS
  - Internal geometry, GDML exchange format

Conclusions

- Modular, script driven analysis package
  - Space users oriented, but trying to be generic
  - Already used in the support of a number of space missions and ground beam tests
- GRAS as
  - Ready-to-use Geant4 tool for common analysis types
  - Framework for Monte Carlo analyses
  - Monte Carlo engine for external packages
- GRAS used as framework for on-going ESA contracts
  - REAT_MS (QinetiQ), Geant4 usability for space applications
    (CAD interface, SEE analysis, Physics lists for space applications)
- Open to comments / contributions for collaborative development
  - http://geant4.esa.int
- We believe GRAS is significantly improving the Geant4 usability
  - Some features could be used directly by the Geant4 kernel
- Related talk
  - Ronnie Lindberg (ESA) with extensive validation and dosimetry / physics investigations