Update Report on Geant4 Radiation Analysis for Space (GRAS), and its Applications

Dr. Fan Lei

High Performance Monte-Carlo Radiation Simulations Workshop

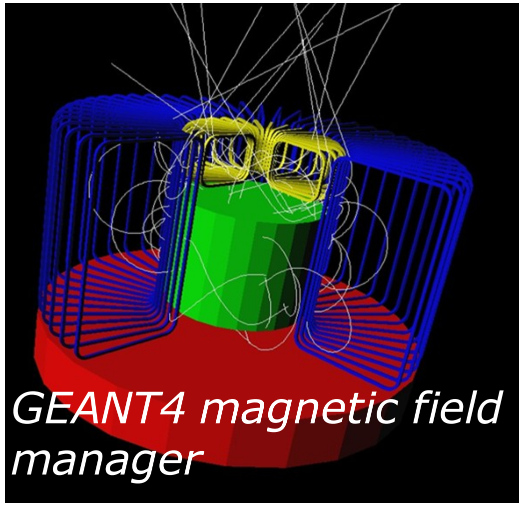
Sykia, Greece, 03/2026

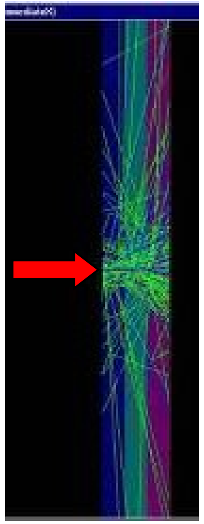
Thanks to Marco Vuolo for permission to use slides from his G4SUWS talk

Geant4 Radiation Analysis for Space (GRAS)

Ready-To-Use tool
Multi-mission approach
Quick assessments
- Ray-tracing ↔ MC
- 1D ↔ 3D
- EM ↔ Hadronics
- LET ↔ SV details

- Modular progress
- Open to collaborations and contributions
- Currently GRAS v6.0
- Available through the ESA Space Software Repository: https://essr.esa.int/

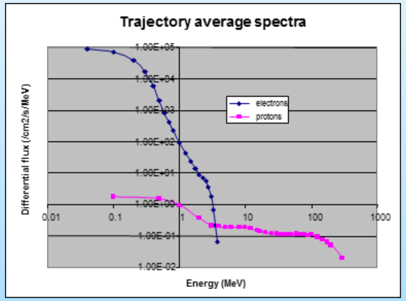




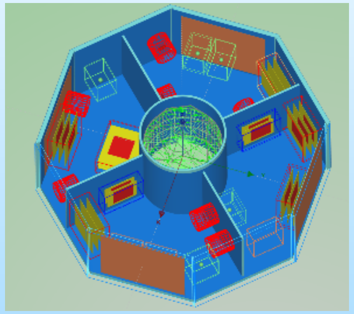
2294 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 52, NO. 6, DECEMBER 2005

GRAS: A General-Purpose 3-D Modular Simulation Tool for Space Environment Effects Analysis

Giovanni Santin, Vladimir Ivanchenko, Hugh Evans, Petteri Nieminen, and Eamonn Daly



Radiation Environment
(e.g. SPENVIS, CREME96) via GPS



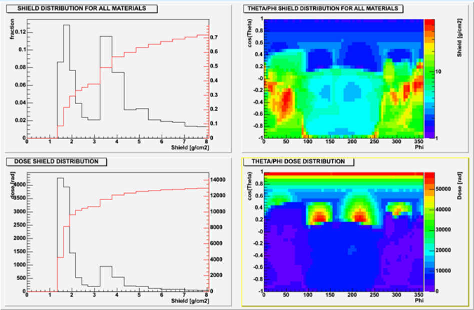
External geometries
GDML, CAD (via GDML)

Built-in geometries
MULASSIS, GEMAT, C++

Geant4 Physics
EM & Hadronic options

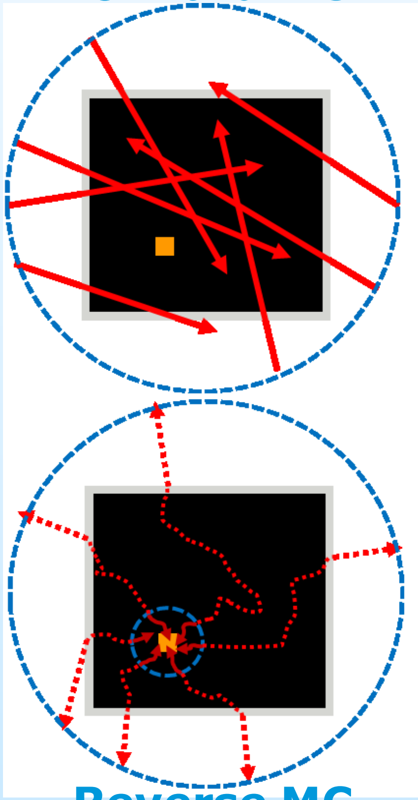
GRAS
Transport, Scoring

Reverse MC
Adjoint physics



Analysis output:
- Scalars, Histograms, Tuples (CSV, AIDA, ROOT, log)
- Several modules available: Dose, Dose eq., Fluence, Niel, LET, Step by Step, Detector, Charge

Forward MC



Reverse MC

- **Adjoint Monte Carlo:**, based on *reverse tracking*
- *Reverse MC method more rapid than forward by orders of magnitude*

G Santin, V Ivantchenko et al, IEEE Trans. Nucl. Sci. 52, 2005

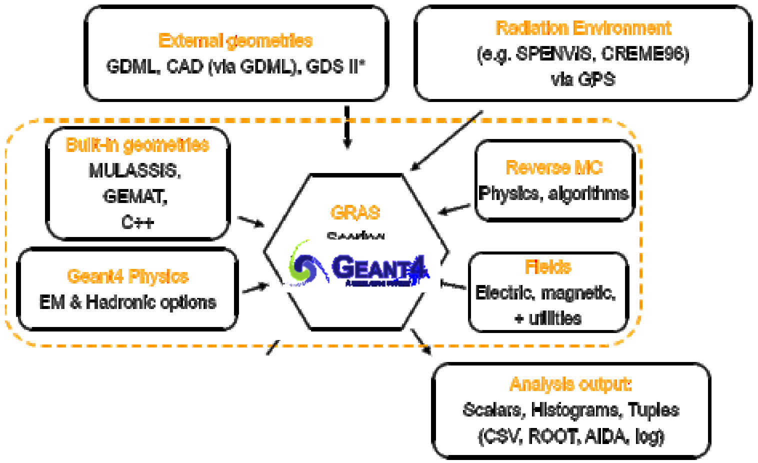
GRAS – Input file and analysis types

```
/control/verbose 2
/run/verbose 1
/run/numberOfThreads 3
############################################
# physics
############################################
/gras/physics/list
/gras/physics/addPhysics  em_standard_opt4
/gras/physics/addPhysics  QBBC
/gras/physics/setCuts    0.1 mm
/gras/physics/describe
#########################################
#                   Geometry
#########################################
/gras/geometry/type gdml
/gras/file Sphere_water.gdml
/gdml/setup Setup
/run/initialize
/gras/geometry/util/listPhysicalVolumes
/gras/geometry/util/listLogicalVolumes
```

Verbosity, Threads number in MT

Physics definition: PL, cuts, processes, etc.

Geometry definition, external GDML file, list of volumes, possible overlaps testing



G Santin, V Ivantchenko et al, IEEE Trans. Nucl. Sci. 52, 2005

```
############################################
#                 Analysis                 #
############################################
/gras/analysis/initialise
/gras/analysis/source/addModule source1
/gras/analysis/initialise
/gras/histo/setHistoByName source1_kine 1000 1 1000. MeV lin

/gras/analysis/charging/addModule chargingDetector
/gras/analysis/charging/chargingDetector/addVolumeInterface * Sphere
/gras/analysis/initialise

/gras/analysis/tid/addModule dose1
/gras/analysis/tid/dose1/addVolume Sphere
/gras/analysis/tid/dose1/addVolumeInterface * Sphere
/gras/analysis/tid/dose1/setUnit MeV
/gras/analysis/setSimPrecision 0.1 # in %
/gras/analysis/tid/dose1/setModulePrecision 0.1
#/gras/analysis/setEventsForPrecision 1000
/gras/analysis/tid/dose1/registerForPrecision true
/gras/analysis/initialise

/gras/analysis/effective_dose/addModule Red_bone_marrow
/gras/analysis/effective_dose/Red_bone_marrow/addVolumeInterface * Sphere
/gras/analysis/effective_dose/Red_bone_marrow/setSpecifier Male Red bone marrow
/gras/analysis/effective_dose/Red_bone_marrow/setWF NASA
/gras/analysis/effective_dose/Red_bone_marrow/setUnit mSv
/gras/analysis/effective_dose/Red_bone_marrow/initialise

/run/initialize
############################################
# SOURCE #
############################################
/control/execute Multi_source.g4mac

#/
#########################
/gras/histo/fileName Sphere_water_flat_new
#########################
/gras/event/printModulo  10000
/run/beamOn              100000
```

Source in GPS form, external macro (e.g. created via Spenvis)

Running parameters, events,

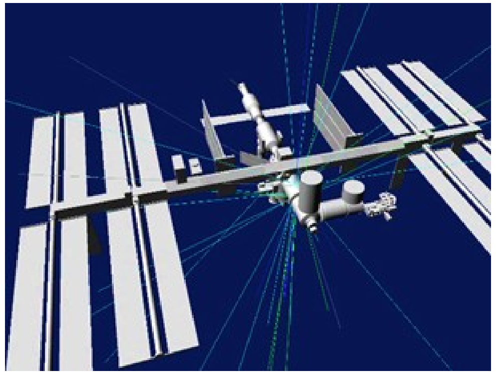
Analysis types

- TID (Total Ionizing Dose) analysis
- Dose equivalent analysis
- Equivalent dose/tissue effects analysis
- Fluence analysis
- NIEL analysis
- NID analysis
- Path length analysis
- LET analysis
- LET_R analysis
- Charging analysis
- Detector analysis
- Source analysis
- Charge Collection Analysis (CCA)
- Activation
- Reaction analysis
- Mesh scoring analysis
- Along step analysis
- PSTrack
- common
- Effective dose analysis
- Generic factors analysis

Note: Visualization possible and other features available (e.g G4 scoring, RMC, geometry testing, Magnetic fields, etc.)
Full Wiki documentation at:
https://spitfire.estec.esa.int/trac/GRAS/wiki/GRAS/GRAS-06-00/UserGuide

GRAS - Code distributi

European Space Software Repository
esa



→ GRAS (GEANT4 RADIATION ANALYSIS FOR SPACE)

GRAS is a Geant4-based tool enabling common radiation analyses types (TID, TNID, fluence, SEE, path length, charge deposit, dose equivalent, equivalent dose, radiat...

Licenses: European Space Agency Public License – v2.4 – Strong Copyleft (Type 1)

READ MORE →

Updated on: 15/06/2022 **Created on:** 02/04/2019

Version Control System: svn

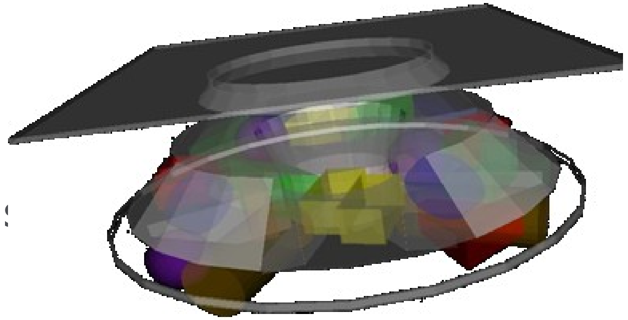
Owner: ESA

Links:

1. Documentation : Main reference paper for GRAS (IEEE Trans. Nuc. Sci. Vol 52 , No 6 , Dec. 2005)
2. Documentation : GRAS documentation and ticket system access details
3. Source code : Source code for GRAS-05-00-01
4. Source code : Source code for GRAS-05.02.01
5. Documentation : Name Main paper for GRAS / Geant4 reverse (adjoint) simulations (NIM A, Vol 621, Issues 1–3, 1–21 September 2010, Pages 247-257)

Tags: Geant4 Radiation Space environment TID Dose TNID

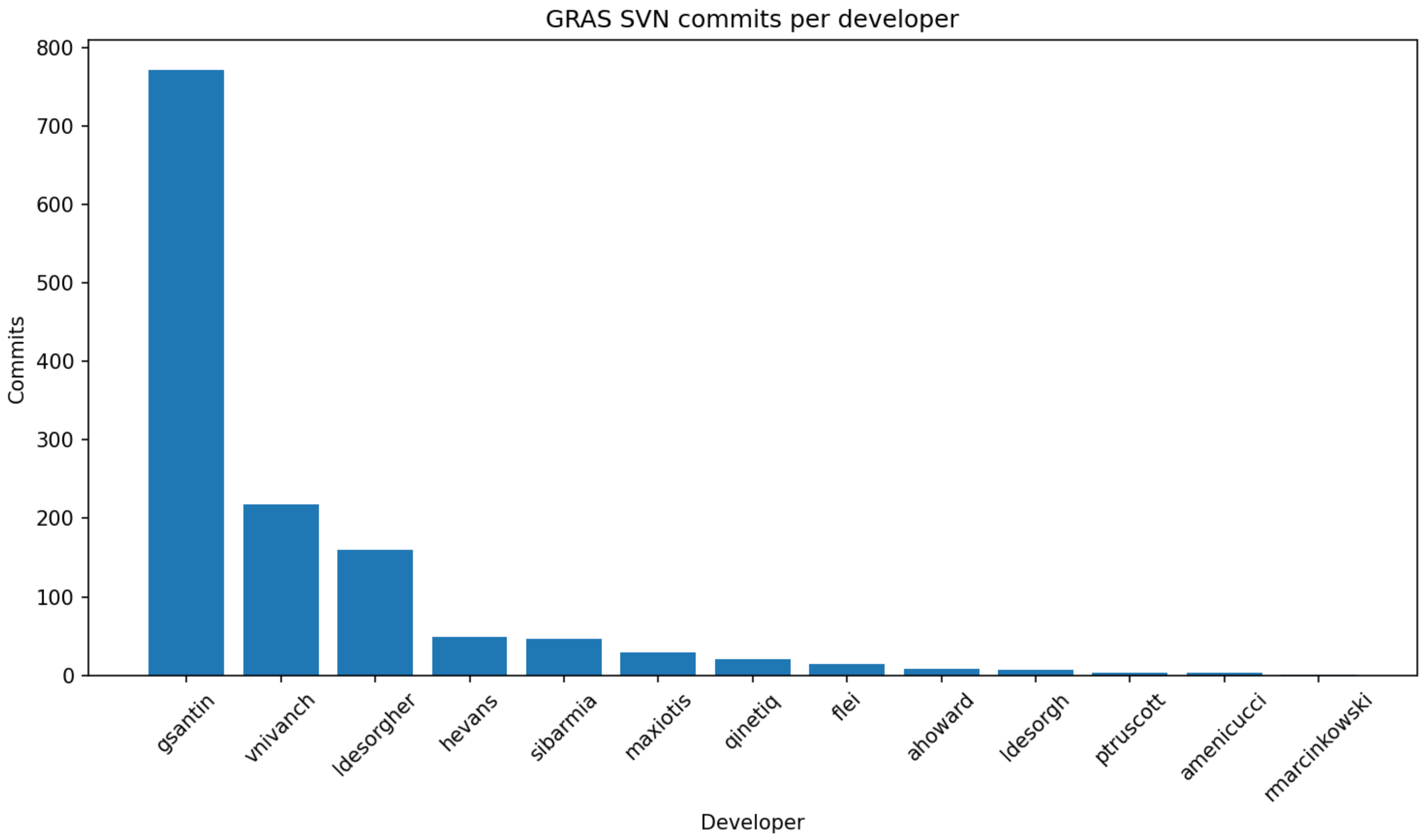
- Up to version **4.2**, available through collaborations
- Since version **5.0**
  - Source code and documentation in European Space Software Repository (ESSR)
  - Licence: European Space Agency **Community** License – v2.4 Strong Copyleft (Type 1)
- Since version **5.2**
  - **World-wide** licence
- Documentation in trac Wiki (installation, user manual)
- **Code repository access** available through collaboration



GRAS SVN Repository History

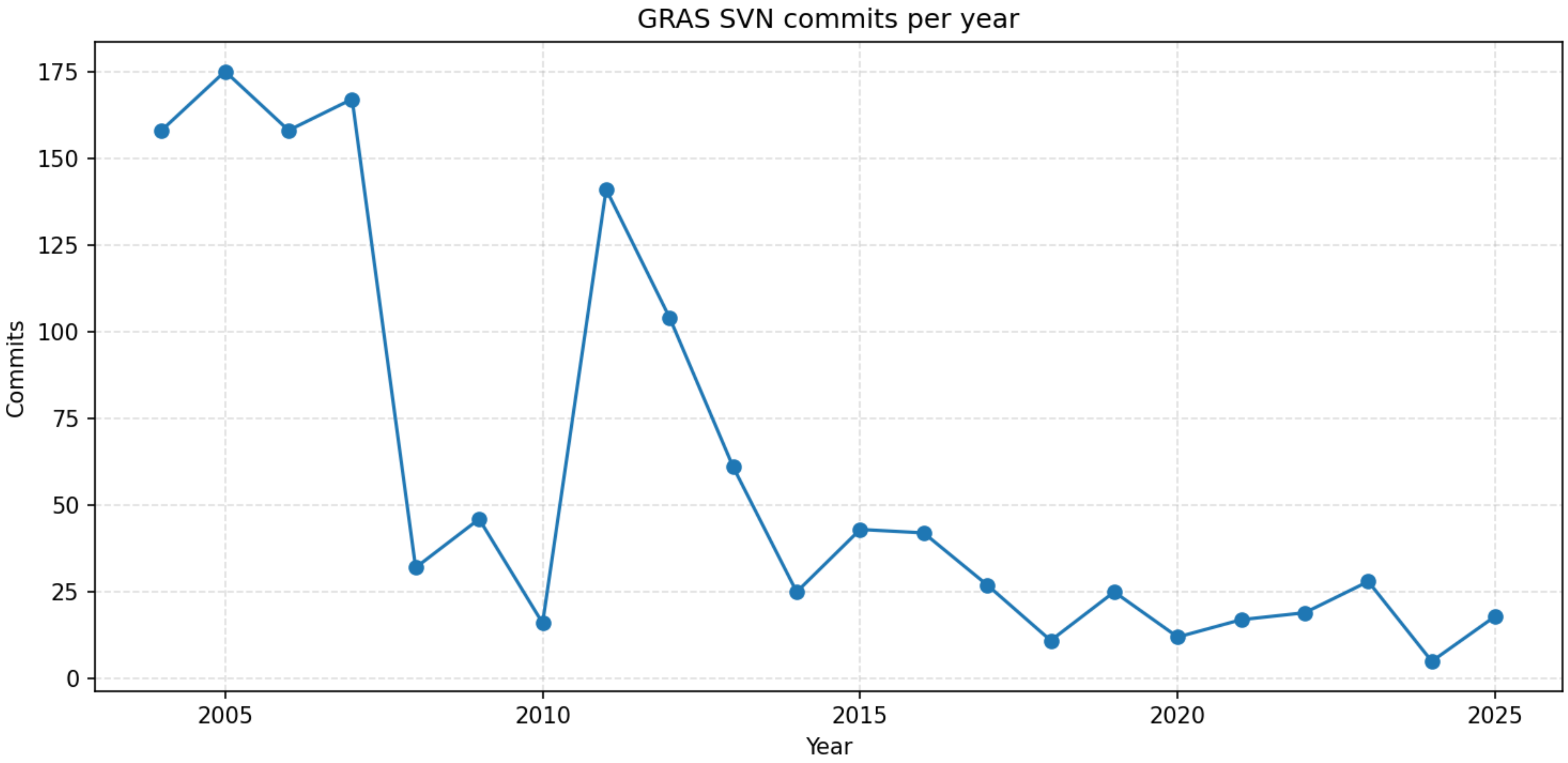
- GRAS development history in SVN spans **21+ years** (from 2004-07-01 to 2025-12-04).
- The codebase shows **1330 commits** by **13 developers**.
- Contribution is concentrated: the top 3 committers account for **1149 / 1330 commits (~86.4%)**.
- Code-only size is **~50.3k LOC** for the core implementation (source/) and **~68.5k LOC** repository-wide (excluding build/doc/generated directories).
- Tests/examples contribute **~17.9k LOC**, indicating substantial validation and usage coverage alongside core implementation.

GRAS Commits Per Developer



Developer	Commits
gsantin	771
vnivanch	218
ldesorgher	160
hevans	49
sibarmia	47
maxiotis	29
qinetiq	20
flei	14
ahoward	8
ldesorgh	7
ptruscott	3
amenicucci	3
rmarcinkowski	1

GRAS Commits Per Year



SURREY SPACE CENTRE

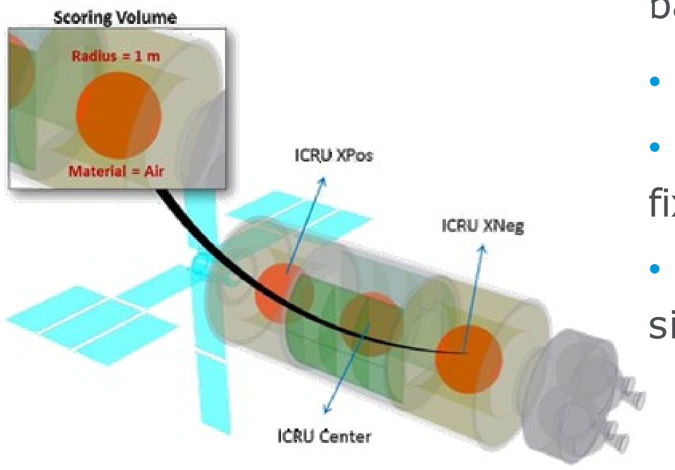
GRAS v6 : Recent developments

GRAS 6.0: thanks in particular to
Mike Axiotis et al
G4G ESA contract

GRAS 5.2.1

May 2022

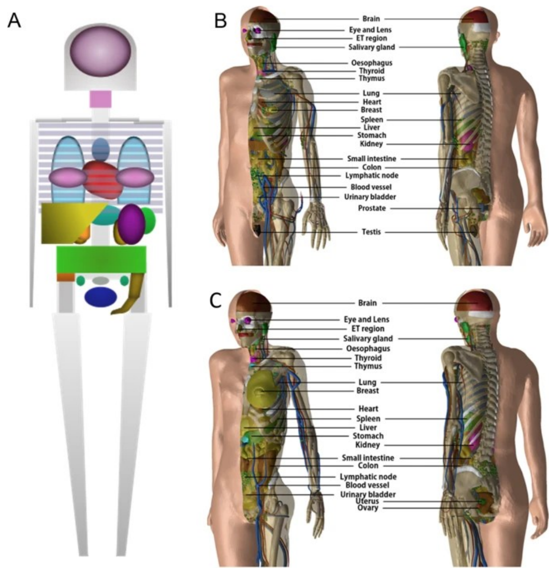
- Based on Geant4 10.07.p03
- **Phase Space** I/O for the “**Two-Stage** Variance Reduction / Analysis”
- Analysis module of the Phase Space
- **Layered Mass** Geometry
- Reverse/**Adjoint MC improvements**: thick shielding and simulation stability
- Improved **automated normalisation** of results (QA)



GRAS 6.0

July 2023

- Based on Geant4 10.07.p03
- **Multi-Threading** support
- **G4 physics** lists options alongside GRAS specific ones
- New **generic factors** analysis module (fluence/step-length/energy-deposition - to - effect)
- New **effective dose analysis** based on **ICRP123**



- Simulation can stop by reached **target precision** (also for FW)
- Improved **histogram** output: management, no ROOT dep., bug fixes
- New **magnetic field maps** from spherical grid for planetary simulations

GRAS 7 (release under preparation) and beyond

- Upgrade to **Geant 4.11**
- Implementation and improvement of the generic **biasing** techniques: Included in the G4 examples (Cross sections biasing, split & kill, geometry importance, forced interactions, etc). The use will be simplified through user commands in the input macro
- More structured output files: CSV including some blocks of information about the run (source, geometry, physics, etc.). Normally this is only available in the log file.
- Improvements in the RMC
- Improving the existing Python Suite for testing: simplification and standardization of the scripts, comparison of results, automatically flags problems, user script for post-installation checks.
- Evaluate the introduction of “factories” in the analysis classes (similar to the physics list approach). Possibility to have customized plugins for users.
- Evaluate the Creation of a generic gras analysis class, based on the G4 generic analysis class to manage histos, stat doubles, tuples. Goal is to simplify the code and the modules by using common classes

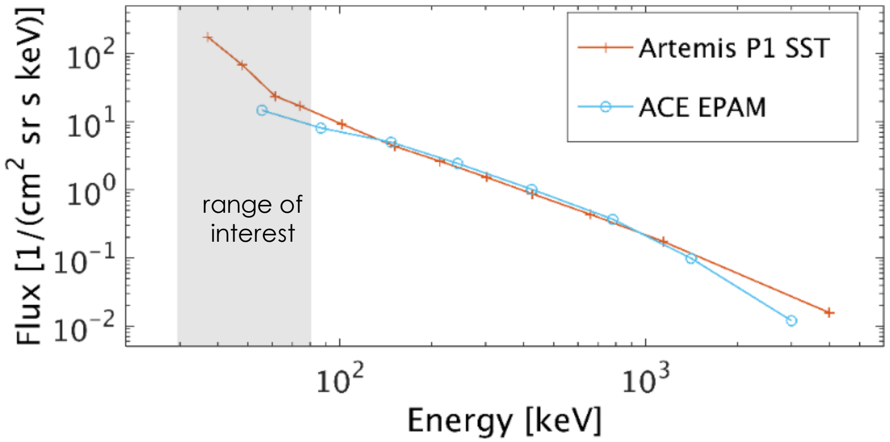
Typical applications

- Total Ionizing Dose
- Total Non-Ionising Dose
- Biological dose
- Single Event Effects in electronic components
- Shielding optimisation 1D/3D
- Internal Charging (meshed volumes)
- Background noise on sensors
- Radiation monitors developments (response functions calculation, instrument design)
- Radiation tests definition in accelerator environment
- Typical particles: electrons (up to 7 MeV), protons, heavy ions (several GeVs)

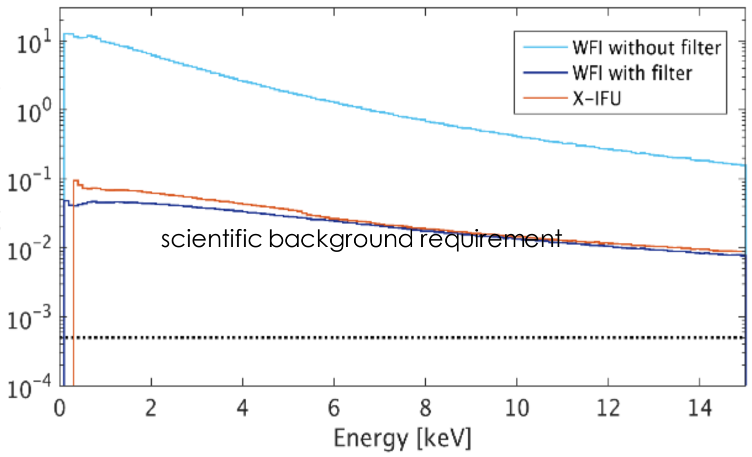
Particle background in the ATHENA X-ray telescope

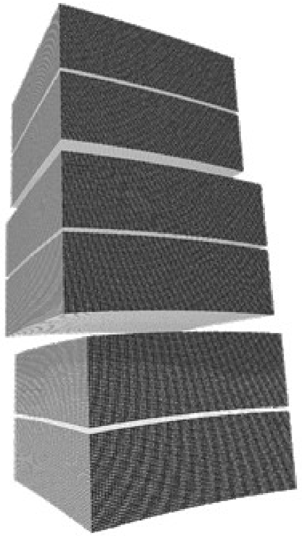
Soft Proton Fluxes in and Around the Earth's Magnetotail, D. Budjas et al. ,March 2017 IEEE Transactions on Plasma Science PP(99):1-7

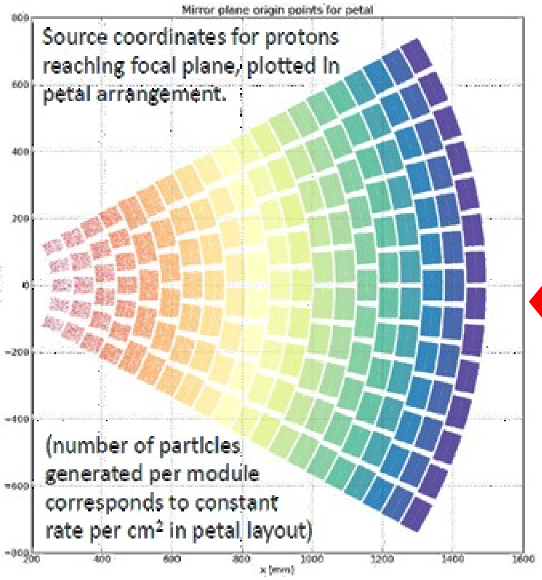
90% worst-case spectra for solar (from ACE) and solar + Earth magnetotail (from Artemis) proton flux

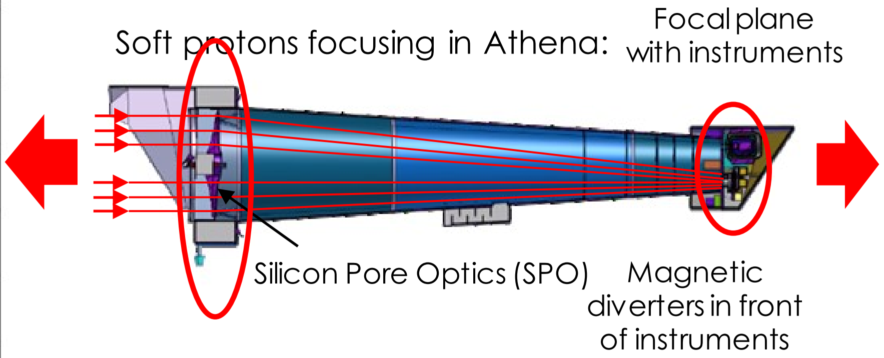


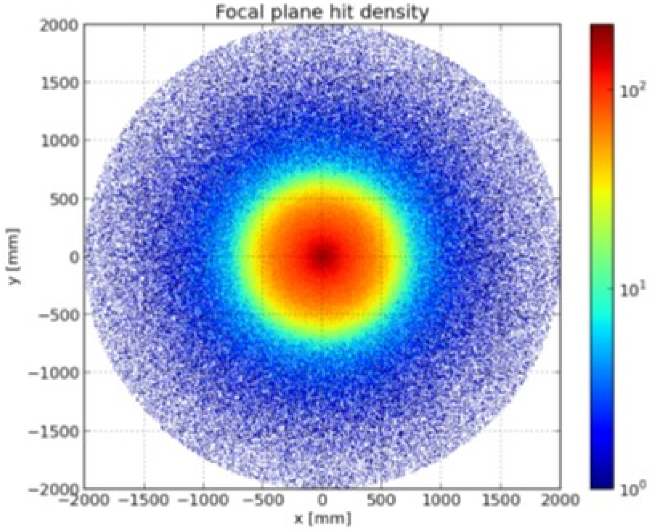
estimate of soft-proton backgroun[illegible]
without magnetic diverters





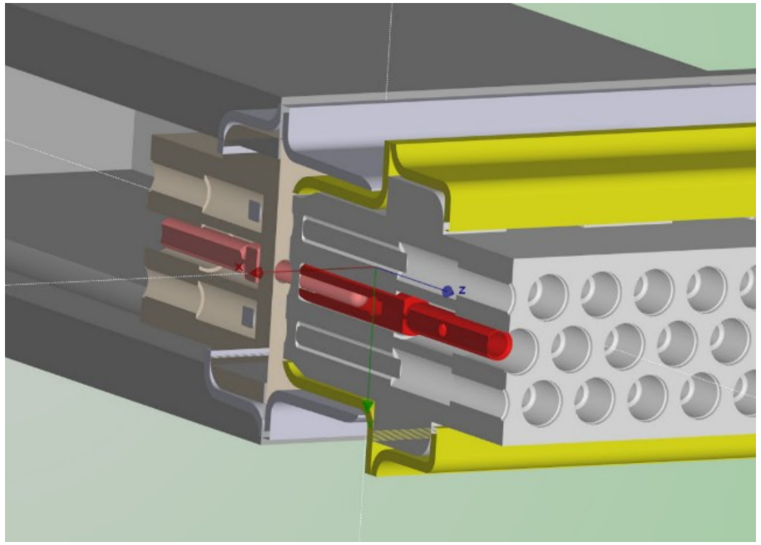


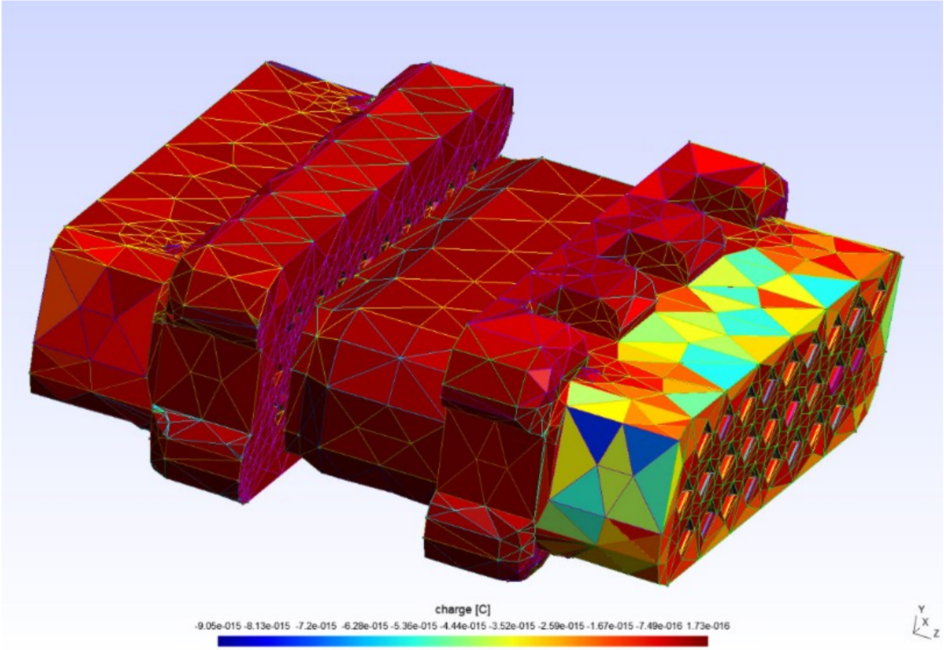




GRAS – recent applications :

Deep dielectric (internal) charging





GRAS

- Simple or detailed CAD geometry models
- 3d detailed map of charge and dose deposition

Coupled to SPIS-IC

- Time evolution - 3d Poisson solver including temperature, dose-rate

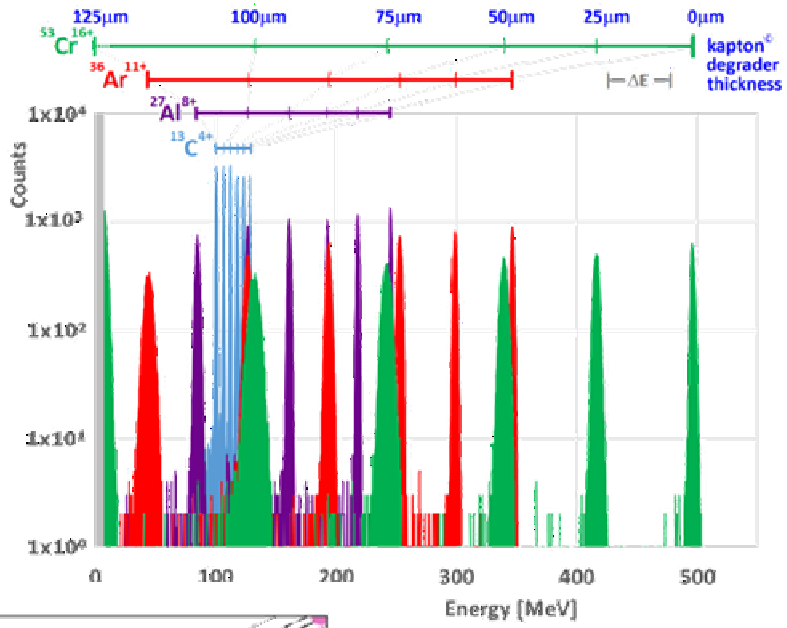
GRAS – recent applications:

Set-up for ion beam characterization

1732 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 8, AUGUST 2023

PIPS Diode Test Setup for Heavy Ion Beam Spectral Characterization

Thomas Borel, Alessandra Costantino, Michele Muschitiello, Heikki Kettunen, *Member, IEEE*, Laurent Standaert, Giovanni Santin, *Member, IEEE*, Marco Pinto, Marta Rizzo, Anastasia Pesce, and Véronique Ferlet-Cavrois, *Fellow, IEEE*



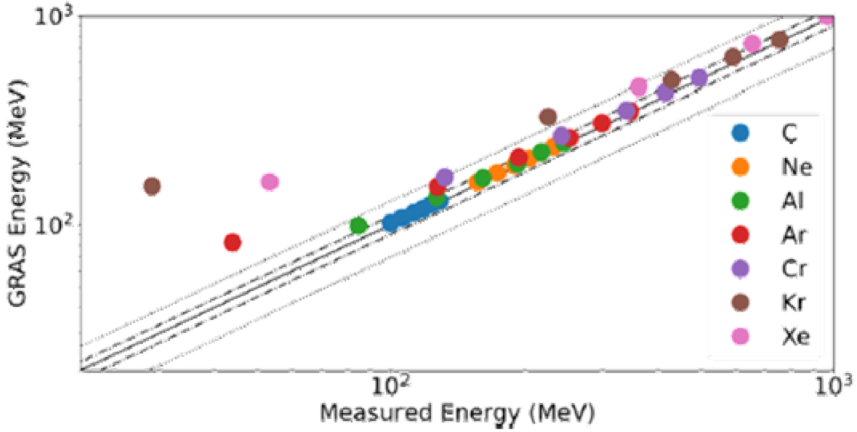


Fig. 11. Comparison between measurements and GRAS simulations for Kapton degrader thicknesses of 25, 50, 75, 100, and 125 μm. The solid, dashed, and dotted lines represent 0%, 10%, and 30% differences, respectively.

he energy spectrum measured with the

Borel et al, 2023

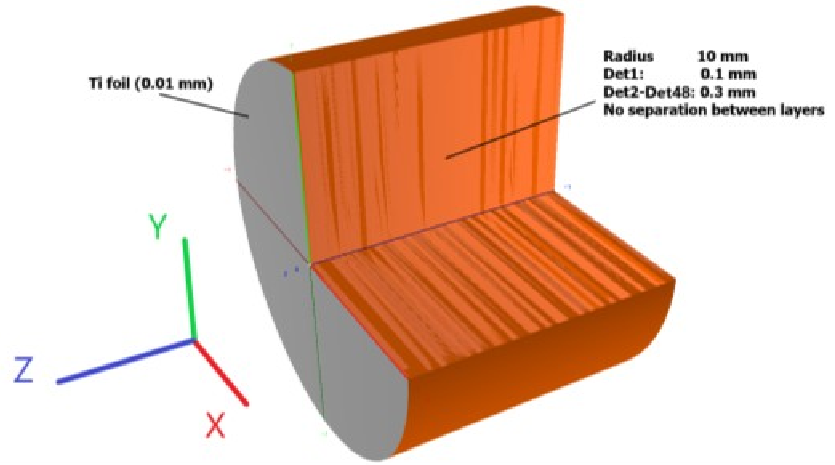
GRAS simulations for Radiation Monitor design

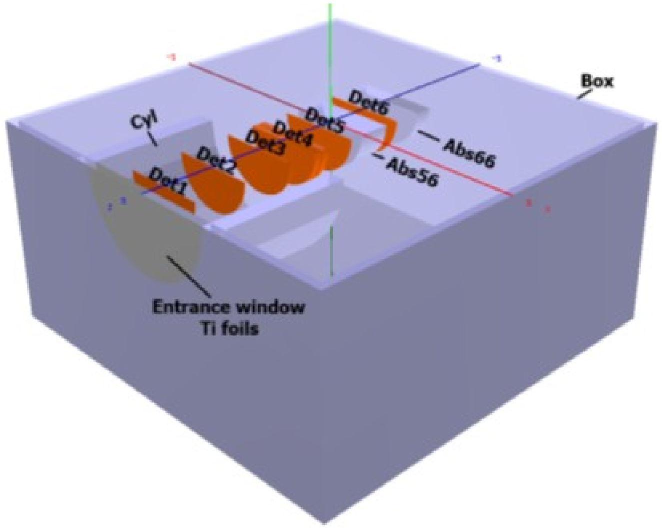
The "D3S RadMag" example by mtaEK

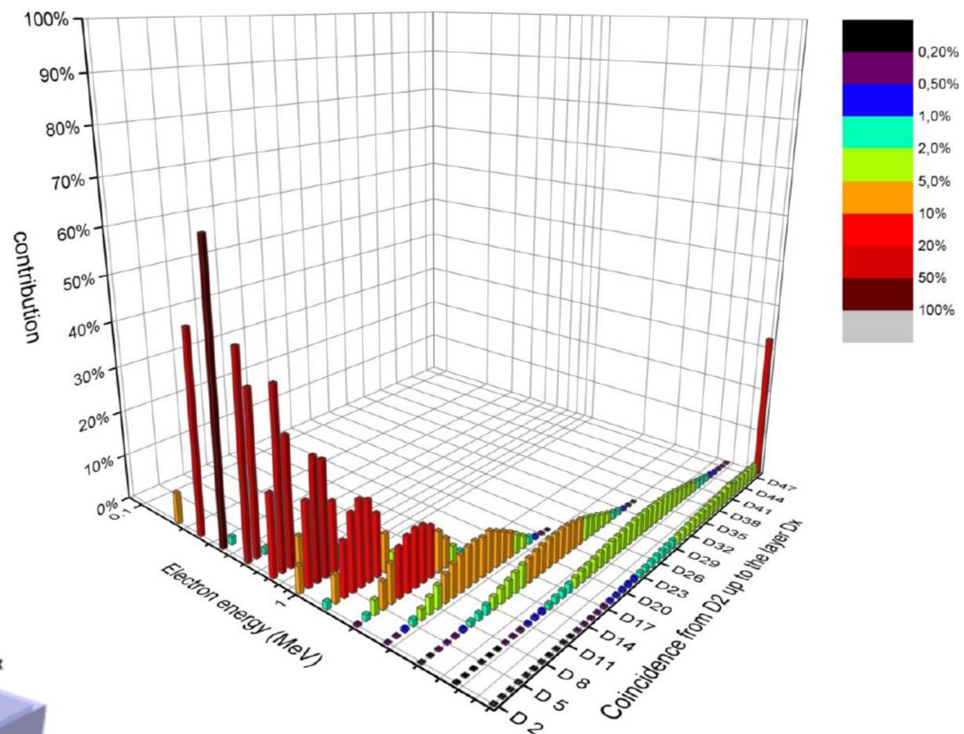
The activity aims to develop a complex instrument package combining the cosmic ray and magnetic field measurement capability for space weather service and directly applicable in the Distributed Space Weather Sensors System (D3S) concept of ESA.

- 1D slab geometry
- Species separation efficiency
- Identification of important layers

- Real design
- Absorber materials
- Channels definition







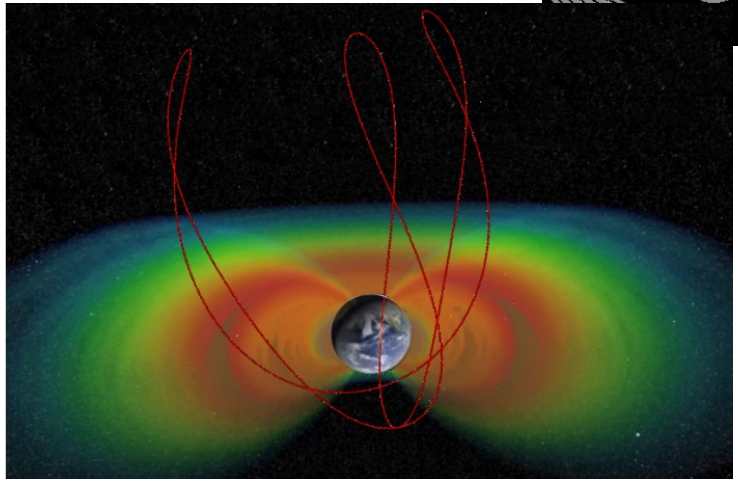
D2-Dx coincidence histogram for electrons

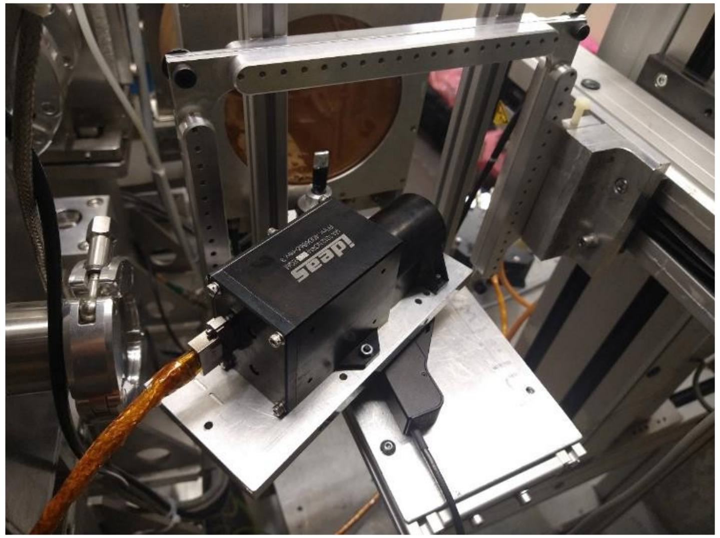
Credit: A.Hirn and B.Zabori (MTA EK)

GRAS – recent applications

NORM response functions

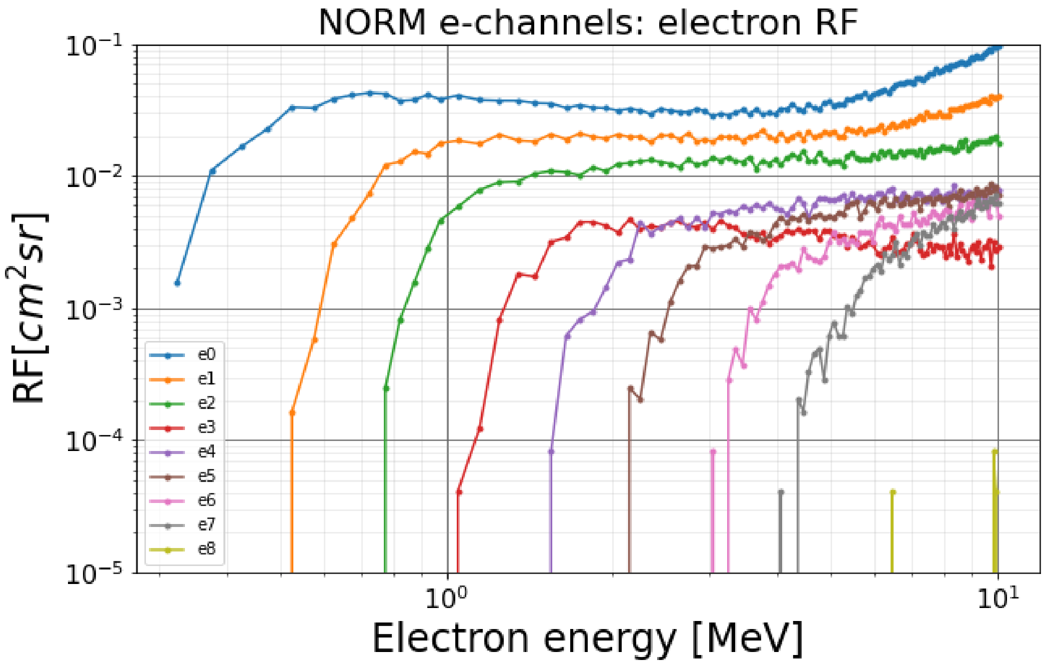
ASBM Norwegian platform
HEO Three-Apogee Orbit
16h, 8746×42878 km, 62.3°





Response function
GRAS “detector” analysis

sparc



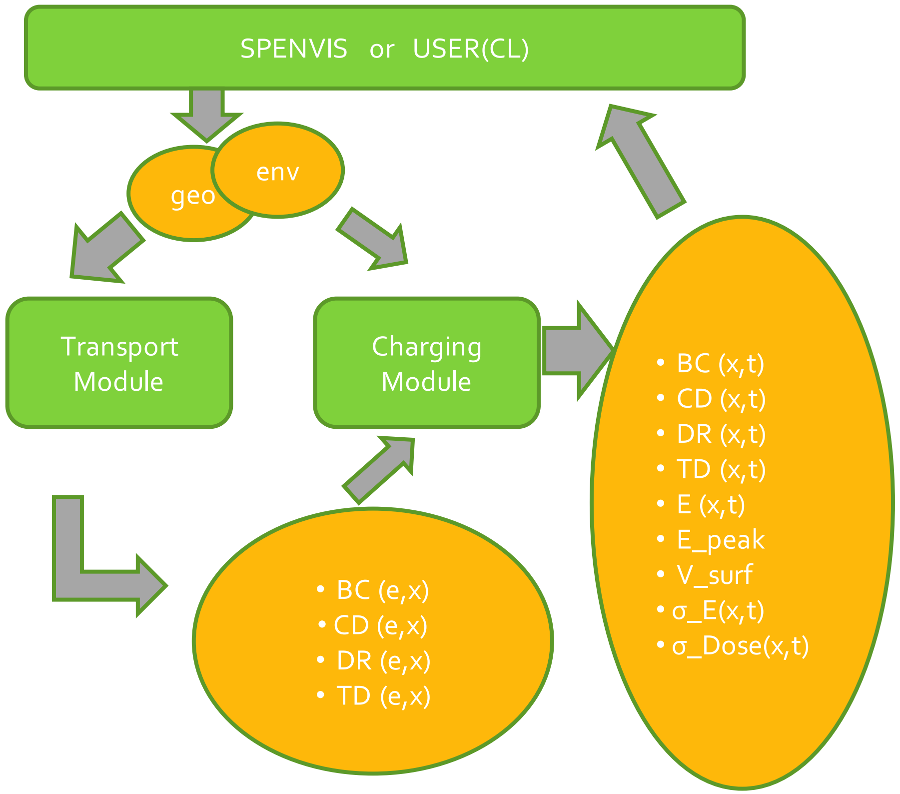
S.Benoit, SPACEMON 20

GRAS @ RadMod & Surrey S[redacted] Centre

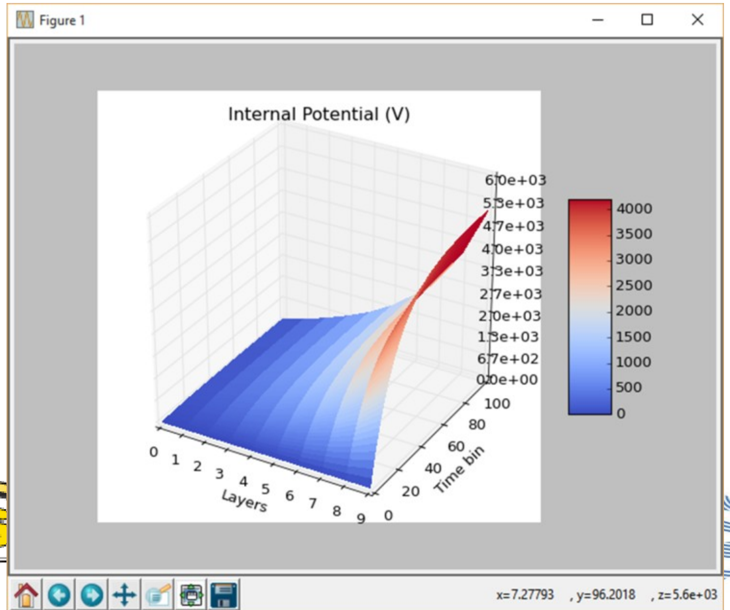
- JUICE mission:
  - JCAT:
    - GRAS as the particle transport engine in MCICT
  - CIRSOS :
    - Mesh tally in GRAS
    - SPIS integration
    - GUI
- ATHENA mission
  - AREMBES
    - PSTrack
    - Validation of space physics list
- Human space flight:
  - IPRAM
    - FASTSHIELD database
  - HIERRAS
    - Two-stage
    - GRAPPA
- VMMO mission
  - CLAIRE instrument
- Instrumentations
  - HEPI
  - ASPIRE

SURREY SPACE CENTRE

MCICT – Code Overview



- Transport Module
  - Updated GRAS
  - Slab/Cylindrical geometry – arbitrary layers of shields and dielectrics
  - Per layer based tallies - > RFs
- Charging Module
  - Convolution of the RFs and the Envs.
  - Field solver – Omh's law
  - Plotting
- Execution:
  - Controlled via a simple ASCII input file

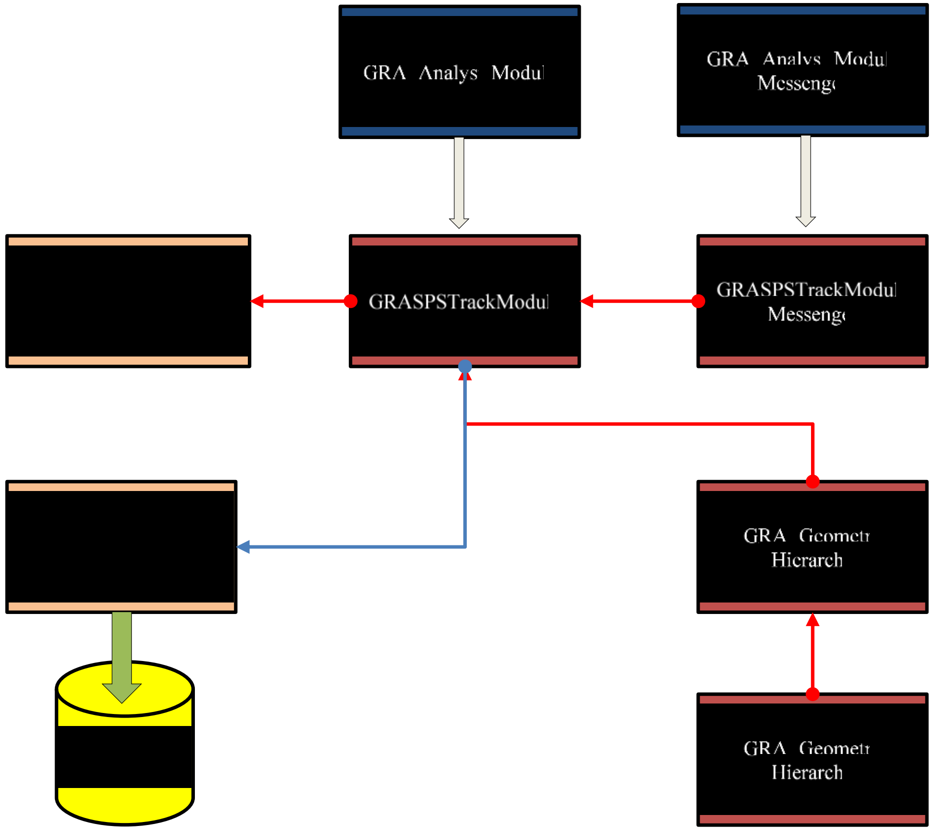


WP5.3: GRAS Developments

- New GRAS Analysis module for phase-space analysis
  - GRAS produces ROOT file phase-space information
  - Full parameters as in ASF-EA- 0020 as updated from discussions with AREMBES members
- Updates to GRAS, Geant4
  - Enhancement to GPS in Geant4
  - Space Physics List in GRAS
- ROOT-to-FITS interface
  - Generates files

    <outputFilePrefix>_0.fits.gz, <outputFilePrefix>_1.fits.gz, <outputFilePrefix>_2.fits.gz
  - Depending number of events, and maximum size FITS file required
  - FITS output is sorted by event#/track#/step# with duplicate records removed
- SUM in CIRSOS Wiki pages and KALLISTO/SUM/17015

  https://spitfire.estec.esa.int/trac/CIRSOS/wiki/SUM/TrackPhaseSpace



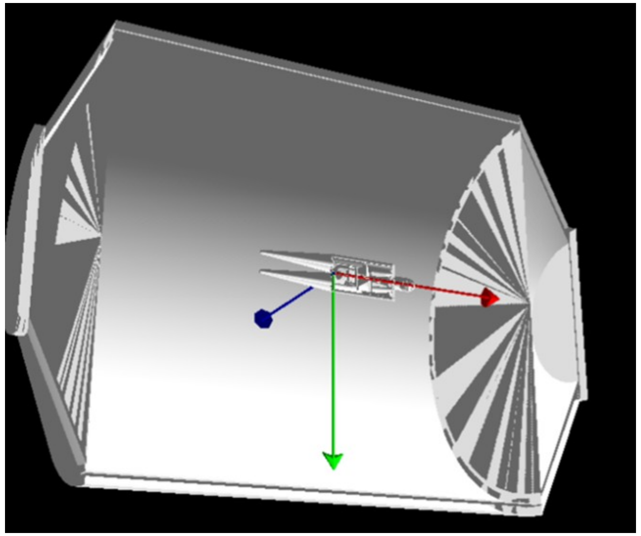
Phase-Space Track Analysis Module in GRAS

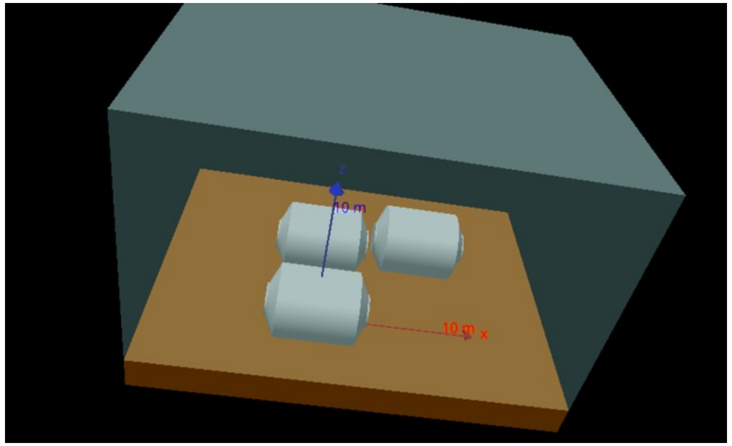
```
/gras/analysis/PSTrack/addModule pst1
/gras/analysis/PSTrack/pst1/addVolume vSiDetector1_PV
/gras/analysis/PSTrack/pst1/addVolume vScintillator1_PV
/gras/analysis/PSTrack/pst1/minEvent 50000
/gras/analysis/PSTrack/pst1/maxEvent 80000
/gras/analysis/PSTrack/pst1/saveModulo 5000

/gras/analysis/PSTrack/addModule pst2
/gras/analysis/PSTrack/pst2/addVolume vSiDetector2_PV 2
/gras/analysis/PSTrack/pst2/addVolume vSiDetector2_PV 5
/gras/analysis/PSTrack/pst2/addVolume vSiDetector2_PV 6
/gras/analysis/PSTrack/pst2/stepLength vSiDetector2_PV 0.6 mm
```

Particle Propagation Module (PPM)

- Direct simulation:
  - GRAS (3D),
  - MULASSIS (1D/2D) geometries
- Response Functions (RPF) generation and convolution:
  - GRAS (3D)
  - MULASSIS (1D/2D)
- Tallies:
  - Detector: Particle flux spectra, TID and TNID
  - Phantom: individual organ and full body
  - Maps: Dose_deposited and fluxes
- Sector Shielding Analysis:
  - SSAT (3D)
- Geometry Tools
  - 3D multi-geometry modeller
  - GDML upload and processing
  - 1D/2D shielding configurator
  - Depth configurator for DDC
  - Detector creator
  - Planetary surface (GRAPPA)





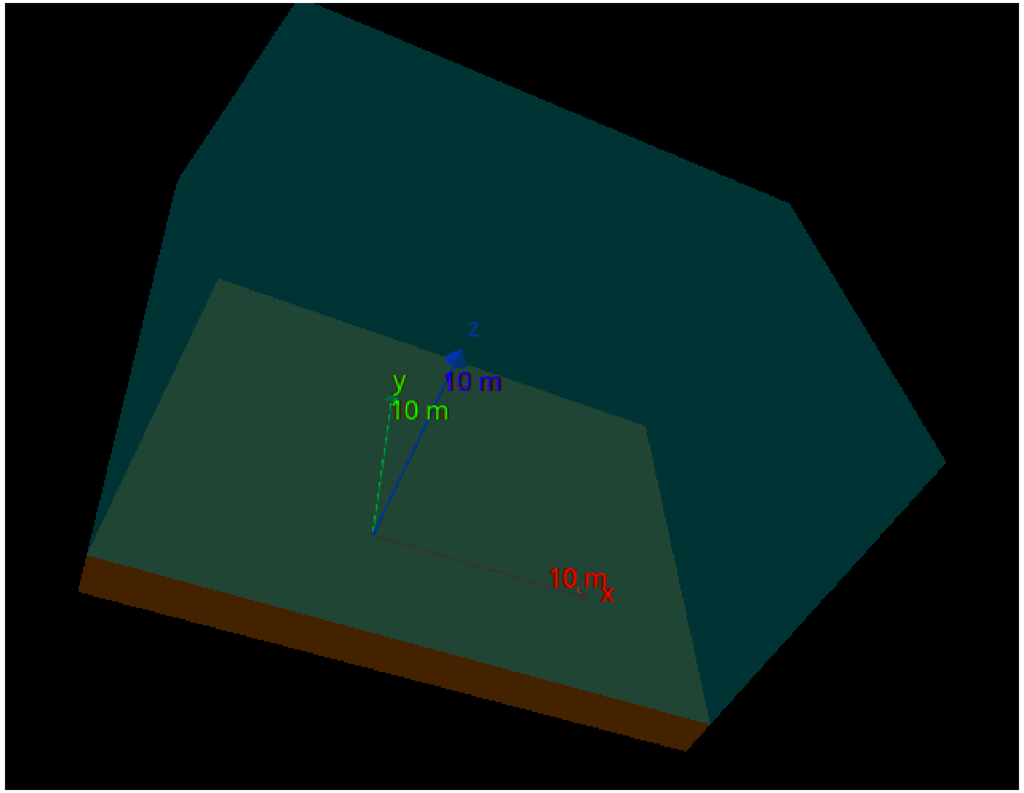
What is GRAPPA?

- GRAPPA = GRAS Pre-processor for Planetary bodies and Asteroids
- Creates GDML geometry representations of Mars and Moon so that ESA's GRAS/Geant4 may be used for 3D particle simulation
- Planar and spherical geometries
  - Simple 1D geometries, or
  - 3D geometries with XY (latitude/longitude) dependence
- Can be used at local scales (~ several metres) to planetary scales
- Treatment of:
  - Atmosphere composition and density as function of altitude
  - Soil as function of depth
  - Precipitates (CO_2 & H_2O)
  - Magnetic fields (for Mars)
- Geometry defined based on a user-selected point on Mars/Moon
  - Will be extended to Phobos and Deimos

This approach means that GRAS (or another Geant4 application) can be used for 3D MC simulation

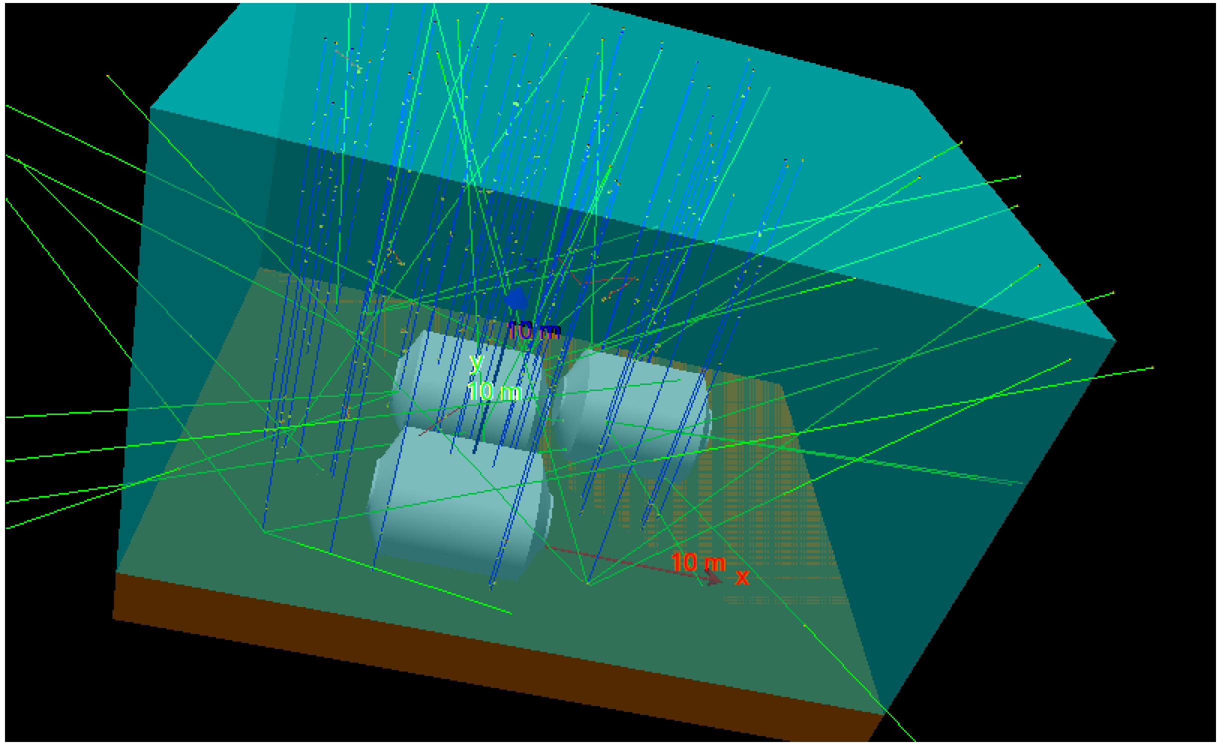
- Better maintainability of software: focus on maintaining GRAS to perform multi-threaded particle simulations with different analysis modules

Mars Case: Local Environment Model & Addition of Mission Equipment



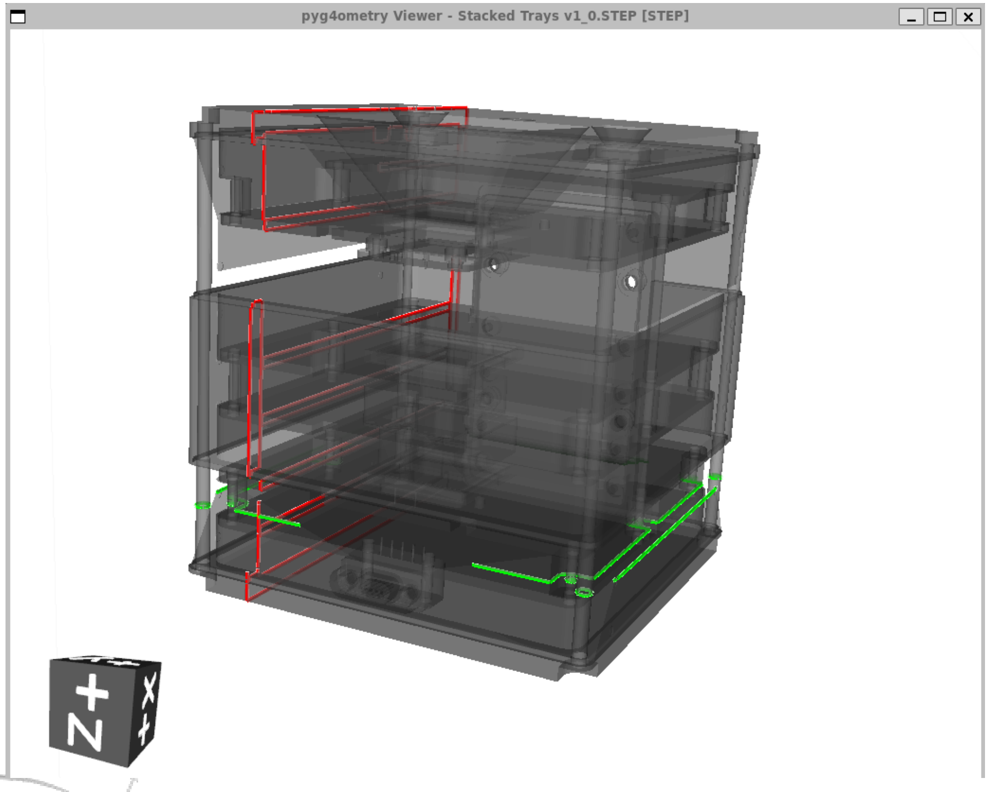
Local environment $25 \times 20 \times 17\ m^3$

Local environment with partially-buried habitat modules (additional GDML files) included in GRAS simulation

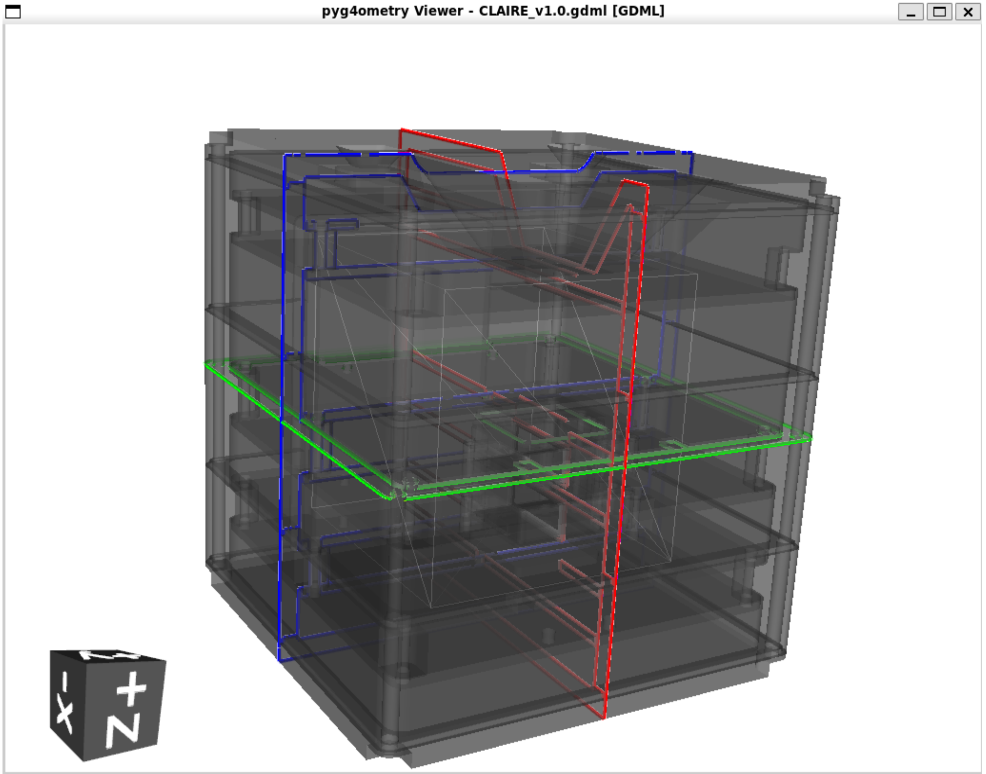


CLAIRE Geometry Models

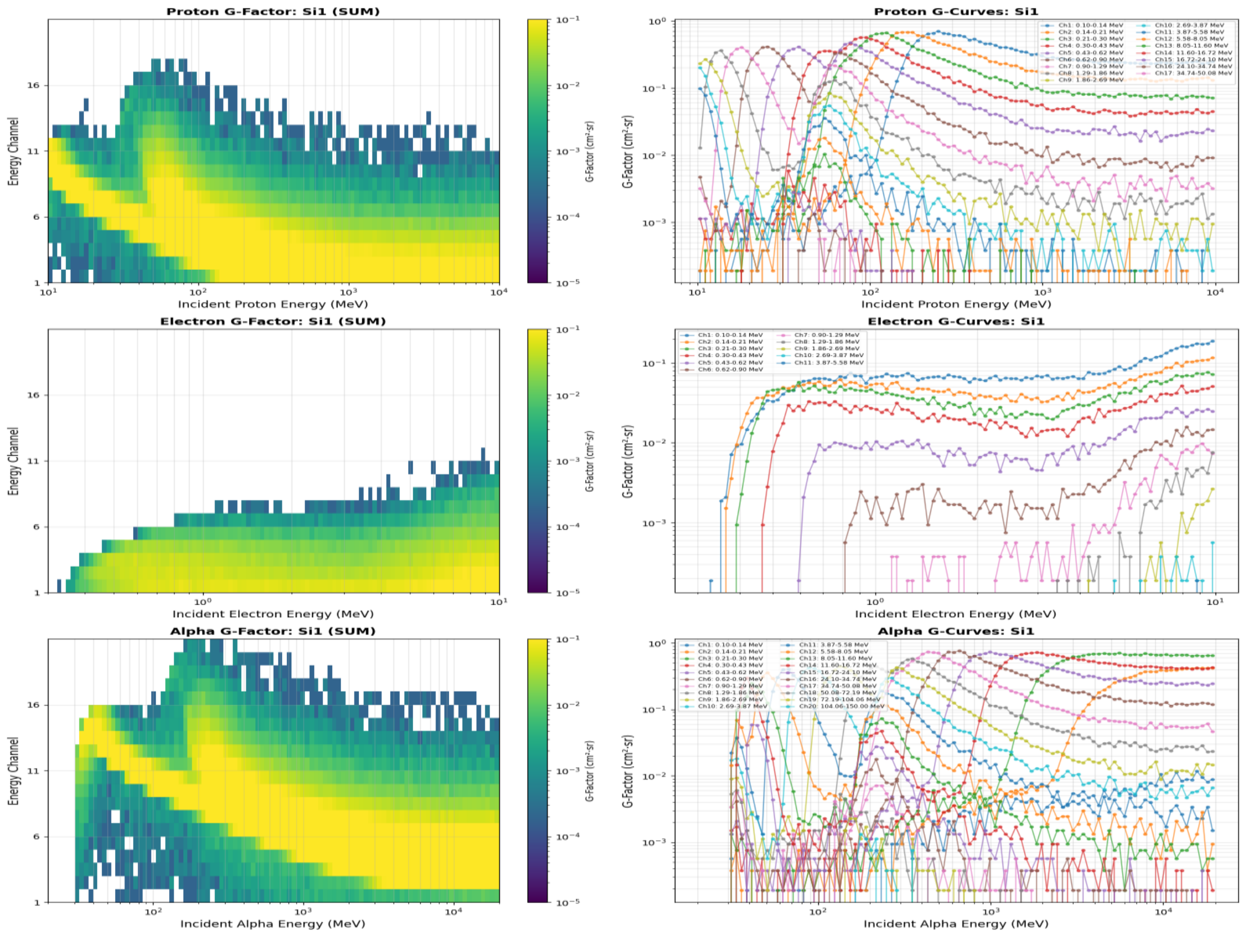
CAD



GDML



GF: D1 alone




```
================================================================================
Si1 Coincidence G-Factor Analysis (Algorithm: SUM)
================================================================================

Protons: 518552 Si1 coincidence events (out of 3739233 total, 13.87%)
Electrons: 100281 Si1 coincidence events (out of 873219 total, 11.48%)
Alphas: 763450 Si1 coincidence events (out of 3184010 total, 23.98%)

================================================================================
Si1 Coincidence Summary (SUM algorithm)
================================================================================

G-Factor Peak Summary:
```

Ch	Edep_Low (MeV)	Edep_High (MeV)	e- G_peak (cm²sr)	p G_peak (cm²sr)	α G_peak (cm²sr)	Primary
1	0.100000	0.144147	0.186045	0.695360	0.011687	Proton
2	0.144147	0.207783	0.114982	0.672741	0.423173	Proton
3	0.207783	0.299512	0.075964	0.659357	0.702523	Alpha
4	0.299512	0.431736	0.051459	0.566241	0.720807	Alpha
5	0.431736	0.622333	0.027143	0.476328	0.728724	Alpha
6	0.622333	0.897072	0.015834	0.412240	0.757375	Alpha
7	0.897072	1.293099	0.009802	0.402815	0.740788	Alpha
8	1.293099	1.863960	0.007540	0.362854	0.585279	Alpha
9	1.863960	2.686835	0.002639	0.266156	0.444284	Alpha
10	2.686835	3.872983	0.000565	0.200182	0.419780	Alpha
11	3.872983	5.582776	0.000188	0.097641	0.403004	Alpha
12	5.582776	8.047385	0.000000	0.017907	0.359650	Alpha
13	8.047385	11.600036	0.000000	0.010367	0.249568	Alpha

CAD -> GDML Geometry Conv

- CLAIRE CAD model in SolidWorks
  - Suppressed unnecessary volumes such as connectors, screws and refilled the space
  - Exported in STEP and STL
- Converted to GDML/G4, using 2 newly created tools, based on pyg4ometry. The tools are released to the public
  - cad_g4_conv
    - https://github.com/drflei/cad_g4_conv
    - https://pypi.org/project/cad-g4-conv/
  - gdml-editor
    - https://github.com/drflei/gdml-editor
    - https://pypi.org/project/gdml-editor/
- Materials, detectors were added using the gdml-editor

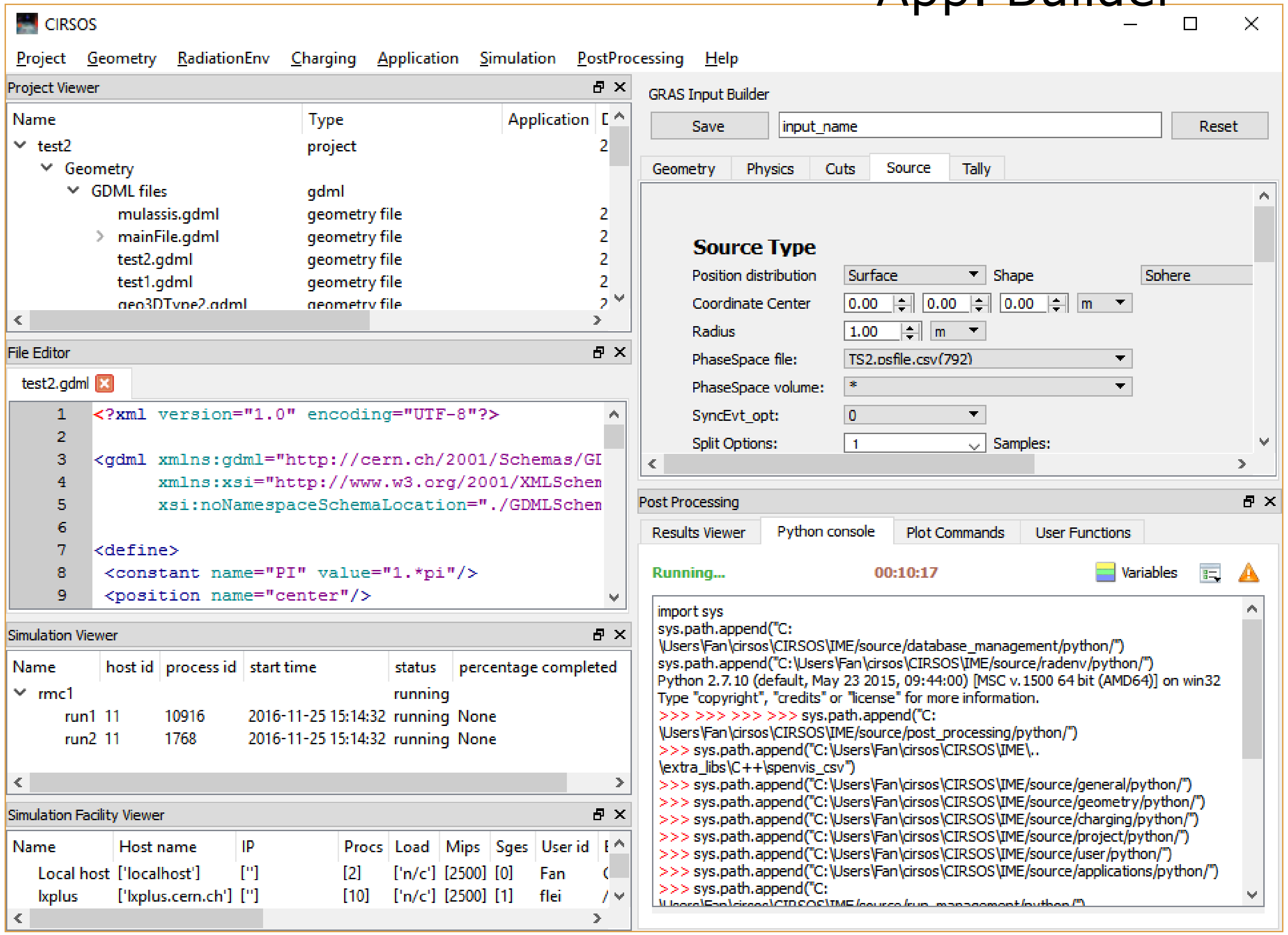
GRAS User Interfaces

- SPENVIS
  - SPENVIS - Space Environment, Effects, and Education System
- NoM
  - Available Models Tree | ESA Network of Models
- CIRSOS
  - CIRSOS

The CIRSOS GUI

- Project management
- File Editor
- Simulation runs
- Parallel computing, clusters

- App. Builder



- Post-processing

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