Geant4 Space Users' Workshop 2018

Geant4 Reverse Monte Carlo GRAS implementation – Status Report

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ESA/ESTEC and RHEA System

Outline

- Reverse Monte Carlo implementation
- Tests and bugs report
- Future activities

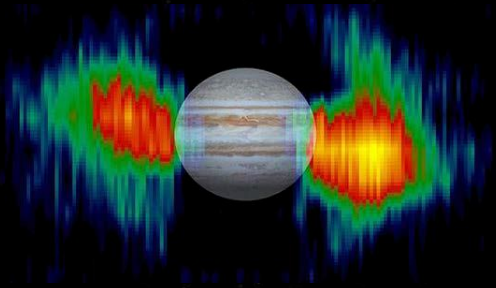
Space Center, Houston, TX
28-30 November 2018

Main topics

- JUICE Radiation environment used for tests
- RMC GRAS implementation introduction
- “Test Spacecraft” geometry definition
- Test Results for different geometries
- Dose depth curves comparisons
- More specific tests performed in the frame of the ESA CIRSOS project.
- Conclusions

JUpiter Icy moons Explorer (JUICE)

- JUICE is the first large-class mission in ESA's Cosmic Vision 2015-2025 programme.
- Planned for launch in 2022 and arrival at Jupiter in 2029,
- It will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa.



Cassini (NATURE 2002)

Very intense magnetic field

- Jupiter rotational period 9 h 56 min
- Plasma torus and radiation belts wobble due to 7° tilt between Jupiter rotational and magnetic axes

Hostile radiation environment

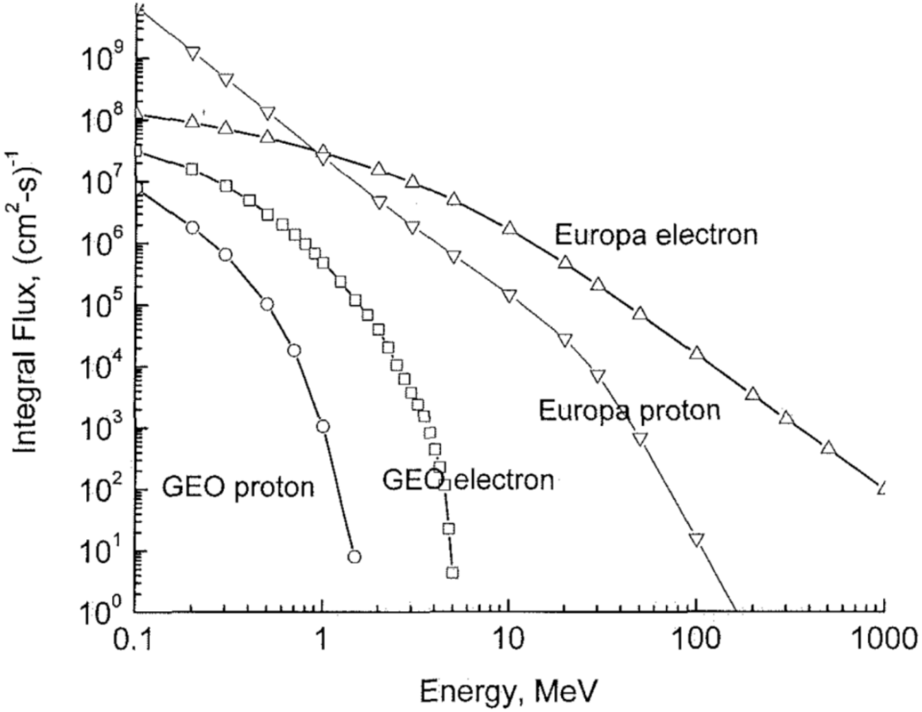
- Trapped electrons with energies >100MeV
- Intense, energetic, variable, difficult to predict

Design driver for JUICE platform and payload

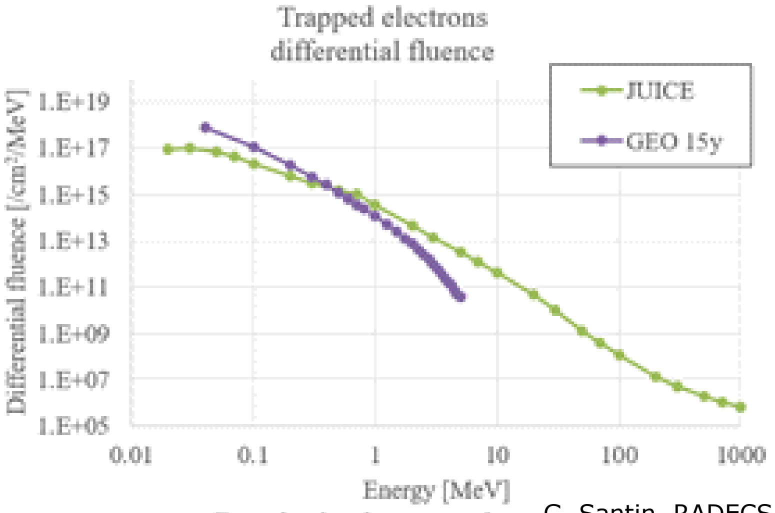
- Sensor / component **degradation**
- High **background** noise for science instruments
- **Electron-induced SEE**

Broad range of radiation analysis activities (TID, charging, DD, noise, SEE) for platform and instruments, **including Geant4 and GRAS**

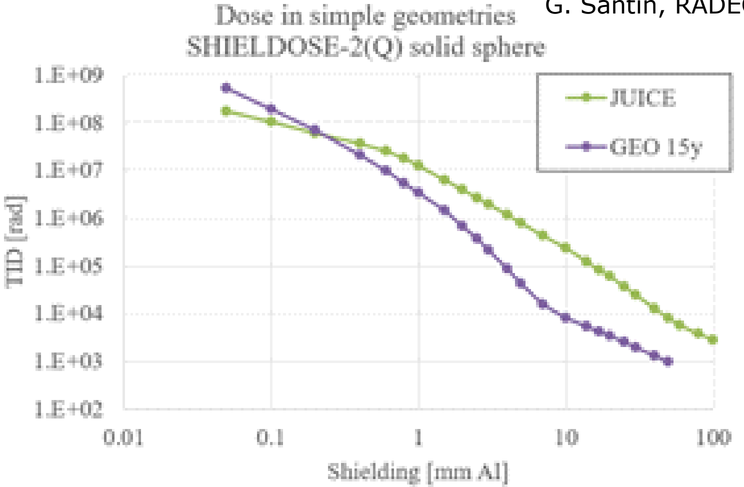
JUICE Radiation environment



I. Jun, H. Garrett, JPL

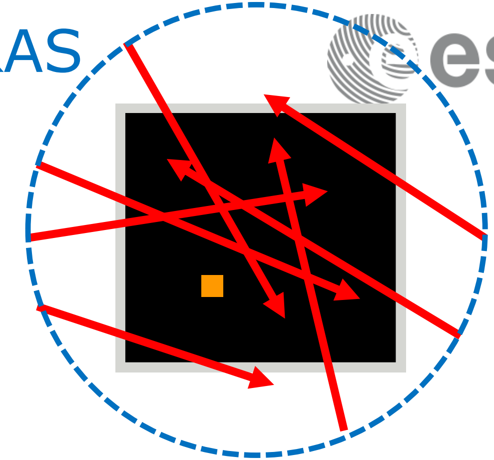


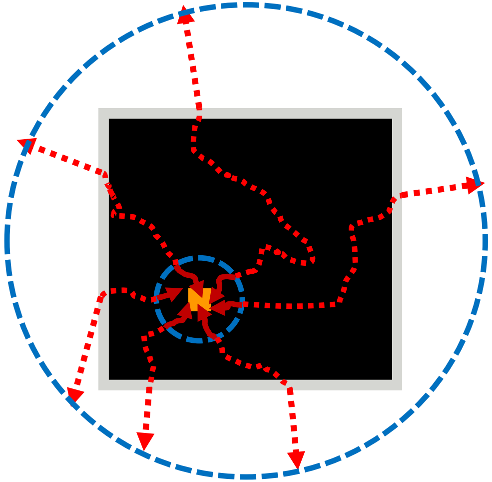
G. Santin, RADECS 2017



Reverse Monte Carlo implementation in GRAS

- Real MC simulation (not back-extrapolation of tracks)
  - New transport eq., “adjoint” to the “forward” eq.
- During reverse transport
  1. Simulation starts at new “adjoint source” close to target and scores at external source
     - Successive points are higher in energy, earlier in time
  2. Check at external source, the adjoint particle must belong to the **real source** phase-space, otherwise it is rejected
  3. Each adjoint physics process modifies **particle weight**
  4. Final weight at external source determines **probability of existence** for tracked particle
  5. This weight is used as **source biasing** for a **forward/direct** simulations, from the adjoint source towards the target





Reverse Monte Carlo implementation in GRAS

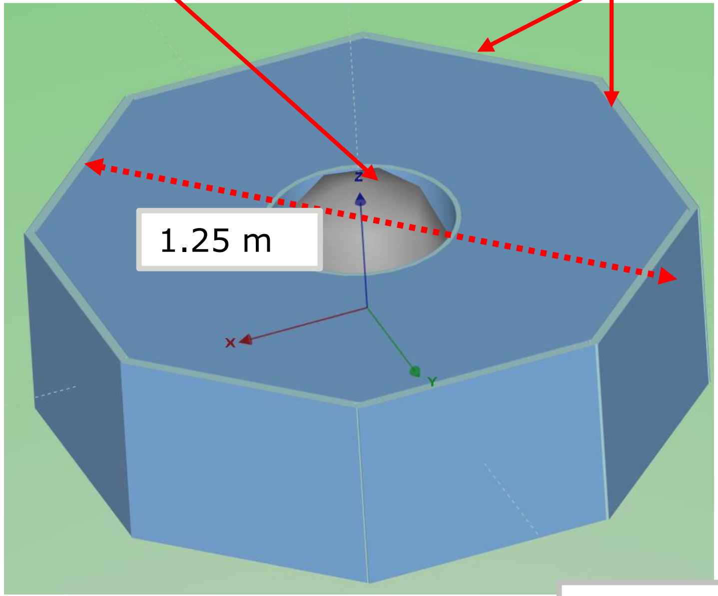
- **Adjoint tracking phase**
  - Adjoint particles are generated (adjoint_e-, adjoint_gamma,...) on the adjoint source
  - random position and direction
  - energy (1/E distribution)
- **Forward tracking phase**
  - Adjoint particles registered with corresponding primary, weights, types, positions, and directions
  - New particles generated and tracked in the forward direction in the sensitive region.
- **Reverse processes**
  - Reverse discrete ionization for e-, proton and ions
  - Continuous gain of energy by ionization and bremsstrahlung for e- and by ionization for protons and ions
  - Reverse discrete e- bremsstrahlung
  - Reverse photo-electric effect
  - Reverse Compton scattering
  - Approximated reverse multiple scattering
  - Continuous weight correction where all forward processes are taken into account
  - Splitting with factor 10 of primary gamma on the adjoint source in the forward tracking phase
  - Forced interaction of reverse gamma (Available since GEANT4 10.3)
- **Normalisation of simulation results to external primary spectrum**
- **Point detector mode available**
  - Fluence scored on a sphere of 10 um radius
  - NIST tabulated mass energy absorption coefficient

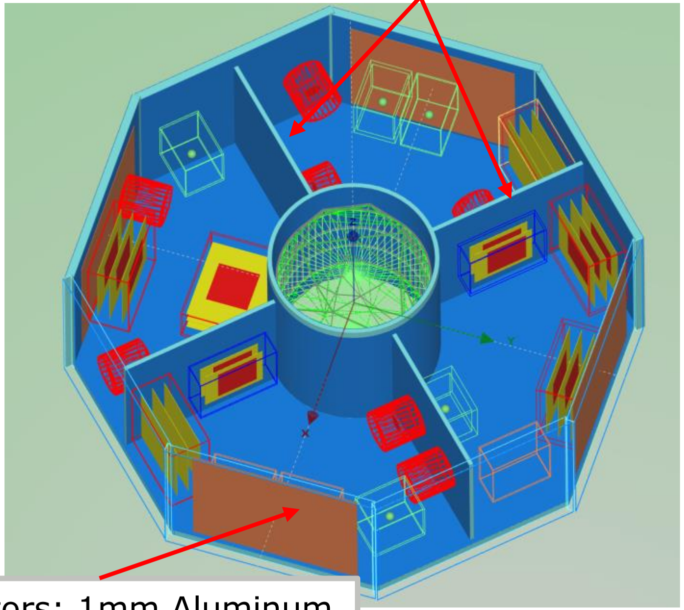
“Test Spacecraft” model design

Ti (1mm) fuel Tank, Hydrazine inside

External structure made of “sandwich” panels:
- 0.6 mm Carbon
- 19 mm Al Honeycomb
- 0.6 mm Carbon

Internal structure made of “sandwich” panels:
- 0.6 mm Carbon
- 10 mm Al Honeycomb
- 0.6 mm Carbon



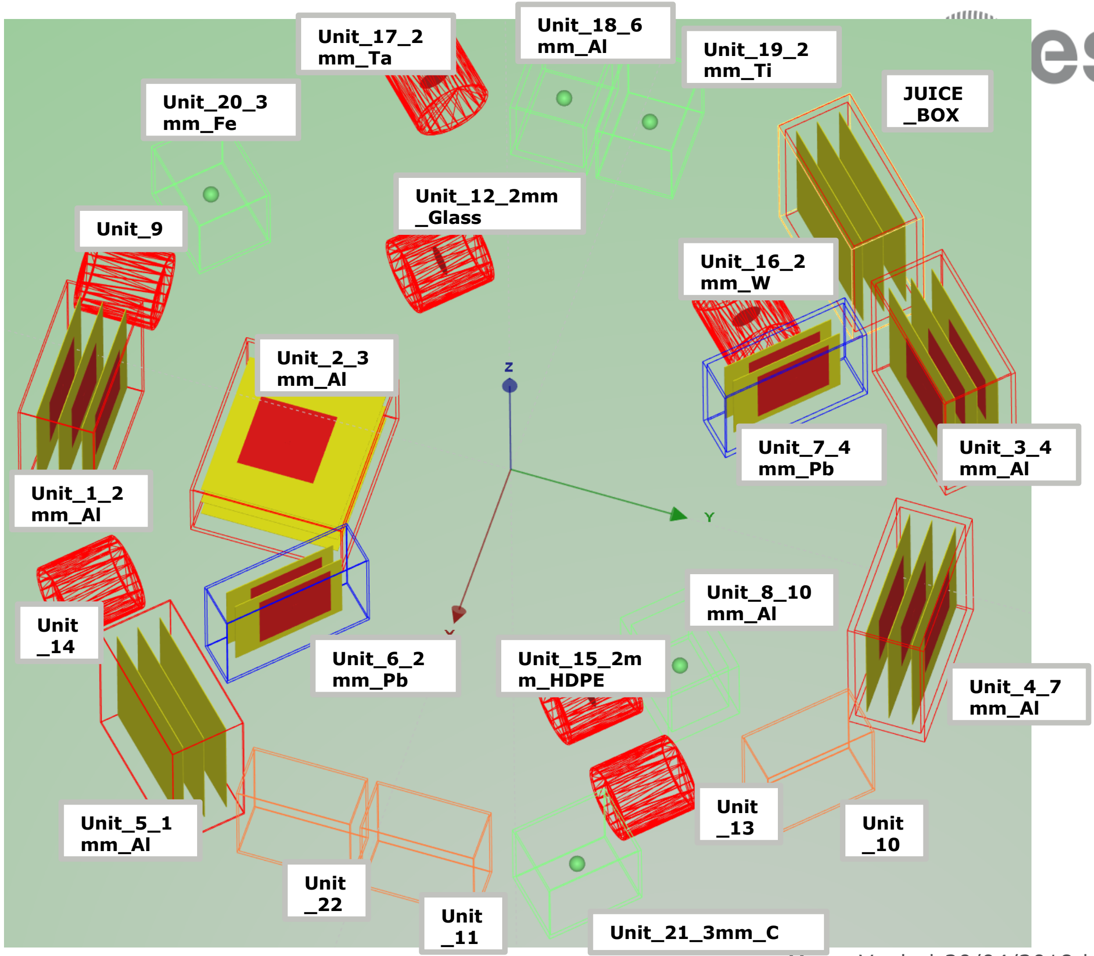


4xRadiators: 1mm Aluminum

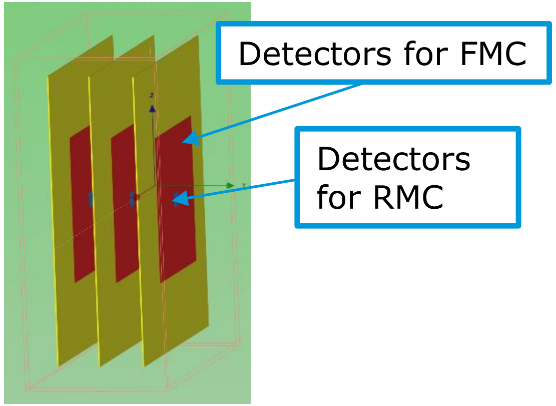
The model was built using the FASTRAD CAD interface and exported to GDML. Overlaps checks run both in FASTRAD and Genat4.

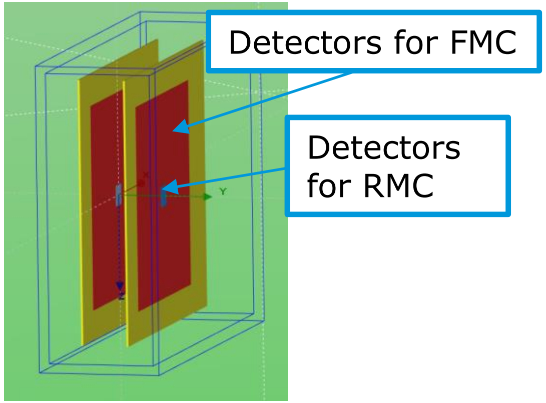
Units name:

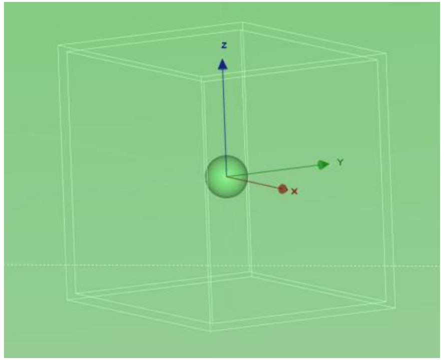
- The units are located in a random way inside the spacecraft
- The units boxes have different thicknesses, shapes and materials.
- Detectors can be:
  - planes
  - discs
  - shells



Units types 1/2





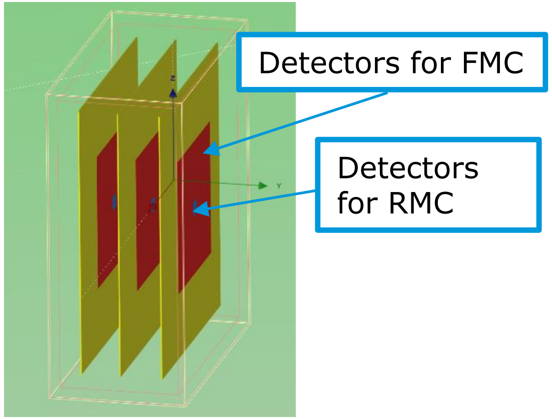


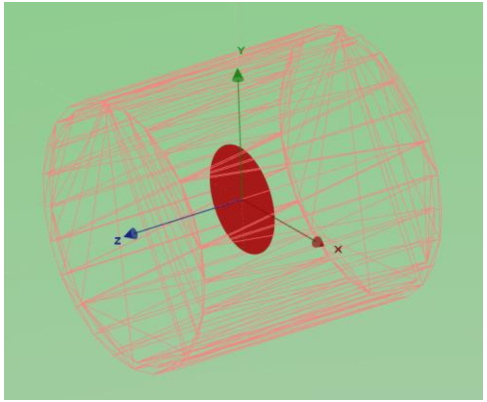
Type1
- External Box
- 3 PCBs
- 3 100x100x0.1 mm planar Si detectors
- 3 10x10x0.1 mm planar Si detectors

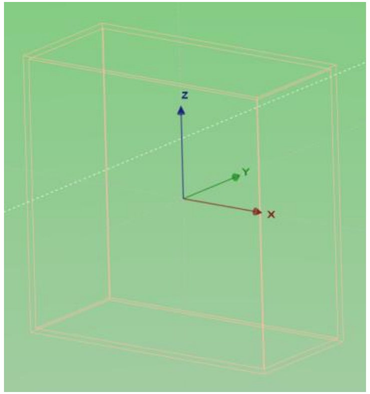
Type2
- External Box
- 2 PCBs
- 2 100x100x0.1 mm planar Si detectors
- 2 10x10x0.1 mm planar Si detectors

Type3
- External Box
- NO PCBs
- 1 Spherical shell Si detector: r=50mm , s=0.1mm

Units types 2/2







Type4: JUICE BOX
- External Box: 1mm Pb+6mm Al
- 3 PCBs
- 3 100x100x0.1 mm planar Si detectors
- 3 10x10x0.1 mm planar Si detectors

Type5
- External Cylindrical Box
- NO PCBs
- 1 Disc Si detector: r=20mm , s=0.1mm

Type6
- External Cylindrical Box
- Empty, No detectors

Summary of the units

				Silicon Detectors		
	N.	Thick.	Mat.	Name	Shape	Box type
Unit_	1	2mm	Al	det_1_1_fw	100x100x0.1mm plane	1
				det_1_1_rv	10x10x0.1mm plane	
				det_1_2_fw	100x100x0.1mm plane	
				det_1_2_rv	10x10x0.1mm plane	
				det_1_3_fw	100x100x0.1mm plane	
				det_1_3_rv	10x10x0.1mm plane	
Unit_	2	3mm	Al	det_2_1_fw	100x100x0.1mm plane	1
				det_2_1_rv	10x10x0.1mm plane	
				det_2_2_fw	100x100x0.1mm plane	
				det_2_2_rv	10x10x0.1mm plane	
				det_2_3_fw	100x100x0.1mm plane	
				det_2_3_rv	10x10x0.1mm plane	
Unit_	3	4mm	Al	det_3_1_fw	100x100x0.1mm plane	1
				det_3_1_rv	10x10x0.1mm plane	
				det_3_2_fw	100x100x0.1mm plane	
				det_3_2_rv	10x10x0.1mm plane	
				det_3_3_fw	100x100x0.1mm plane	
				det_3_3_rv	10x10x0.1mm plane	
Unit_	4	7mm	Al	det_4_1_fw	100x100x0.1mm plane	1
				det_4_1_rv	10x10x0.1mm plane	
				det_4_2_fw	100x100x0.1mm plane	
				det_4_2_rv	10x10x0.1mm plane	
				det_4_3_fw	100x100x0.1mm plane	
				det_4_3_rv	10x10x0.1mm plane	
Unit_	5	1mm	Al	det_5_1_fw	100x100x0.1mm plane	1
				det_5_1_rv	10x10x0.1mm plane	
				det_5_2_fw	100x100x0.1mm plane	
				det_5_2_rv	10x10x0.1mm plane	
				det_5_3_fw	100x100x0.1mm plane	
				det_5_3_rv	10x10x0.1mm plane	

Unit_	6	2mm	Pb	det_6_1_fw	100x100x0.1mm plane	2
				det_6_1_rv	10x10x0.1mm plane	
				det_6_2_fw	100x100x0.1mm plane	
				det_6_2_rv	10x10x0.1mm plane	
Unit_	7	4mm	Pb	det_7_1_fw	100x100x0.1mm plane	2
				det_7_1_rv	10x10x0.1mm plane	
				det_7_2_fw	100x100x0.1mm plane	
				det_7_2_rv	10x10x0.1mm plane	
Unit_	8	10mm	Al	det_8	Shell r=50mm, s=0.1 mm	3
Unit_	9	2mm	Al	-	-	5
Unit_	10	2mm	Al	-	-	6
Unit_	11	2mm	Al	-	-	6
Unit_	12	2mm	Glass_Pyrex	det_12	Disc r=20mm, s=0.1mm	5
Unit_	13	2mm	Al	-	-	5
Unit_	14	2mm	Al	-	-	5
Unit_	15	2mm	HDPE	det_15	Disc r=20mm, s=0.1mm	5
Unit_	16	2mm	W	det_16	Disc r=20mm, s=0.1mm	5
Unit_	17	2mm	Ta	det_17	Disc r=20mm, s=0.1mm	5
Unit_	18	6mm	Al	det_18	Shell r=50mm, s=0.1 mm	3
Unit_	19	2mm	Ti	det_19	Shell r=50mm, s=0.1 mm	3
Unit_	20	3mm	Fe	det_20	Shell r=50mm, s=0.1 mm	3
Unit_	21	3mm	C	det_21	Shell r=50mm, s=0.1 mm	3
Unit_	22	3mm	Al	-	-	6
JUICE_BOX		1mm Pb+6mm Al		JUICE_PCB1_fw	100x100x0.1mm plane	4
				JUICE_PCB1_rv	10x10x0.1mm plane	
				JUICE_PCB2_fw	100x100x0.1mm plane	
				JUICE_PCB2_rv	10x10x0.1mm plane	
				JUICE_PCB3_fw	100x100x0.1mm plane	
				JUICE_PCB3_rv	10x10x0.1mm plane	

GRAS 4.0: point vs volume detector dose [krad]

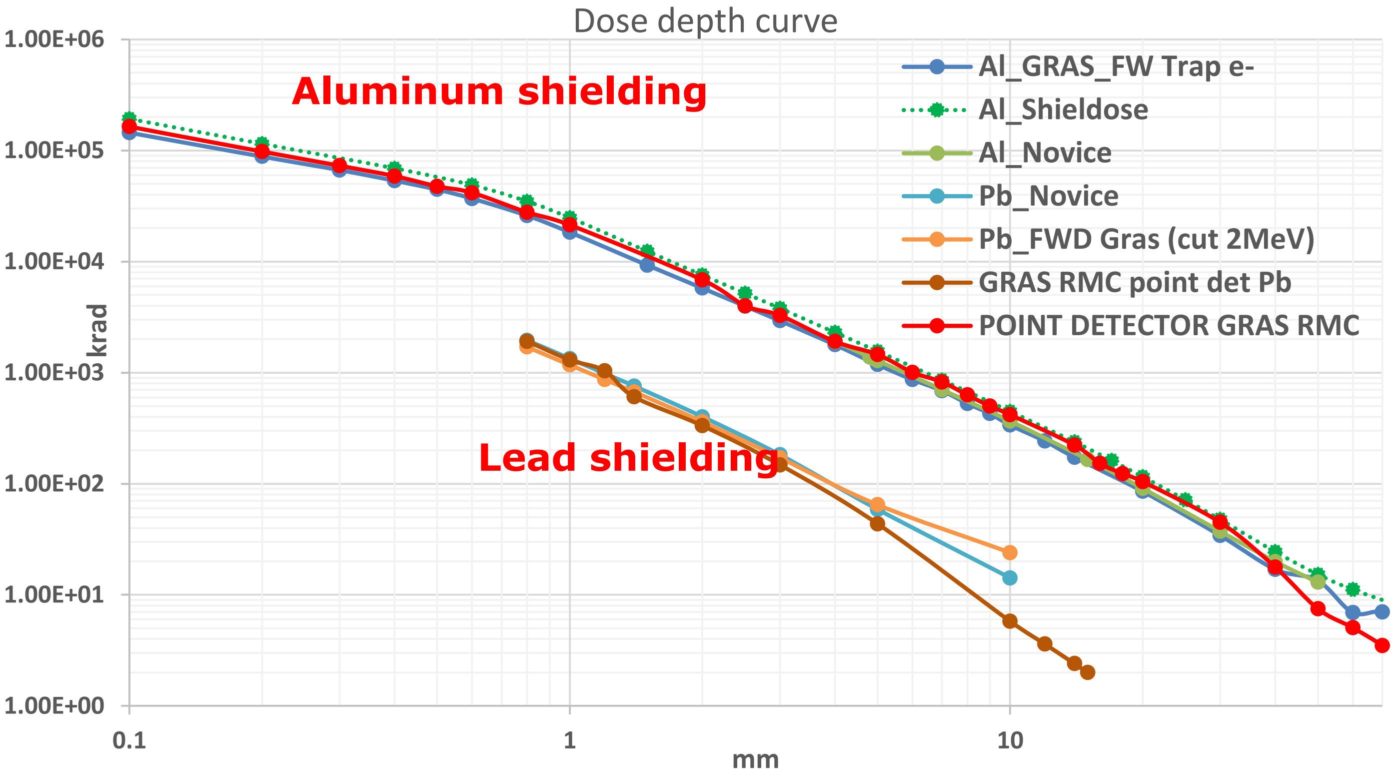
Targets	Point Det p_trap	Point Det e_trap	Point Det p_sol	Point Det Total	Volume Det p_trap	Volume Det e_trap	Volume Det p_sol	Volume Det Total	Diff%
Det_1_1	7.2	674.9	9.1	691.2	7.2	612.7	8.8	628.6	9.0%
Det_1_2	7.0	656.5	8.8	672.3	7.1	581.8	9.0	597.9	11.1%
Det_1_3	6.2	629.8	8.3	644.2	6.5	565.2	8.1	579.7	10.0%
Det_2_1	5.3	494.3	7.1	506.8	5.2	434.3	7.1	446.6	11.9%
Det_2_2	5.2	502.3	7.1	514.5	5.2	438.8	7.1	451.0	12.3%
Det_2_3	5.4	533.1	7.1	545.7	5.1	471.4	7.0	483.5	11.4%
Det_3_1	4.4	389.3	6.2	399.9	4.4	326.1	6.1	336.6	15.8%
Det_3_2	4.2	359.7	6.1	370.0	4.0	317.8	6.1	327.9	11.4%
Det_3_3	3.7	340.8	5.5	349.9	3.9	301.8	5.7	311.4	11.0%
Det_4_1	2.3	168.2	3.8	174.3	2.3	139.8	3.7	145.8	16.3%
Det_4_2	2.4	165.9	3.9	172.2	2.4	144.6	3.9	150.9	12.3%
Det_4_3	2.2	166.7	3.6	172.4	2.2	138.3	3.7	144.3	16.3%
Det_5_1	12.6	1319.1	13.5	1345.2	13.1	1212.8	13.5	1239.3	7.9%
Det_5_2	11.2	1192.9	12.6	1216.6	11.5	1136.8	12.5	1160.8	4.6%
Det_5_3	11.2	1238.3	12.3	1261.8	11.4	1104.9	12.4	1128.7	10.5%
Det_6_1	3.0	61.6	4.6	69.3	2.9	47.9	4.6	55.5	20.0%
Det_6_2	3.2	61.6	4.8	69.6	3.1	50.6	4.7	58.4	16.2%
Det_7_1	1.1	8.1	1.9	11.0	1.0	6.5	1.9	9.4	15.1%
Det_7_2	1.2	9.0	2.1	12.2	1.1	6.7	2.0	9.8	19.9%
Det_JUICE_1	1.9	69.7	3.2	74.8	1.9	60.3	3.3	65.5	12.5%
Det_JUICE_2	2.0	72.4	3.3	77.7	2.0	61.7	3.5	67.1	13.6%
Det_JUICE_3	1.8	69.4	3.1	74.3	1.8	60.0	3.1	64.9	12.7%

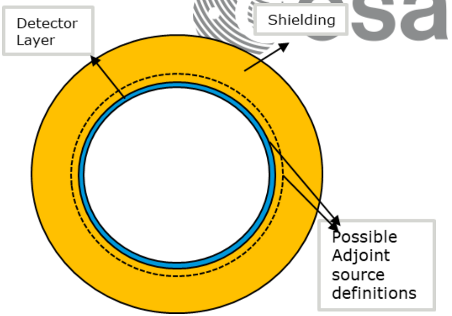
- Simulations are performed using JUICE environment (Jovian trapped particles and solar protons)
- In the frame of JUICE similar comparisons with other MC tools (FASTRAD, NOVICE) were performed and showed a good agreement for TID values (+/-20%)

Differences:

- Point detector results are 4-20% higher
- This is strongly dependent on the detectors geometry:
    - Sphere, disc, slab
    - dimensions

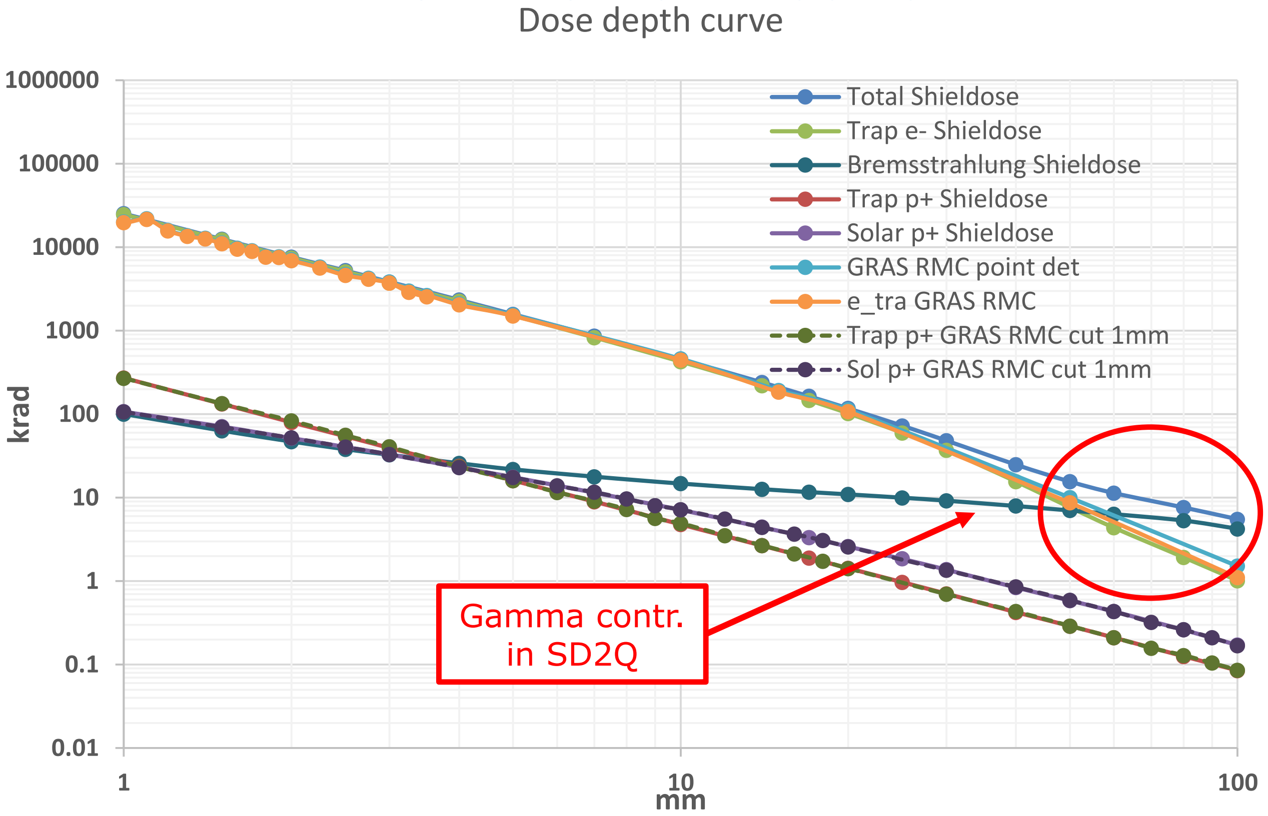
Dose-Depth Curves





- Simulations are performed using JUICE environment (Jovian trapped particles and solar protons)
- NOVICE results provide by T.Bouchet (AIRBUS) in the framework of JUICE simulations validation
- Novice/GRAS (FWMC) are 15-20% lower then Shieldose

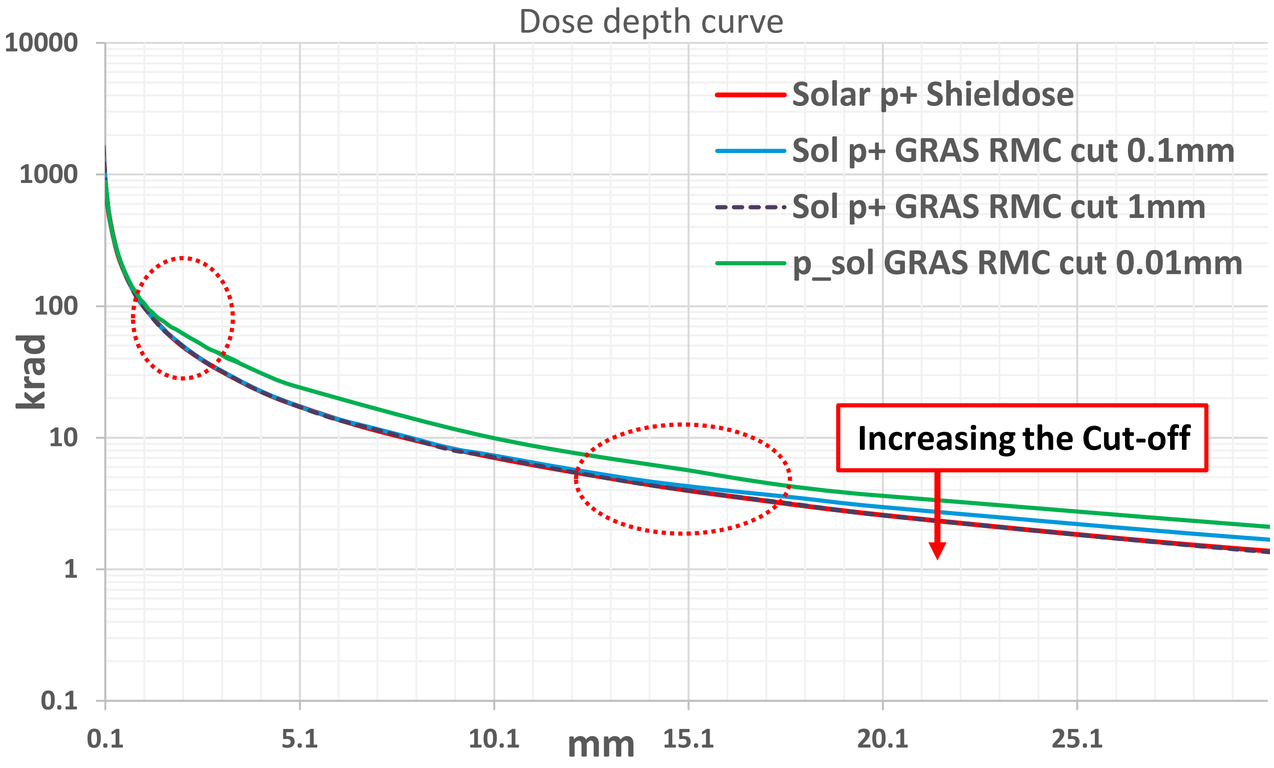
GRAS RMC: Gamma contribution



Gamma contribution:
Results in the output Spectrum1.csv file, for very thick shielding, seems to be underestimated in comparison with Shieldose.

- Some new tests Possible errors in physics or in the normalization.

GRAS RMC: Cut-off for protons



- Shieldose curve is eq. to GRAS with cut off 1mm
- Increasing the cut off -> lower dose values
- Differences are more visible for thick shielding

Tests in the frame of the ESA CIRSOS project

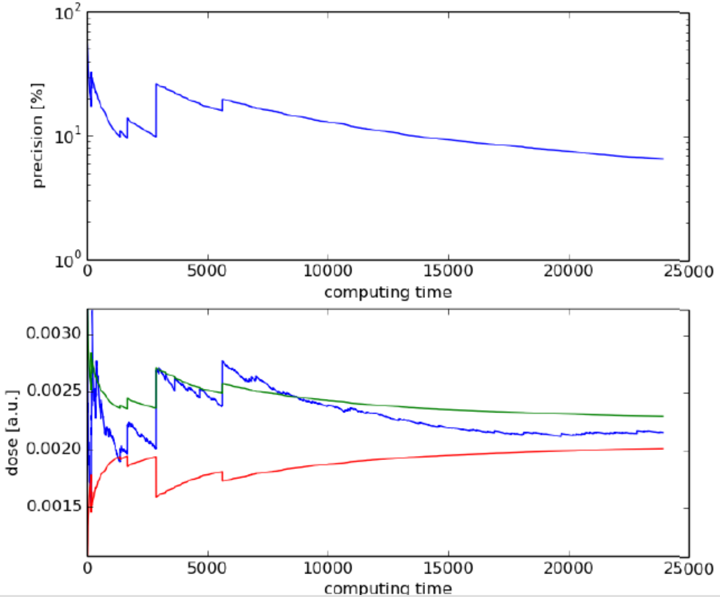
1. ***The execution of the GRAS tests (1D spherical geometry + 3D models) 2016-2018***
2. ***Comparison of the dose calculation using the GRAS RM, FMC and SD2Q***
3. ***The investigation of source definition effect in RMC***
4. ***The evaluation of the importance of pair-production process for JUICE type simulations***

Analysis and tests made by:
F.Lei supported by
L.Desorgher and **P.Truscott**

The 1D spherical geometry tests:

- Big difference in the dose-vs-kinetic energy spectra between the FMC and RMC cases
    - Probably due to the GRAS tally implementation (to be investigated)
- Output file *Spectrum1.csv was incorrect due to the wrong weights for adjoint gamma splitting algorithm (Now fixed by L.Desorgher in a new GRAS patch!)
- Individual large energy depositions in > 5mm cases lead to the instability in convergence
- Generally the ADJ dose is lower than the FWD

50 mm Al + JUICE spectrum e-

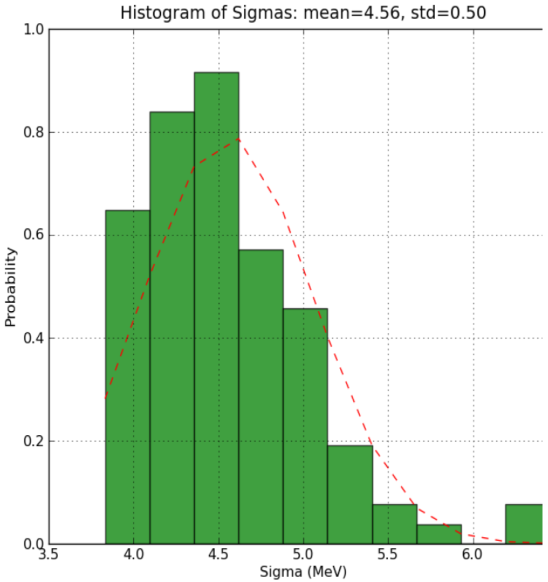


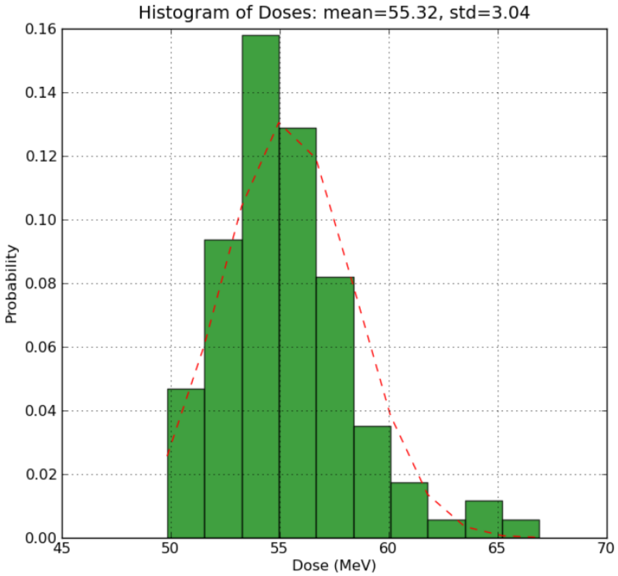
Investigation of the RMC Convergence

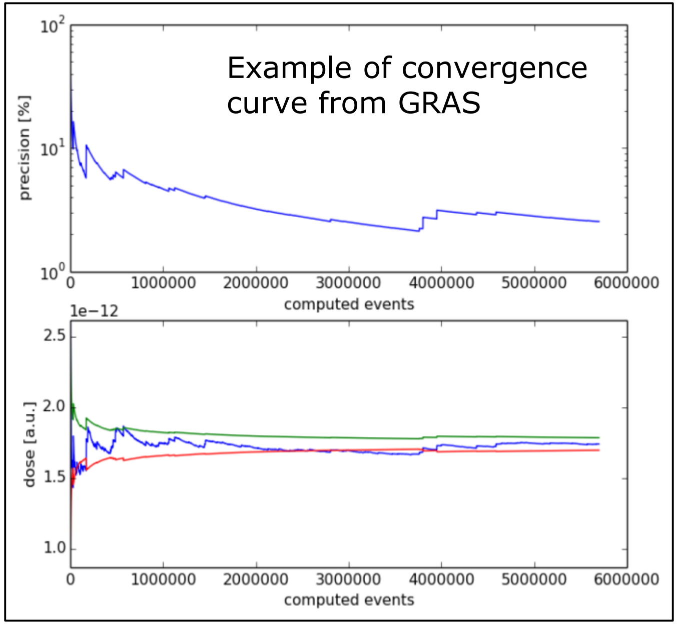
Statistical analysis of the RMC calculated TID and its associated error

Incident particle: Alpha = 1 Power law, e- spectrum, 0.1 – 1000 MeV

- 1D spherical geometry with 20 mm Al shield
- RMC only: 10^5 events, repeated 100 times



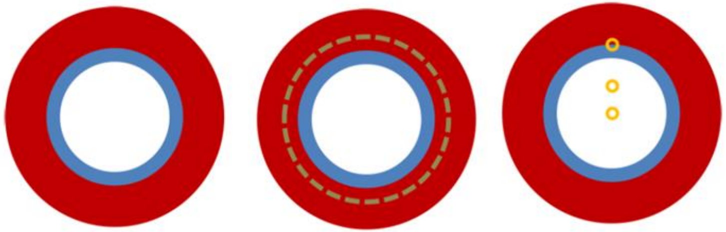




- The TID dose and its error, as well as the convergence curve, all behaved as expected.
- The calculated TID follows a Poisson/normal distribution with a mean of 55 MeV and a standard deviation of 3.04 MeV.

Adjoint source definition

50mm Al + JUICE spectrum



The radius of the sensitive shell is 10% of the shielding layer thickness and it is 10um thick Si.

Two types of adjoint sources are simulated:

- at the surface of the sensitive volume (ADJ), or artificial sphere X1 and X2(radius x2);
- point detectors at various locations within the sensitive volume (PD).

	Dose (rad)		Percentage
	Value	Error	
ADJ	1.07E-012	1.40E-014	-
X1	1.10E-012	1.46E-014	2.89%
X2	1.40E-012	5.08E-014	31.58%
PD-centre	1.74E-012	1.45E-014	63.37%
PD-halfway	1.71E-012	1.60E-014	60.35%
PD-surface	1.55E-012	1.21E-014	45.78%

- The doses calculated ADJ and X1 are statistically equivalent.
- The dose from simulations using adjoint source surface defined as on sphere with a radius 2x the sensitive volume is systematically higher, up to 30%.
- Doses calculated using point detectors systematically higher than those calculated using sensitive volume.

Summary and conclusions

- Several tests performed considering the important parameters:
  - Geometry of the detector
  - Materials and shielding thickness
  - Different sources
- Gamma contribution for thick shielding investigated
- Bug fixed in the gamma splitting normalization (TBC with more tests)
- Bug related to the physics “Cut off” identified
- Convergence study performed providing positive feedback
- Comparisons with other MC tools were done
- Test Spacecraft GDML 3D model used
- A new ESA activity will start soon to fix the open issues

Thanks for your attention!