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Internal charging simulation at a Galileo like orbit Effect of the anisotropic shielding and of the environment definition

Pierre Sarrailh

ONERA - Toulouse
Department Physics, Instrumentation, Environment, spacE (DPhIEE)

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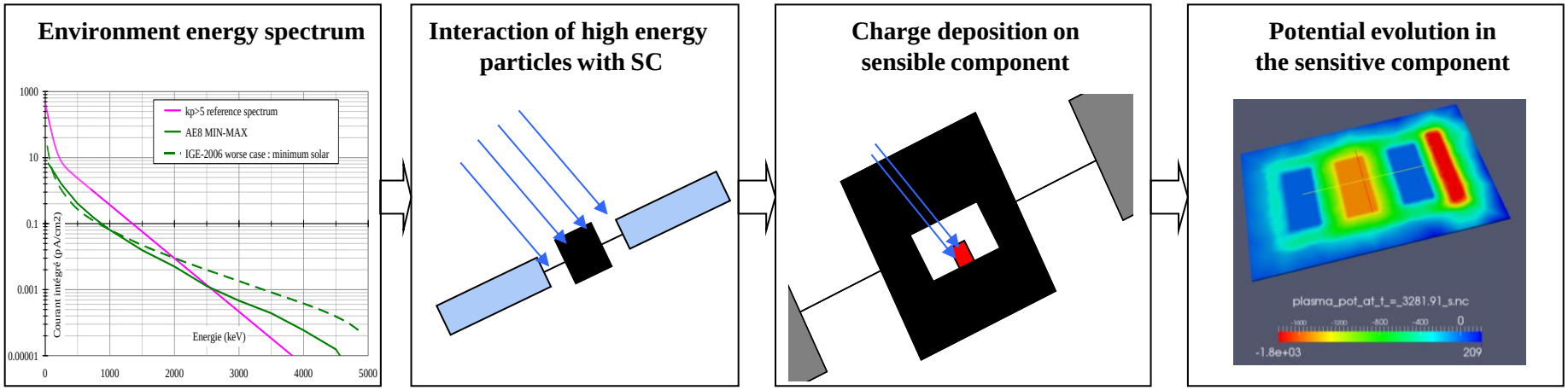
return on innovation

Internal charging context



1) High energy particles from the radiation belts: electrons or protons

2) Depending on the shielding:

- Electron with energy from 100s keV to 10s MeV
- Ion with energy > MeV

→ Stopped inside the payload components (i.e. charge deposition)

→ Deposit energy inside material (i.e. dose deposition)

3) Deposition of the charge and creation of a Radiation Induce Conductivity

→ Electric field buildup

→ Risk of electrostatic discharge inside the SC payload and/or subsystems

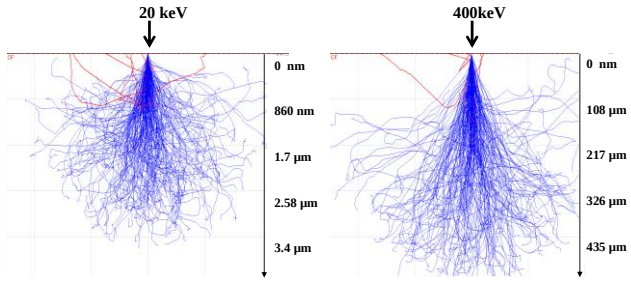
Simulation approach

Geant4/GRAS and SPIS coupling history:

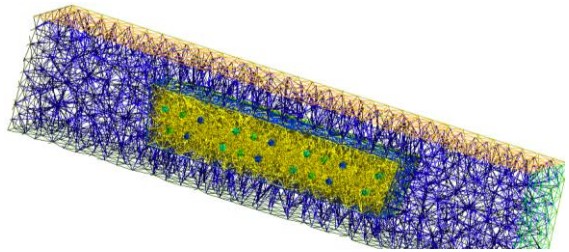
- ElShield project (ESA funded, 2009) → Electron shielding modeling and internal charging :
  - Geant4/GRAS for radiation transport in 3D geometry
  - SPIS: 3D plasma surface interaction code (electrostatic problems and conductivity)
  - Applied to MEO cases
- CIRSOS project (ESA funded, 2013) :
  - Same simulation approach
  - Development of the collaborative capabilities of the tools
  - Improvement of the user interfaces and data exchanges
  - Applied to Jupiter orbit cases
- 3DMICS project (ESA funded, 2014) :
  - Implement new conductivity models in SPIS
  - Validate wrt ground experiment the simulation approach Geant4 + SPIS
  - 4 validation cases defined from simple 1D geometry with constant beam to 3D realistic sample with time varying electron beam

Charging model

Monte Carlo radiation transport (Geant4/Gras)



Charge and dose deposition on the computational mesh (Geant4/GRAS)



Internal charge transport equations solved on the computational mesh by a finite element method:

- Poisson equation
- Continuity equation for the net charge
- Ohm's law

$$\begin{cases} -\nabla \bullet \left(\varepsilon_0 \varepsilon_r \nabla V\right) = \rho \\ \dfrac{\partial \rho}{\partial t} + \nabla \bullet J = \dot{\rho} \\ J = \sigma E \end{cases}$$

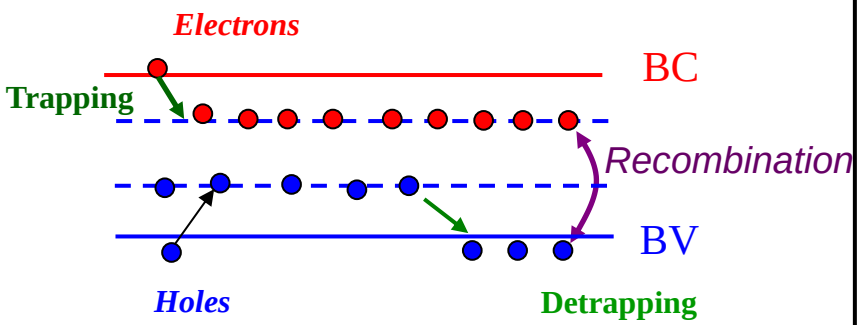
Conductivity model (based on band theory of solids):

- Zero-D model based on band theory:
  - Temperature and Electric field effects
  - Charge and dose deposition rate and accumulation
  - Temporal evolutions → RIC build-up and delayed RIC
- Conductivity not affected by charge transport (1 Zero-D model by mesh element)

Conductivity model

Model based on band theory of solid :

- Single level of localized traps for electrons and holes → deep levels
- Electron / hole pairs Generation by the electron beam (ionization)
- Trapping of free charges
- Free charge recombines with a localized charge



System of 4 evolution equations

$$\frac{dn}{dt} = g - \alpha n p_t - \frac{n}{\tau_n} + \frac{n_t}{\tau_{nt}}$$

$$\frac{dn_t}{dt} = \frac{n}{\tau_n} - \frac{n_t}{\tau_{nt}} - \alpha p n_t$$

$$\frac{dp}{dt} = g - \alpha n_t p - \frac{p}{\tau_p} + \frac{p_t}{\tau_{pt}}$$

$$\frac{dp_t}{dt} = \frac{p}{\tau_p} - \frac{p_t}{\tau_{pt}} - \alpha n p_t$$

Free charge transport (convection and diffusion) **not take into account** at the local scale

With generation rate:

$$g = \frac{\Delta E}{W}.\exp\left(-e^2/\varepsilon.k.T.r_0\right)\left(1+e^3.E/8.\pi.\varepsilon.k^2.T^2\right)$$

Conductivity from local transport equation :

$$J = J_n + J_p = (n.\mu_n + p.\mu_p).E$$

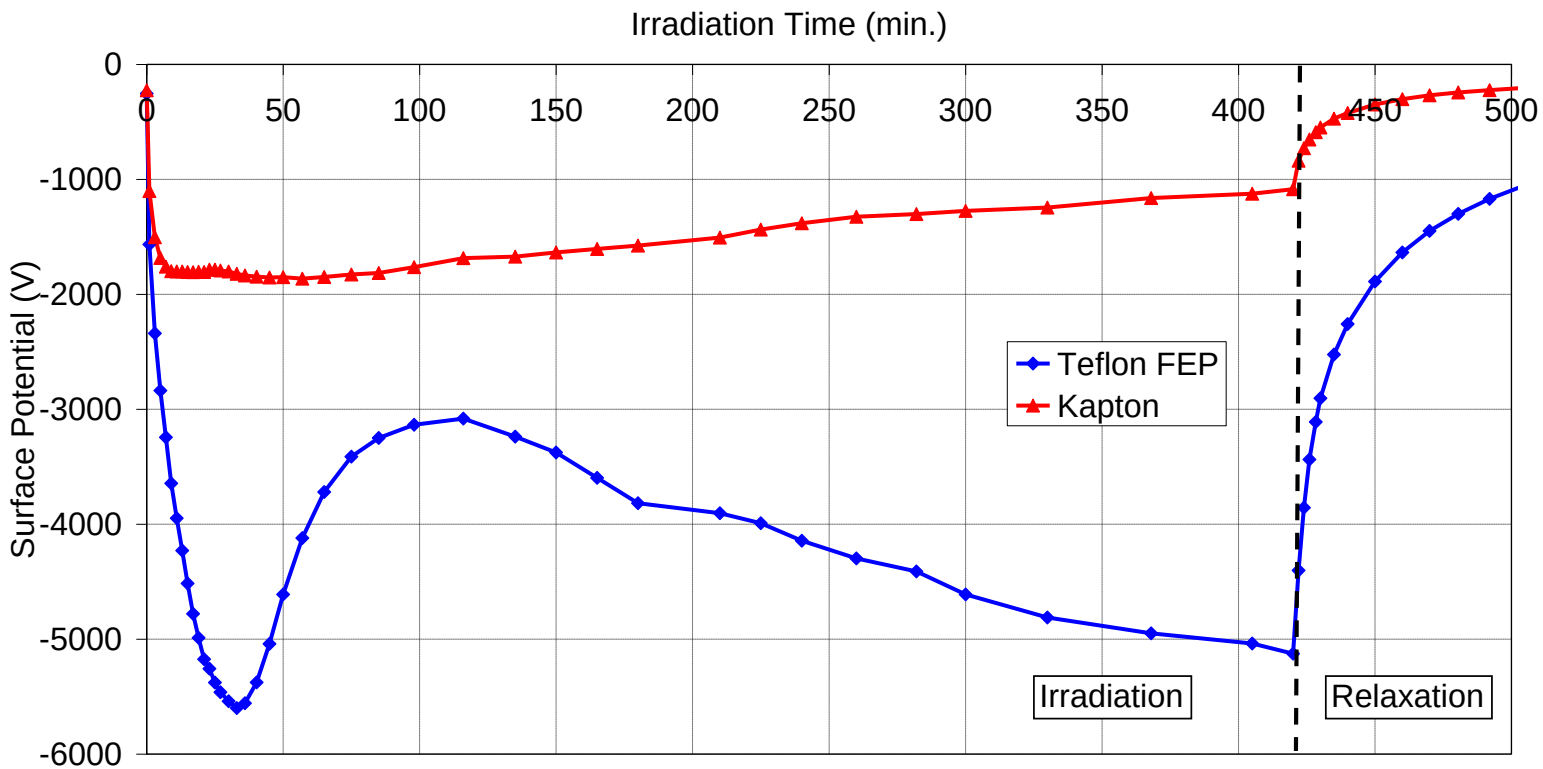
$$J = \sigma.E$$

Conductivity used in IC solver

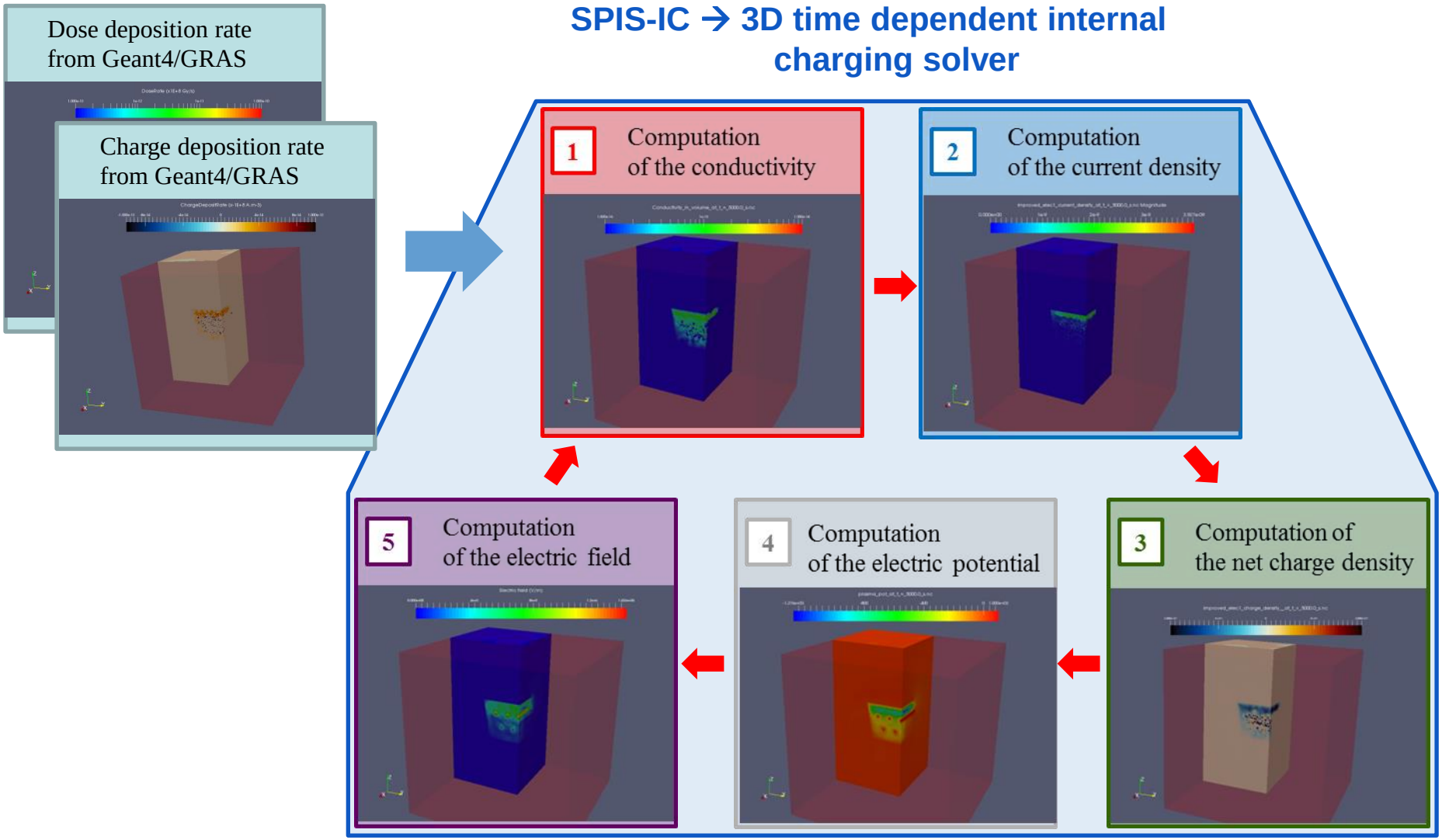
$$\sigma = n.\mu_n + p.\mu_p$$

Time dependent effect of the RIC

Electron irradiation under GEO-like conditions [20-400 keV]



Internal charging effect modelling chain



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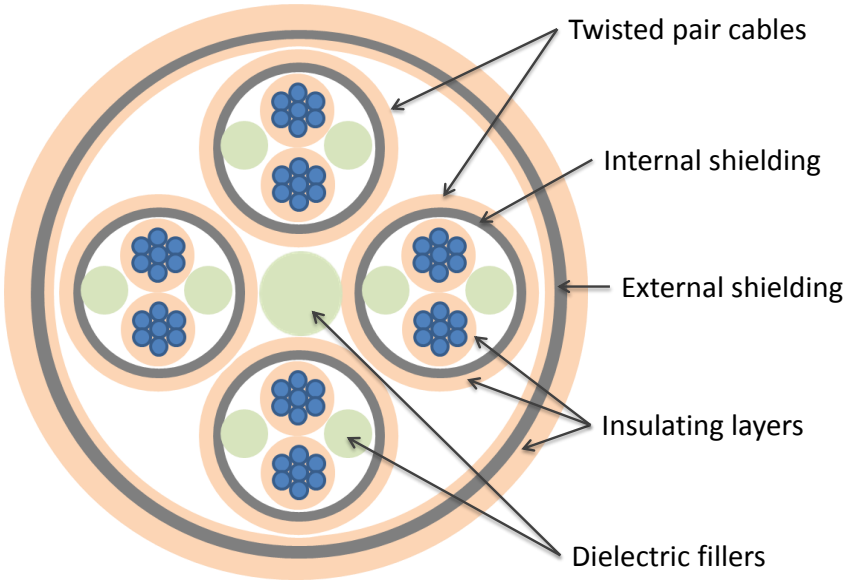
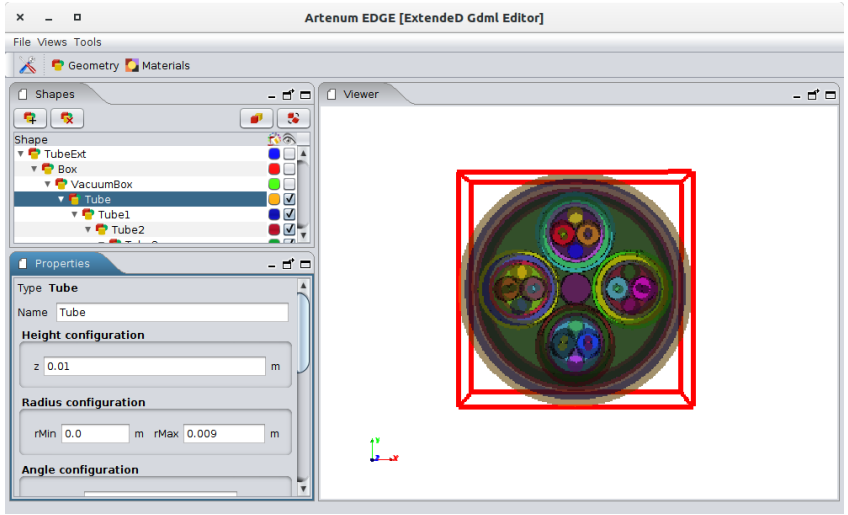
Geometry and conditions

Spacewire cable geometry (from the CIRSOS component catalog) :

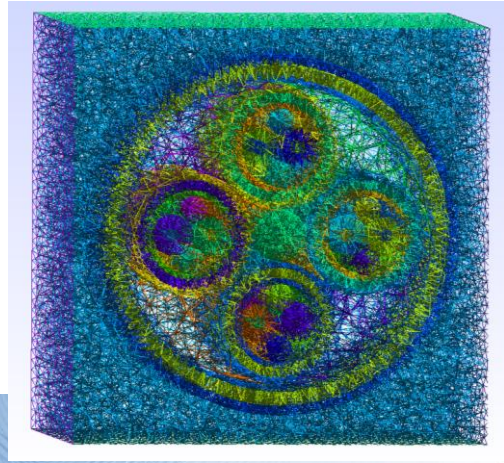
- **GDML geometry including “radiation” material properties**
- **GMSH geometry (unstructured mesh) for scoring dose and charge (IC material properties not included)**



GDML geometry of the component including the external shielding



GMSH geometry including vacuum volumes (~ 150 000 elements)



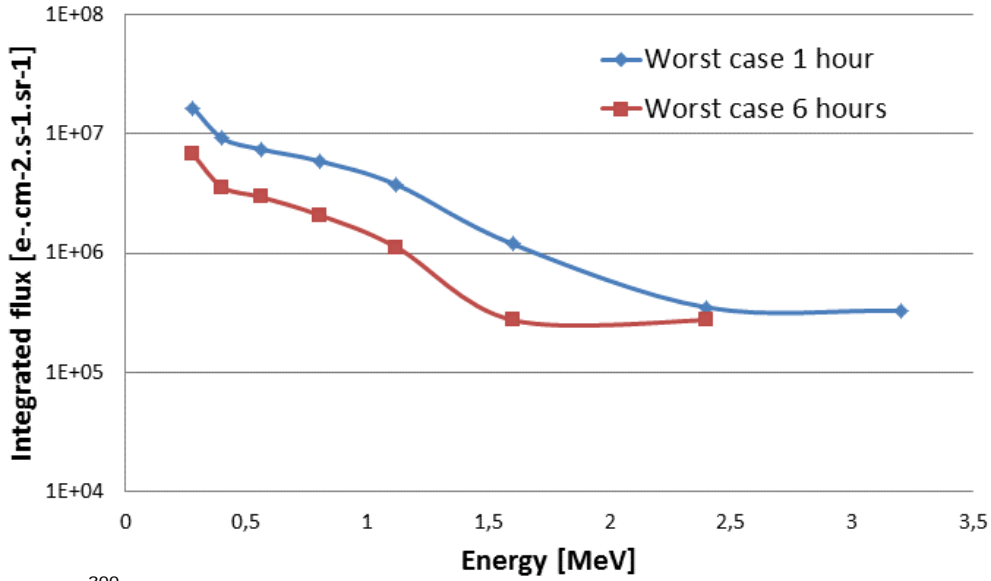
MEO environment for internal charging

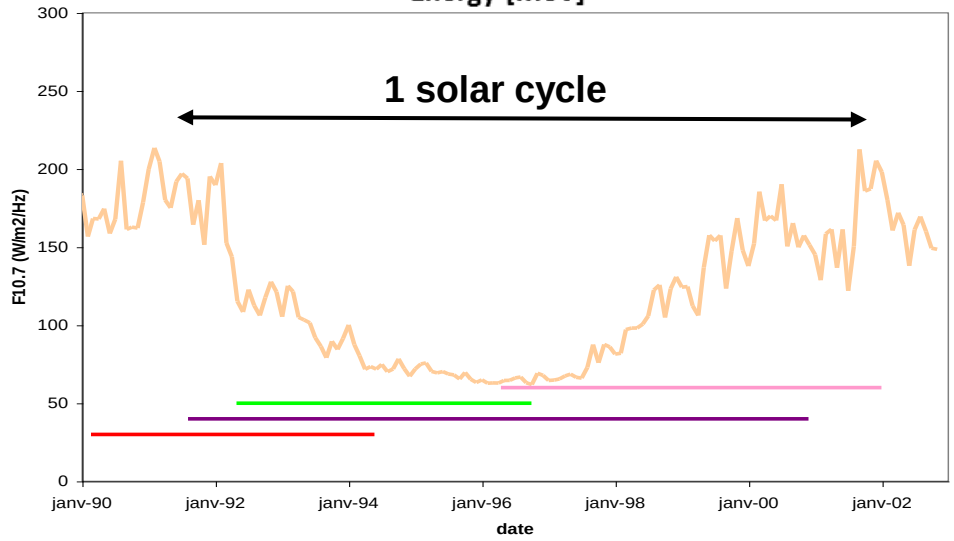
Electron environment relevant for internal charging:

- Averaged environment spectrums useless → internal charging events have typical time scale of **hours to days** (not months or years)
- Worst measured environment "too extreme" → fast change of the radiation belts during a geomagnetic event
- Definition of worst cases averaged on a relevant time for internal charging (here 1 hour and 6 hours)

Result extracted from ONERA/CNES R&T study (2005)

- Detector BDDII on 4 Spacecrafts
- NavStar (GPS) from LANL (1990 to 2001)





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Geant 4 / GRAS → Simulation of charge and dose deposition

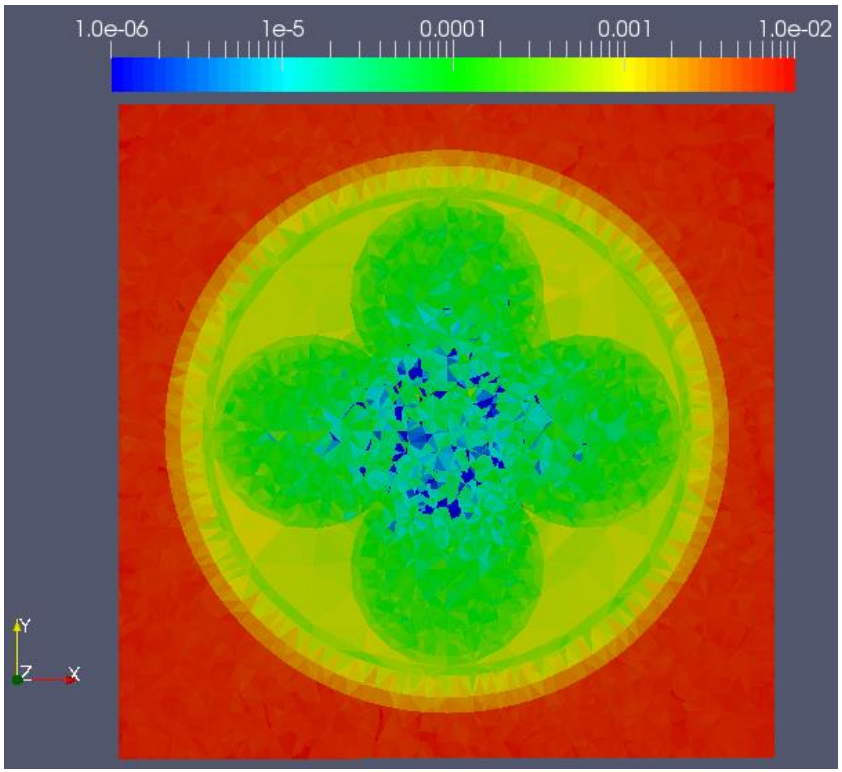
Geant4/GRAS simulation results using:

- Low energy electron physics
- Mesh scoring implemented in GRAS
- Results with $3x10^9$ events

Worst case 1h
Isotropic 1mm Al shielding

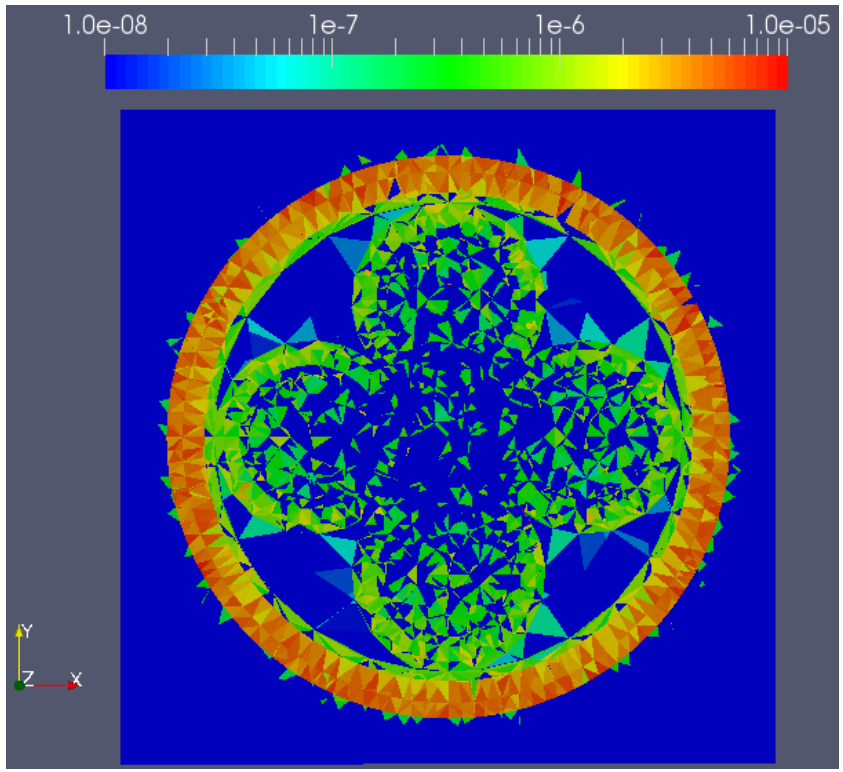
Dose deposition rate [Gy/s]

[10^{-6} to 10^{-2} Gy/s]



Charge deposition rate [A/m3]

[0.01 – 10 pA/cm3]



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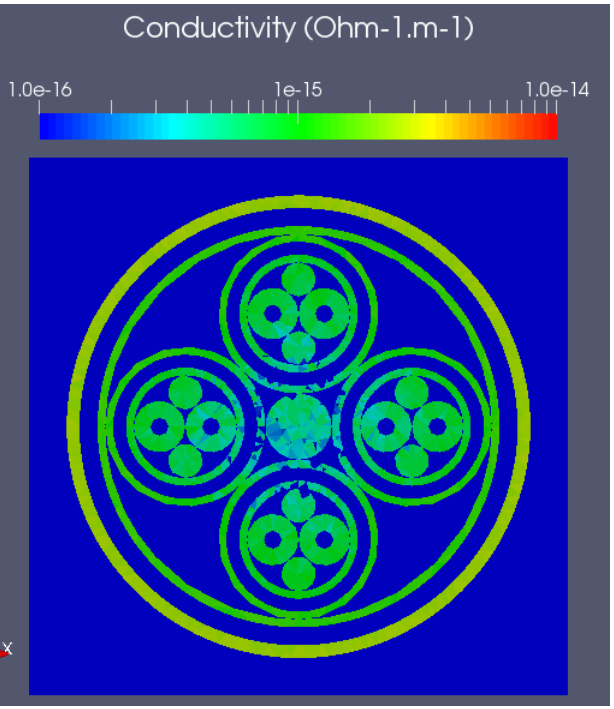
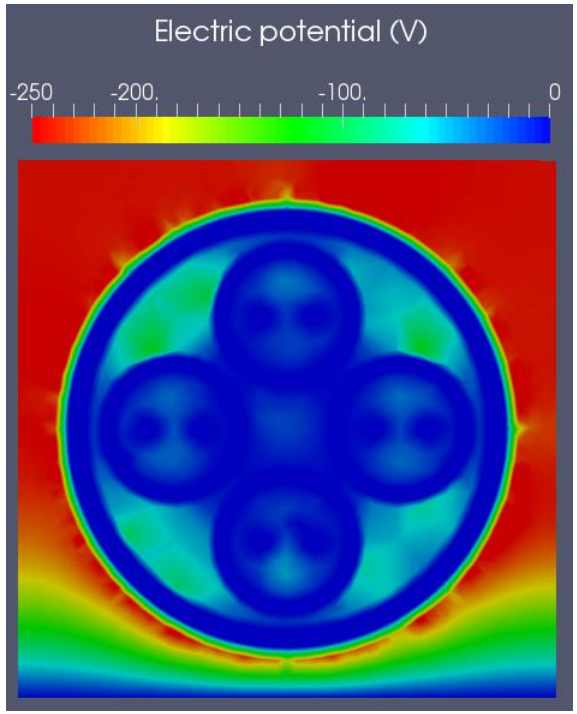
SPIS-IC results → Electric potential and electric field as a function of time

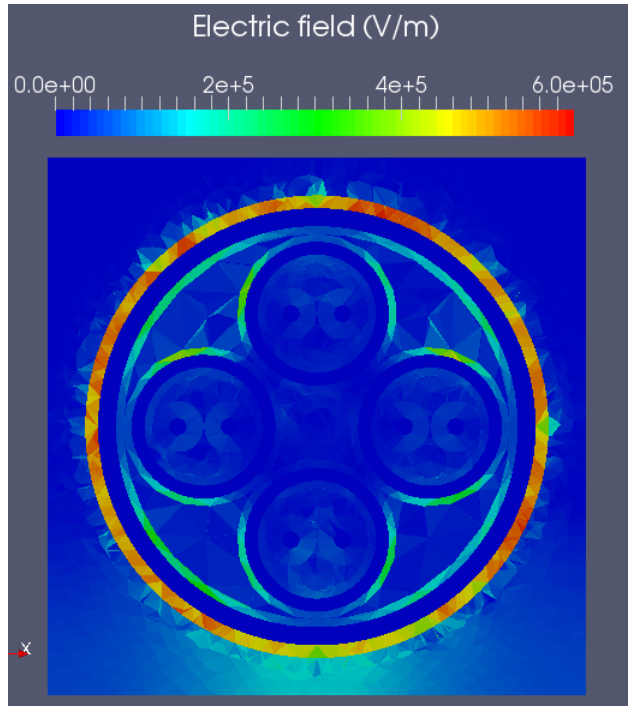
Internal charging simulation using SPIS-IC version 5.1.0

- Implicit time dependent solver
- Simulation over 6 hours

Worst case 1h
Isotropic 1mm Al shielding





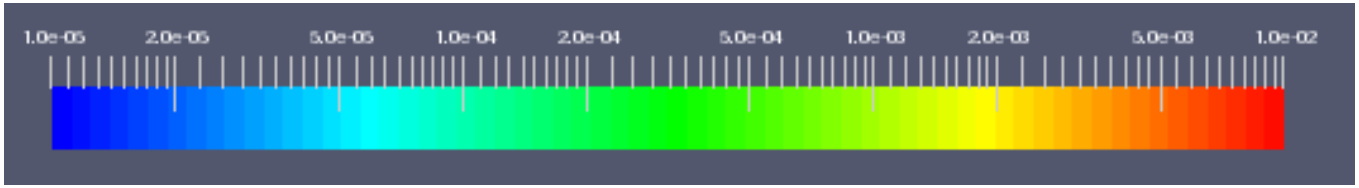


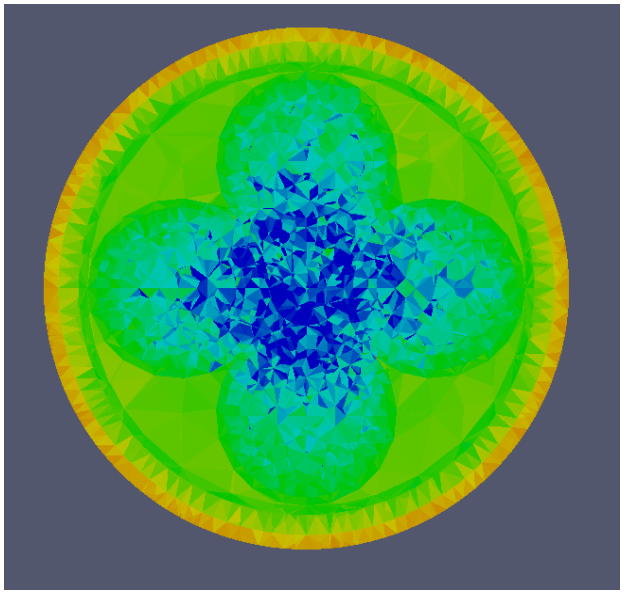
→ **Conductivity of dielectric not-uniform**

→ **Potential higher than 250 V in 6 hours but probably not discharge risk**

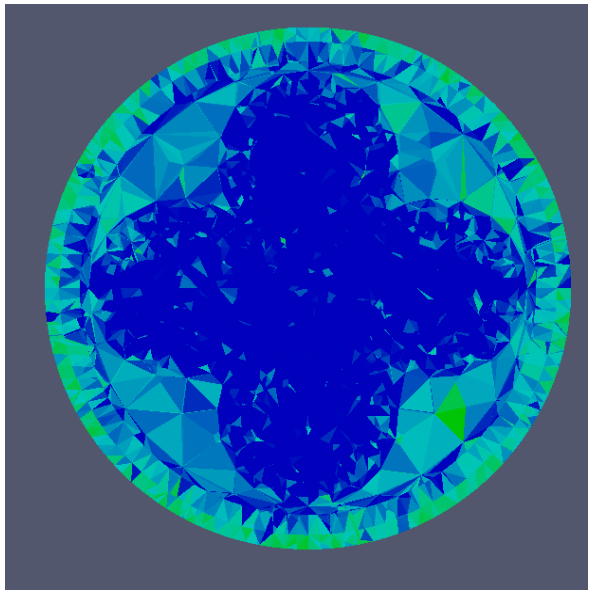
Effect of shielding – Dose

Dose deposition rate [Gy/s]
[10^{-6} to 10^{-2} Gy/s]

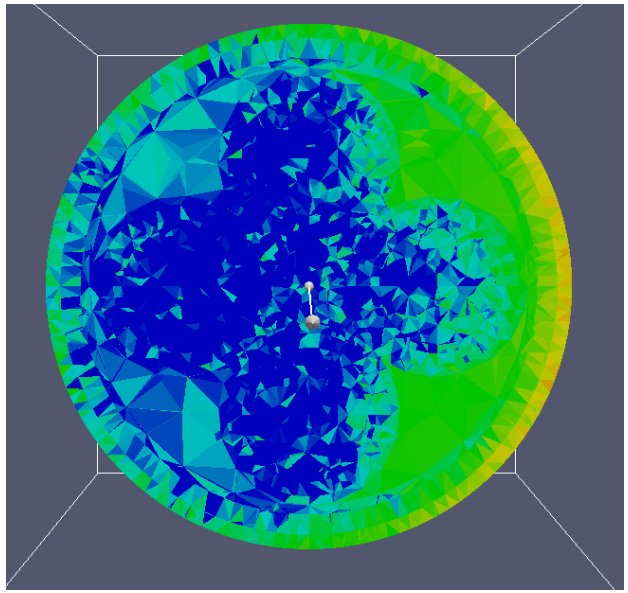




Worst case 1h
Isotropic 1mm Al shielding

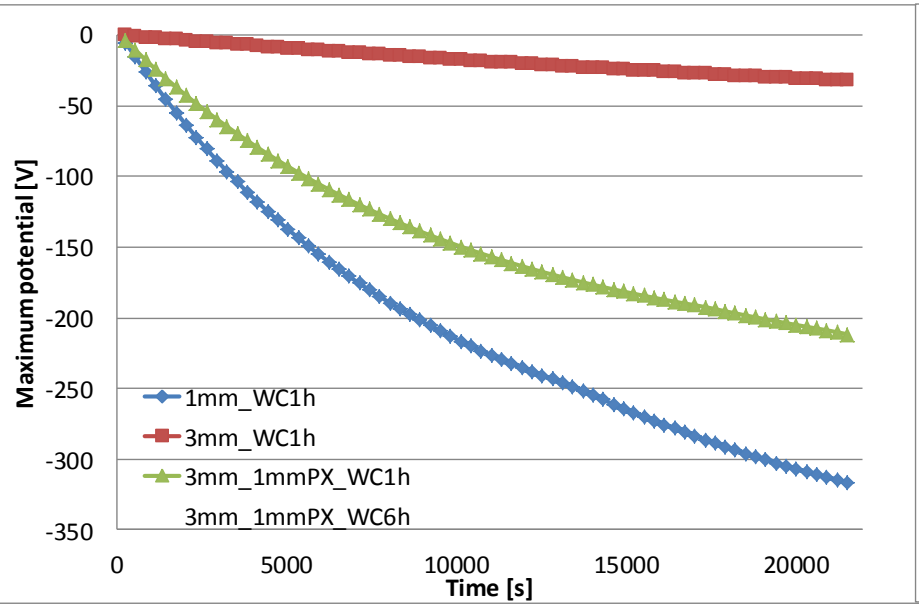


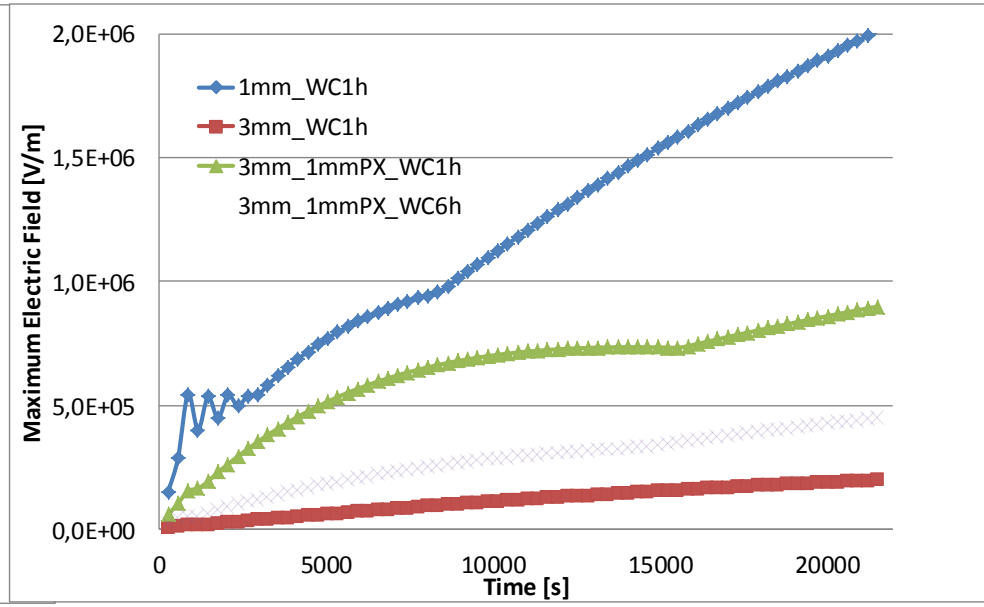
Worst case 1h
Isotropic 3mm Al shielding



Worst case 1h
Non-isotropic shielding Al:
1mm in +X
3mm others directions

Maximum electric field andpotential vs time





Time dependent evolution :

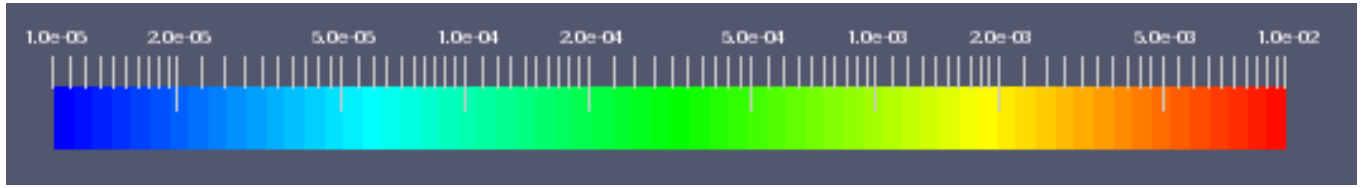
- Not a linear increases of the potential → effect of the conductivity
- Change in E field behavior → dielectrics reach a steady state (another one still charging)

Shielding effect :

- As expected, the shielding decreases the electric potential at a fixed time
- The stationary solution can be higher or smaller depending on the ratio charging current over conductivity (→ but stationary state never reached due to environment changes)

Effect of the environment – Dose

Dose deposition rate [Gy/s]
[10^{-6} to 10^{-2} Gy/s]



Total flux (> 0.28 MeV) from the environment:

1h WC → 1.64×10^{7} $cm^{-2}.s.sr^{-1}$

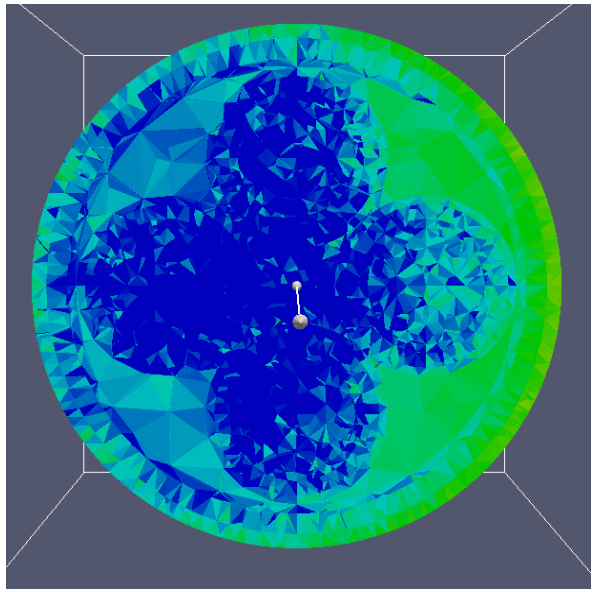
6h WC → 6.68×10^{7} $cm^{-2}.s.sr^{-1}$

➔ Factor of ~ 2.5

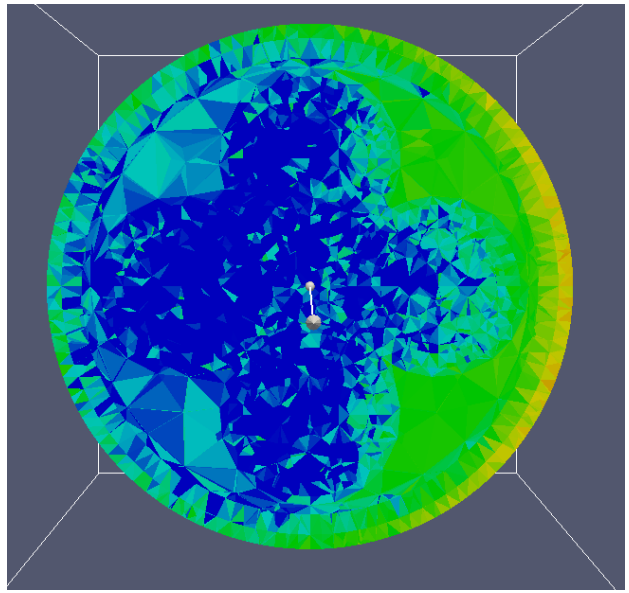
3D dose map results far from been proportional to the environment flux

➔ 3D geometry effects dominates

➔ Energy spectrum sufficiently different to see an effect

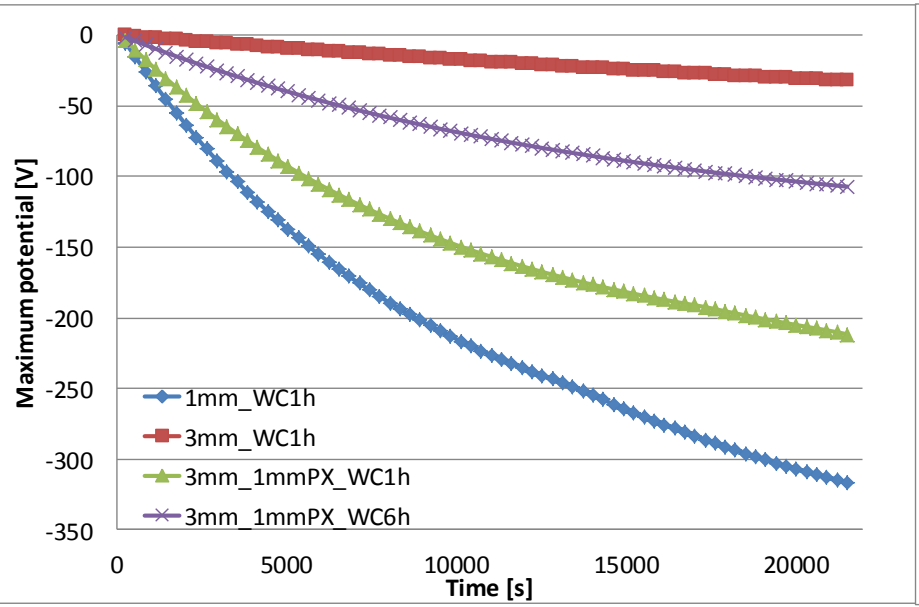


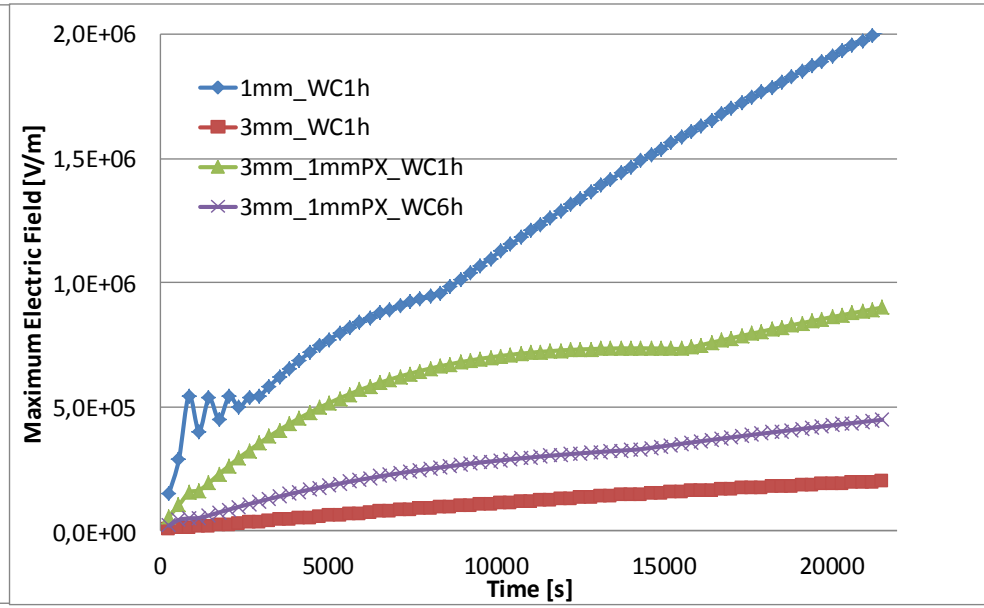
Worst case 6h
Non-isotropic shielding Al:
1mm in +X
3mm others directions



Worst case 1h
Non-isotropic shielding Al:
1mm in +X
3mm others directions

Maximum electric field and potential vs time



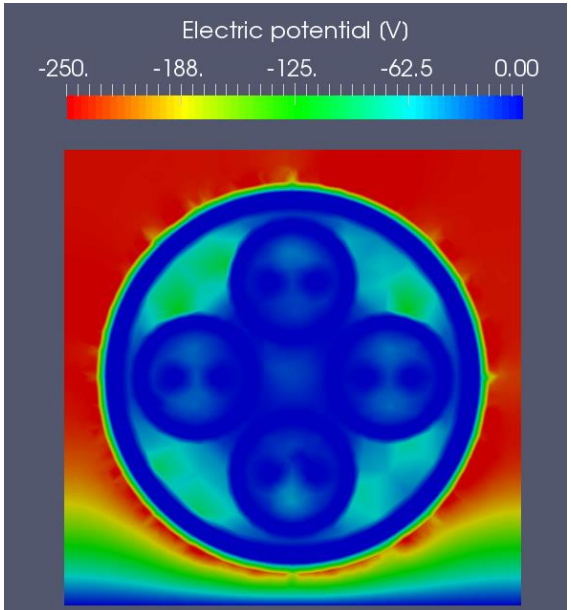


Environment WC effect:

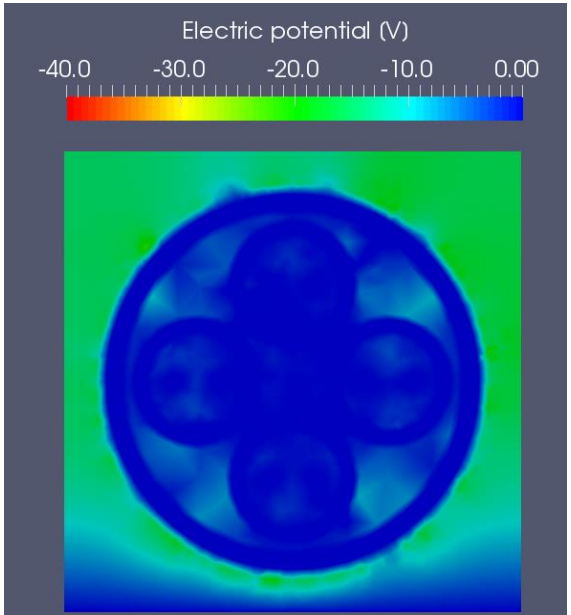
- Not a linear increases of the potential wrt total flux → flux x 2.5 but potential x by 2
- Change in E field behavior in time → dielectrics reach a different steady state with a different time scale

Charging maps after 6 hours irradiation

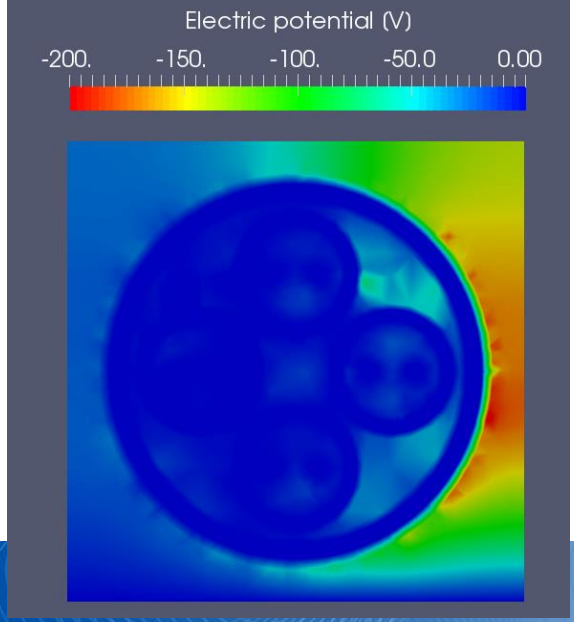
Worst case 1h
Isotropic shielding
Al: 1mm



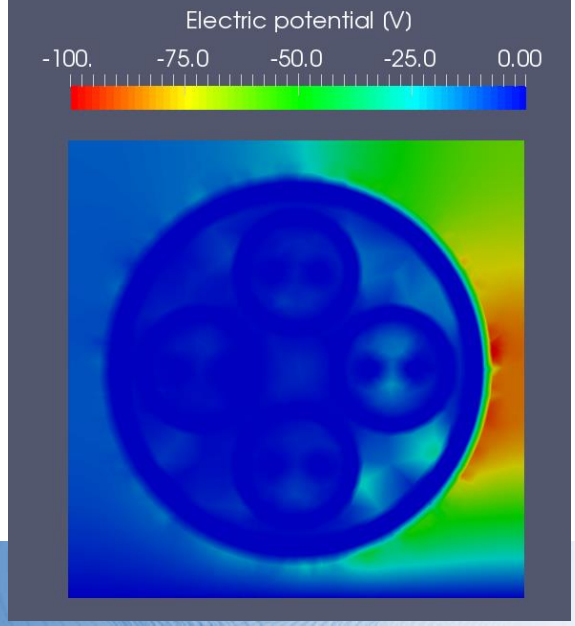
Worst case 1h
Isotropic shielding
Al: 3mm



Worst case 1h
Non-isotropic shielding Al: 1mm in +X
3mm others directions



Worst case 6h
Non-isotropic shielding Al: 1mm in +X
3mm others directions



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Conclusion and perspectives

Geant4/GRAS and SPIC-IC dedicated to internal charging charge transport:

- 3D time dependent fast and accurate IC solver
- New conductivity model based on band theory of solids that allow to take into account time dependent RIC effect
- Validated on experimental cases
- To assess the discharges risk in payload

MEO case simulation:

- Time dependent effect of the RIC → RIC could never be at steady state
- Geometry dependency of charge conduction
- Effect of the environment WC definition

Some physical phenomena are still not modelled in the IC simulations.

- Effect of the secondary electrons
- Surface conductivity
- Physics at the material interface

Environment effect

- Worst case for IC (probably not the highest flux for all the energies)
- Time fluctuations of the environment and the EOR orbits