3D Internal Charging Analysis with FASTRAD

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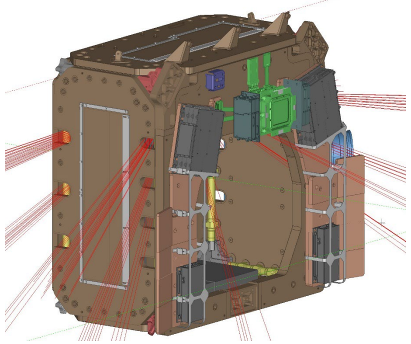
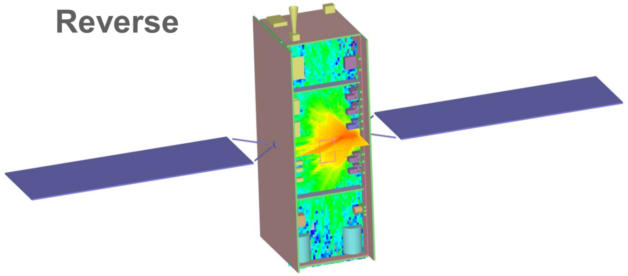
Introduction

Dose calculation (TID & TNID) based on two methods:

- **Sector analysis**
  Ray-Tracing

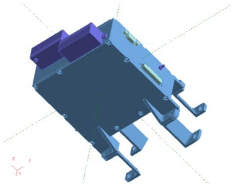


- **Particle transport based on GEANT4: Monte Carlo**
  Forward
  Reverse



Analysis process:

Import geometry from CAD softwares
(.STEP, .IGES)



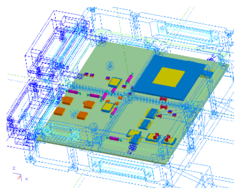
FASTRAD

MODELING
- Graphical user interface, material, components

Environment
(Dose curve, flux)

CALCULATIONS
- Sector analysis
- Monte Carlo
  - Forward
  - Reverse

POST PROCESSING
- Shielding, comparison to specifications

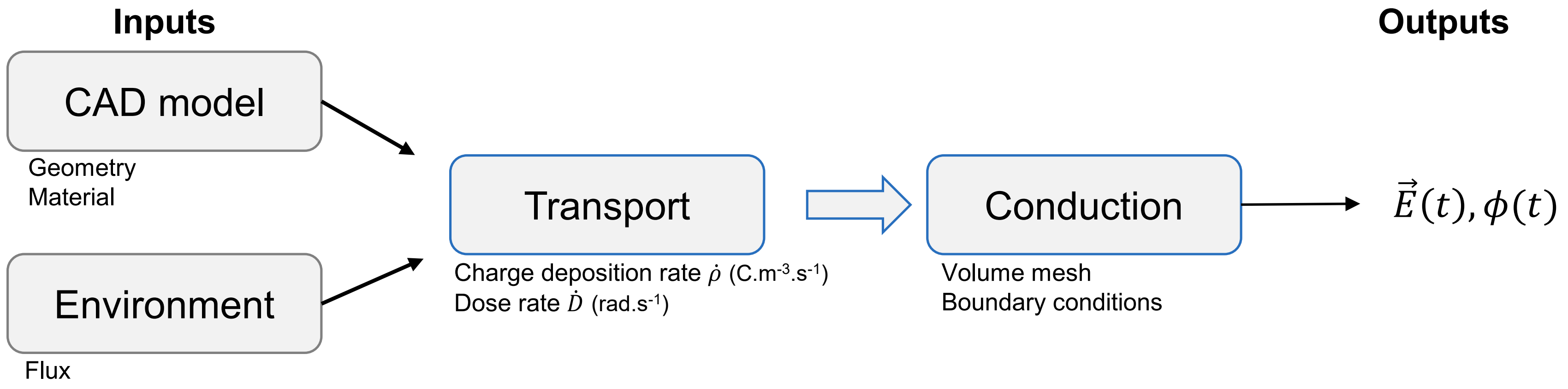


x Specifications not achieved

✓ Specifications achieved

Introduction

- General approach for the ESD risk assessment:



- Starting from the charge deposition $\dot{\rho}$ and the dose rate $\dot{D}$, the potential is solved in 3D.

Gauss equation

$$-\nabla\varepsilon\nabla\phi = \rho$$

Continuity equation

$$\frac{\partial\rho}{\partial t} + \nabla\vec{J} = \dot{\rho}$$

Ohm's law

$$\vec{J} = -\sigma\nabla\phi$$

Differential equation for the potential

$$-\nabla\varepsilon\nabla\frac{d\phi}{dt} - \nabla\sigma\nabla\phi = \dot{\rho}$$

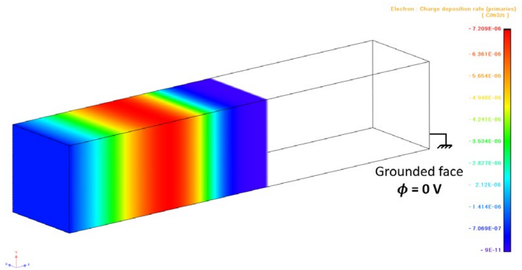
⇒

Outputs

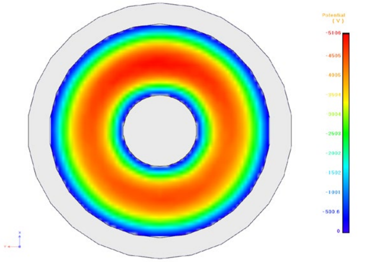
- $\phi(\vec{r}, t)$
- $\vec{E}(\vec{r}, t) = -\nabla\phi$

Outline

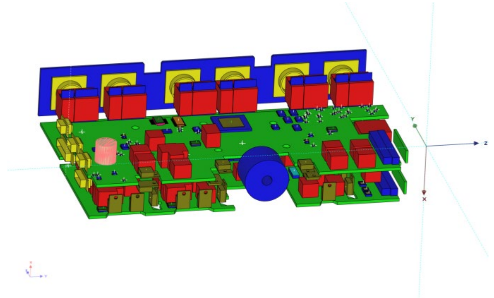
- 1D Validation
  - Planar electron beam irradiation of PTFE
  - Comparison to analytical calculations



- 3D Validation
  - Planar electron beam irradiation of a coaxial cable
  - Comparison to 3D NUMIT



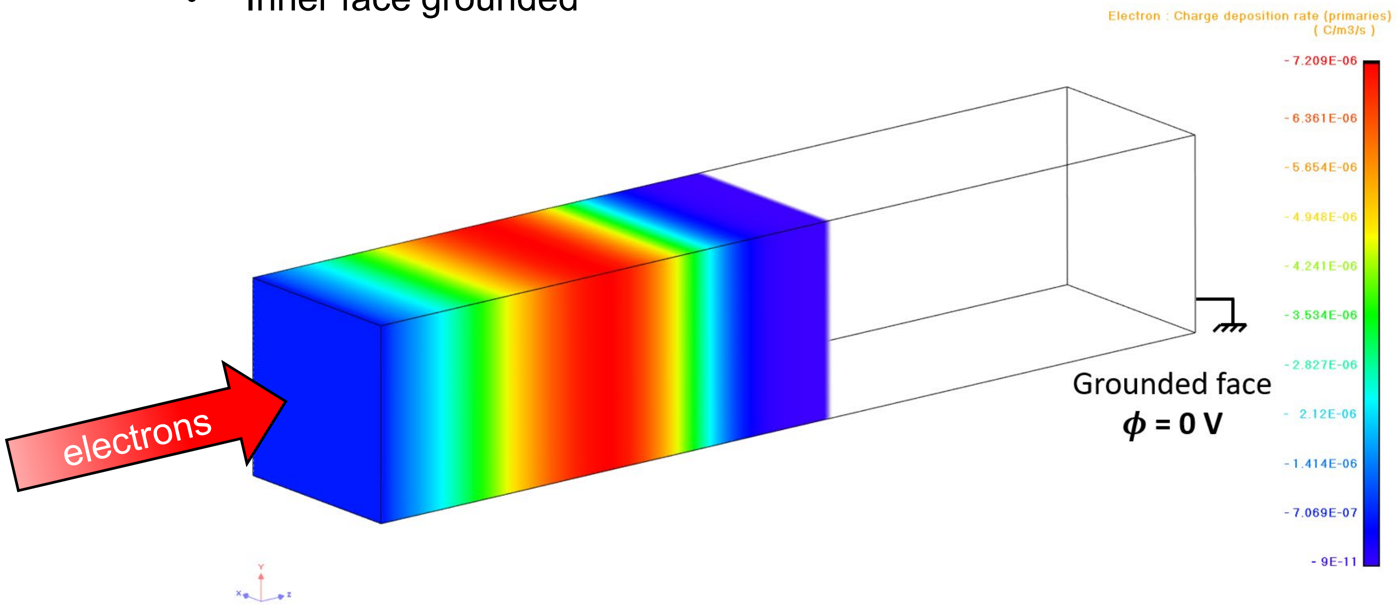
- Application case: telecom spacecraft
  - Internal charging analysis of a K111T capacitor with 3 methods:
    - Simple method from NASA-HDBK-4002A
    - Simplified planar model with FASTRAD
    - Complex 3D model with FASTRAD



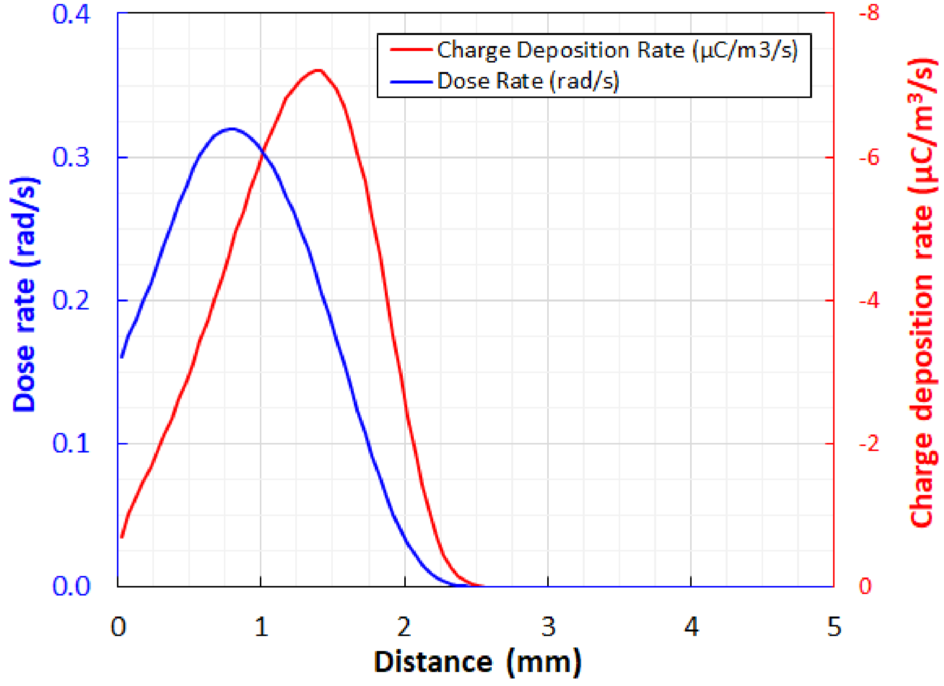
- Conclusion

1D Validation – 1/2

- Electron beam irradiation of PTFE
  - Planar irradiation
  - 1 MeV - 1 pA/cm^2
  - 24h irradiation
  - PTFE C_2F_4
  - Inner face grounded



Charge and dose rates obtained by Monte Carlo calculations.



Differential equation for the potential

$$-\nabla\varepsilon\nabla\frac{d\phi}{dt} - \nabla\sigma\nabla\phi = \dot{\rho}$$

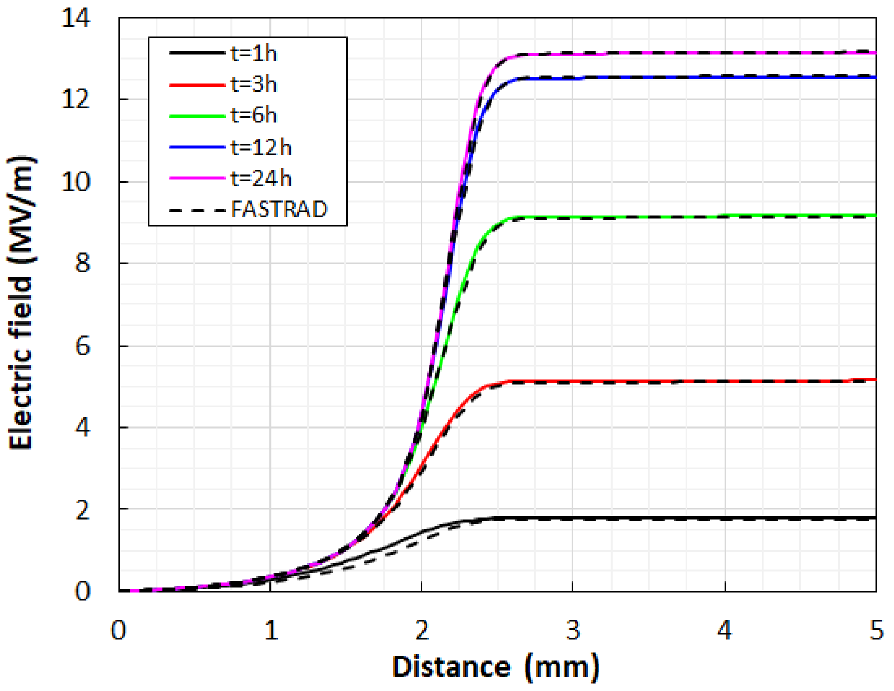
Conductivity

- Models from ECSS-E-ST-20-06C-Rev.1

$$\sigma(t) = \sigma(T,E) + \sigma_{RIC}(\dot{D})$$

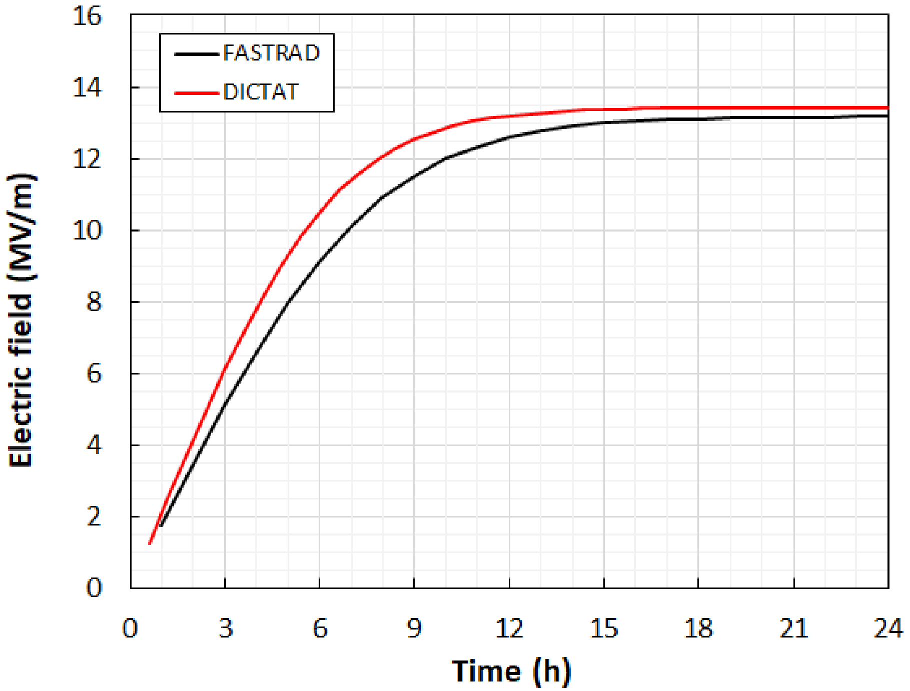
1D Validation – 2/2

- Comparison with 1D analytical solution
  - Same charge and dose rate profiles are used.
  - Same conductivity models.



- Comparison with DICTAT
  - Same source (planar monoenergetic electron beam).
  - Same conductivity models.
  - FASTRAD is slightly lower than DICTAT
    - -2% at steady-state
    - maximum of -16% during the increase

Evolution of the maximum electric field.



- Comparisons of FASTRAD to a simple 1D case are in good agreement.

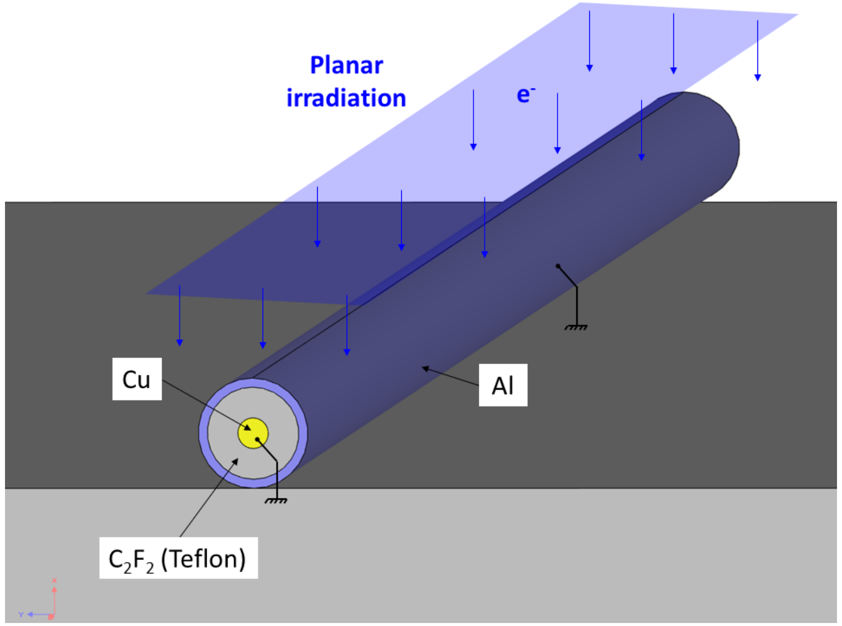
3D Validation – 1/3

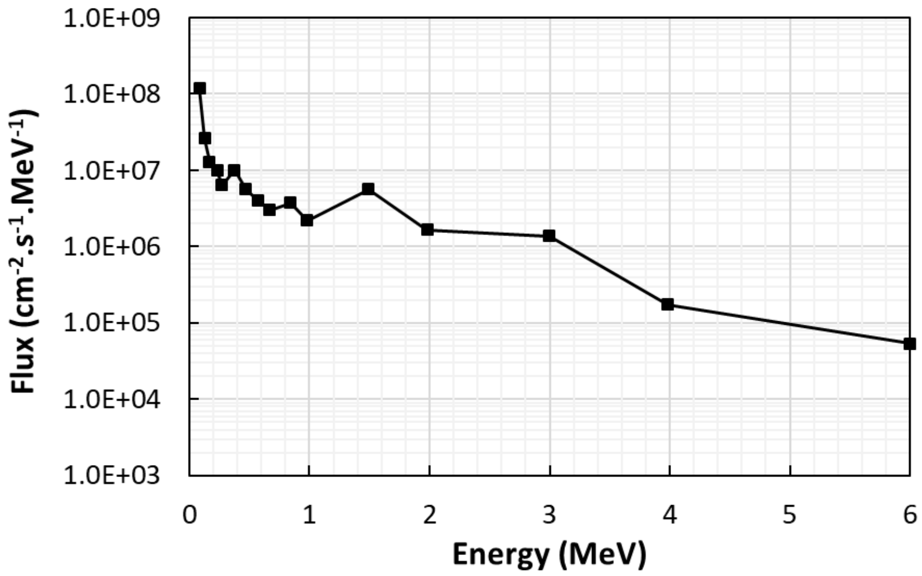
- Coaxial cable on ground plane
  - Comparison to 3DNUMIT [1, 2].
  - Same geometry and environment as in [2].
  - Planar irradiation – 400h
  - Outer and inner conductors are grounded.
  - Only RIC is used (no field induced conductivity).

$$\sigma_0 = 2.6 \times 10^{-19} S/m$$
$$\sigma_{RIC} = 6.1 \times 10^{-16} S/m \,;\, \Delta = 1$$

[1] W. Kim, J. Z. Chinn, I. Katz and K. F. Wong, "3D NUMIT: A General Three Dimensional Internal Charging Code," 14th Spacecraft Charging Technology Conference, 2016

[2] J. Likar, B. Neufeld and J. Chinn, "Benchmarking internal dielectric charging simulation platforms," Applied Space Environments Conference, 2019.

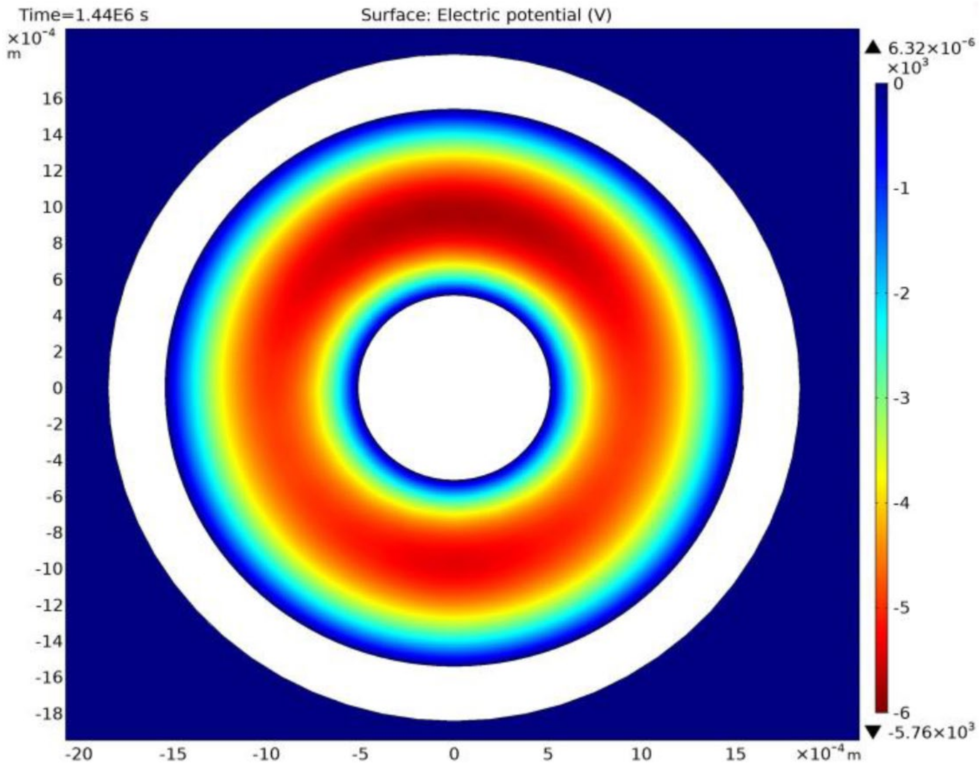




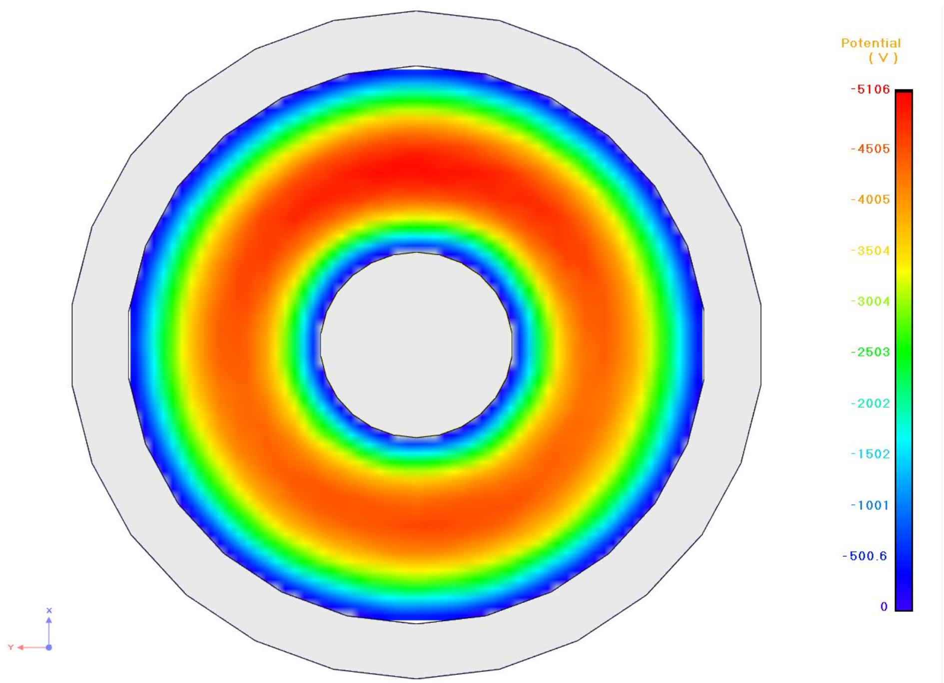
3D Validation – 2/3

- Potential
  - Comparison to 3D NUMIT results after 400h irradiation.
  - Spatial distribution is quite similar.
  - Values are close, FASTRAD gives a maximum potential 11% lower than 3DNUMIT.

3DNUMIT
Maximum potential -5760 V



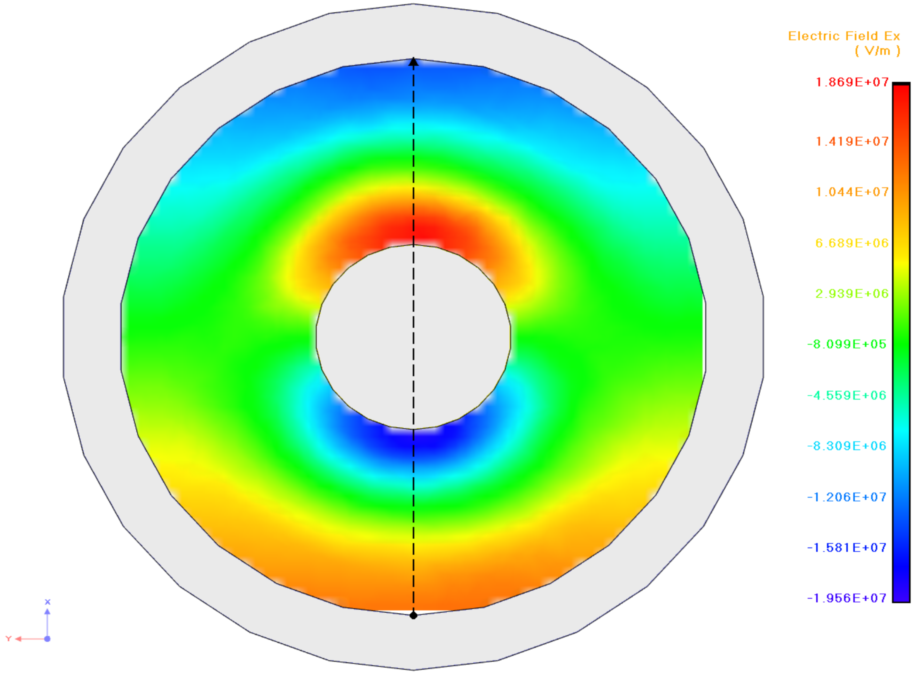
FASTRAD
Maximum potential -5106 V



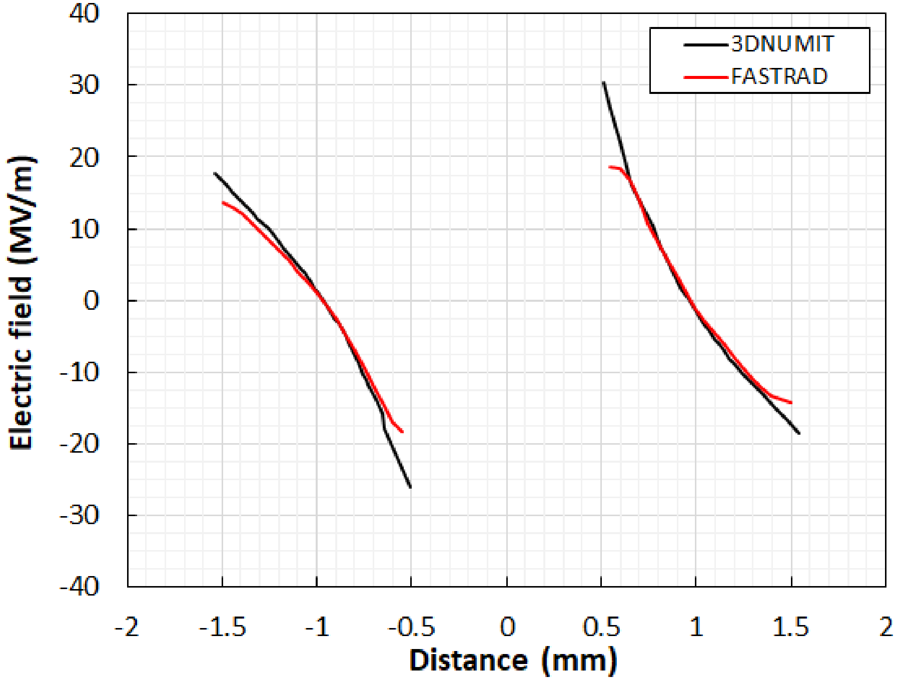
- Electric field
  - Spatial distribution inside the dielectric is quite similar.
  - Discrepancy near the conductors: between -23% and -38%.
  - Use of cartesian mesh for charge deposition in FASTRAD can induce slight error.

Peak electric field	r = -1.5 mm	r = -0.5 mm	r = 0.5 mm	r = 1.5 mm
FASTRAD	14 MV/m	-18 MV/m	19 MV/m	-14 MV/m
3DNUMIT	18 MV/m	-26 MV/m	30 MV/m	-18 MV/m

FASTRAD
Radial electric field distribution

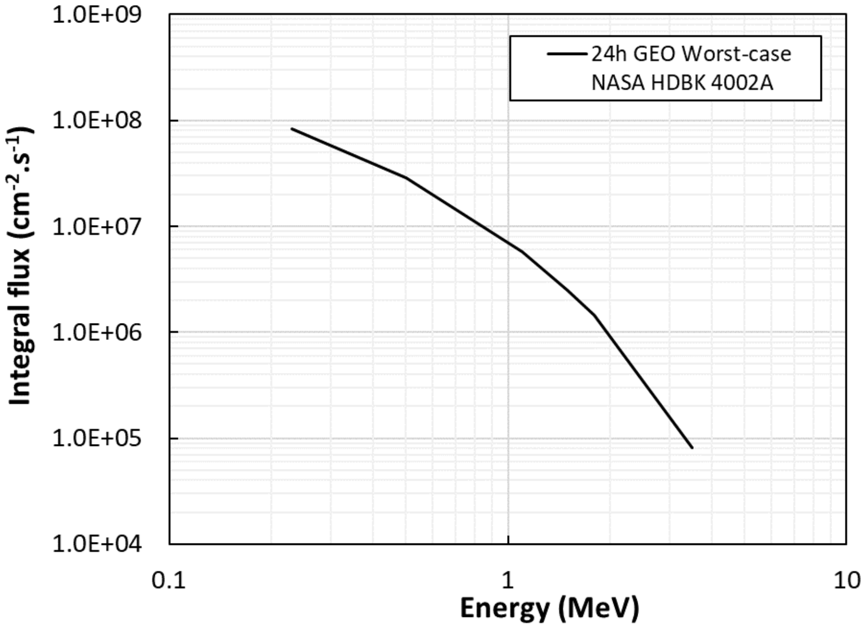


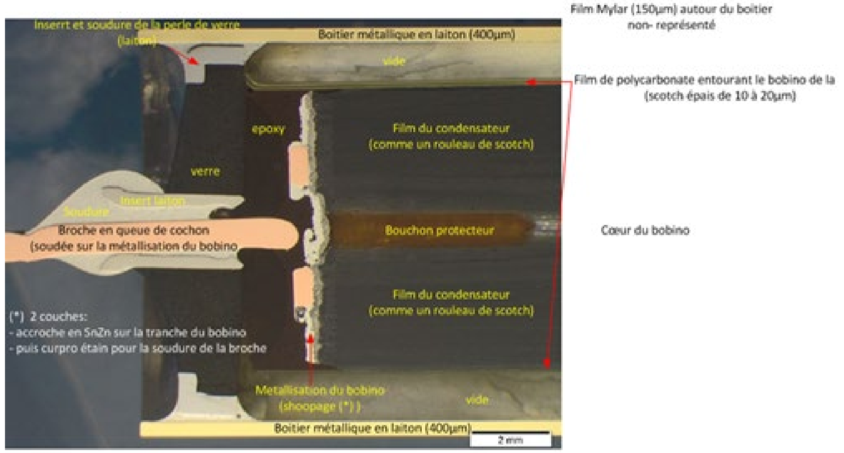
Radial electric field at t = 400 h

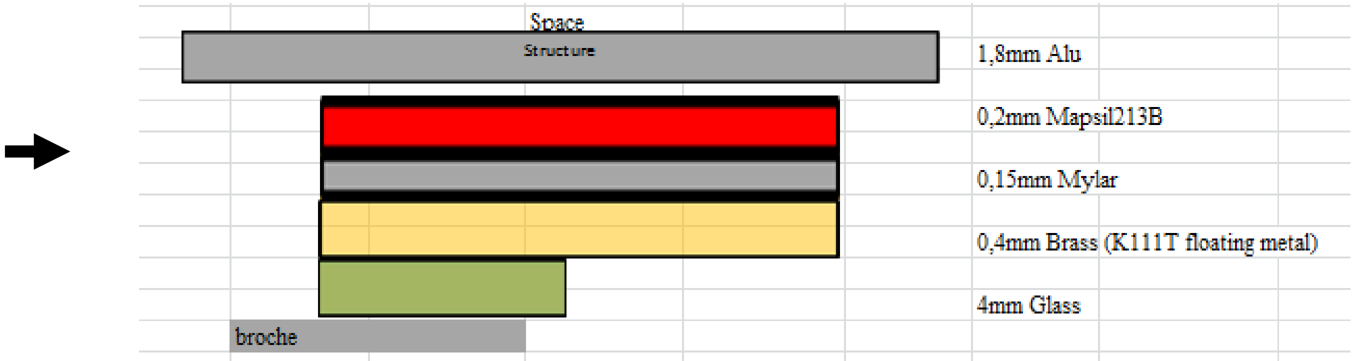


Application case – 1/6

- Telecom spacecraft
  - Capacitor K111T on Power board of Electrical propulsion equipment.
  - Metal case of the capacitor is floating and coated with Mylar and Mapsil: no grounding possible, ESD assessment is needed.
- Internal charging analysis by comparing three methods:
  - Simple method from the NASA Handbook 4002A
  - Simplified planar model with FASTRAD
  - Complex 3D model with FASTRAD
- Environment
  - Integral flux averaged over 24h for a typical GEO mission, from the NASA Handbook 4002A.
- Geometry
  - Simplification of the capacitor geometry for 1D calculation.







Application case – 2/6

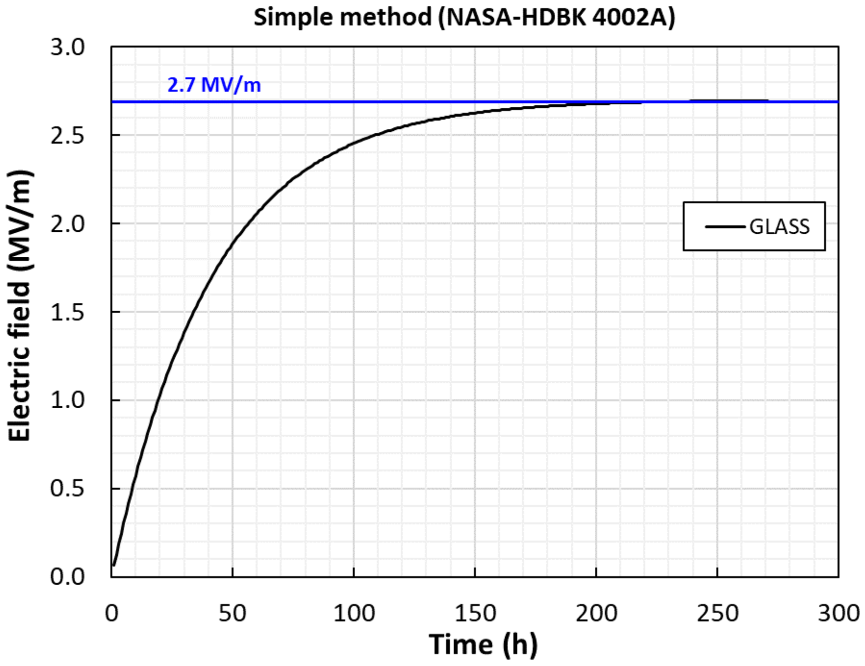
- Simple method from NASA-HDBK-4002A
  - Electron flux in layers determined from electron range in aluminum.

Layer	Material	Density (% alu)	Aluminum equivalent thickness (mm)	Min energy of exiting electrons (MeV)	Exit integral flux (e-/(cm2.s.sr))	Current (A/cm²)	Electric field (V/m)
1	Aluminum	1.00	1.80	0.900	7.86E+05	-	-
2	Mapsi	0.37	1.87	0.937	7.12E+05	3.57E-14	2.50E+04
3	Mylar	0.51	1.95	0.976	6.42E+05	3.37E-14	1.70E+06
4	Brass	3.15	3.21	1.538	1.86E+05	2.19E-13	8.54E-17
5	Glass	0.66	5.85	2.799	2.12E+04	7.94E-14	2.70E+06

- Electric field evolution in glass
  - Relative permittivity ε = 5
  - Conductivity σ = 2.94x10^{-16} S/m
  - Initial electric field is null.

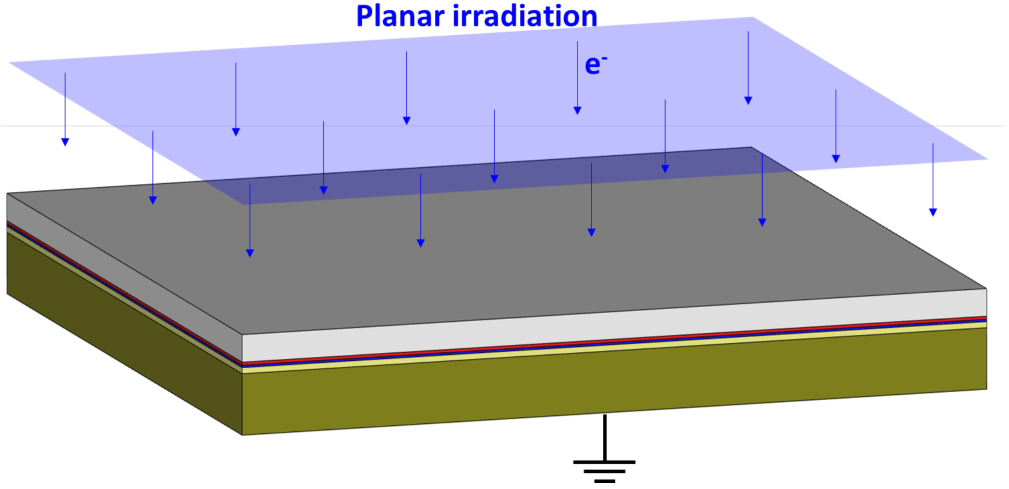
$$E = (J_R/\sigma)[1 - \exp(-\sigma t/\varepsilon)]$$

- Electric field at steady state: **2.7 MV/m**

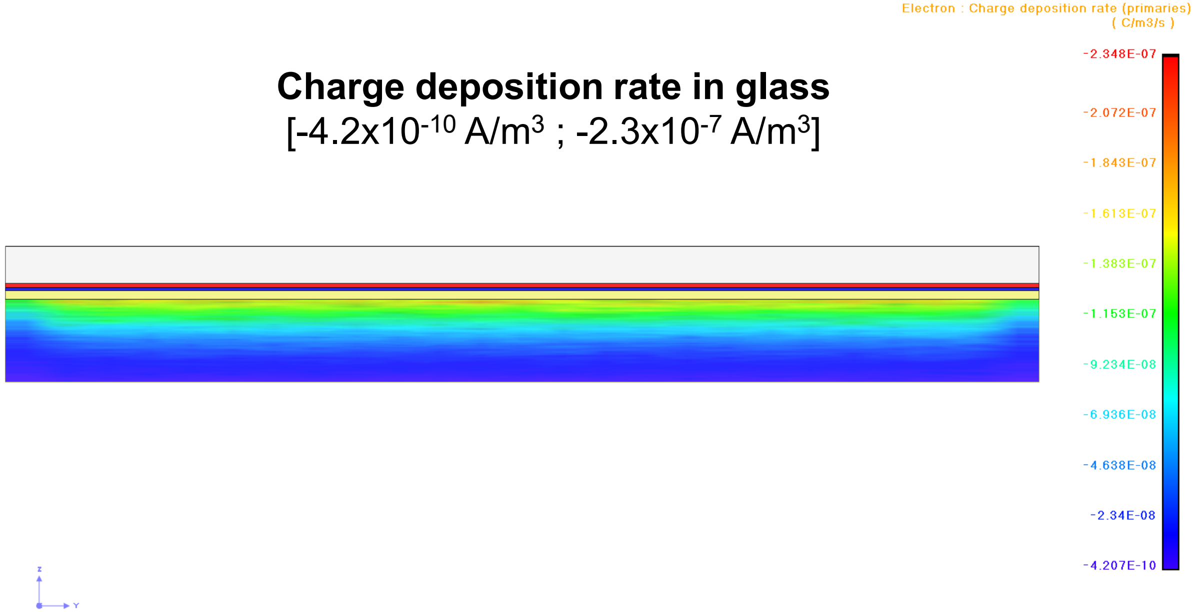


- Simplified planar model with FASTRAD
  - Planar model 50x50mm
  - Electron Source 50x50mm
  - Reference Potential (0V): underneath Glass layer

Layer	Thickness (mm)	Density (g/cm^3)	Atomic weight
Structure	1.80	2.70	Al
Mapsi	0.20	1.07	$H_{0.01}\ C_{0.102}\ N_{0.067}\ O_{0.392}\ Si_{0.327}\ Br_{0.102}$
Mylar	0.15	1.35	$C_{0.625}\ H_{0.04196}\ O_{0.333}$
Brass	0.40	8.48	$Cu_{0.615}Zn_{0.3524}Pb_{0.03252}$
Glass	4.00	1.90	$B_{0.05}\ O_{0.38}\ Na_{0.06}\ Si_{0.41}\ K_{0.08}\ Ba_{0.02}$



Charge deposition rate in glass
[-4.2×10^{-10} A/m^3 ; -2.3×10^{-7} A/m^3]

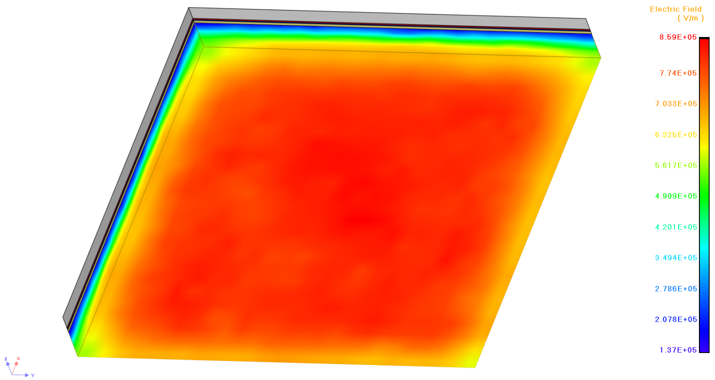


Application case – 4/6

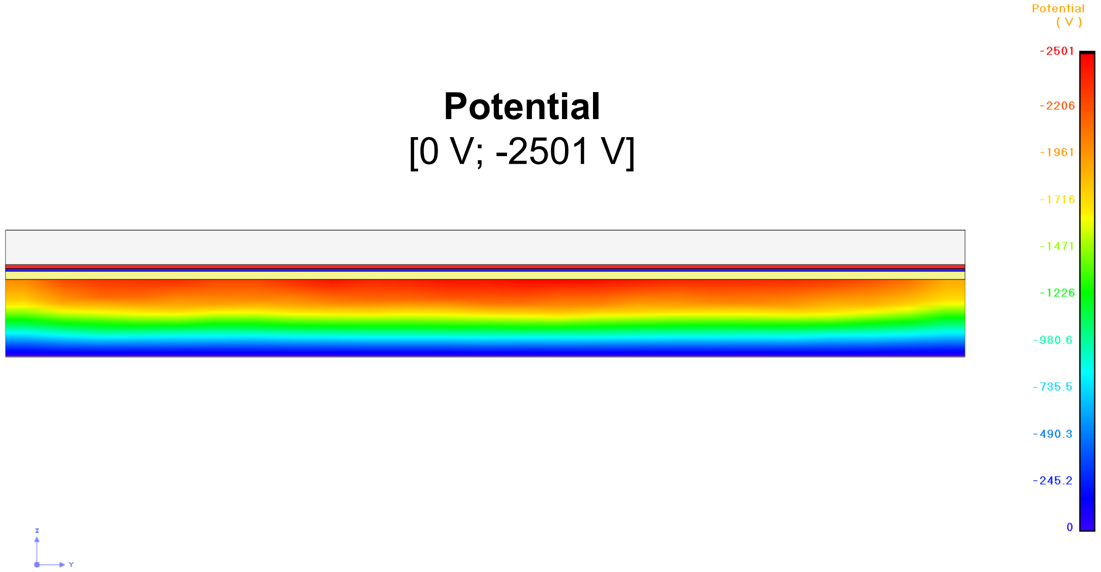
- Simplified planar model with FASTRAD
  - Potential and electric field are calculated for steady state.
  - The use of the planar model with FASTRAD allows decreasing the electric field of 68% with respect to the NASA Handbook simple method.
  - The use of Monte Carlo in detailed materials instead of using aluminum range can optimize the calculated charge deposition rate and hence decrease the final electric field.

	1D Model (NASA HDBK method)	Planar model (FASTRAD)
Efield	2.70 MV/m	0.86 MV/m (1/3)

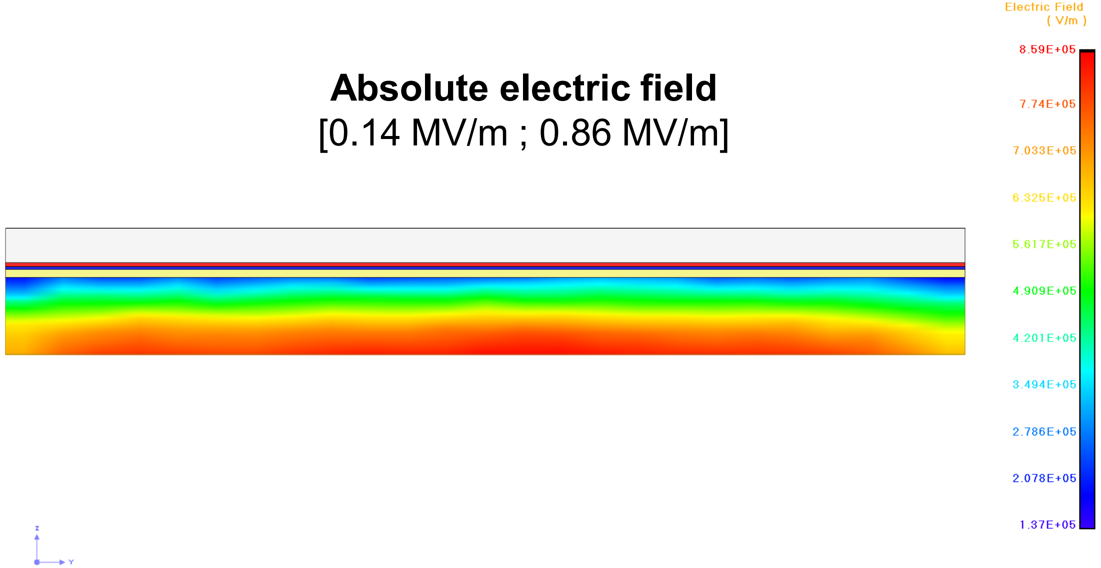
Absolute electric field



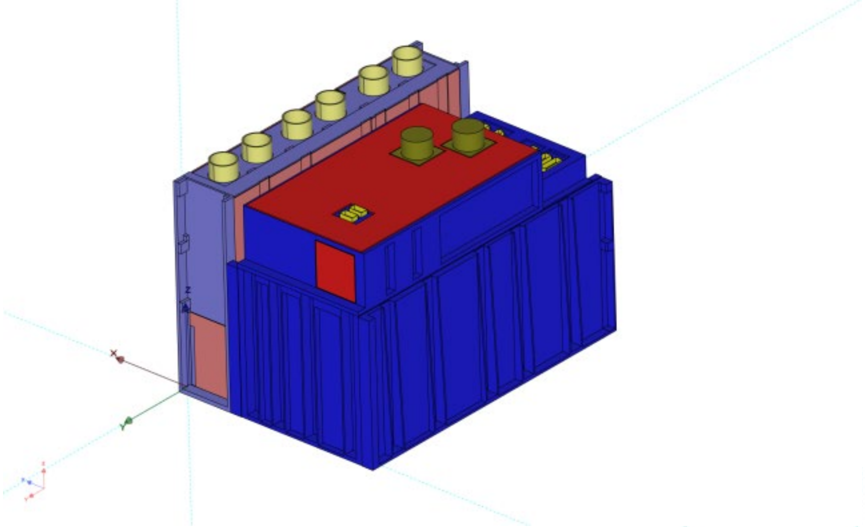
Potential
[0 V; -2501 V]

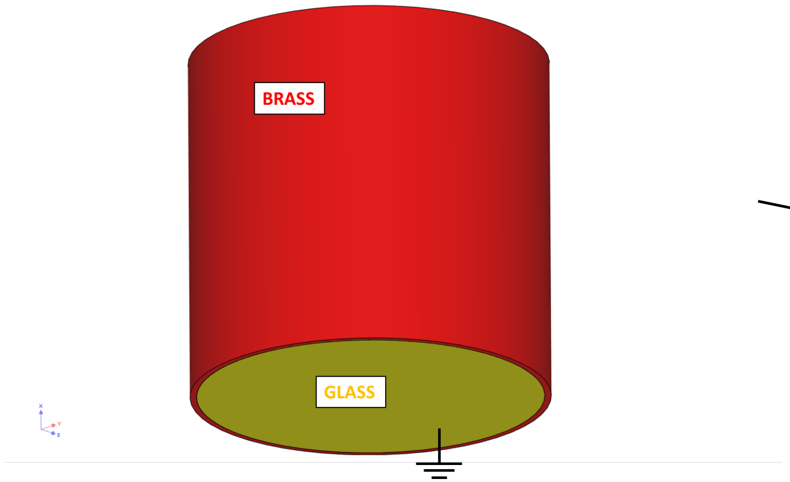


Absolute electric field
[0.14 MV/m ; 0.86 MV/m]

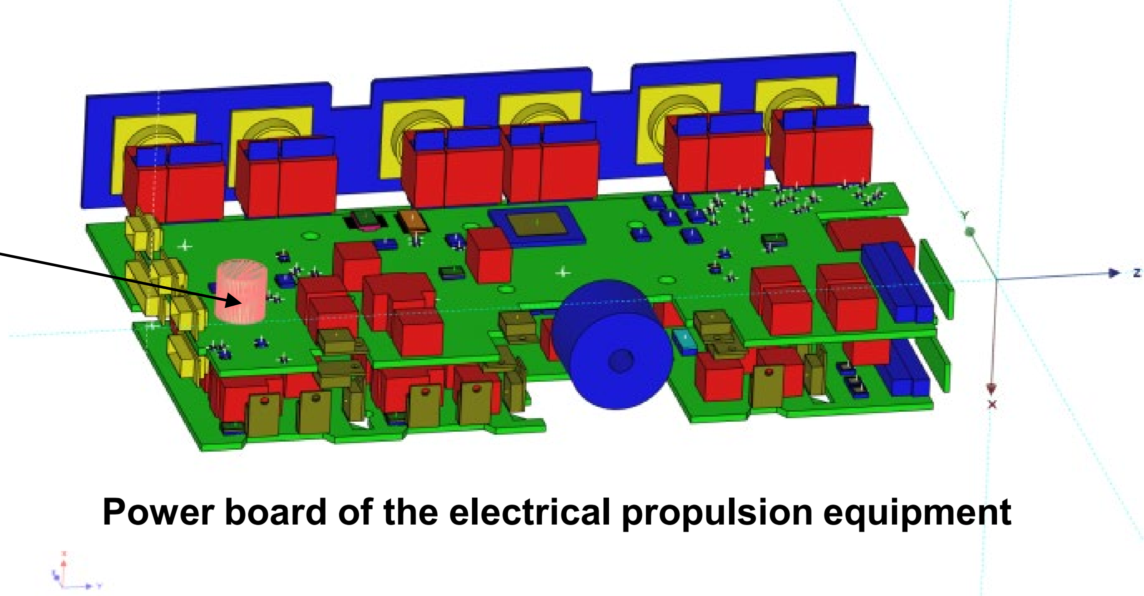


- Complex 3D model with FASTRAD
  - Electrical propulsion equipment from a telecom spacecraft.
  - The Reverse Monte Carlo method is used to compute charge and dose deposition and consider the real geometry.
  - The underneath face is grounded.





K111T capacitor model

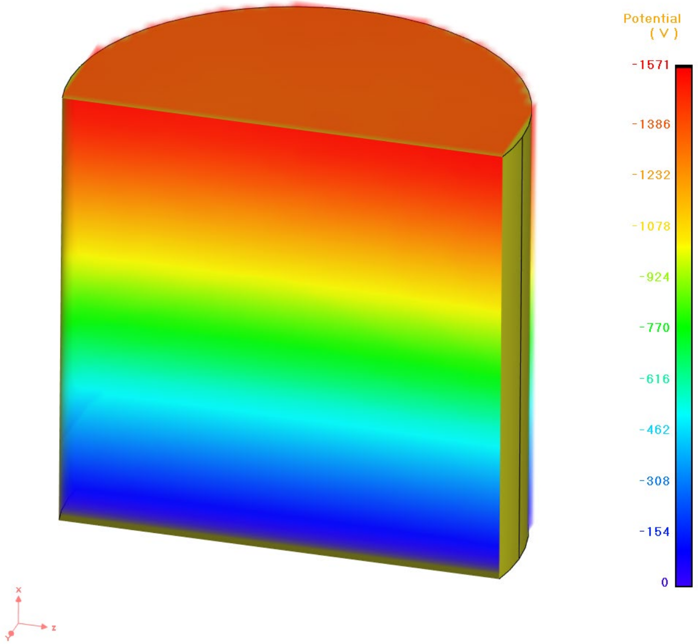


Power board of the electrical propulsion equipment

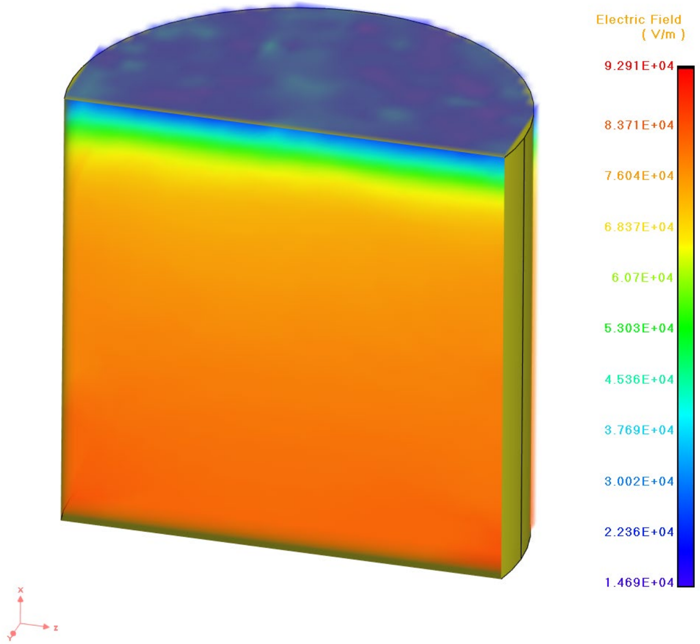
Application case – 6/6

- Complex 3D model with FASTRAD

Potential
[0 V; -1571 V]



Absolute electric field
[0.01 MV/m ; 0.09 MV/m]



	1D Model (NASA HDBK method)	Planar model (FASTRAD)	Complex model (FASTRAD)
Efield	2.70 MV/m	0.86 MV/m (1/3)	0.09 MV/m (1/30)

- The use of a 3D internal charging tool helps to reduce by a factor 30 the electric field estimated by a 1D simple method.
- 3D analysis can be run prior to shield after a simple 1D calculation.
- Allow to optimize mass budget and design hardening.

Conclusion

- Validation
  - 1D case: comparison to analytical solution and to the DICTAT tool were performed to validated the potential calculation.
    - Standard models of conductivity are used for radiation induced and field induced conductivities.
    - As a worst-case, a constant conductivity can be considered if no material parameters are known.
  - 3D case: comparison to 3DNUMIT with the example of a coaxial cable.
    - Space distribution of potential and electric field are similar but there some discrepancies near conductors for electric field.
    - This can be due to different particle transport methods (GEANT4 vs MCNP) and due to different types of volume mesh for charge and dose deposition (cartesian vs tetrahedral mesh).
  - Validation with experimental data are in progress.
- Application case
  - Capacitor in an electrical propulsion equipment for from a telecom spacecraft.
    - The electric field is mainly driven by the charge deposition. It is computed by considering the real geometry surrounding the capacitor by using the Reverse Monte Carlo method.
  - Comparison of three methods (simple method NASA-HDBK-4002A, Planar model, Complex model)
    - Very good correlation with other calculations, less conservative than HDBK method : allow to optimize mass budget (unit/equipment shielding) and design hardening (floating parts grounding).