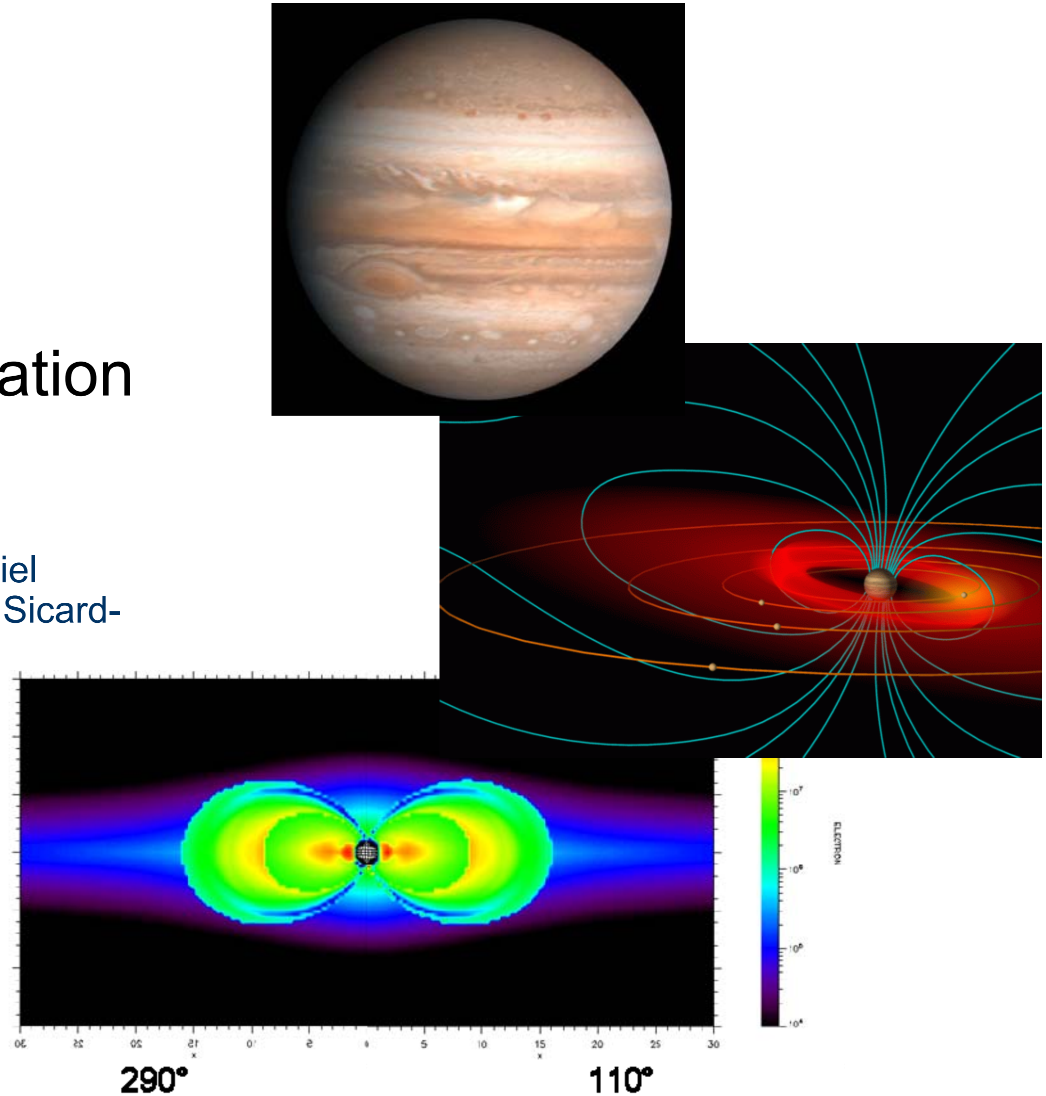

Integrated Radiation Mitigation and Shielding Design

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ONERA

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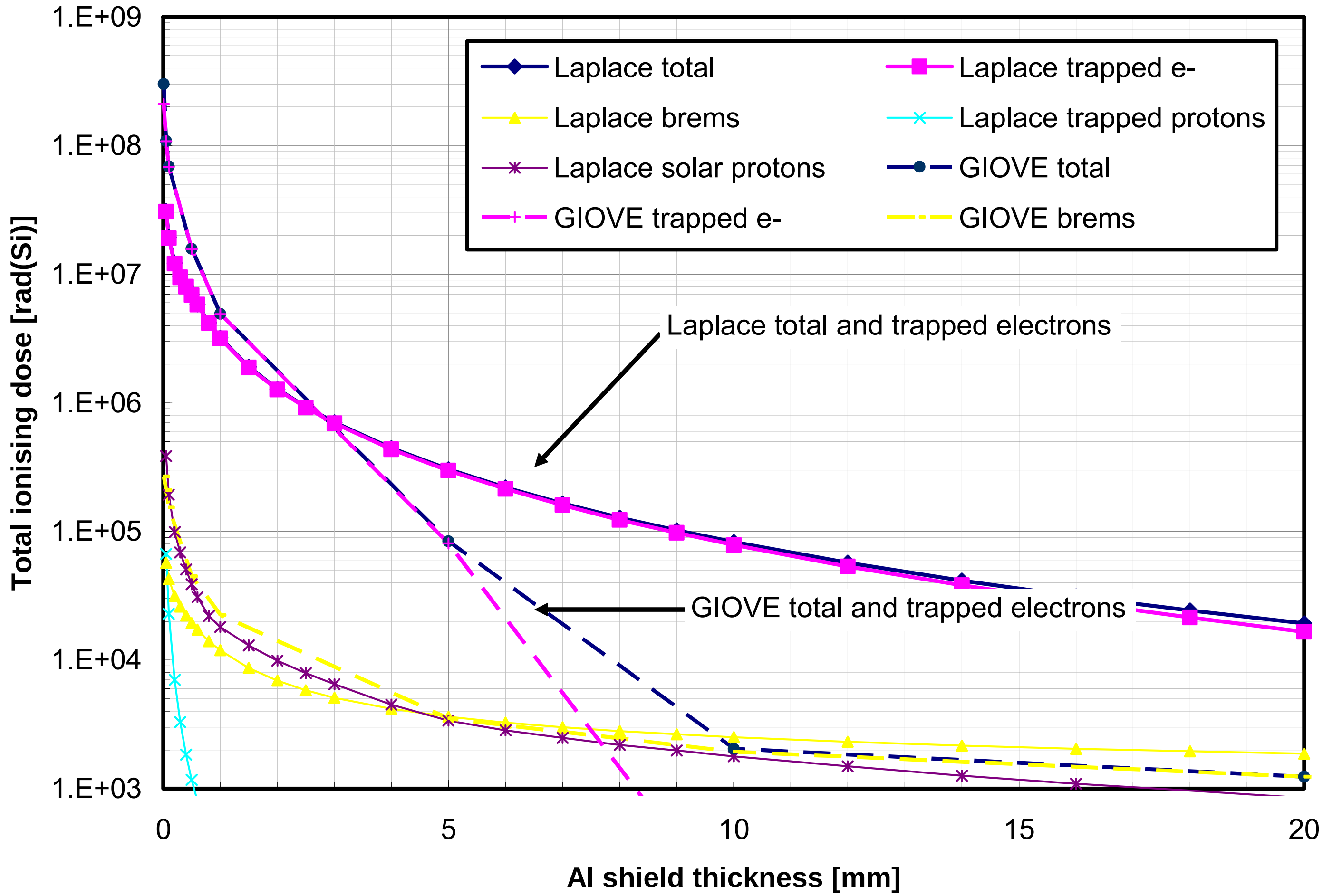
Effects of the Jovian Radiation Environment

- Significantly enhanced radiation environment compared with near Earth
  - Particle energies and fluxes (electron energies beyond 100 MeV)

- **Total ionising dose** – microelectronics, MEMS, sensors, materials
- Total non-ionising dose (displacement damage) – sensors/FPA, solar arrays
- **Deep dielectric charging**
- Single event effects (upset, latch-up, burn-out, gate-rupture, etc)

- Several standard tools are not intended for use in this regime:
  - SHIELDOSE (10MeV) and SHIELDOSE-2 is based on Monte Carlo data for up to 50MeV
  - EQFLUX
- Environments in vicinity of Galilean moons

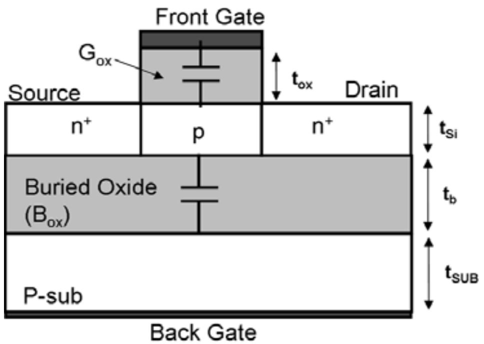
Effects of the Jovian Radiation Environment
Comparison with MEO (GIOVE solar max, 939 days)

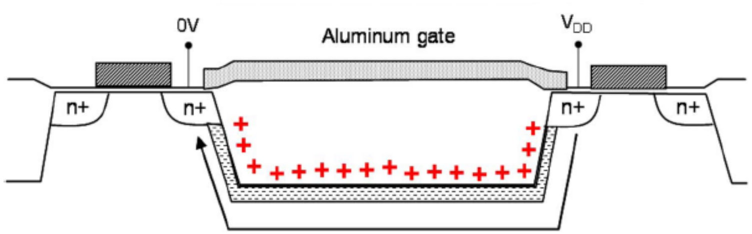


Data from J Sørensen and G Santin (Laplace), and QinetiQ (GIOVE, VALCOMPT project)

Review of mitigation measures

- Shield
  - Judicious positioning of more sensitive equipment to shield using less sensitive systems
  - Compact system distribution
  - Addition of deliberate shielding (at equipment box level, spot shielding, thicker cover glasses …)
  - “Radiation vault” design
- Component and technology selection
  - Radhard / Rad-tolerant
  - Exploit difference in tolerances due to different commercial designs
  - Watch-out for potential effects of new (especially high-Z materials) introduced in microelectronics!
- Hardening at circuit level
  - Less susceptible to effects of *e.g.* voltage shifts
  - Circuit compensation for *e.g.* threshold shifts, gain drift
  - EDAC





Leakage path

Review of mitigation measures

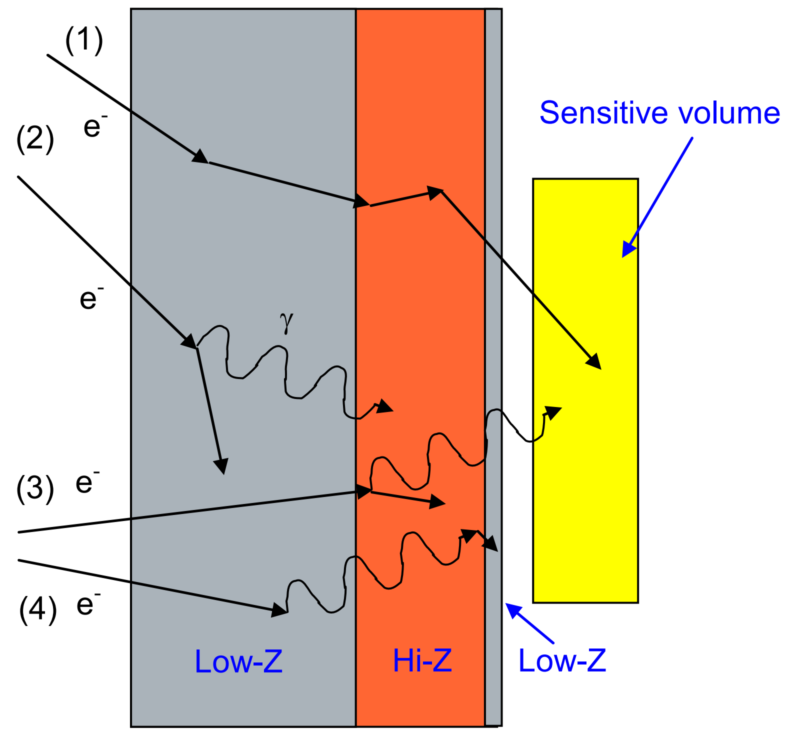
- Provision for annealing
  - Particularly for scientific instrument technologies
- Duty cycling & cold redundancy
  - Mitigate some TID effects by unpowering equipment during intense irradiation periods
- Hide

Mitigation for internal or deep dielectric charging

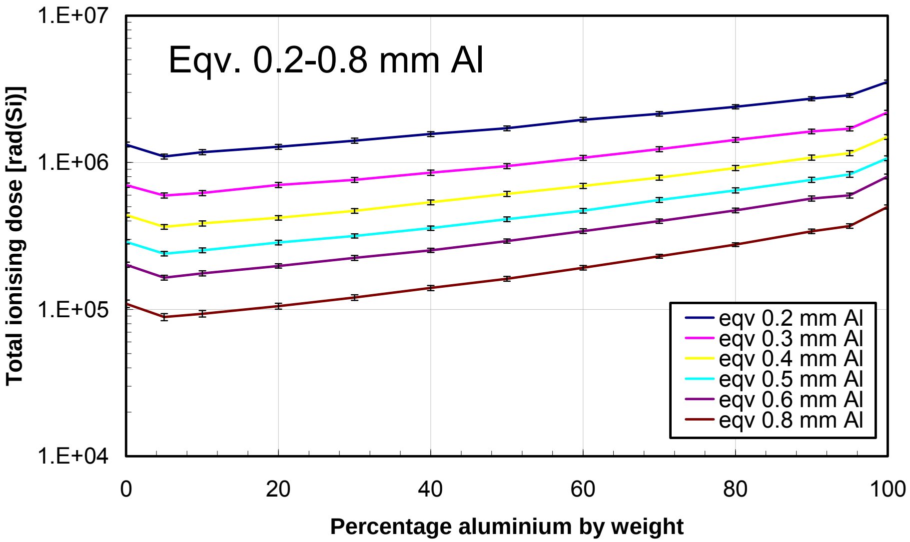
- Shield
- Reduction in material thickness / selection of dielectric
- Ensure common grounding
- De-rating of electrical/electronics systems (reduce-f, filter)
- Avoid cold temperatures

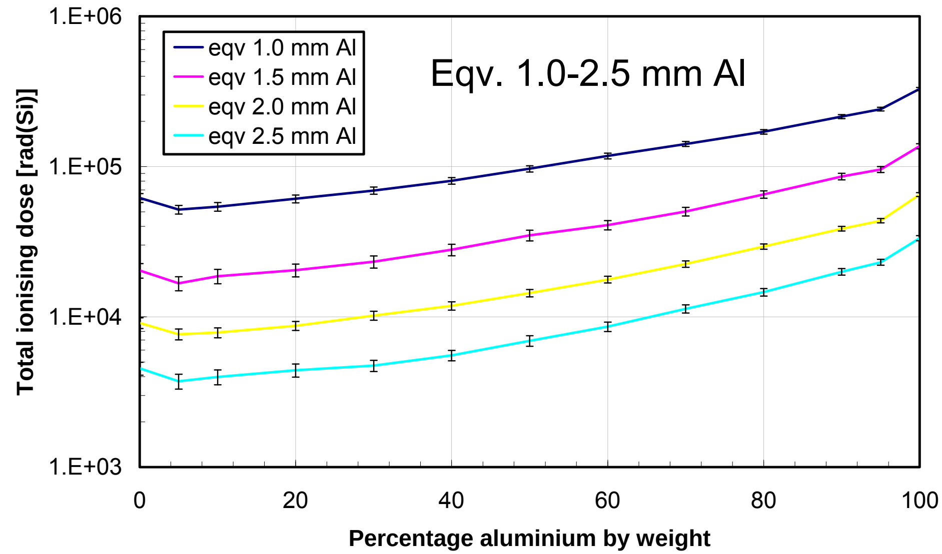
Shielding and influence of shielding materials

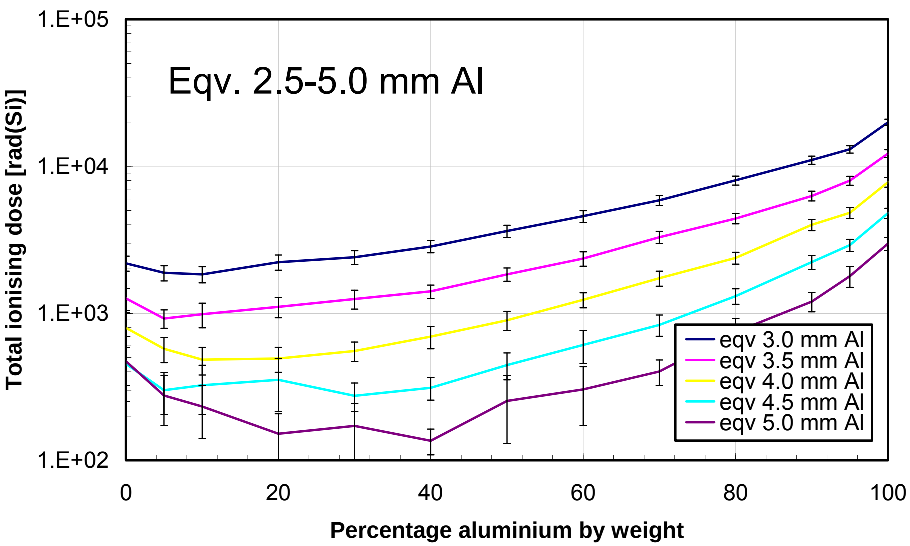
- Shielding in context of Al? Why?
- High-Z materials better at scattering electrons
- However, per unit mass, high-Z materials also
  - Have lower stopping powers (fewer electrons per unit mass)
  - Generate more bremsstrahlung (cross-section scales as Z^2)
- Graded shields use combinations of low and high-Z materials to:
  - Efficiently stop electrons with low bremsstrahlung production (low-Z)
  - Efficiently absorb any bremsstrahlung, and scatter any residual low-energy electrons
  - Absorb any residual photoelectrons or Auger electrons
- Provide significant mass-saving for electron environments



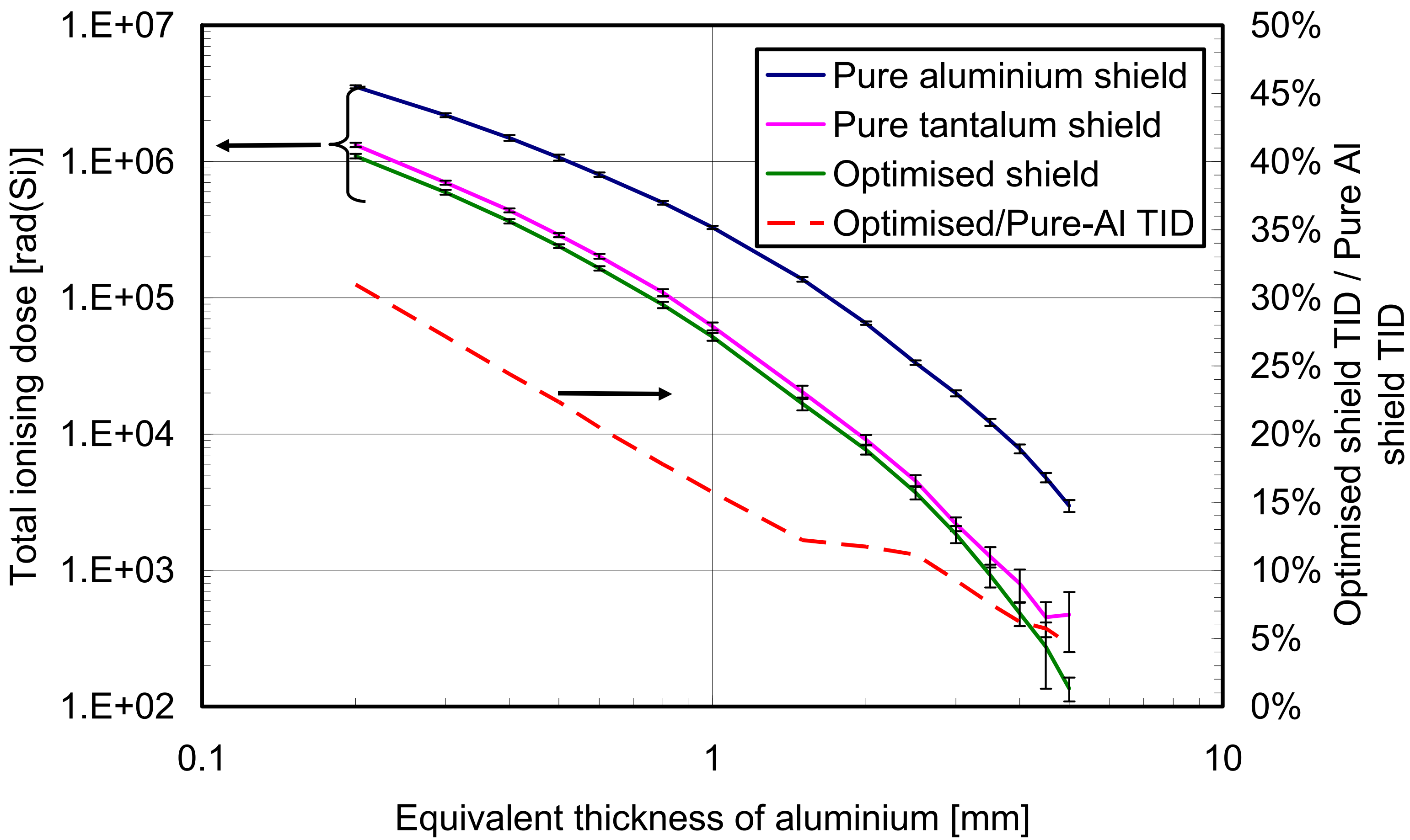
Graded shielding example for GIOVE orbit
1 year at solar maximum



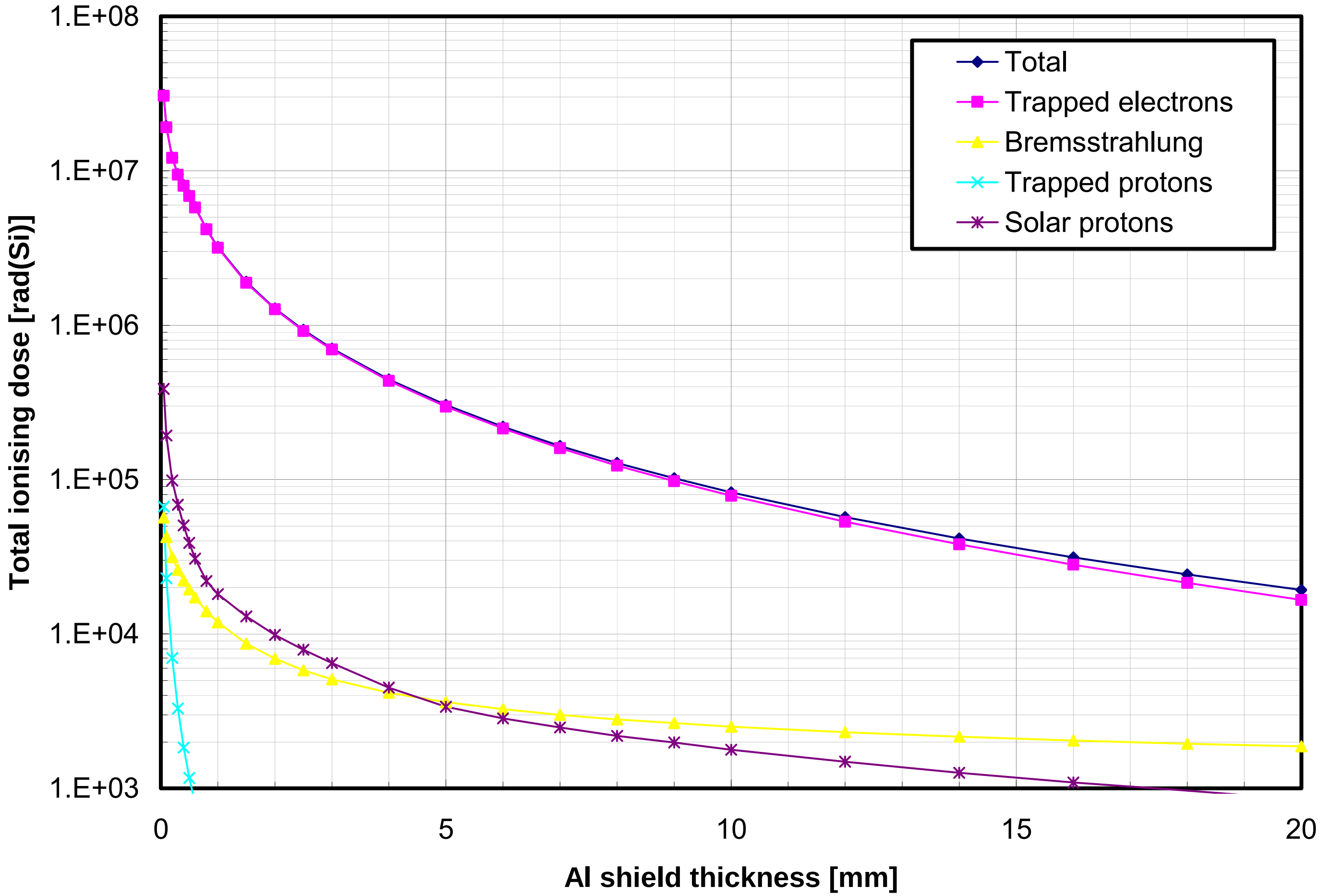




Graded shielding example for GIOVE orbit 1 year at solar maximum

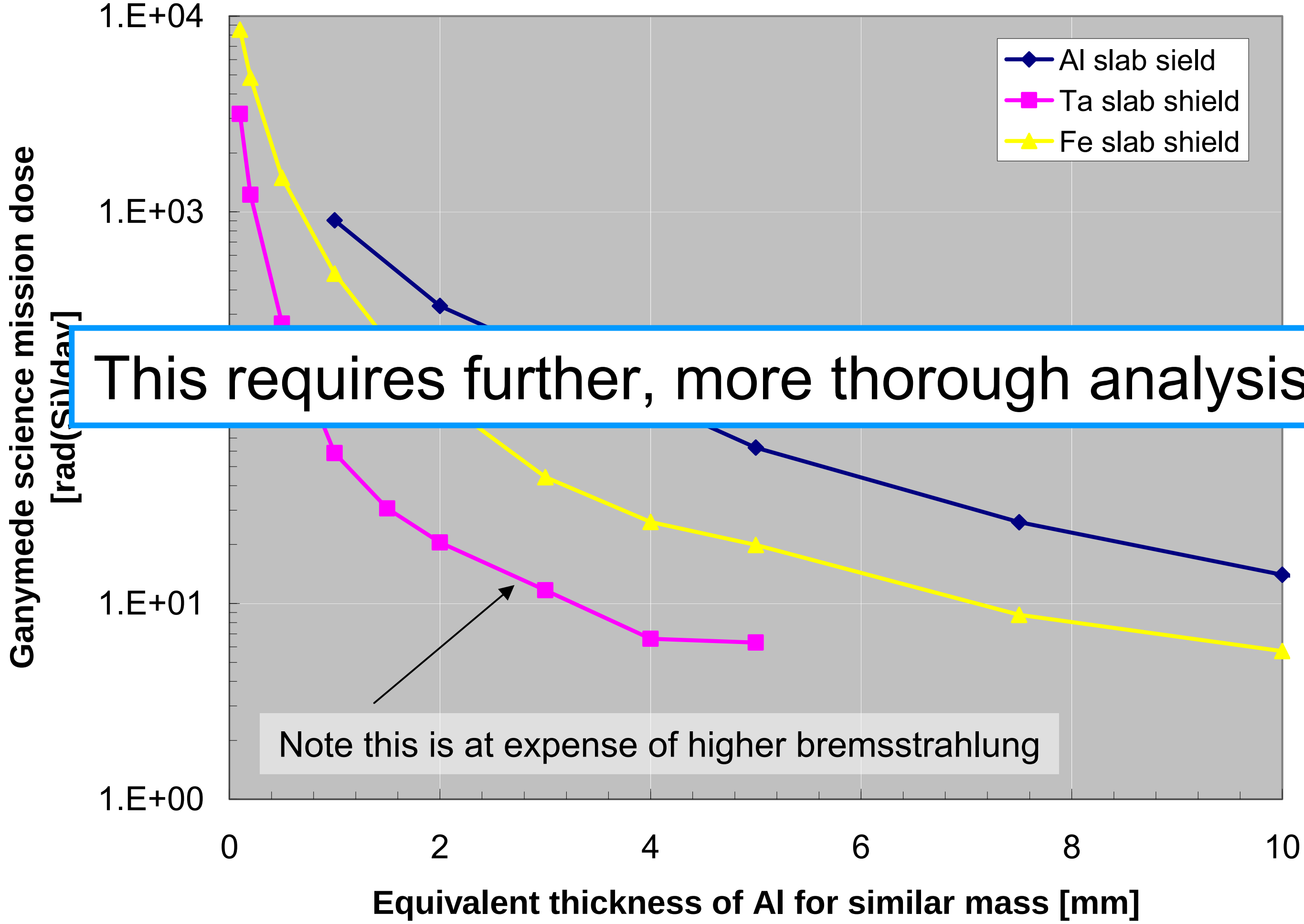


Radiation dose versus depth in spherical Al shields



Data from J Sørensen and G Santin

Comparison of TID for Al, Fe and Ta slab shields
NOTE: Based on earlier (Jan 2009) spec for environment

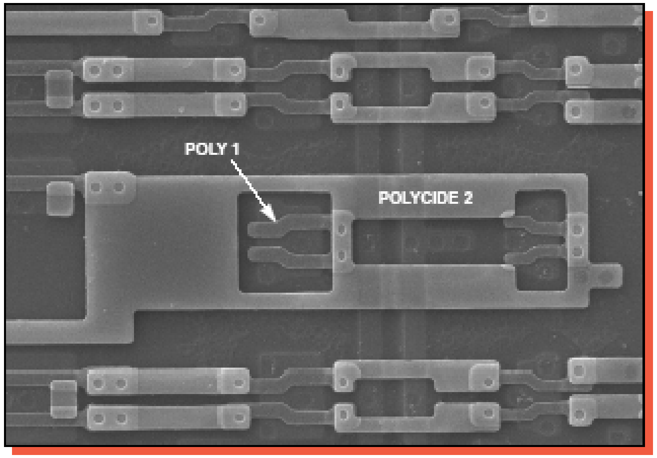


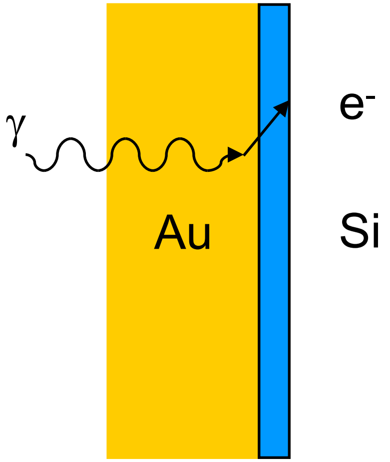
This requires further, more thorough analysis

Beware of dose enhancement effects

In environments which are photon / bremsstrahlung-dominated, dose enhancement effects are a risk

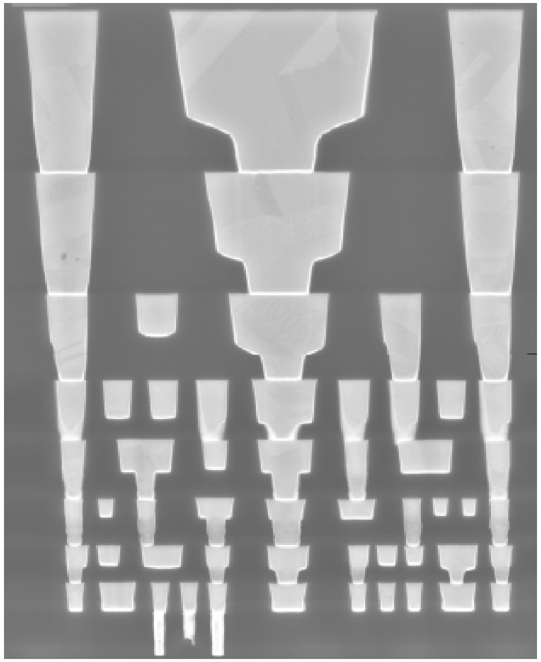
- High-Z materials produce low-energy photo- and Auger e^- in bremsstrahlung environment
- Very localised enhancement of dose
- Au contacts, W-vias and silicides (WSi)

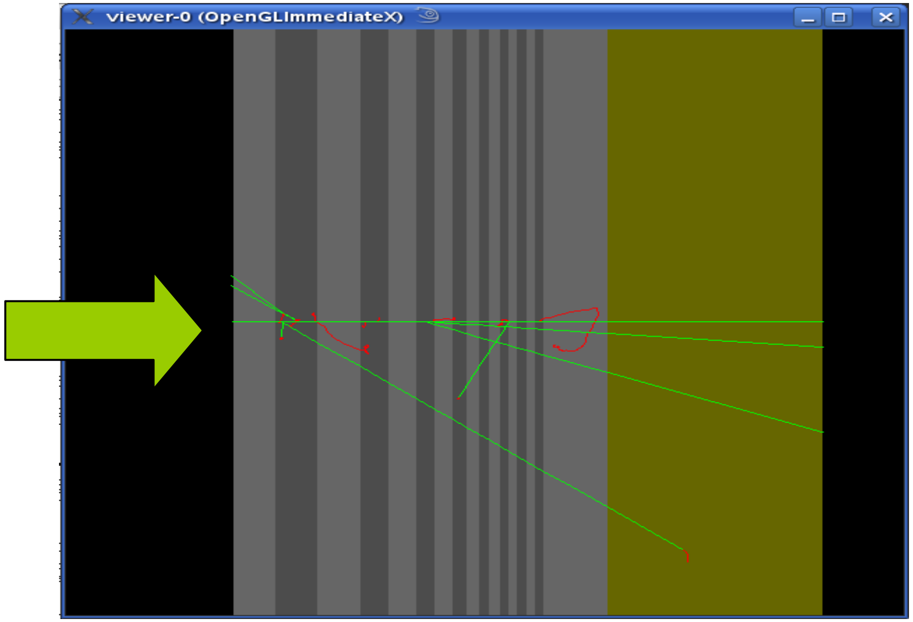


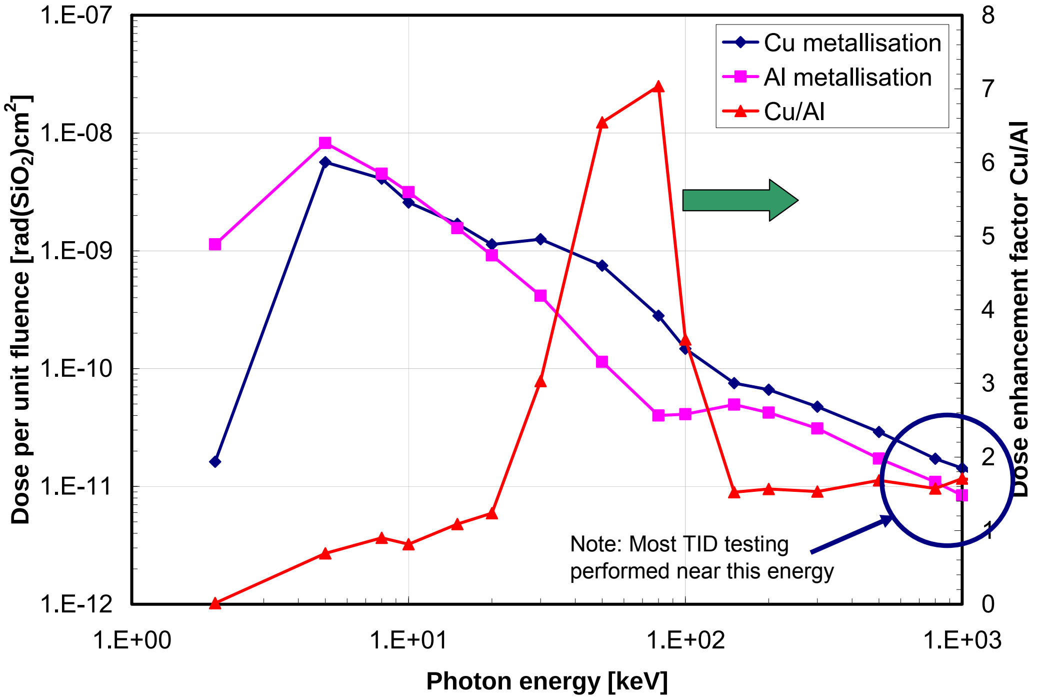


Beware of dose enhancement effects

- Detailed Geant4 microdosimetry analysis performed for Cu metallization layer
- Need to use MC tools like MULASSIS







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ESA JORE^{2}M^2 Project (Jovian Radiation Environment and Effects, Models and Mitigation) Objectives

- Assess the requirements for radiation and plasma environment models, and effects and mitigation tools for future Jupiter-system missions (including Jupiter flyby).
- Review the available models and tools used to predict the Jovian radiation and plasma environments and their effects, and identify a strategy for software development and update.
- Design, develop, validate and install at a model for predicting the environment within the Jovian magnetosphere (including the Galilean moons), and effects and mitigation tools. The tools shall permit assessment of radiation-related quantities for engineering purposes, including where possible, confidence levels.
- All tools and models will be such as to allow operation over the Internet (World-Wide Web), and are to be compatible data interfaces with SPENVIS.

Effects Tools Questionnaire

Which existing models do you know or which ones do you use to define Jupiter radiation environment?

	Current use:	Relevant for future use:
SHIELDOSE / SHIELDOSE-2	**8**	**6**
MULASSIS	4	2
SSAT	2	2
GEMAT	1	1
FASTRAD	5	2
OMERE	3	1
DOSRAD	3	2
NIEL (within SPENVIS)	4	2
EQFLUX	2	1
GRAS	2	2
DICTAT	**6**	3

- Others include SPIS, Tiger/MCNP, NUMIT

Effects Tools Questionnaire

Which radiation effects are you interested in and what are their relative importances?

	Not imp. :	Quite imp.:	Very imp.:
• Total Ionising Dose (TID)	0	1	**9 SD2/ML**
• Non-Ionising Energy Loss (NIEL) (to microelectronics)	0	5	5 ML
• Non-Ionising Energy Loss (NIEL) EQFLUX (to solar arrays)	2	1	5
• Single Event Effects (SEE)	0	2	**8 GEMAT**
• Sensor background effects	2	2	**6 GEMAT**
• Surface charging	1	4	4
• Deep-dielectric charging	1	3	**6 DICTAT**

- Other: material degradation
- Need for both web-based tools and local applications which deal with radiation effects
- Operating systems: ~75% Windows, ~25% Linux (but also one expression of interest in Mac-based solution!)

JORE²M² Project Integrated Solution for Environment and Effects Simulation for Jupiter Missions

- Coherent set of interfaced tools to simulate environment and effects in a SPENVIS-compatible framework
- JOSE for energetic environment, and Divine + Garrett plasma models
- Requirement to extend existing engineering tools, in particular generate new SHIELDOSE-2 database which:
  - Extends the energy range for electrons to >50MeV
  - Allows treatment of non-Al shields
- Allow modelling of radiation environment at moons, taking into consideration influence of intrinsic and induced fields as well as structure of the moons (PLANETOCOSMICS-based)
- Development of genetic algorithm software to optimise 1-D shields (composition and thickness)
- Standard tools such as DICTAT and GEMAT are also to be available within Framework

SHIELDOSE-2 Enhancement Shield and target materials

Shield materials

- Al, Ta, Fe
- 1mm Al followed by Ta
- CW80 and Ti

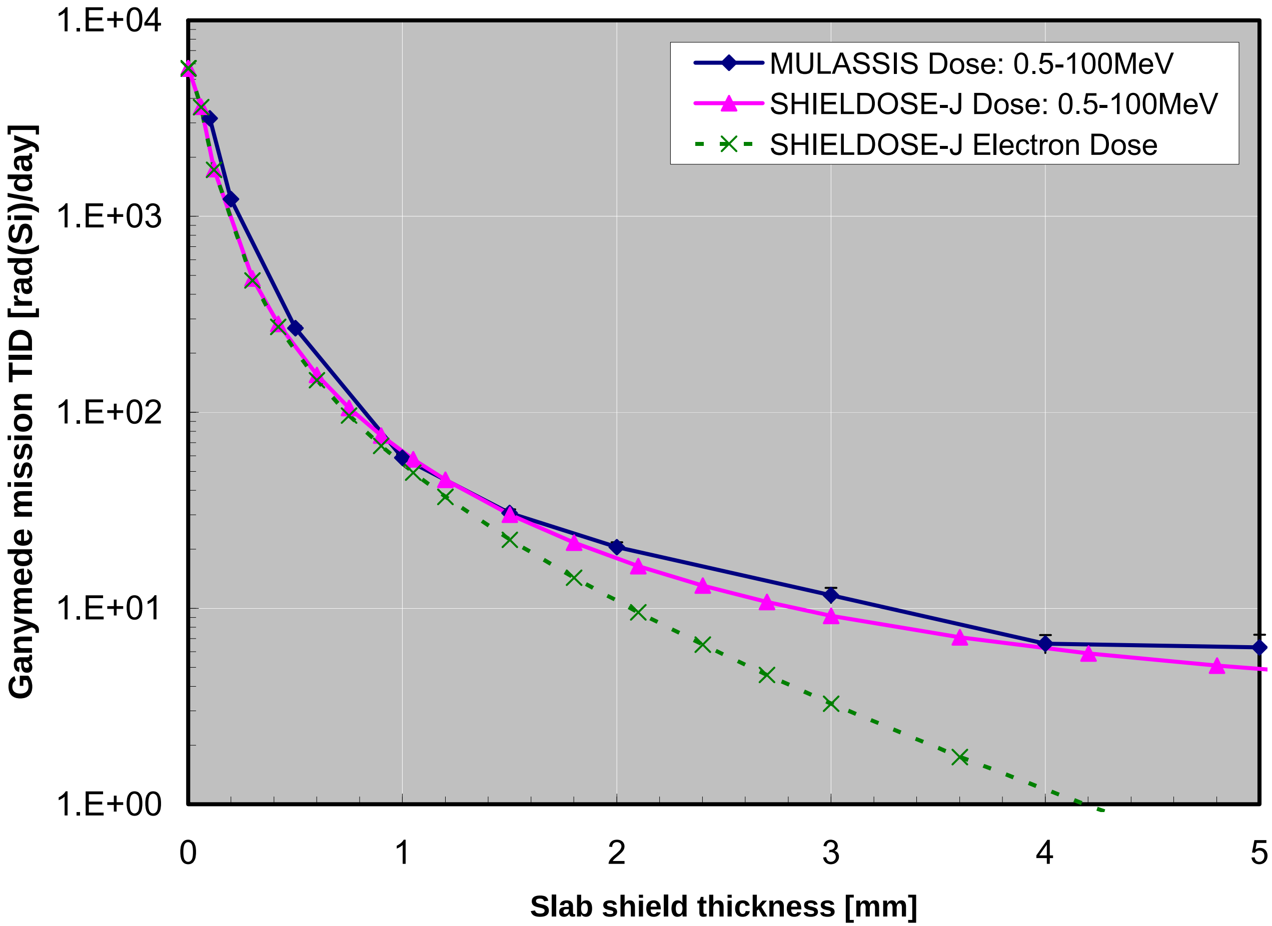
Targets - Materials in which energy is considered deposited (TID)

- Al, Si, H_2O, SiO_2, C (graphite), bone, CaF_2, GaAs, LiF, tissue (in SHIELDOSE-2).
- plastics to represent polyimide ($C_{22}H_{10}O_5N_2$ 1.42 g/cm^3), and epoxy ($C_{18}H_{19}O_3$, 1.85 g/cm^3).
- HfO_2, SiC, and InGaAs (assumed $In_{0.5}Ga_{0.5}As$), HdCdTe (assumed to be $Hg_{0.7}Cd_{0.3}Te$ for MWIR sensors), NaI, MgO, CdZnTe ($Cd_{0.96}Zn_{0.04}Te$ for LWIR sensors) and Ge.

Targets - Materials in which energy is considered deposited (TNID)

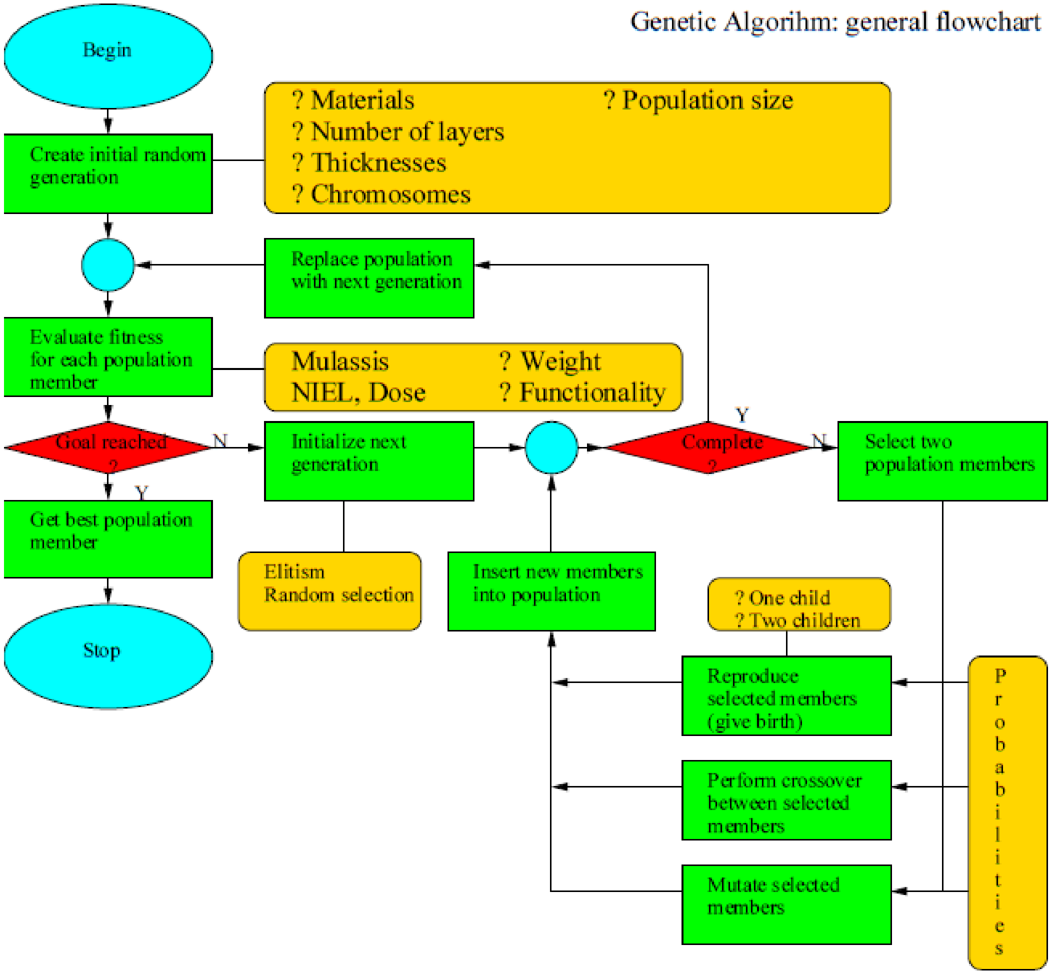
- **Si and GaAs (based on ECSS-E-10-12 NIEL coefficients)**

SHIELDOSE-2 Enhancement Dose predictions for Ta slab shield: Laplace science mission (Env specification v1.0)



Genetic Algorithm-based shielding tool

- Uses a genetic algorithm software package + MULASSIS to help identify optimal shield configurations
- Use cases
  - Case 1: Identify lowest-mass design meeting a specific shielding performance
  - Case 2: Best shielding performance for a given areal mass budget



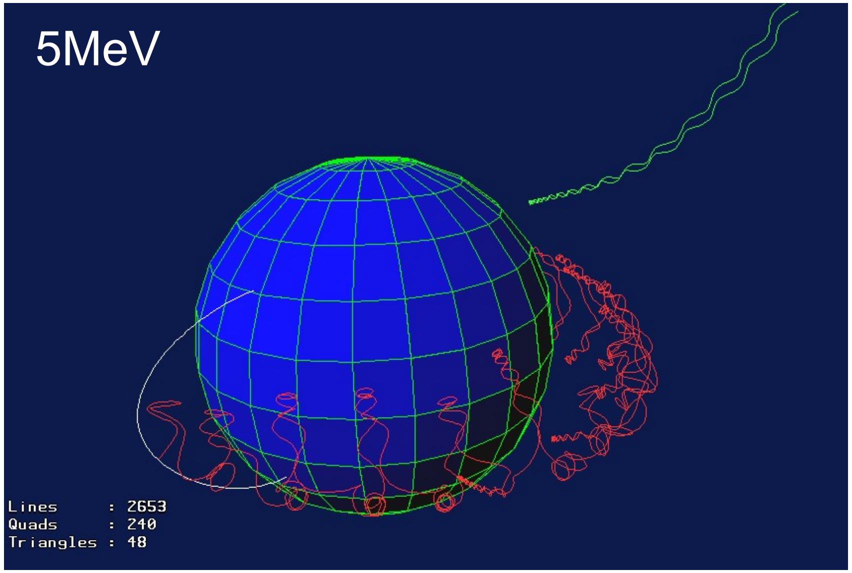
PLANETOCOSMICS Enhancement Galilean Moon Environment Tool

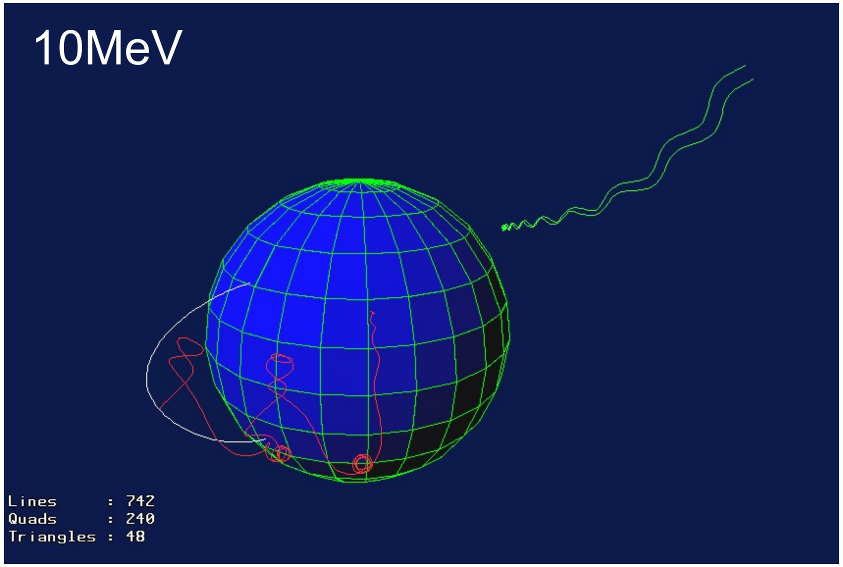
Update L Desorger's PLANETOCOSMICS model, which simulates particle interactions in planetary magnetic fields and atmospheres

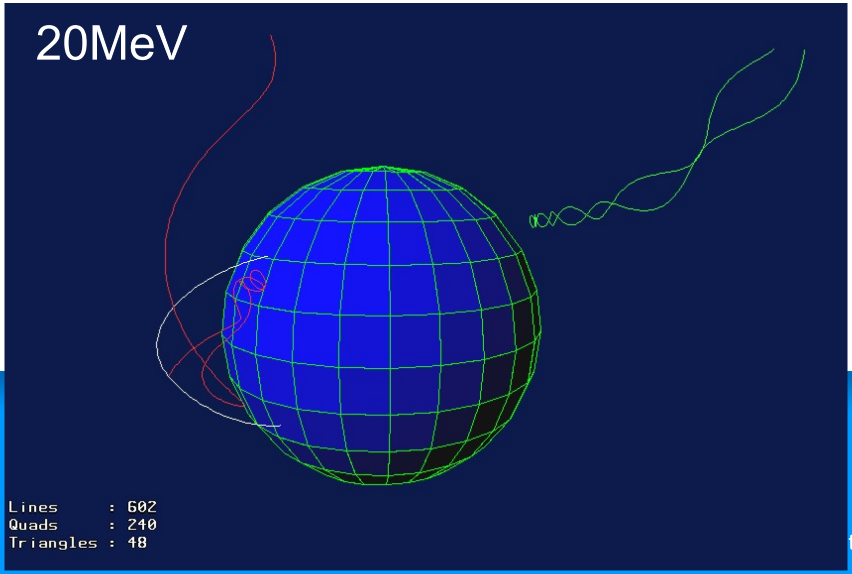
Use-cases:

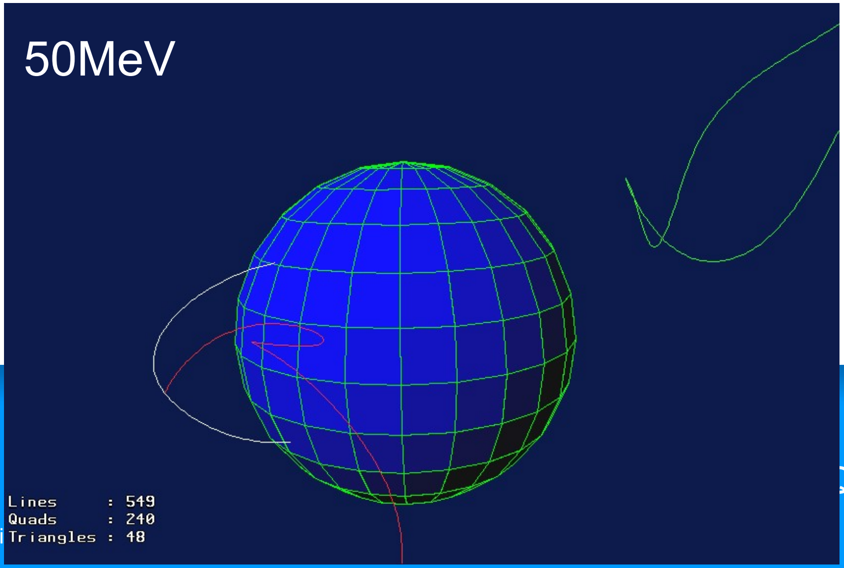
1. Treat the radiation environment at the Galilean moons, including:
   - particle propagation in internal/induced magnetic + uniform field representing Jovian field
   - predictions of the trapped radiation levels at the surface of the moons
   - Treatment of secondary radiation backscatter (albedo) from the surface
   - Outputs should be particle fluence spectra and ionizing and non-ionising dose.
2. Determine cutoff rigidities in the Ganymede internal magnetic field
   - Apply to Jovian electron and proton fluence

PLANETOCOSMICS Enhancement Motion of electrons in Ganymede field

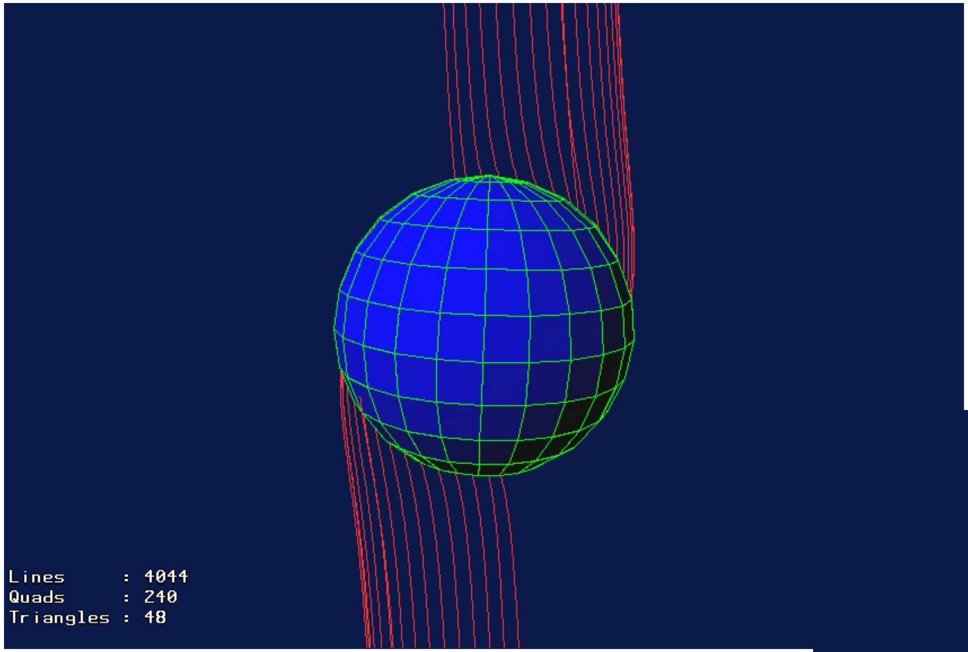


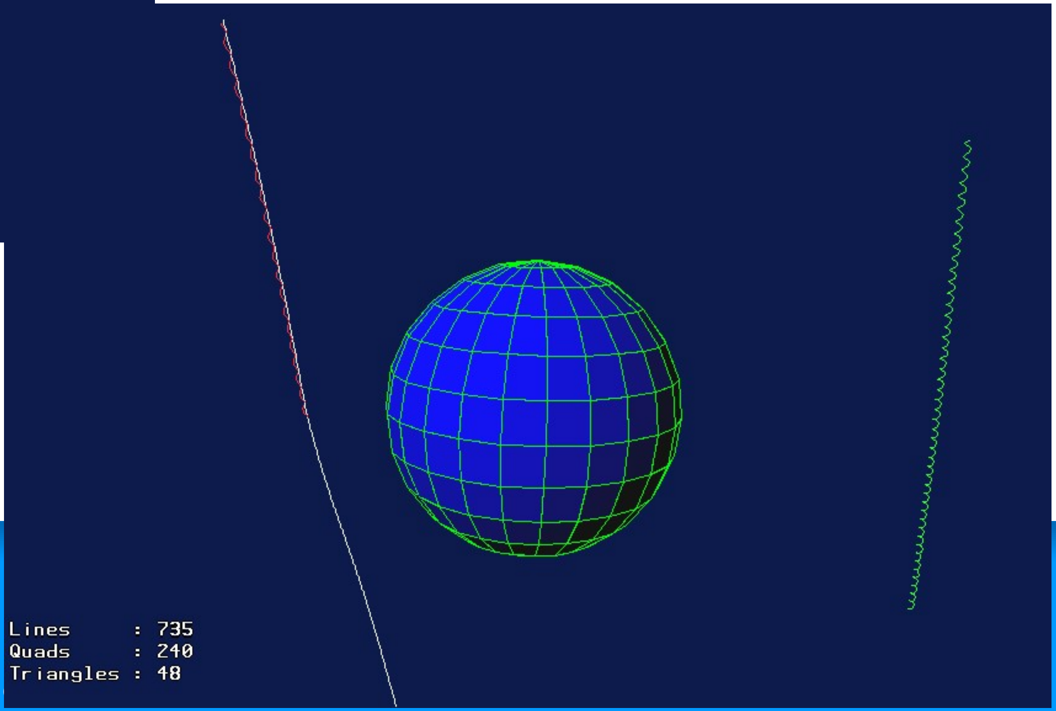




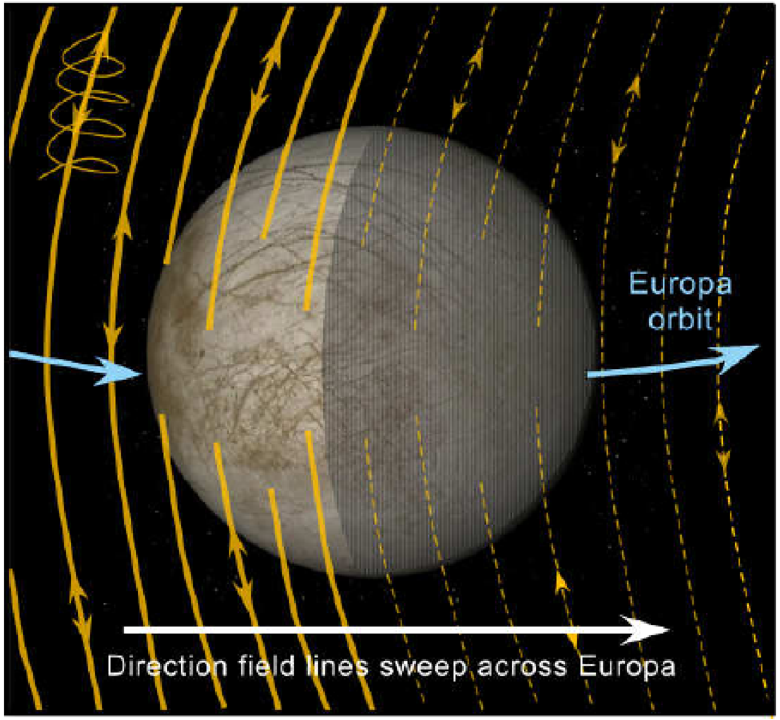


PLANETOCOSMICS Enhancement Motions of electrons in Europa field (15MeV electrons)





PLANETOCOSMICS Enhancement Depletion of trapped radiation belts



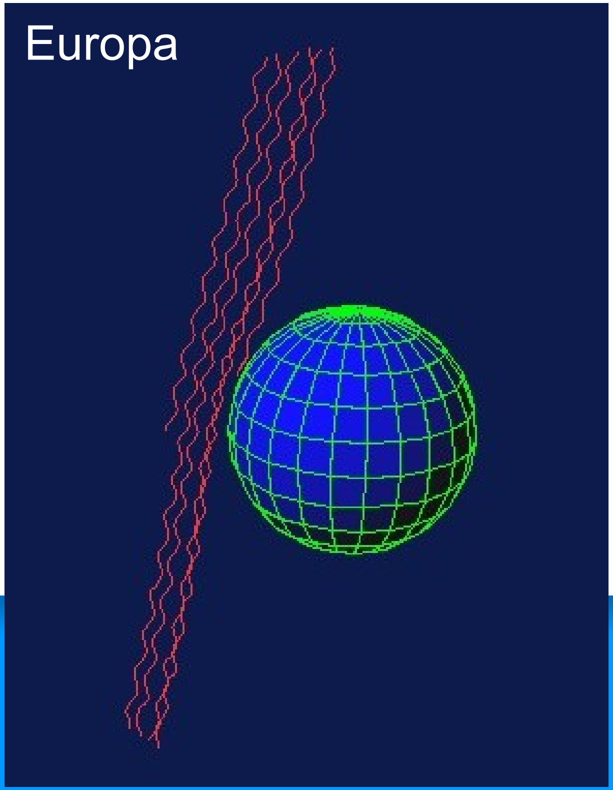
- Added complexity from the slower orbital period of Europa with respect to the combined effects:
  - rotation of the Jovian magnetic field
  - drift period of the particles
- Since the field lines of Jupiter's sweep from the trailing hemisphere to the leading hemisphere, the plasma overtakes the moon, resulting in
  - particle deposition in the trailing hemisphere
  - Depleted particle populations at leading hemisphere

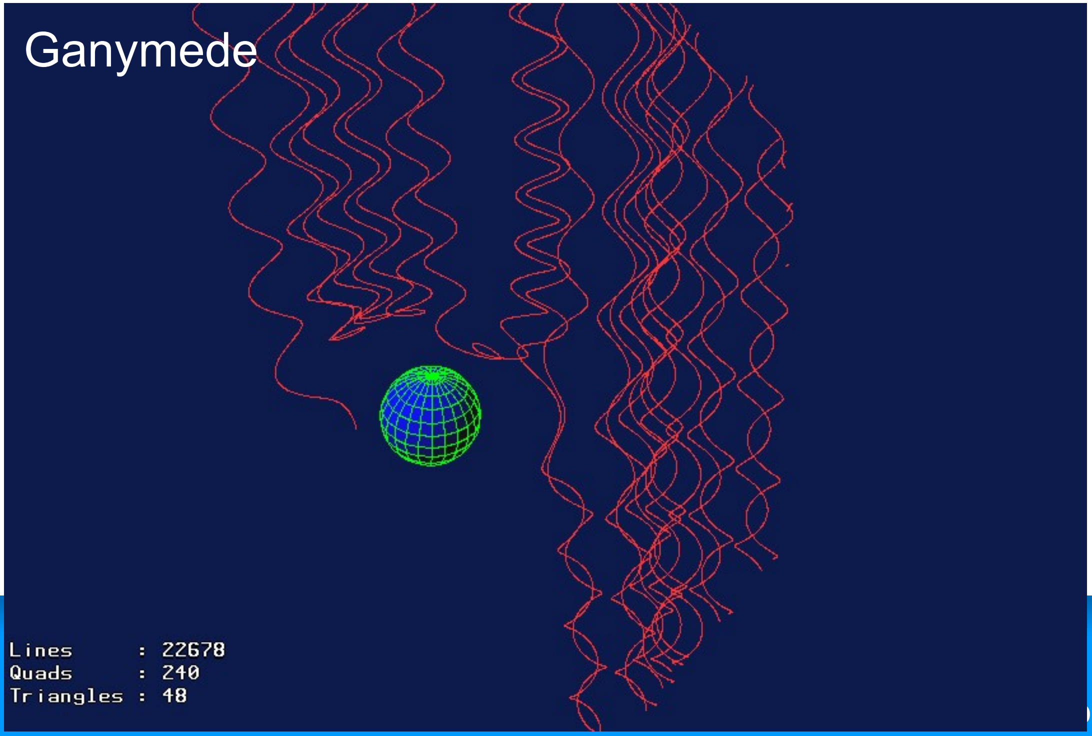
PLANETOCOSMICS Enhancement Depletion of trapped radiation belts

- Algorithm included to calculate the drift of particles relative to the moons between bounce
- No need to simulate whole of Jupiter field
- 15 MeV e- shown

$$\tau_b = \frac{4r_0}{v}\int_{\theta_m}^{\pi/2} \frac{\sin\theta\,(1+3\cos^2\theta)^{\frac{1}{2}}\,d\theta}{\left(1-\frac{\sin^2\alpha_0\,(1+3\cos^2\theta)^{\frac{1}{2}}}{\sin^6\theta}\right)^{\frac{1}{2}}}.$$

$$\langle\tau_d\rangle \approx \frac{\pi q B_E R_E^2}{3LW}(0.35+0.15\sin\alpha_{eq})^{-1}$$





Summary

- Jupiter system environment presents a unique, hostile radiation threat to future missions
- Range of traditional methods for mitigation and also more innovative solutions
- Use of high-Z shields could offer significant mass savings
  - Electron penetration may not make it appropriate to consider graded shields
  - Other practical issues?
- Beware of subtleties in testing for electron/X-ray environment?
- JORE^{2}M^2 Project leading to an integrated system of tools to model environment and effects for future Jupiter system missions
- On effects side:
  - Rapid calculation of dose (TID/TNID) for new shields/targets through updated SHIELDOSE2
  - Shield optimisation models
  - Moon environment simulation based on comprehensive Geant4 physics

Backup slides

General Susceptibilities of Microelectronics Technologies TID effects

Semiconductor technology	Ionisation failure threshold rad(Si)
ECL	$>10^5$
Bipolar	10^5 upwards*
Standard TTL	$>10^5$
I^2L	10^5
bipolar linear	Approximately 10^4 - 10^5
PMOS	10^4 upwards
NMOS	10^3
bulk CMOS	$3x10^3 – 10^5$
CMOS/SOS – SOI (commercial)	$>10^4$?
CMOS/SOS – SOI (rad-hard)	10^6 upwards
Commercial CCDs	10^3-10^4

*Bipolar technology subject to adverse dose-rate dependent TID effects.

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