Internal Charging

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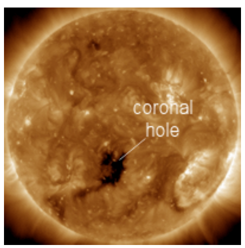
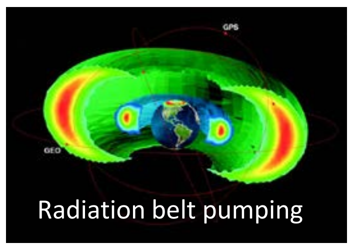
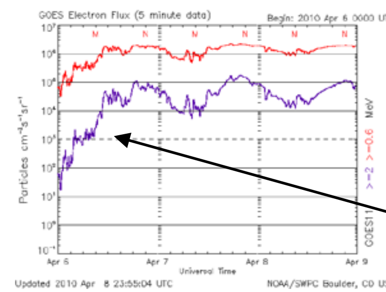
Close out meeting, Cambridge, UK, 23 March 2017

Background

- Energetic trapped electrons in Van Allen belts pose a threat to satellites through internal charging of dielectric materials:
- The outer electron belt is extremely dynamic - large changes in flux occur over short timescales, driven by coronal holes and coronal mass ejections (CMEs)

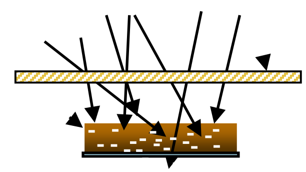






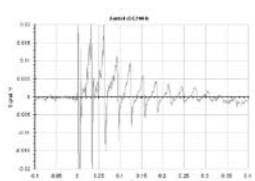
e.g. April 2010:

>2 MeV flux at GEO increases by ~4 orders of magnitude in a few hours!

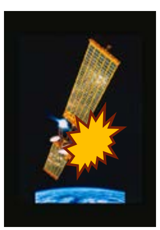


Electrostatic charging of spacecraft materials

Electrostatic discharge



Energy coupling into circuit



Satellite anomaly / outage /failure

Internal Charging in SPACESTORM

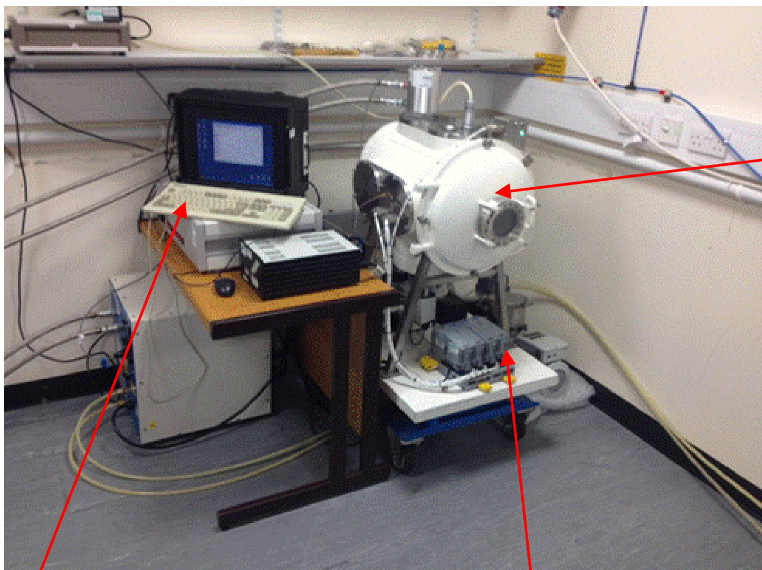
- Work Package 8: Risk assessment for internal charging and radiation dose
  - To make an assessment of the risk to satellites in MEO and GEO from internal charging based on the reconstructed 30 year data set and under extreme conditions using the modelling outputs from other WPs
  - Make an assessment of the cumulative dose for MEO and GEO satellites using the historical (30 year) and extreme storm environments to understand the degree of satellite ageing (if any) and the potential need for early replacement.

- Work Package 11: Experimental analysis of low level long duration internal charging
  - To determine by experiment whether long-term low-flux (~0.01 pA cm^{-2}) irradiations lead to risks of electrostatic discharges as has been postulated based on modelling and observed in-orbit behaviour
  - To investigate by experiment the internal charging behaviour of dielectrics under irradiation over long periods much closer to satellite-relevant timescales (**many months**) to determine if risks of a discharge increase, decrease or stay the same over time.

(complemented by ONERA experiments)

Experimental Campaign (WP11)

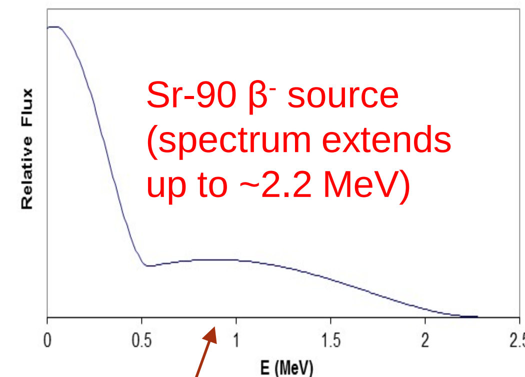
- Realistic Electron Environment Facility (REEF) installed at University of Surrey
- Continuous low intensity experiments since mid-2015

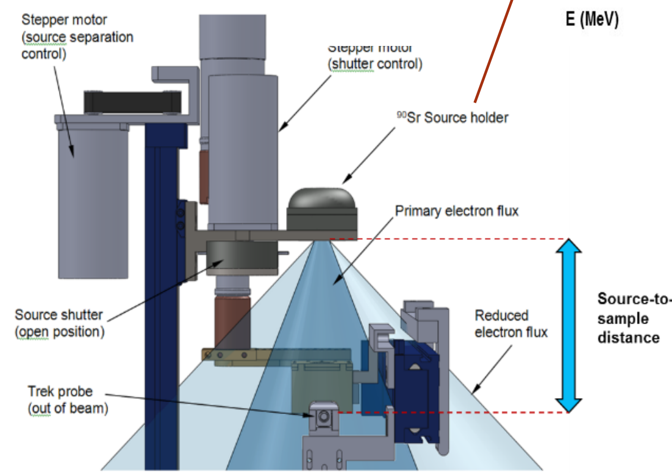


Vacuum Chamber

Control PC

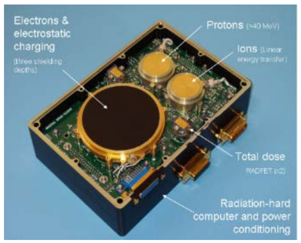
Axis control

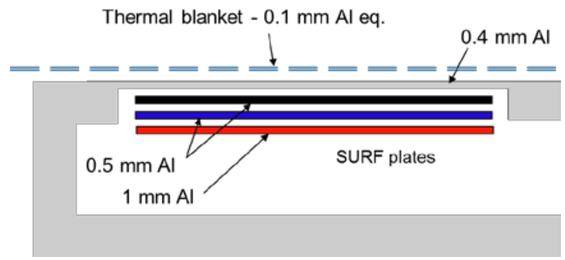


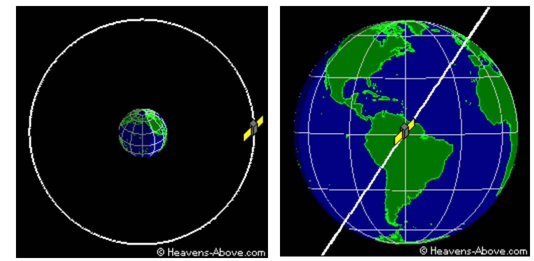


Experimental Campaign (WP11)

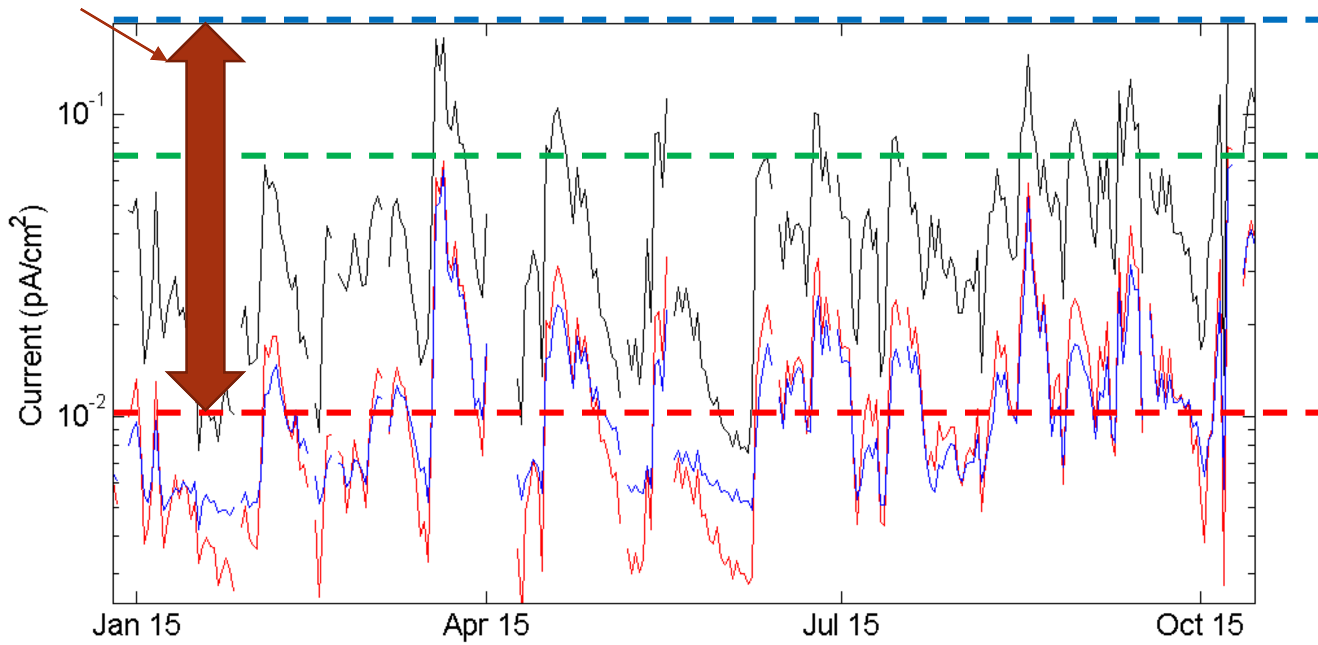
- Incident current range compared to MEO instrument data (SURF):







WP11 range



Incident currents:

High: 0.22 pA/cm^2

Medium: 0.07 pA/cm^2

Low: 0.01 pA/cm^2

(difficult to get much lower without losing high E component)

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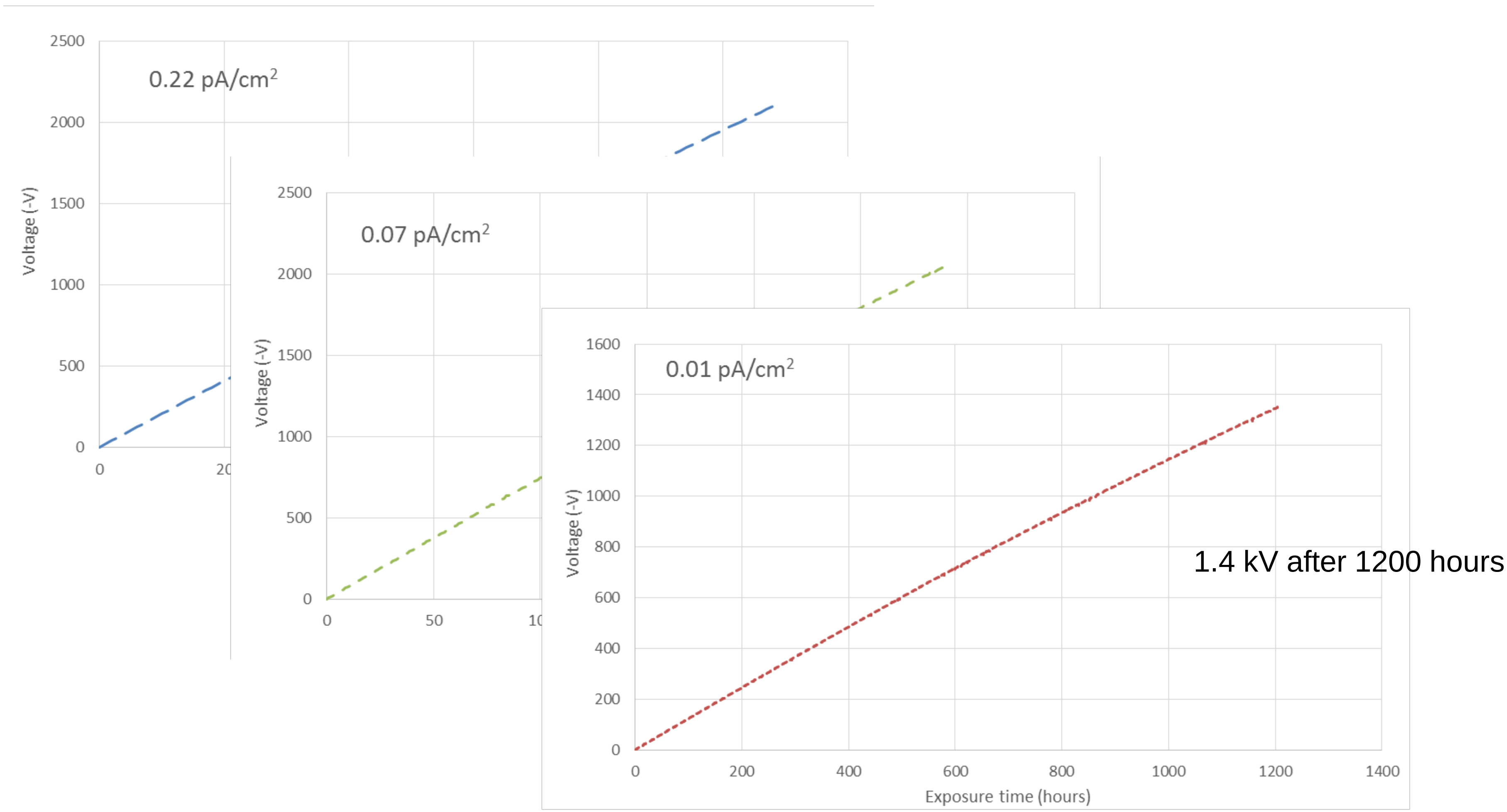
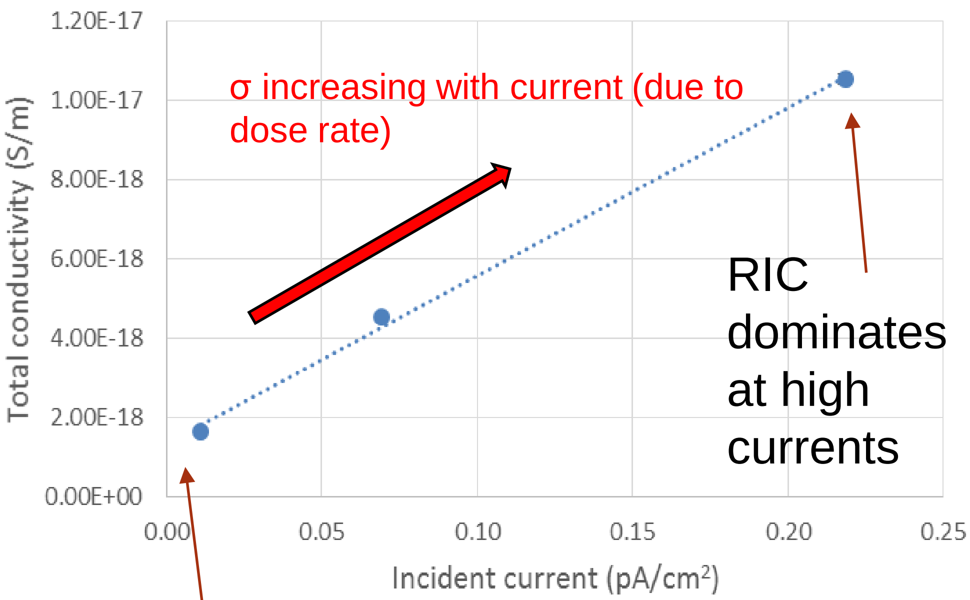
Results from 1st Sample: PEEK



High voltages observed, but not reaching equilibrium

Charging Parameters

- Exponential function fitted to charging profiles
- Electrical conductivity (σ) extracted from curvature



$$\sigma_{total} = \sigma_T + \sigma_{RIC}$$

Bulk conductivity at room temperature

'Extra' (radiation-induced) conductivity

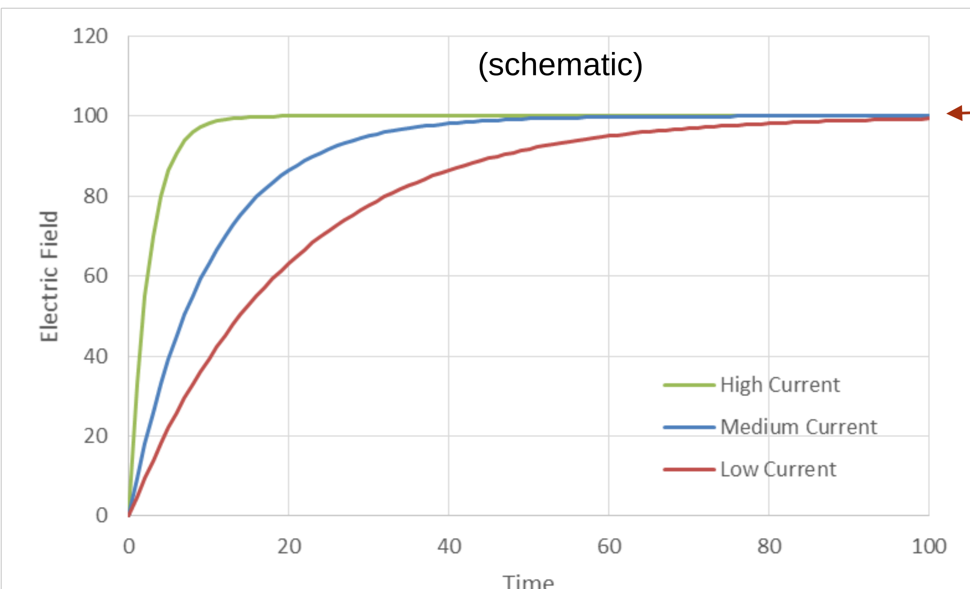
$$\sigma_{RIC} = k.\dot{D}^{\Delta}$$

Dose rate

Low (bulk) conductivity corresponds to long time constants (>6 months)
→ charge stays trapped in quiescent periods

Implications

- Key findings of long-duration irradiations of PEEK:
  1. Radiation-induced conductivity >> bulk conductivity for electron current > 0.1 pA/cm^2
  2. RIC index (Δ) is approximately 1
- Implication is that total conductivity is (to first approximation) inversely proportional to current
- Therefore maximum electric field is independent of the intensity of the environment



$$E = \frac{J_d}{\sigma}.\left(1 - e^{-t/\tau}\right)$$

Plateau ≈ constant (environment affects only the time taken to reach equilibrium)

A Hands & K Ryden, Experimental Measurement of Low-Intensity, Long-Duration Internal Charging Behaviour, accepted in *IEEE Trans. Plasma Sci.*

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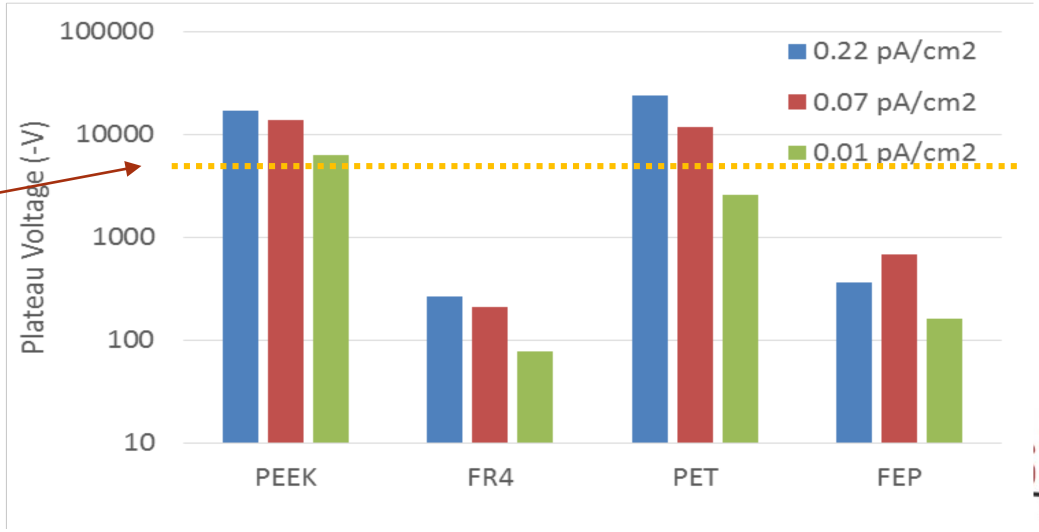
Other Materials

- Four materials tested:

Material	Description	Sample thickness (mm)	Relative permittivity
PEEK	Thermoplastic polymer	1.0	3.3
FR-4	Epoxy-fibreglass	0.76	4.7
FEP-Teflon	Thermoplastic polymer	1.0	2.1
PET	Thermoplastic polymer	1.0	3.4

- Maximum Voltage and Electric Field estimated from fits:

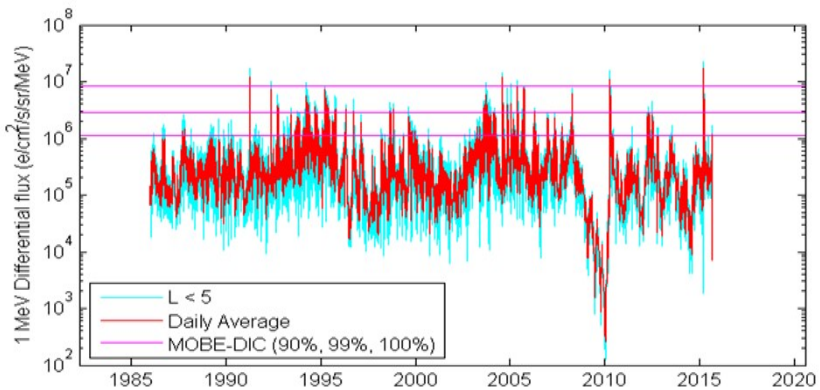
Critical Electric field threshold (~10^7 V/m) exceeded even at 0.01 pA/cm^2



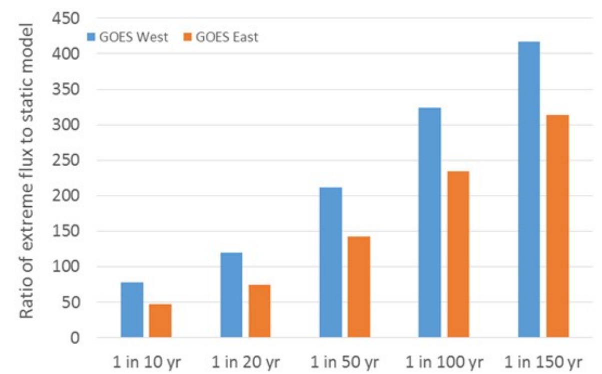
Analysis of Effects (WP8)

- Inputs:
  - WP11 material parameter results (PEEK)
  - Radiation belt models (FLUMIC, MOBE-DIC)
  - SPACESTORM extreme environment scenarios, e.g.:

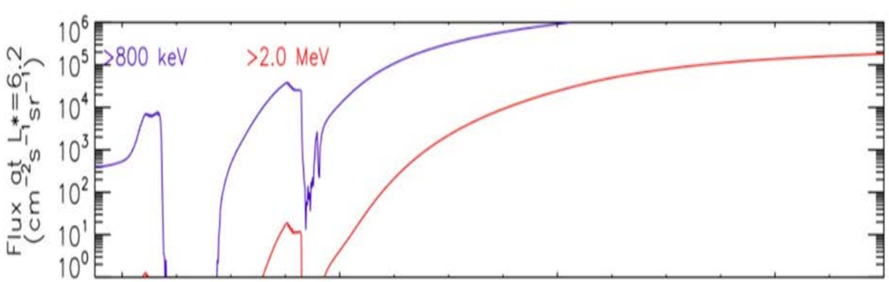
30 year reconstructed data set:



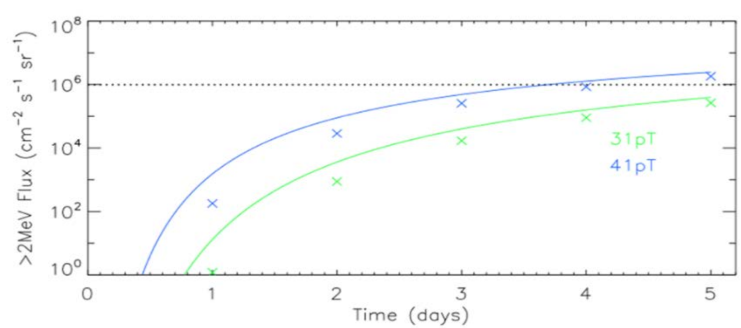
Statistical GEO fluxes:



July 2012 CME:



Extreme event from physical principles:

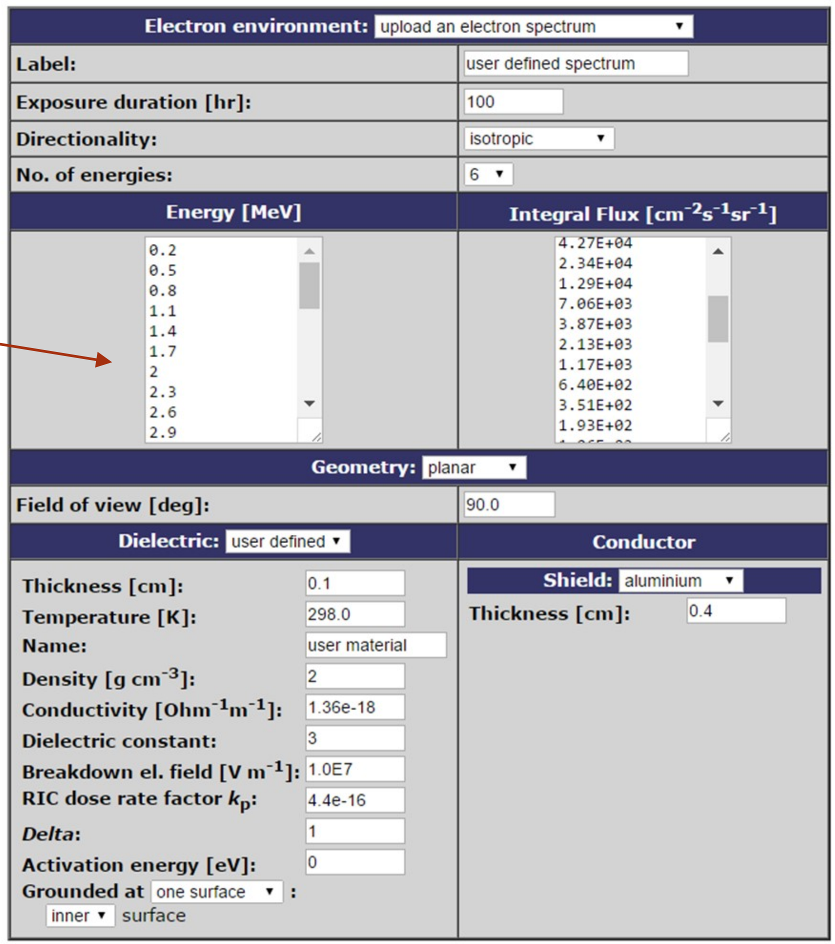


Charging Simulations

- DICTAT used to simulate electric field build up in dielectric samples:

Spectrum

Material parameters


Electron environment: upload an electron spectrum

Label:	user defined spectrum
Exposure duration [hr]:	100
Directionality:	isotropic
No. of energies:	6

Energy [MeV]	Integral Flux [$cm^{-2}s^{-1}sr^{-1}$]
0.2	4.27E+04
0.5	2.34E+04
0.8	1.29E+04
1.1	7.06E+03
1.4	3.87E+03
1.7	2.13E+03
2	1.17E+03
2.3	6.40E+02
2.6	3.51E+02
2.9	1.93E+02

Geometry: planar

Field of view [deg]: 90.0

Dielectric: user defined

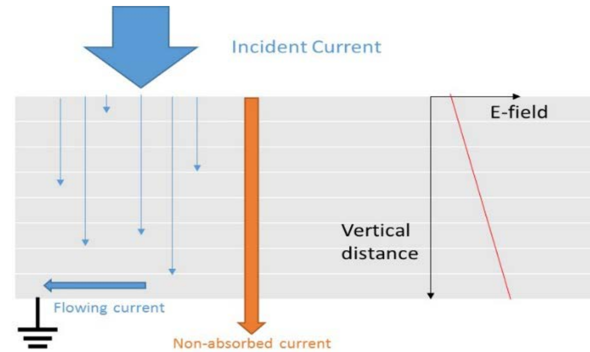
Thickness [cm]:	0.1
Temperature [K]:	298.0
Name:	user material
Density [$g\ cm^{-3}$]:	2
Conductivity [$Ohm^{-1}m^{-1}$]:	1.36e-18
Dielectric constant:	3
Breakdown el. field [$V\ m^{-1}$]:	1.0E7
RIC dose rate factor k_p:	4.4e-16
Delta:	1
Activation energy [eV]:	0

Grounded at one surface : inner surface

Conductor

Shield: aluminium

Thickness [cm]: 0.4



Inputs:

- 1 mm sample
- 1 mm shield
- 298 K
- PEEK dielectric parameters (large uncertainties)

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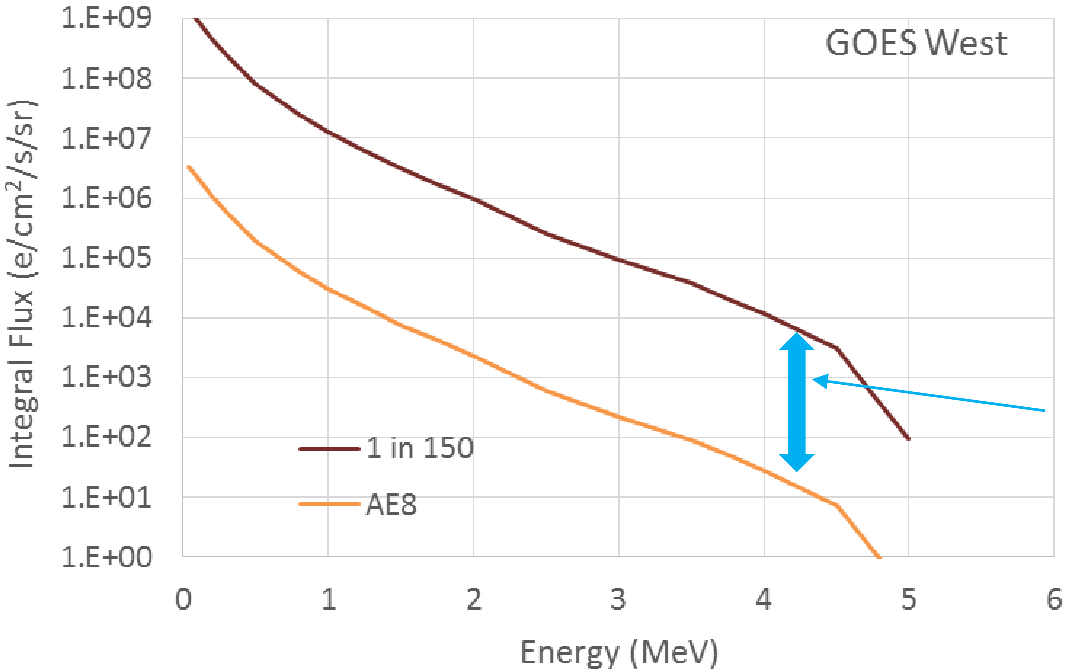
Geostationary Orbit (GEO)

- Worst Case Environment: 1 in 150 year event from statistical analysis of GOES data

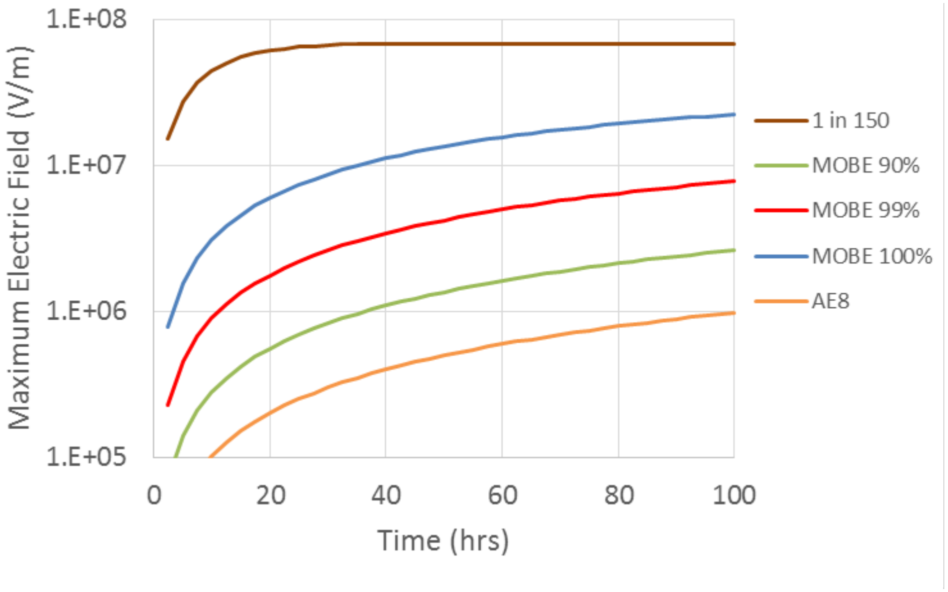


~400x more intense than quiescent background (use AE8 spectral shape)

Geostationary Orbit (GEO)

- DICTAT predictions over 100 hours:

Threshold breached after 36 hours

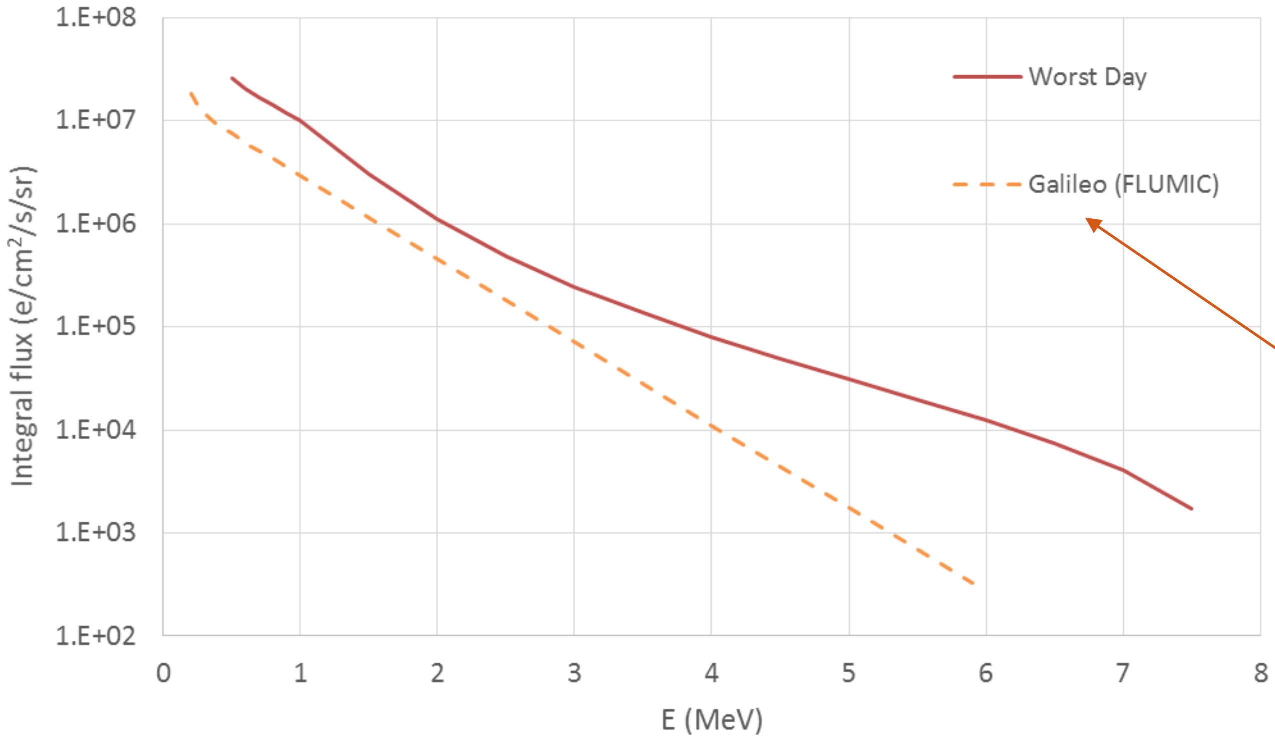


(NB rule-of-thumb estimate for electrostatic discharge is 10^7 V/m)

Worst case: 1 in 150 year event, threshold breached in <2 hours

Medium Earth Orbit (MEO)

- Worst Case Environment: “Worst Day” from BAS 30 year reconstructed data set at MEO



Galileo mission specification

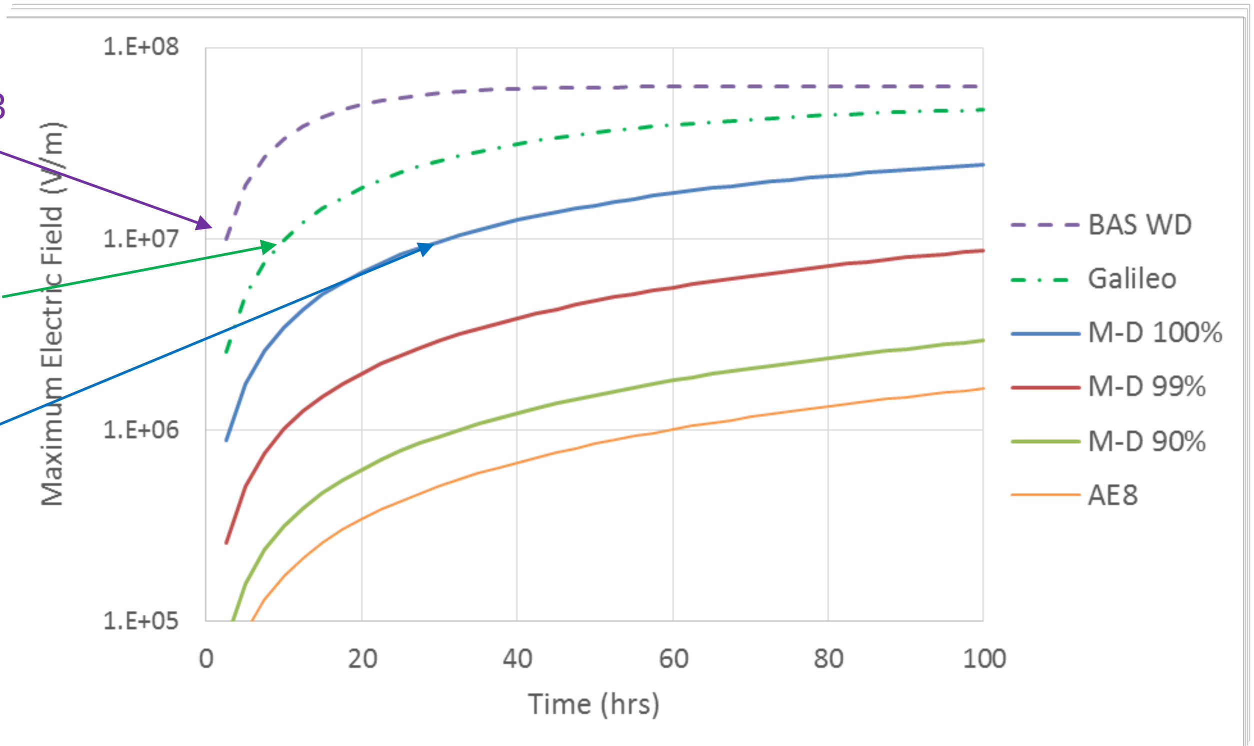
Medium Earth Orbit (MEO)

- DICTAT predictions over 100 hours:

10^7 V/m breached after 3 hours

10^7 V/m breached after 11 hours

10^7 V/m breached after 32 hours



(NB rule-of-thumb estimate for electro-static discharge is 10^7 V/m)

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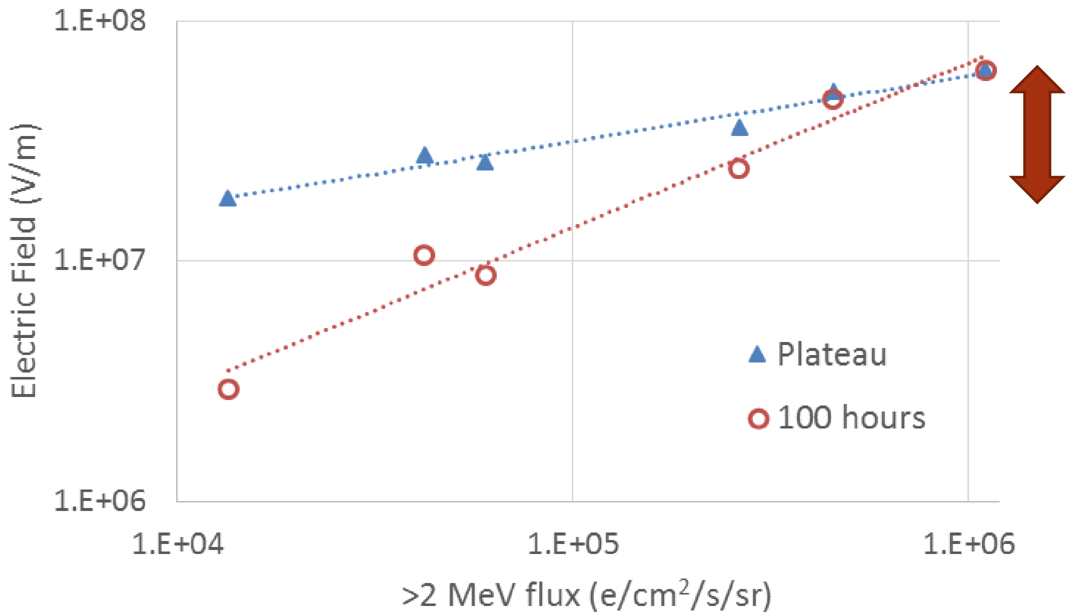
Diminishing Returns

- Large difference in electric field build-up after 100 hours, much smaller difference in plateau voltage



Max E-field *almost* independent of environment

- In this scenario an extreme event *accelerates* progress towards ESD (but ESD could occur weeks or months afterwards)

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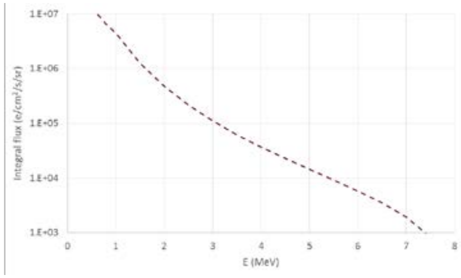
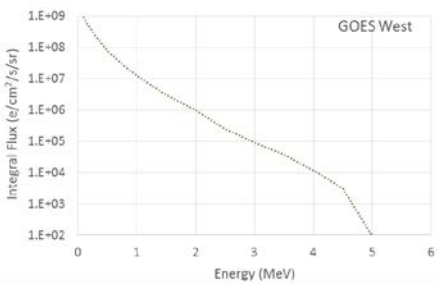
Other Effects – Total Ionising Dose

- Ionisation from high energy electrons and protons causes cumulative damage to electronic components

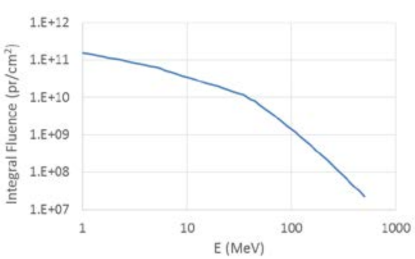
Worst Week at MEO:



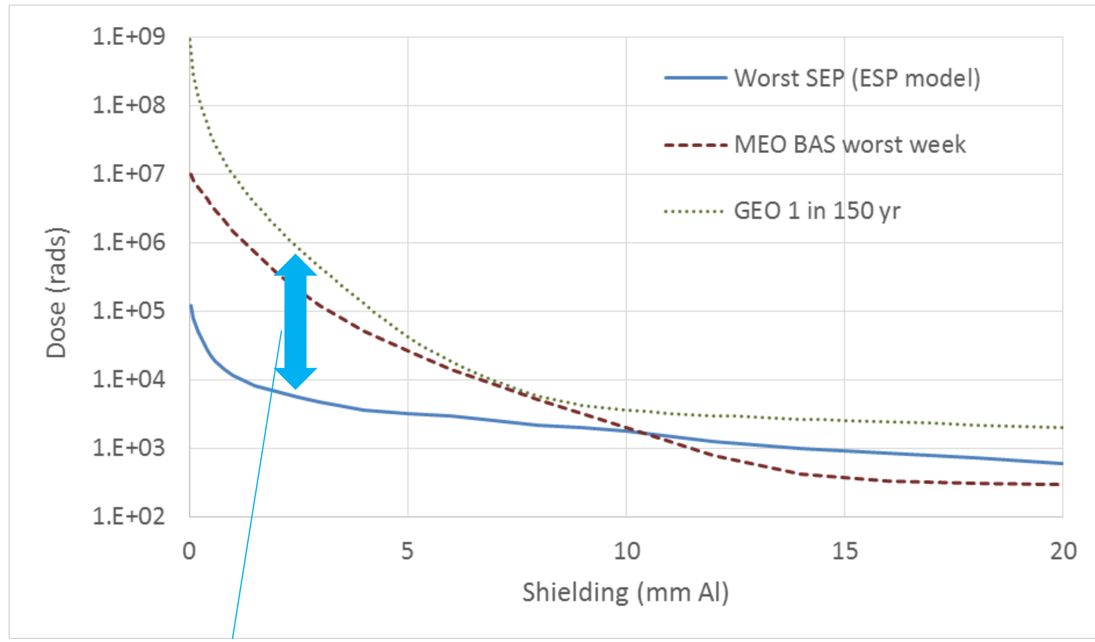
1 in 150 year event at GEO:



ESP "Worst Event":



Dose as a function of shielding depth:



Electron worst case >> proton worst case up to relatively high shielding levels

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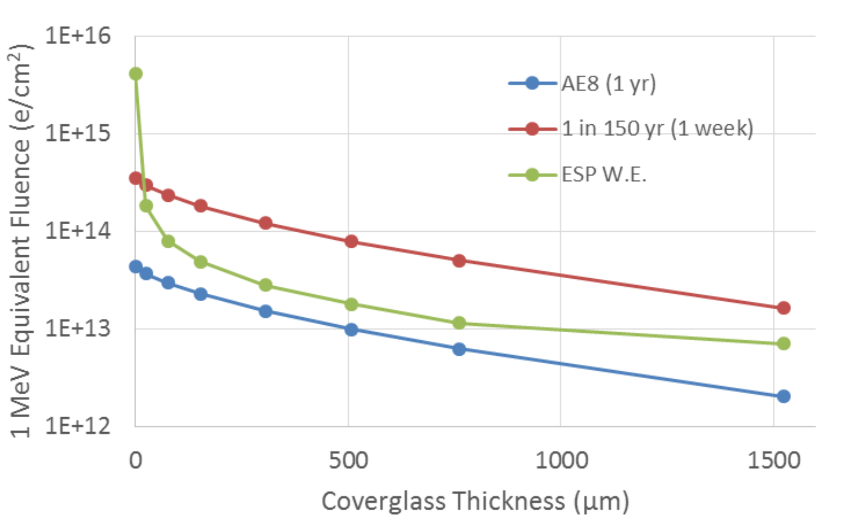
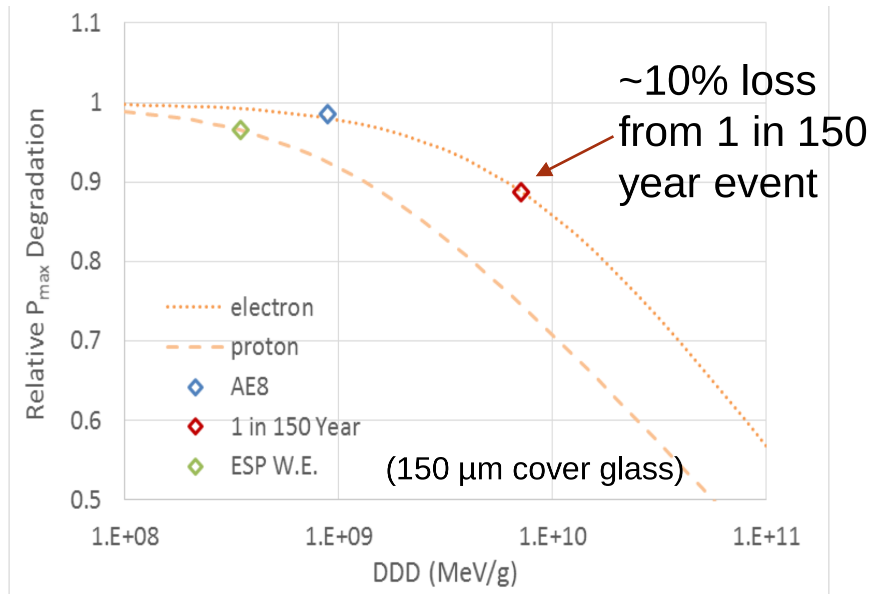
Other Effects – Solar Cell Degradation

- Electrons (and protons) cause degradation to power-generating capacity of solar cells through displacement damage dose (DDD)
- E.g. single junction GaAs:

Equivalent Flux:



Maximum Power Loss:



Worst case electrons >> worst case protons, if sustained for one week

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Conclusions

- New facility at UoS established for realistic testing of internal charging behaviour
- Two dielectric samples tested as part of SPACESTORM show strong charging response at very low incident current (0.01 pA/cm^2)
- Using SPACESTORM extreme event scenarios, simulated electric fields exceed commonly used ESD threshold within a few hours
- Long charging time constants mean there is a significant risk of ESD even in ‘quiescent’ environments (but extreme storms exacerbate risk)
- Internal Charging more of an acute threat than dose or solar cell damage
- In the absence of accurate knowledge of material parameters – best practice is… test, test and test again!