Experimental Measurement of Low-Intensity, Long-Duration Internal Charging Behaviour

A Hands (1) & K Ryden (1)

(1) University of Surrey, Surrey Space Centre, UK

The research leading to these results funded in part by the European Union Seventh Framework Programme (FP7) under grant agreement No 606716 SPACESTORM

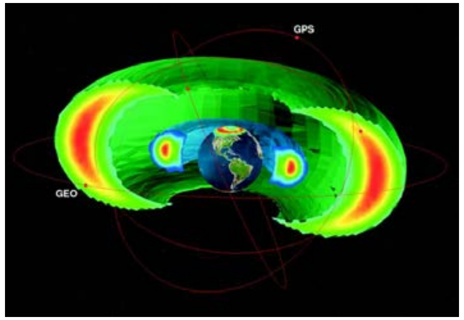
14th Spacecraft Charging Technology Conference, ESA/ESTEC, Noordwijk, NL, 04-08 APRIL 2016

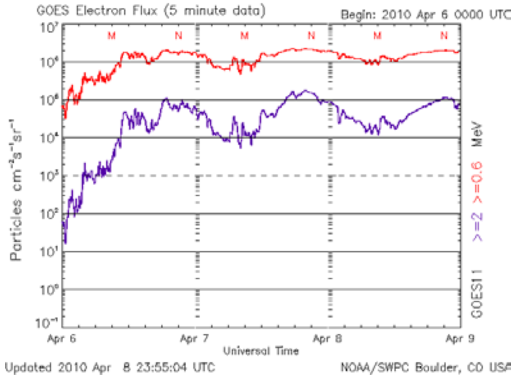
Experimental Measurement of Low-Intensity, Long-Duration Internal Charging Behaviour

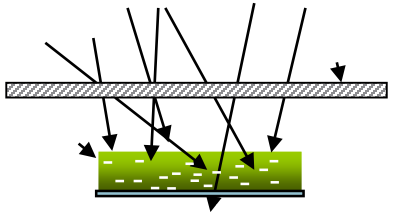
A. Hands and K. Ryden

Spacecraft Charging and Technology Conference

April 2016

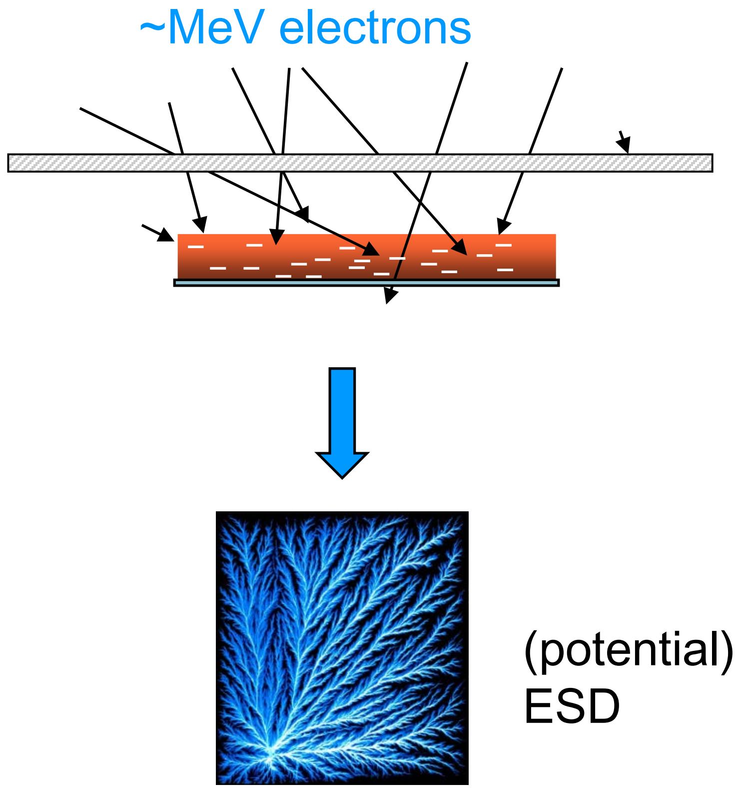






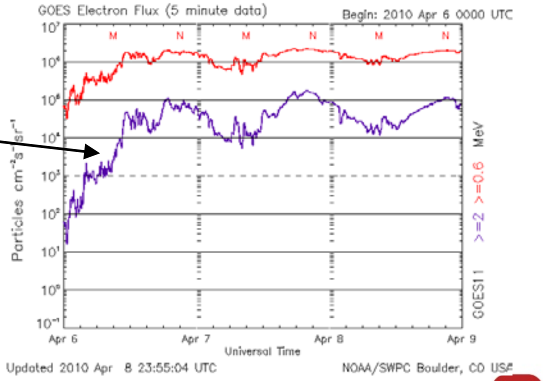
Background

- Internal charging poses a significant risk to satellites operating inside the Van Allen belts
- High energy (MeV) electrons penetrate spacecraft shielding and cause charge to build-up in dielectrics and isolated conductors
- The increase in electric field can lead to electrostatic discharge (ESD) and possible equipment failure
- The threat becomes much more severe during radiation belt enhancements due to large coronal holes or coronal mass ejections (CMEs)



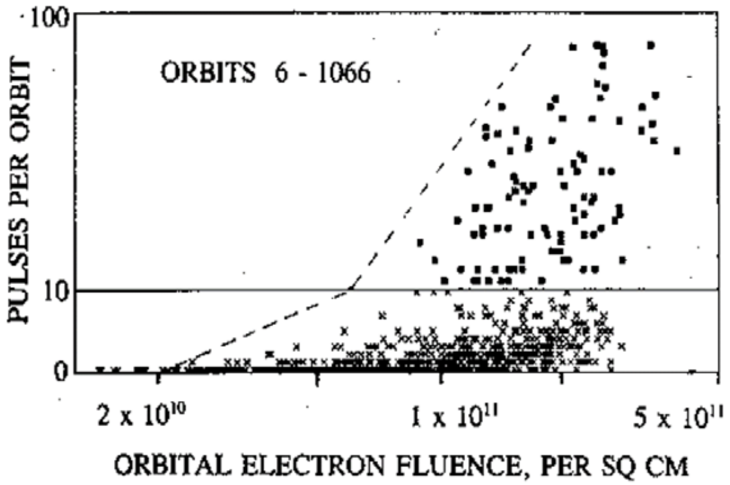
e.g. April 2010:

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



Safety Thresholds

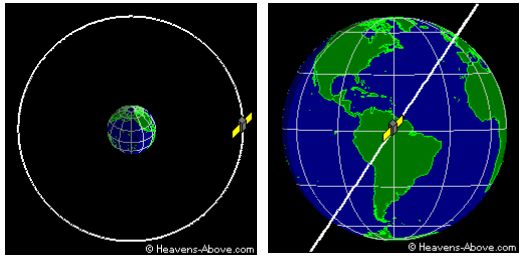
- The threat from internal charging led to the development of engineering safety/design standards
- Defined by minimum acceptable material conductivities and ‘safe’ levels of incident electron current
- E.g.:
  - NASA Handbook 4002A advises using shielding to reduce incident current to 0.1 pA/cm^2 (based on CRRES measurement of 2×10^{10} e/cm^2 ESD threshold over 10 hr orbit)
  - ECSS-E-ST-20-06C also adopts 0.1 pA/cm^2 threshold for charging current, reduced to 0.02 pA/cm^2 for temperatures below 25 °C
- It has been suggested (Bodeau, 2010) that an even lower threshold could be required for materials with long time constants (low conductivity) – 0.01 pA/cm^2



Bodeau (2010)

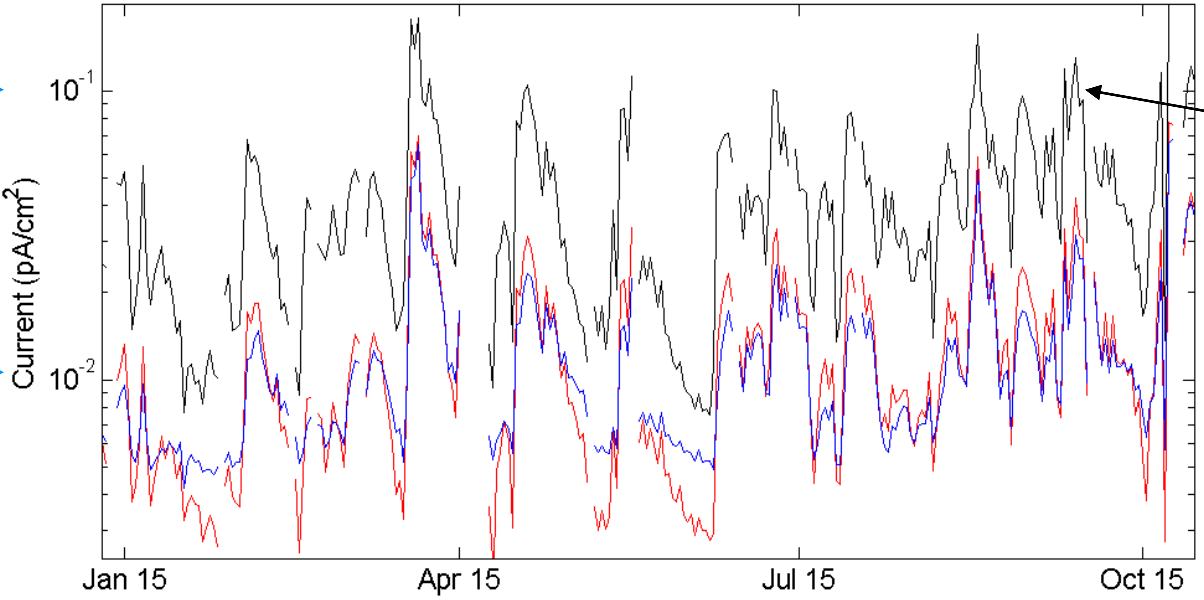
Real Environment (Medium Earth Orbit)

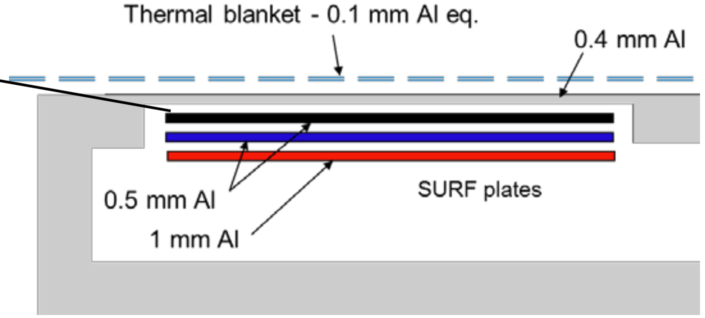
- Direct measurement of electron currents in MEO with SURF instrument (on Giove-A)
- E.g. Daily-averaged currents for three current plates from 2015:

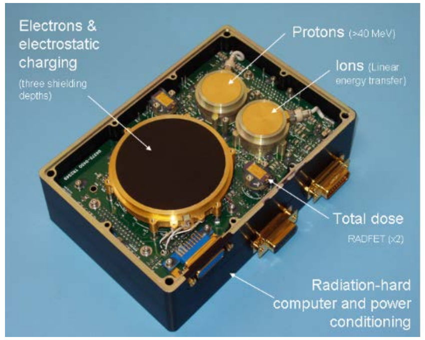


0.1 pA/cm^2 rarely exceeded

0.01 pA/cm^2 regularly exceeded (~100% for top plate)

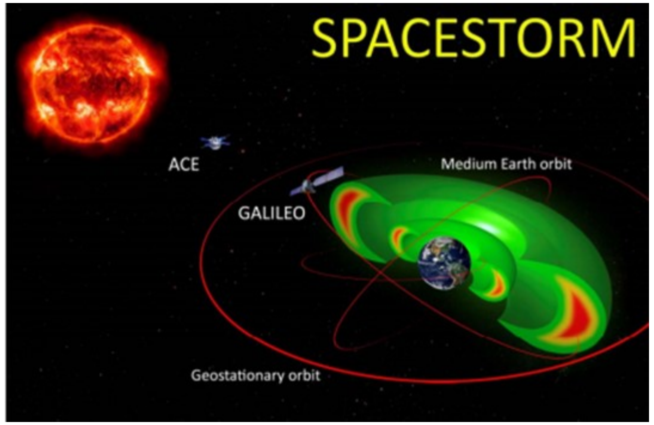






➡ Important to determine whether lower currents are significant!

Spacestorm



- Funded under EU Framework 7

  (http://www.spacestorm.eu/)

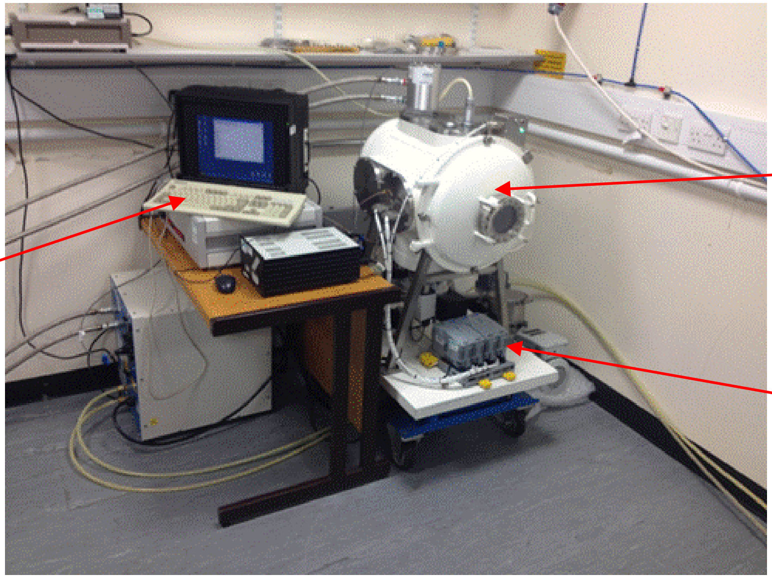
  The goal of the SPACESTORM proposal is to model space weather events and mitigate their effects on satellites through better mitigation guidelines, forecasting of events and experimental testing of new materials and methodologies to reduce satellite vulnerability.

- Work Package 11: Experimental analysis of low level long duration internal charging
  - To determine by experiment whether long-term low-flux (~0.01pA 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.

The REEF Facility

- Meeting Spacestorm WP11 objectives required the commissioning a bespoke facility at the University of Surrey
- REEF (Realistic Electron Environment Facility) acquired from QinetiQ in 2015
- Uses Sr-90 (pure β emitter) to ‘emulate’ trapped electron spectrum in Van Allen belts

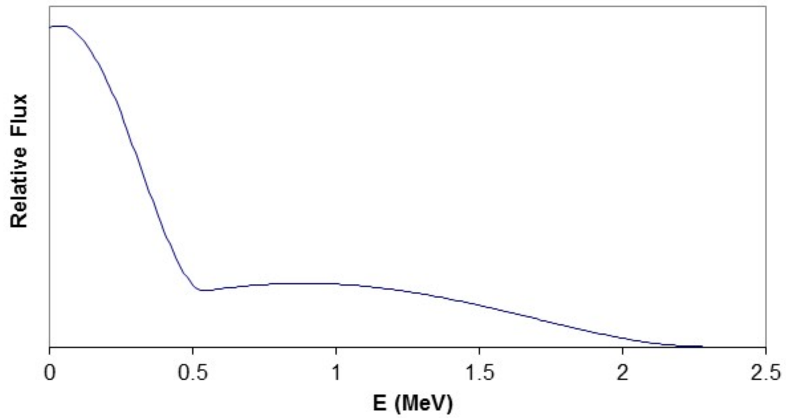
PSU / Control PC



Vacuum Chamber

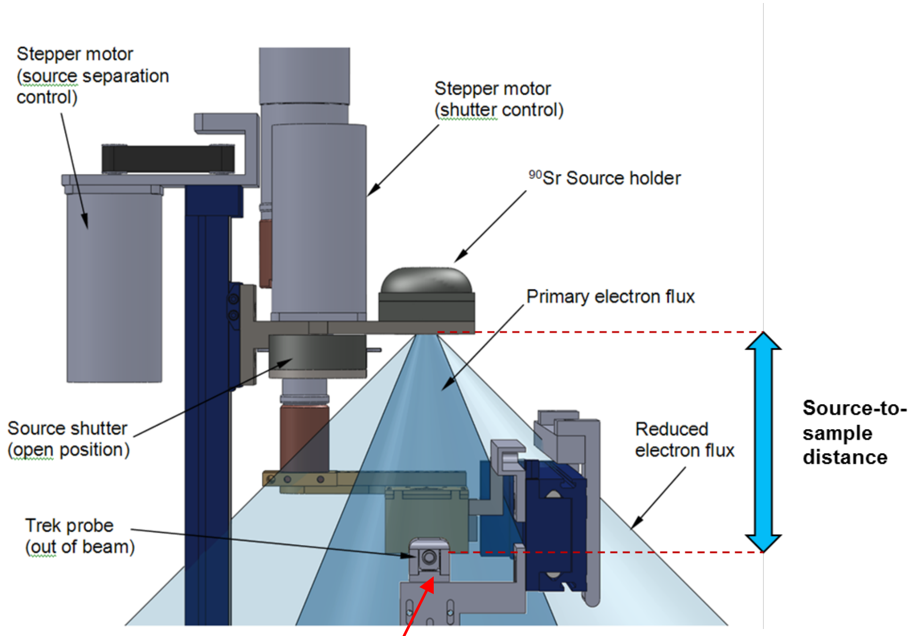
Axis control

Sr-90 spectrum extends up to ~2.2 MeV:

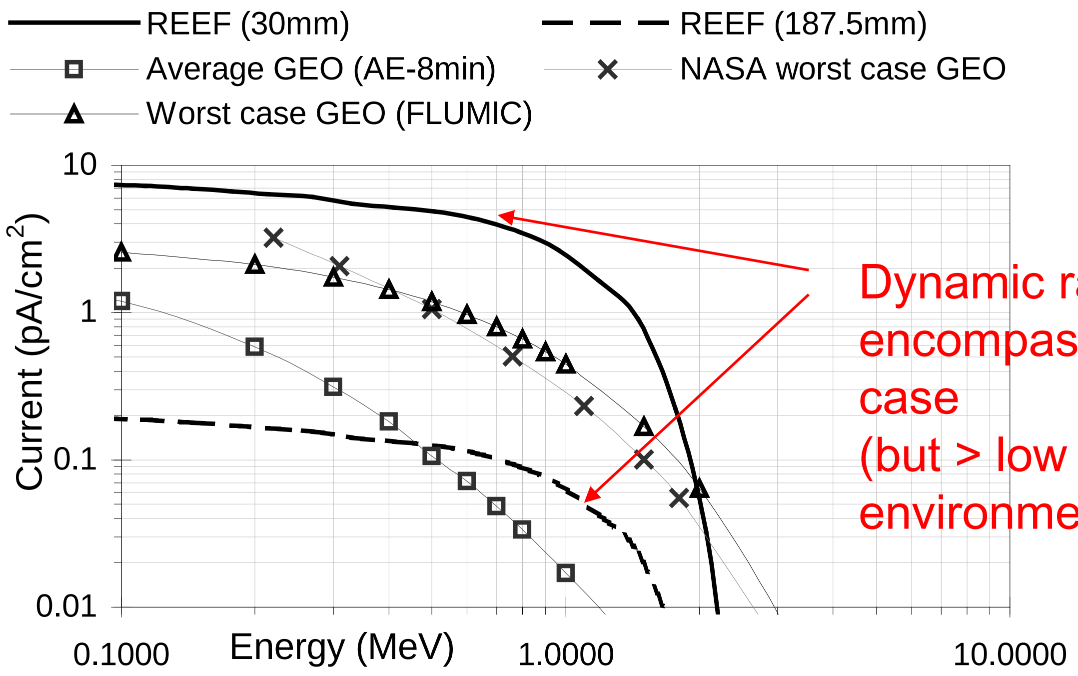


REEF Setup

- Intensity varied by raising/lowering source housing:



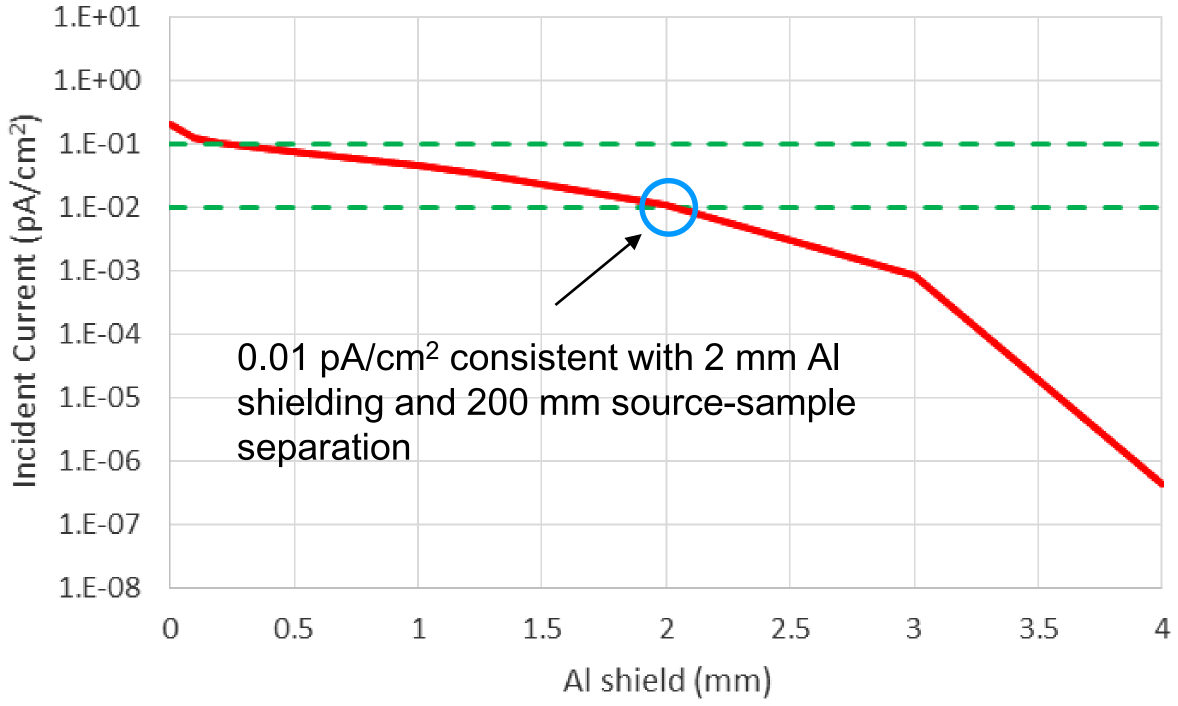
(Surface potential measured with non-contact Trek probe)



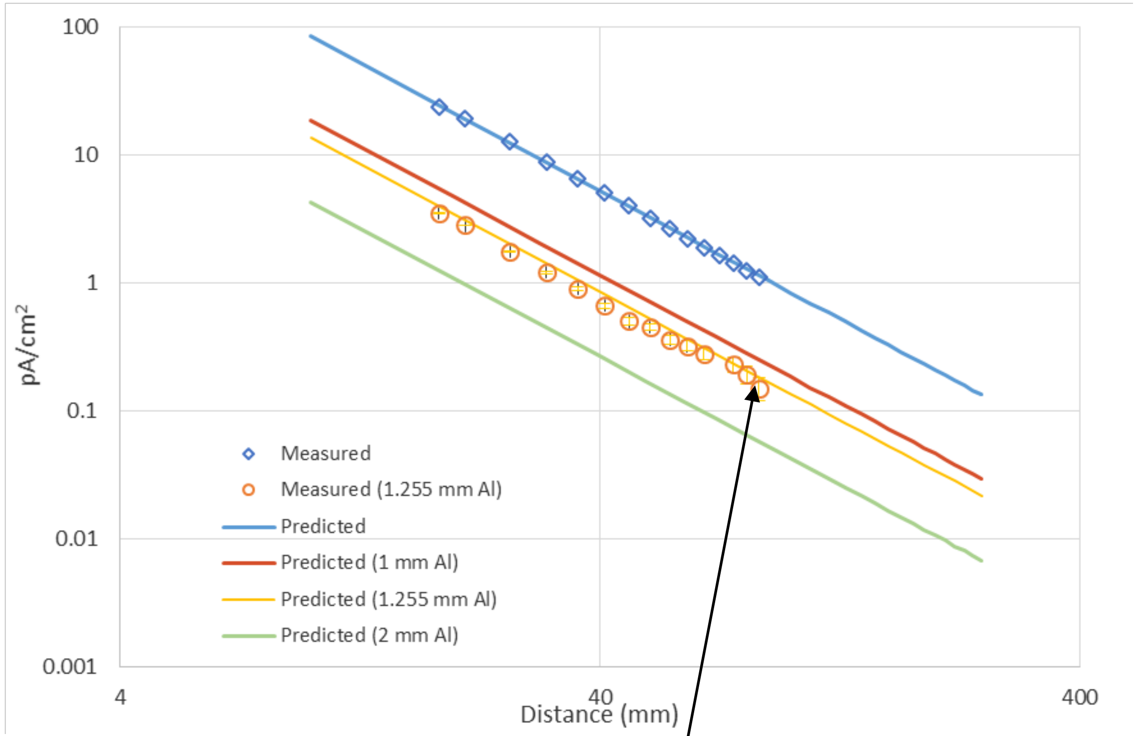
Dynamic range encompasses worst case
(but > low intensity environment)

REEF Currents

- Intensity reduced further with shielding:



Faraday cup measurements cf. simulations:



Shielded measurements consistent with simulations

Materials

- Four dielectric materials selected (all planar samples, metallised on one side)

This presentation

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

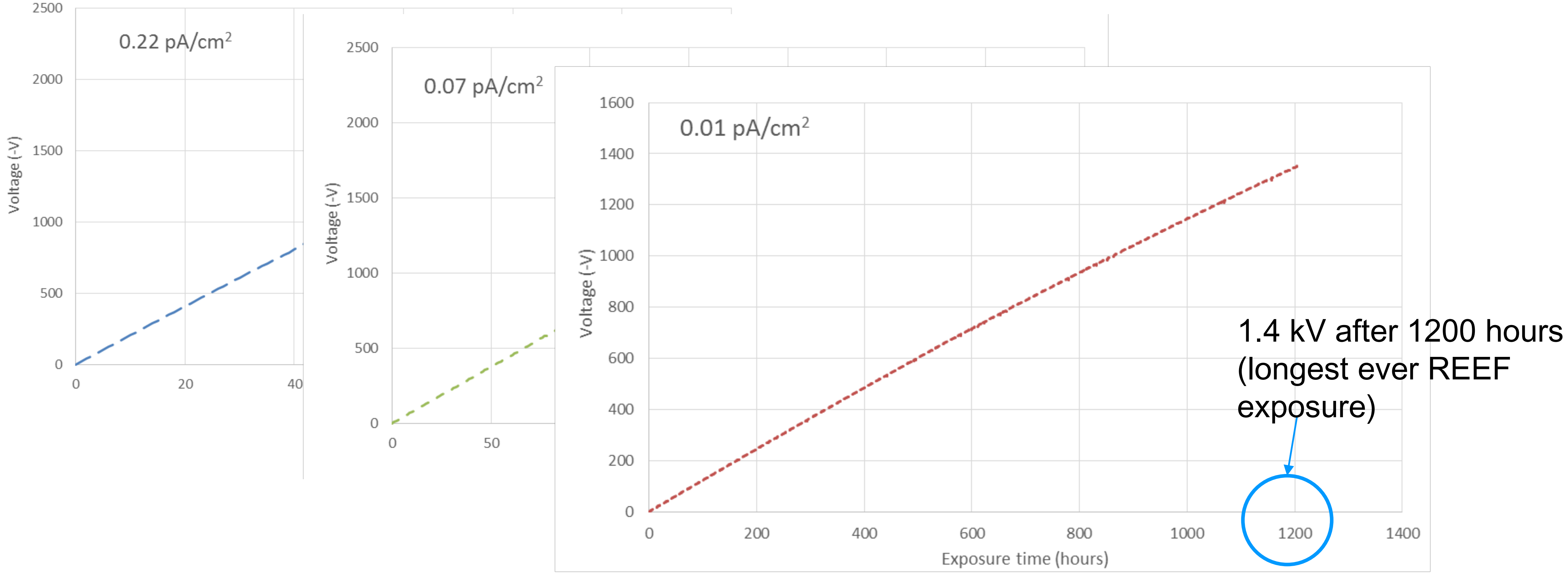
- Three levels of incident current selected for the experiments:

Low: 0.01 pA/cm^2

Medium: 0.07 pA/cm^2

High: 0.22 pA/cm^2

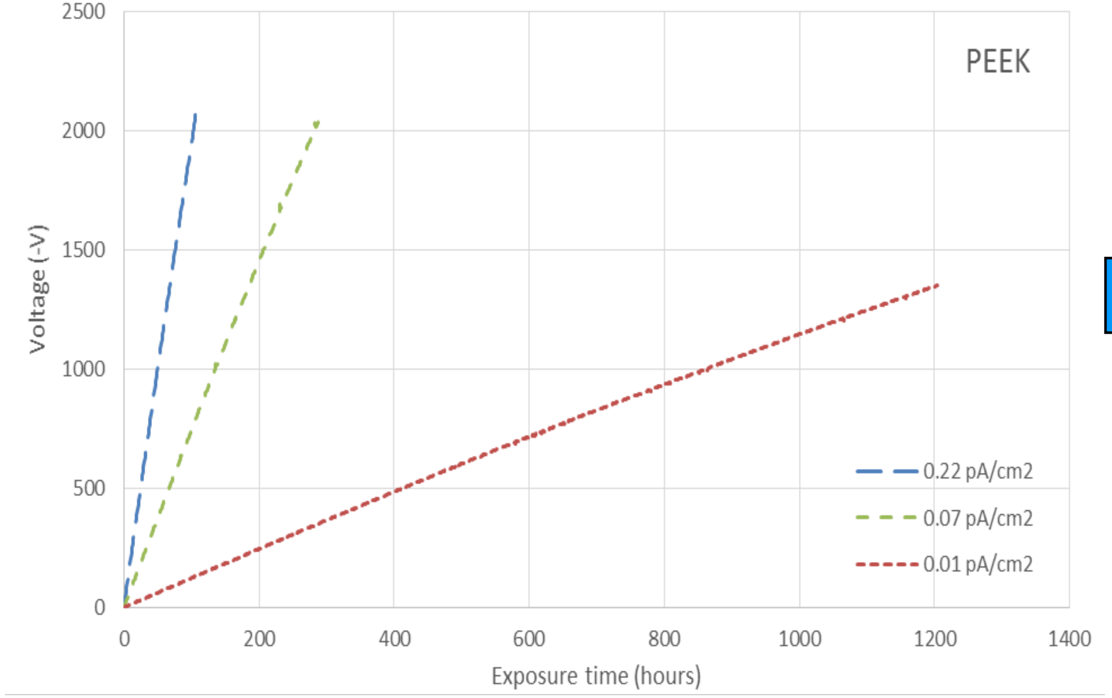
Results from 1st Sample: PEEK

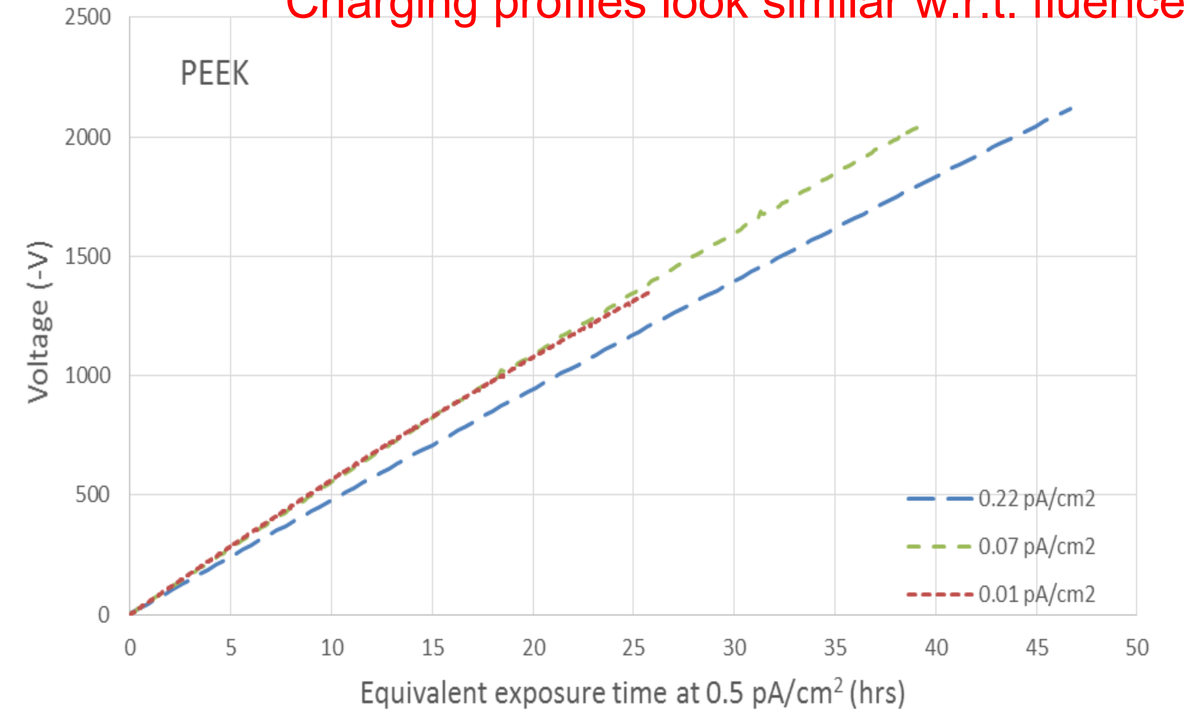


High voltages observed, but not reaching equilibrium

Charging relative to Electron Fluence

- Adjust x-axis for fluence (equivalent exposure time) instead of time:

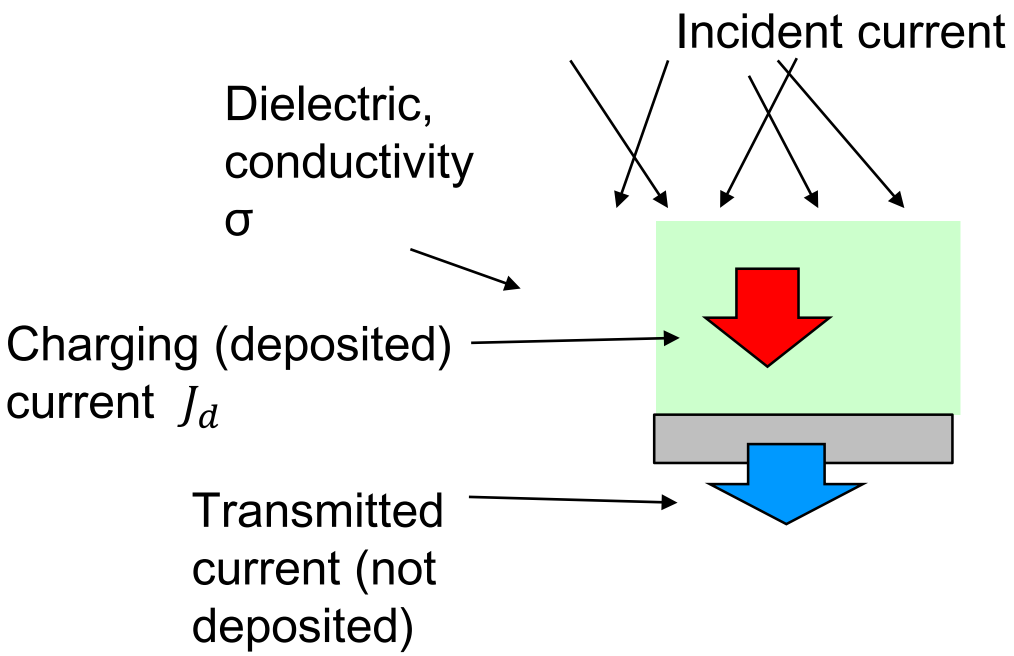




Charging profiles look similar w.r.t. fluence!

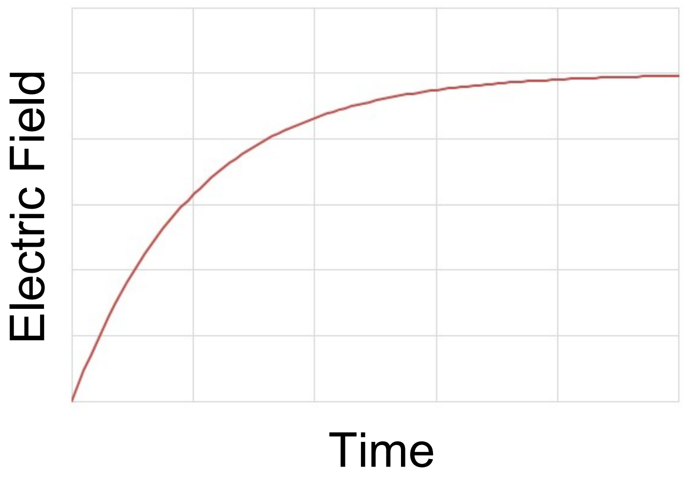
Basic Theory

- Simple calculations predict exponential charge build-up under constant current:



Electric field:

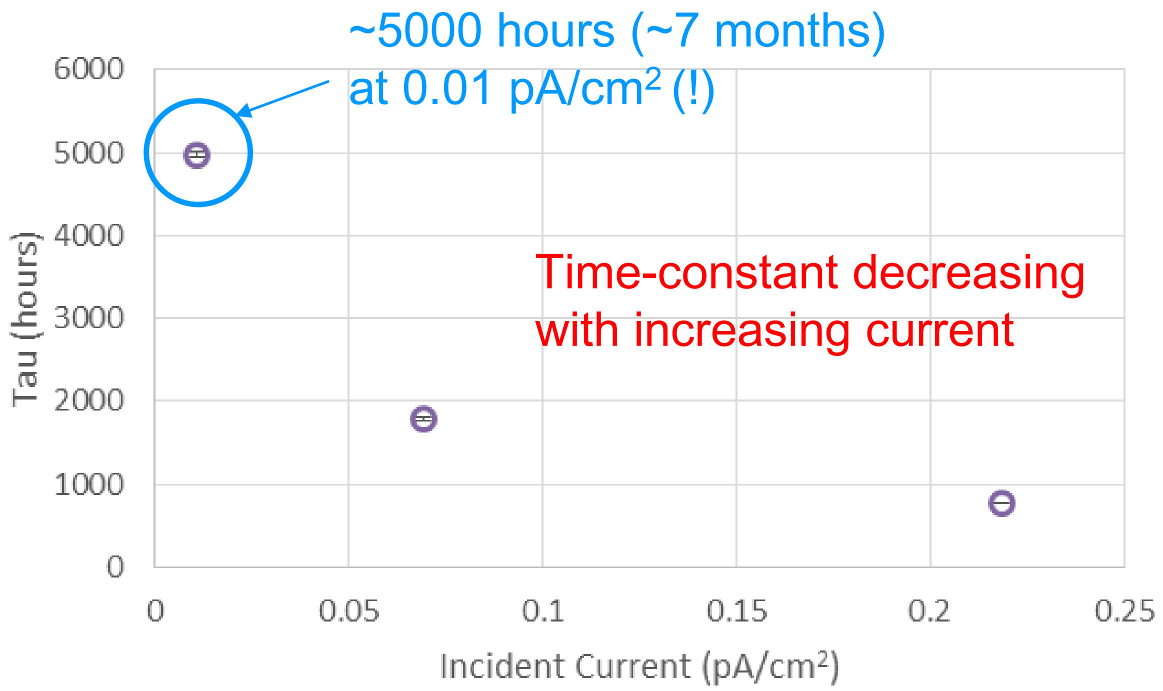
$$E = \frac{J_d}{\sigma}.\left(1 - e^{-t/\tau}\right) \qquad \tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma}$$

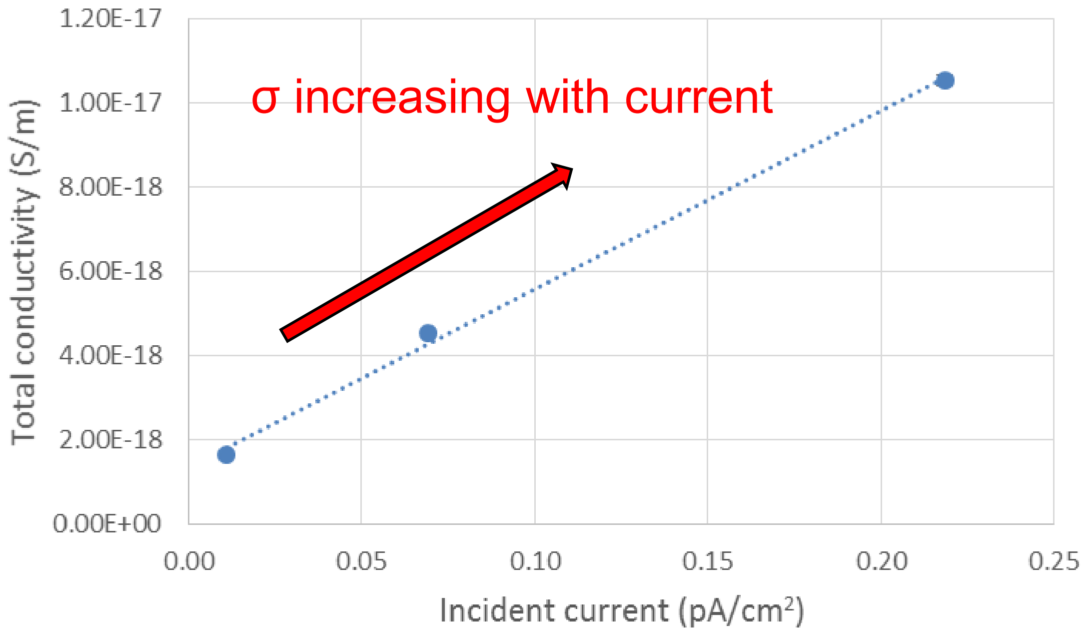


Exponential build-up of electric field (or surface voltage), eventually reaching equilibrium

Charging Parameters

- Exponential function fitted to charging profiles
- Time constant extracted from curvature → conductivity from $\tau = \dfrac{\varepsilon_0 \varepsilon_r}{\sigma}$





Radiation-Induced Conductivity

- Ionising dose rate from electrons passing through the dielectric can increase charge leakage through radiation-induced conductivity (RIC)
- Additive component to total conductivity:

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

Bulk conductivity at room temperature

'Extra' (radiation-induced) conductivity

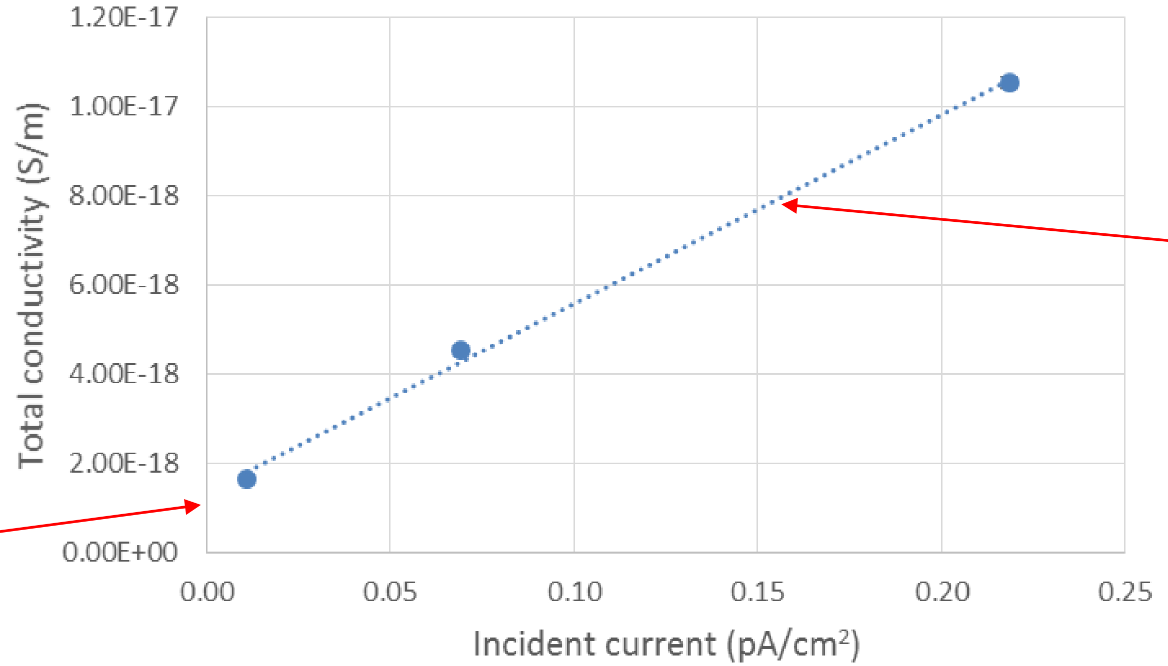
$$\sigma_{RIC} = k.\dot{D}^{\Delta}$$

Dose rate

Radiation-Induced Conductivity (2)

- Return to the data…

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



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

Slope gives σ_{RIC}

Y-intercept gives σ_T

$\sigma_T = 1.36 \times 10^{-18}$ S/m

(Dose rate proportional to incident current)

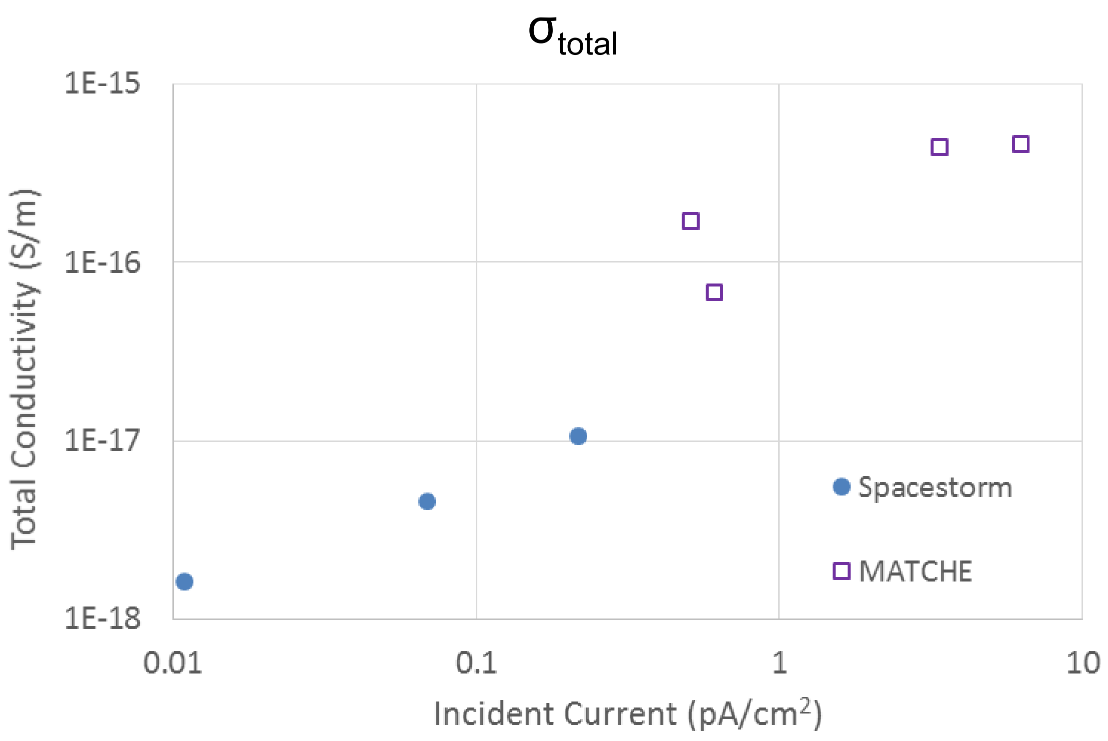
$k = 4.4 \times 10^{-16}$ S/m $[\text{rad/s}]^{-1}$

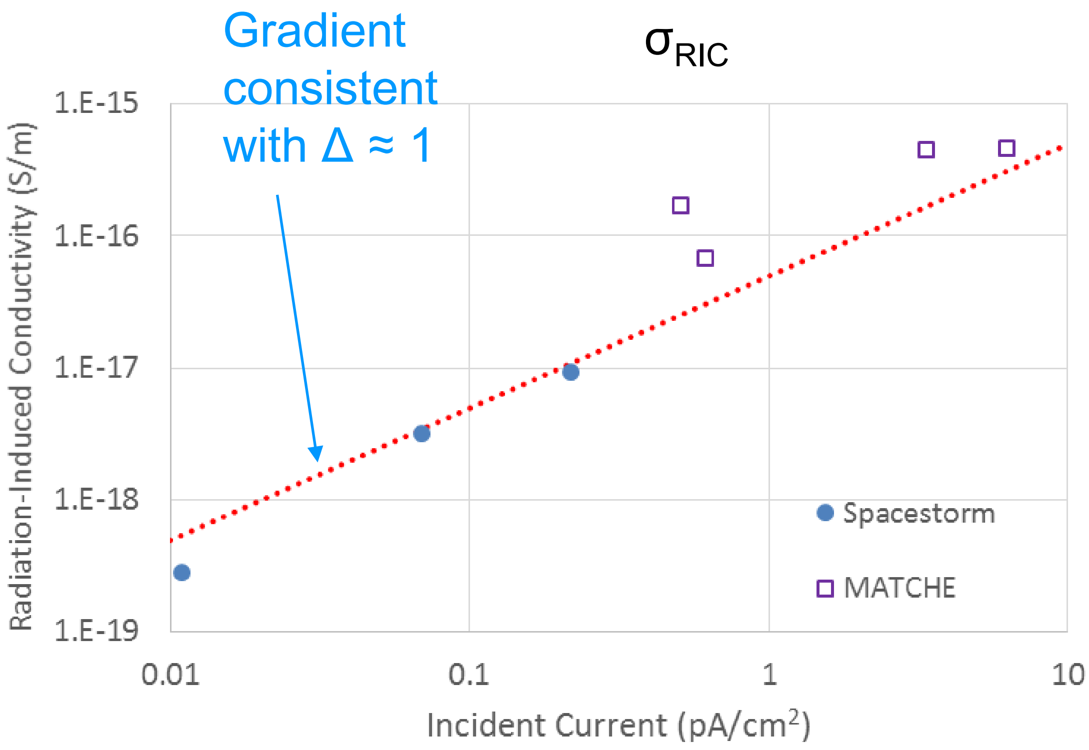
$\Delta \approx 1$

However… value of Δ uncertain due to few data points - need more…

Supplementary Data

- Identical PEEK samples were irradiated (at much higher currents) in ESA's Materials Charging Effects under Extreme Environments (MATCHE[3]) study
- Combine with Spacestorm results:

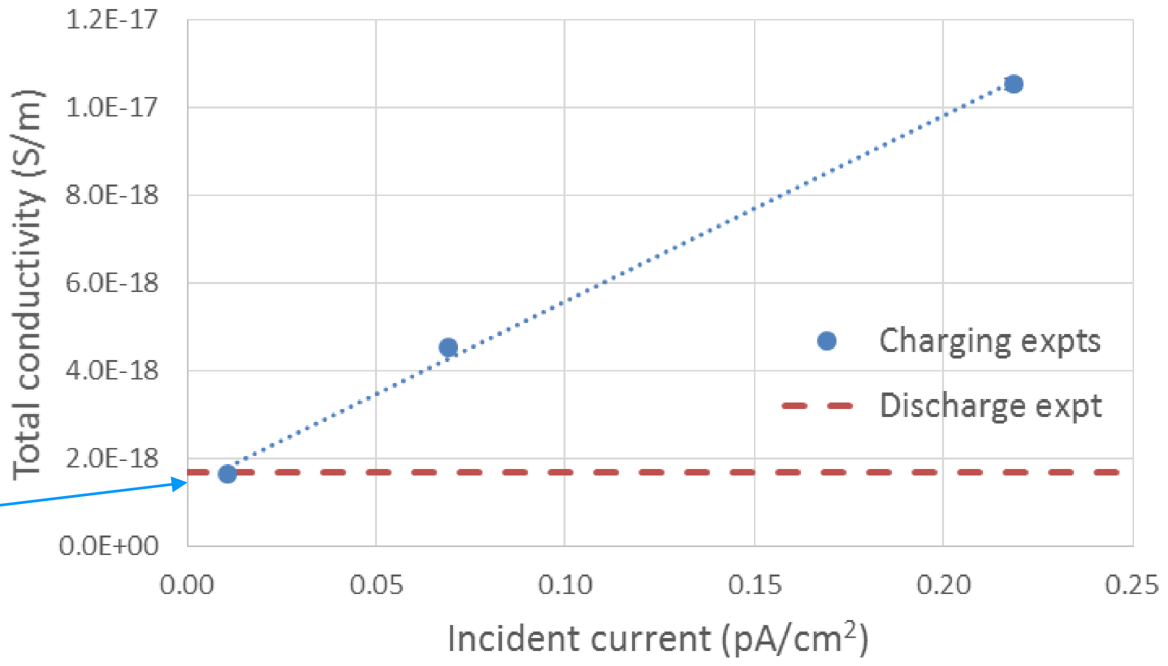




Sanity check – discharging current

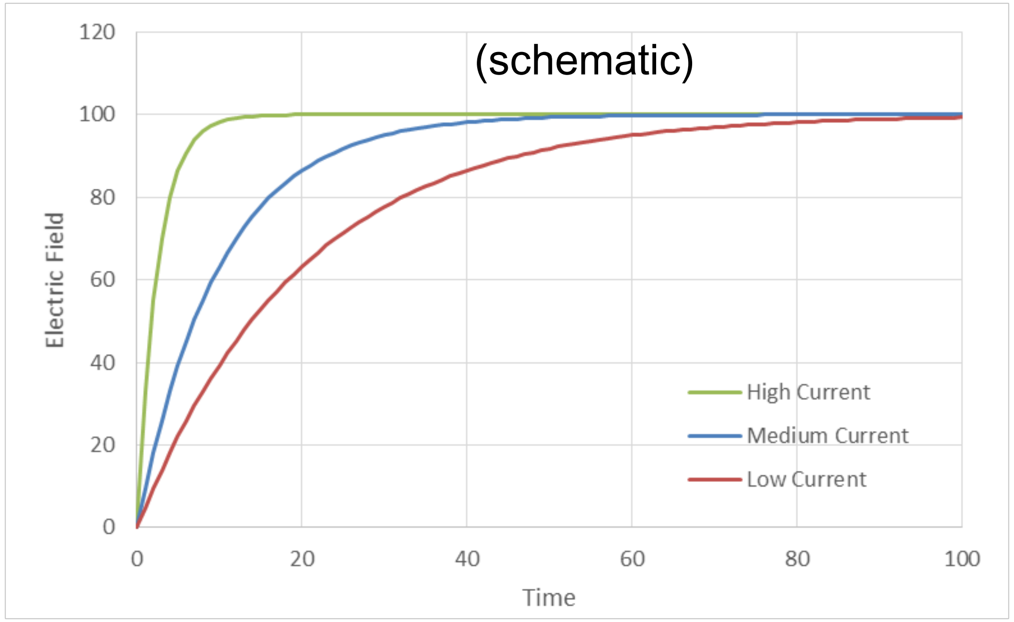
- Samples allowed to slowly discharge after irradiations
- Due to large time scales, not enough time for significant decay (only ~2%)
- Approximate bulk conductivity calculated from observed time-constant:

Reasonable agreement with y-intercept



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
- Implications 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)

Summary

- Long-duration low-intensity experimental campaign with Sr-90 source continuing as part of Spacestorm FP7 project
- REEF has been running for ~6 months, maximum exposure length to date ~2 months
- PEEK samples irradiated at three electron currents
- Very long (months) time constant observed at lowest current (0.01 pA/cm^2)
- Results indicate a very large impact from radiation-induced conductivity (>> bulk) at higher currents
- $\Delta \approx 1$, hence RIC proportional to dose rate
- In such circumstances the maximum (equilibrium) electric field is independent of environment intensity
- Usual assumptions of ‘quiescent periods’ leading to net charge dissipation could be invalid
- Modelling of internal charging will need to take possibility of very long time constants and minimal charge leakage into account
- Irradiations of other samples underway.

Acknowledgements

Many thanks to Paul Morris, Dave Mundy, Dave Fishlock and Andy Walker for help setting up the REEF facility.

This work was funded by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement 606716 (SPACESTORM).