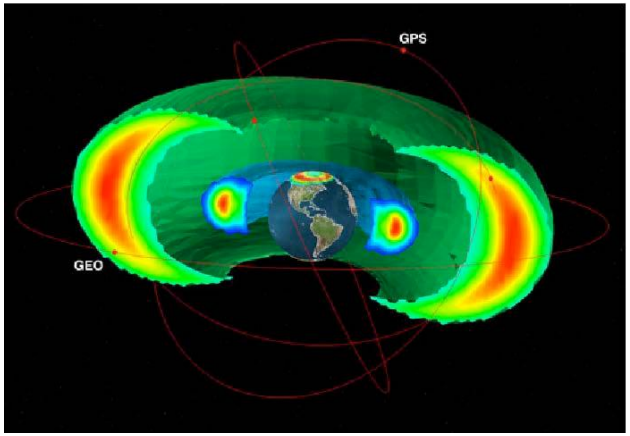
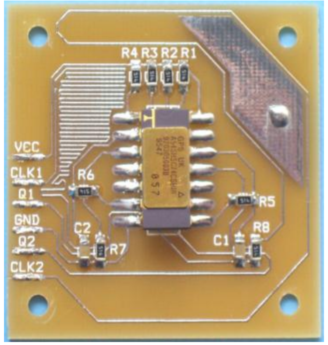


Internal Charging: Principles, Tools and Measurements

SPENVIS Workshop, Brussels, May 2013

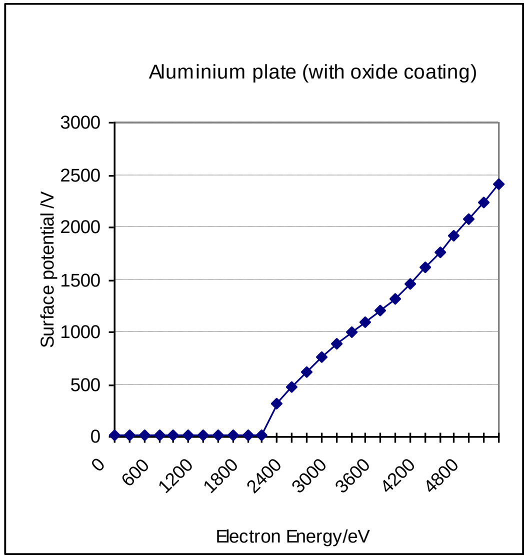
Keith A. Ryden
Surrey Space Centre
(k.ryden@surrey.ac.uk)

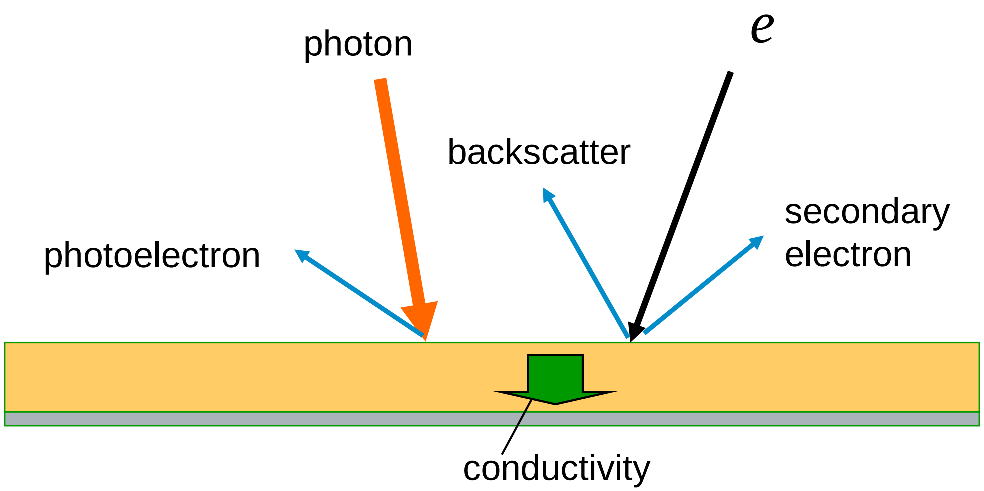


Electrostatic discharge (surface charging)

A significant issue in the 1970s-80s (e.g. MARECS)

Recently again a cause of problems (e.g. solar arrays)




photon

e

backscatter

secondary electron

photoelectron

insulator e.g. kapton blanket

ground

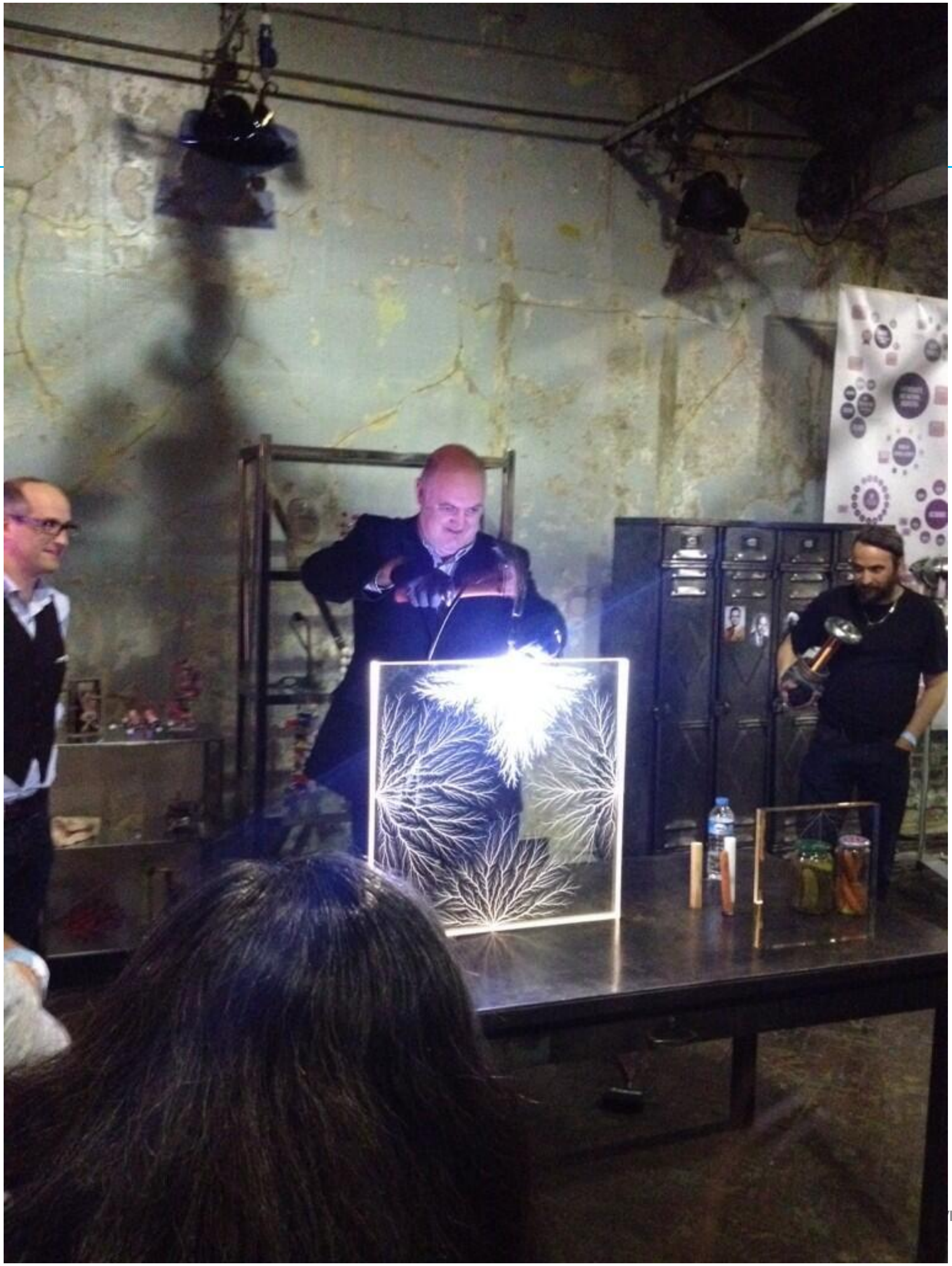
conductivity

$$j = j_e - j_{photo} - j_{secondary} - j_{conduct} - j_i$$

BBC

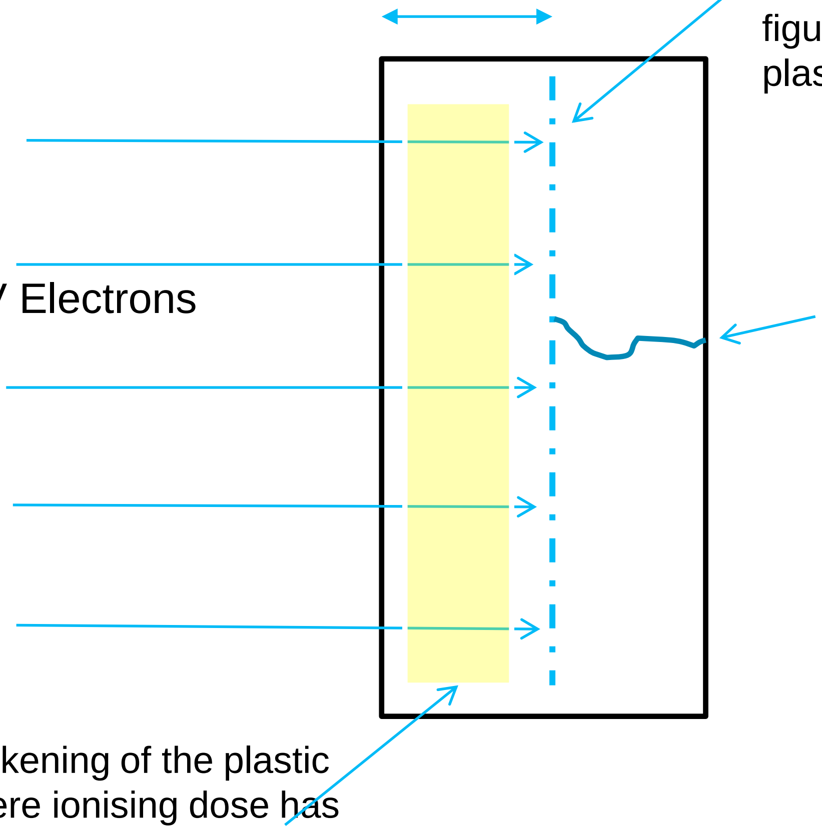
Dara O’Briain’s Science Club

Deep dielectric discharge!



Internal charging and deep dielectric discharge

The plastic object has been irradiated with electrons which do not fully penetrate the width of the material



Electron range

Plane of the Lichtenberg
figure (tubes where
plastic has vaporised)

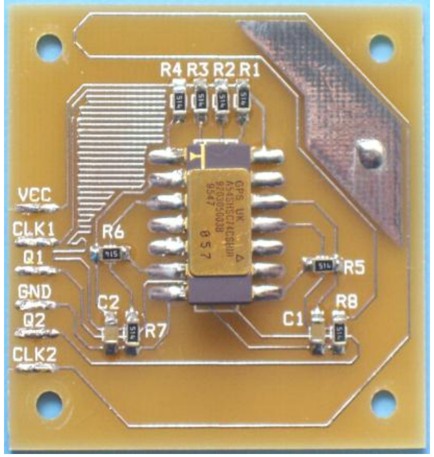
MeV Electrons

Exit route of discharge –
i.e. of the vaporised
material in plasma form

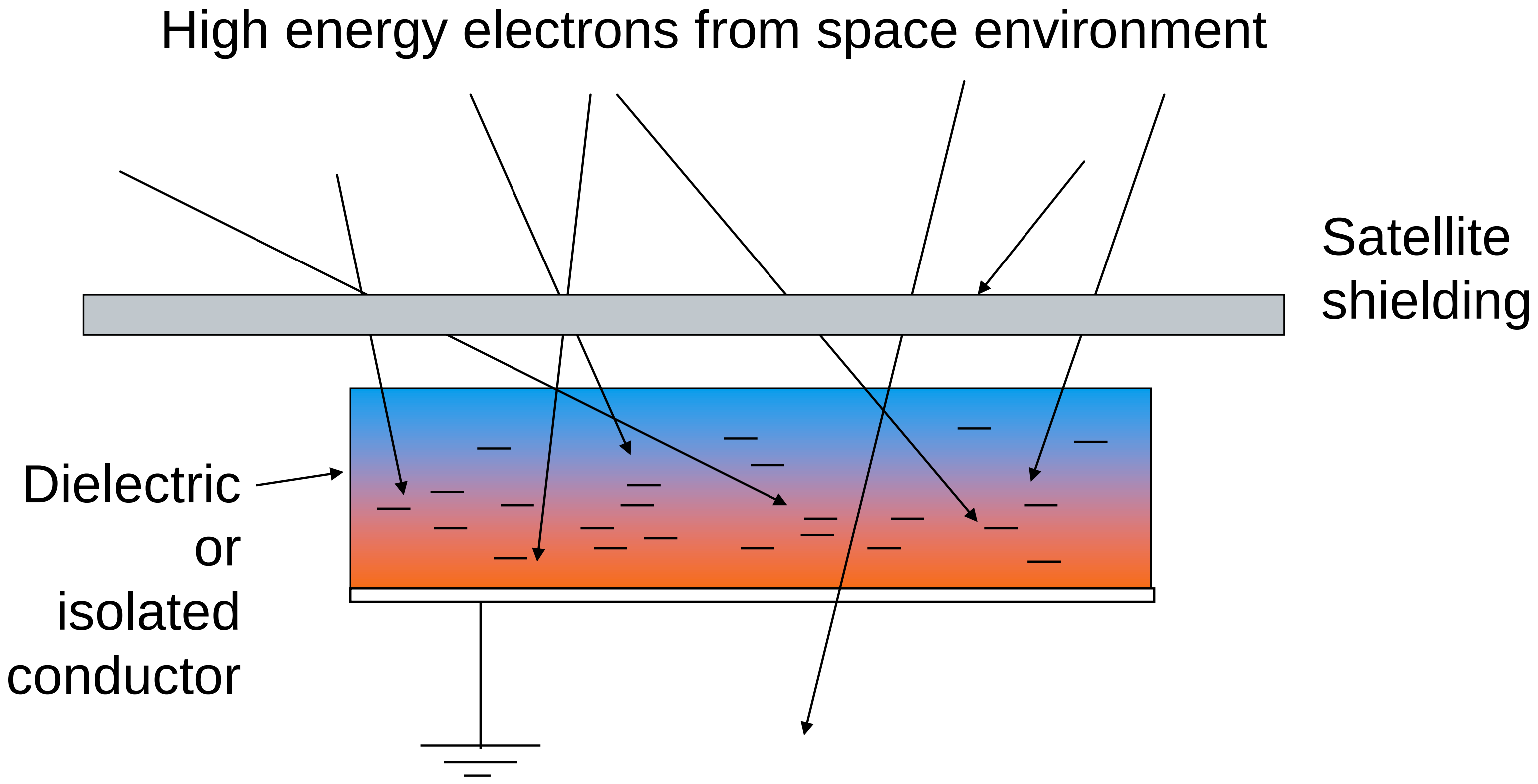
Darkening of the plastic
where ionising dose has
caused discolouration

Internal charging / Deep dielectric discharge

- Generally occurs in insulating polymers, but can occur in glass
- Energetic, penetrating electrons (>100keV)
- Small currents <1pA cm^{-2}
- Slow charge build up (>24 hours) leading to ESD



Internal charging in space

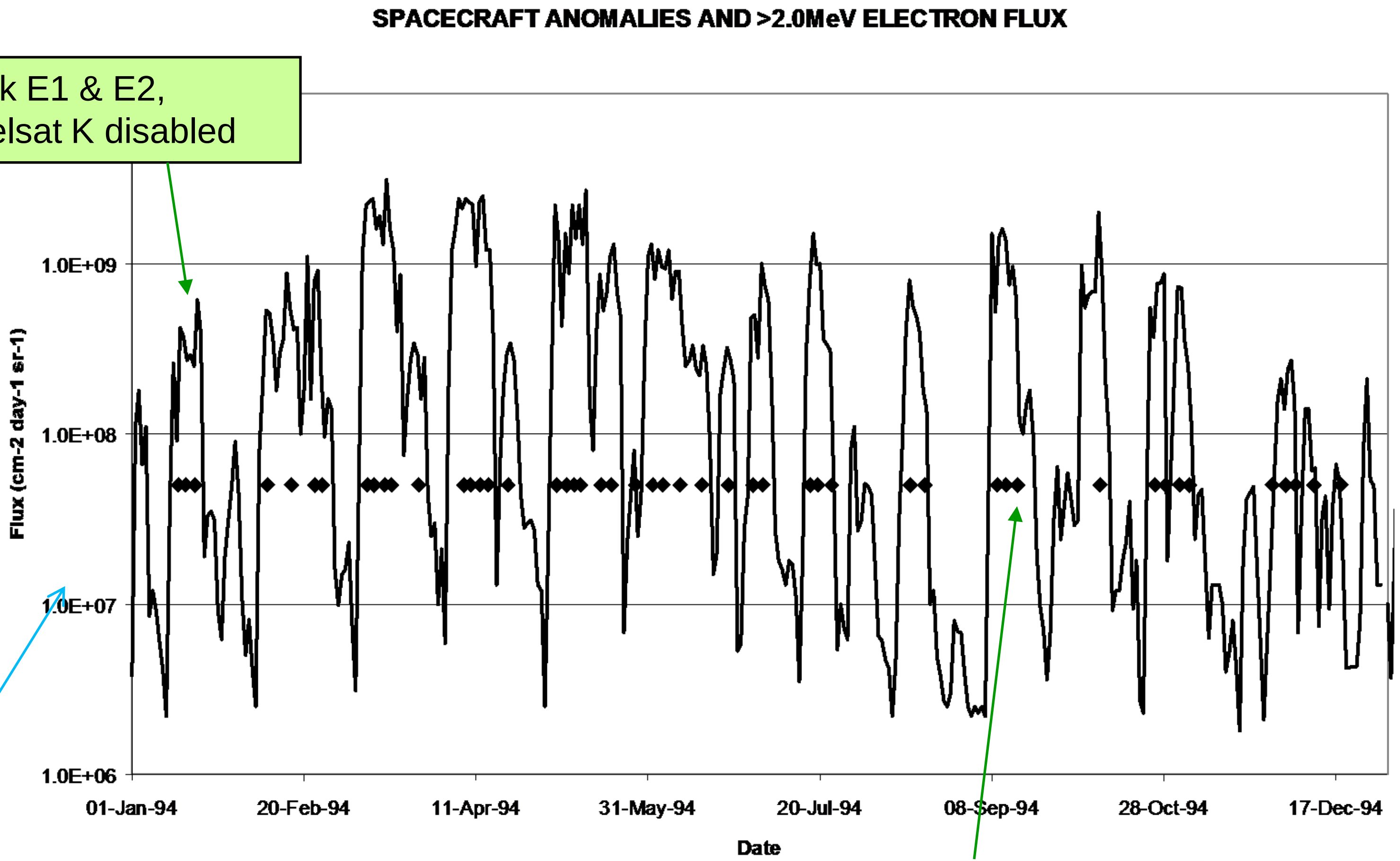


High energy electrons from space environment

Satellite shielding

Dielectric or isolated conductor

Outer belt electron intensity variation and effects on satellites

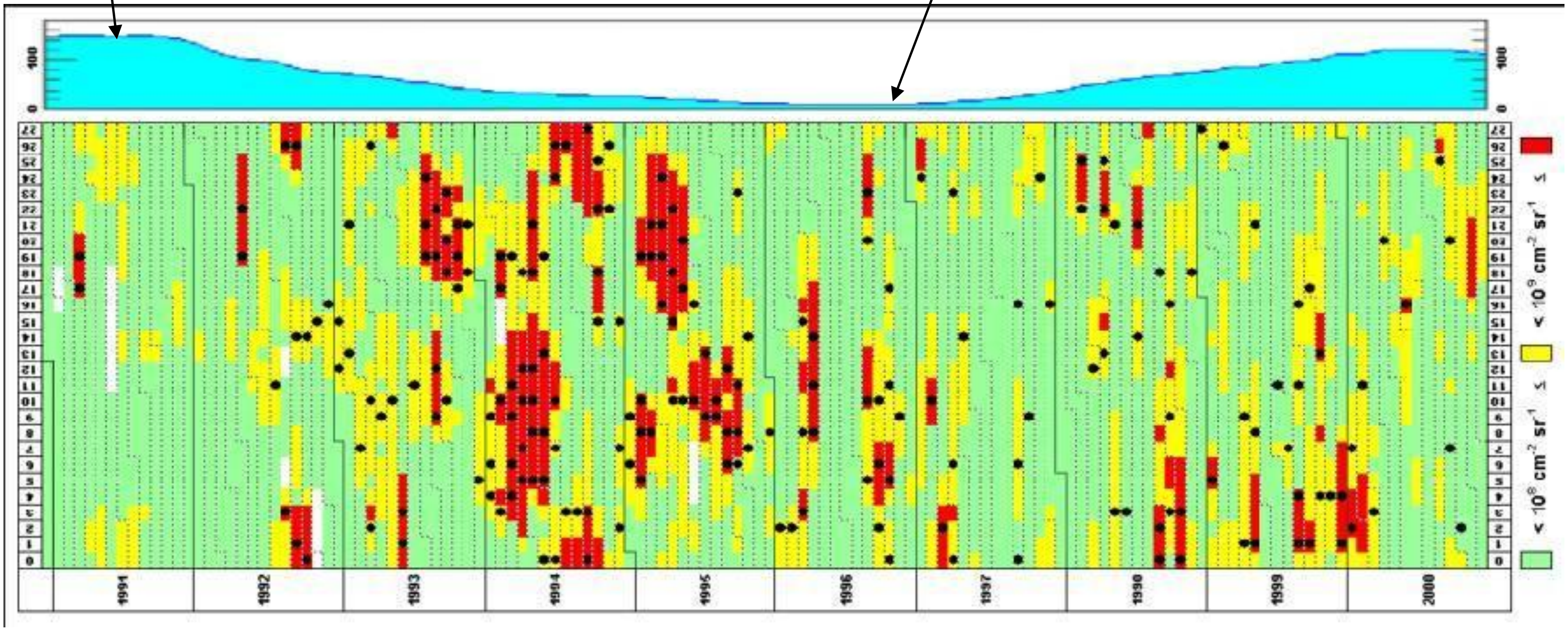


Anik E1 & E2, Intelsat K disabled

DRA-Δ anomalies

Note log scale – outer belt is highly dynamic due to buffeting by the solar wind

GEO comsat switching anomaly



Solar maximum

Solar minimum

G. Wrenn, D. Rodgers, K Ryden, Annales Geophysicae (2002) 20: 953–956

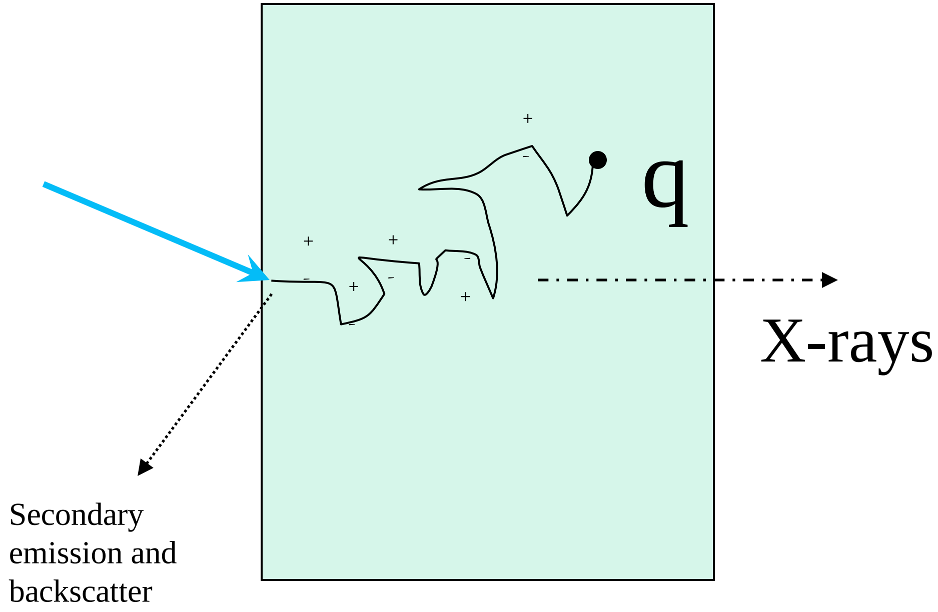
Electrons

Electrons are light and highly scattered within materials

Cause ionization and also deposit charge

Can be shielded out but produce penetrating secondary X-rays (or Bremsstrahlung)

If electrons are stopped in insulator they cannot easily escape



Key factors for internal charging

Space environment and space weather

Electron transport though shielding and into dielectric

Dielectric intrinsic (thermal) conductivity

Radiation induced conductivity

Charge and electric field accumulation

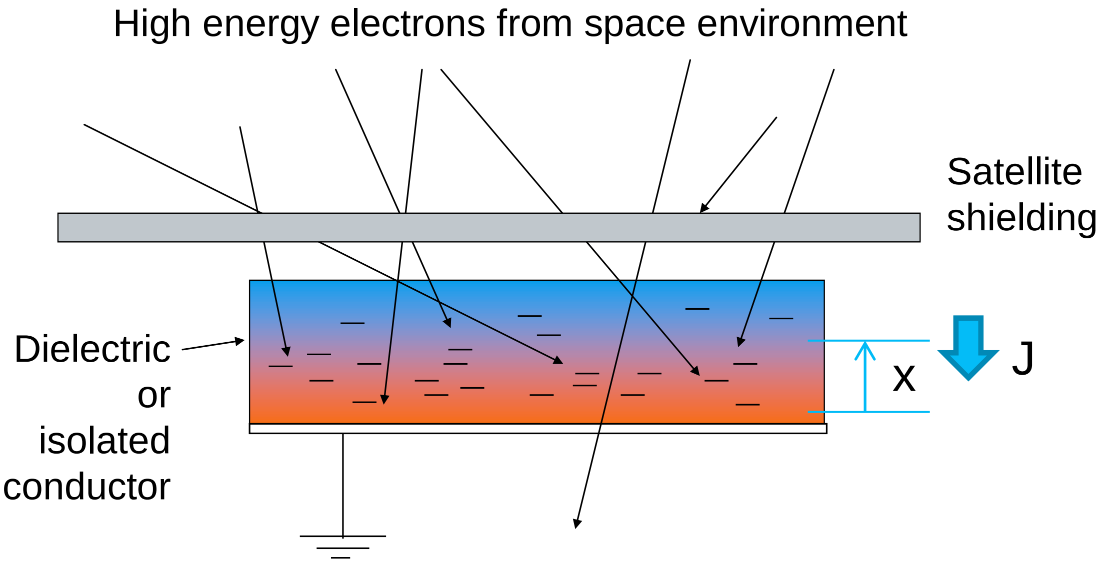
Breakdown strength

Breakdown propagation

Effect on circuit and component

1-D charging equation

$$\varepsilon_0 \varepsilon_r \frac{dE(x,t)}{dt} + \sigma(x,t)E(x,t) = -J_R(x,t)$$



where:

E is electric field

t is time

x is linear position

σ is conductivity

J_R is radiation current (density)

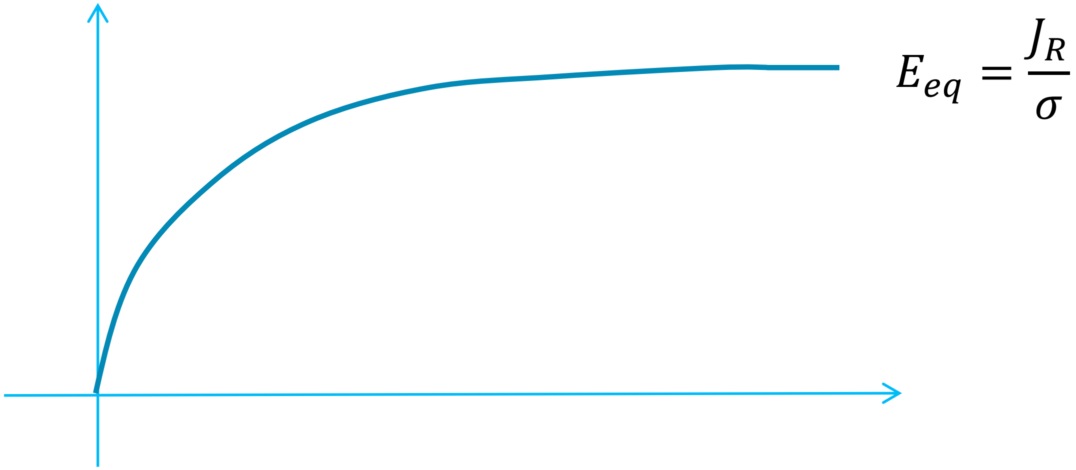
[dJ/dx is the charge deposition rate at x]

Charging curve at given depth

At a given depth and assuming non-varying conductivity:

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

where $\tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma}$



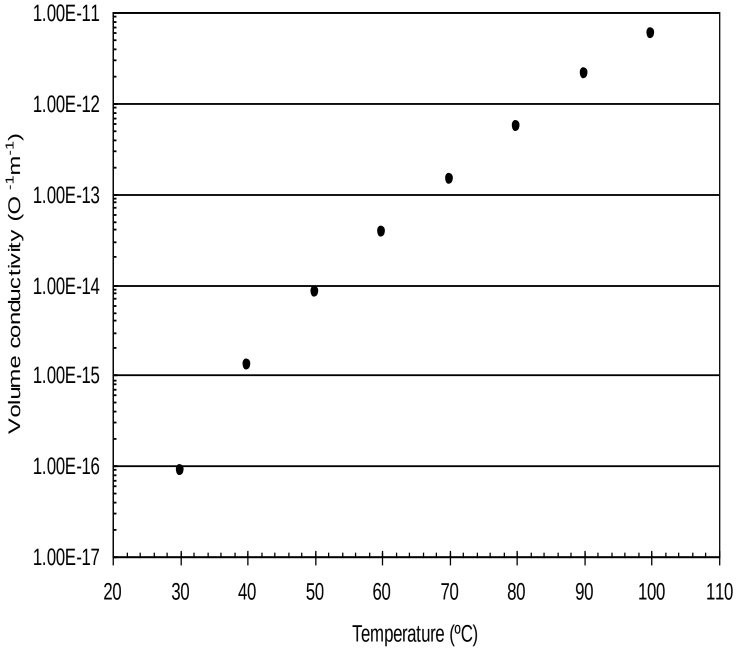
If σ is small (leading to large equilibrium E-fields) then time constant is long

Thermal / intrinsic / dark conductivity

Activation of electrons across the wide ‘band gap’

Conductivity is determined by Arrhenius-type equation

$$\sigma = \sigma_{\infty} \exp\left(-\frac{E_A}{kT} \right)$$



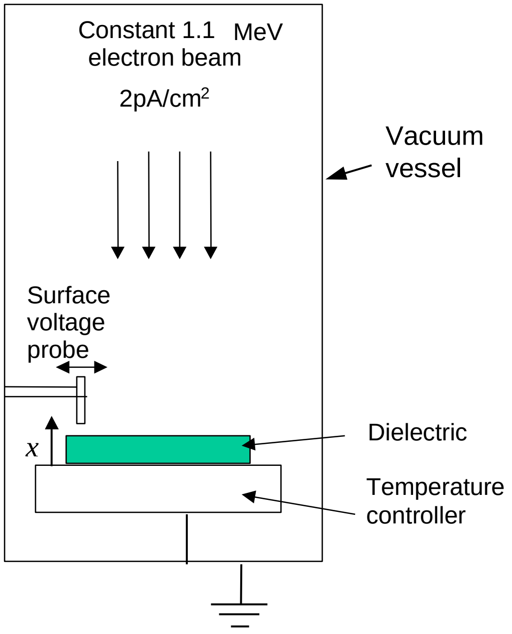
Changes rapidly with temperature

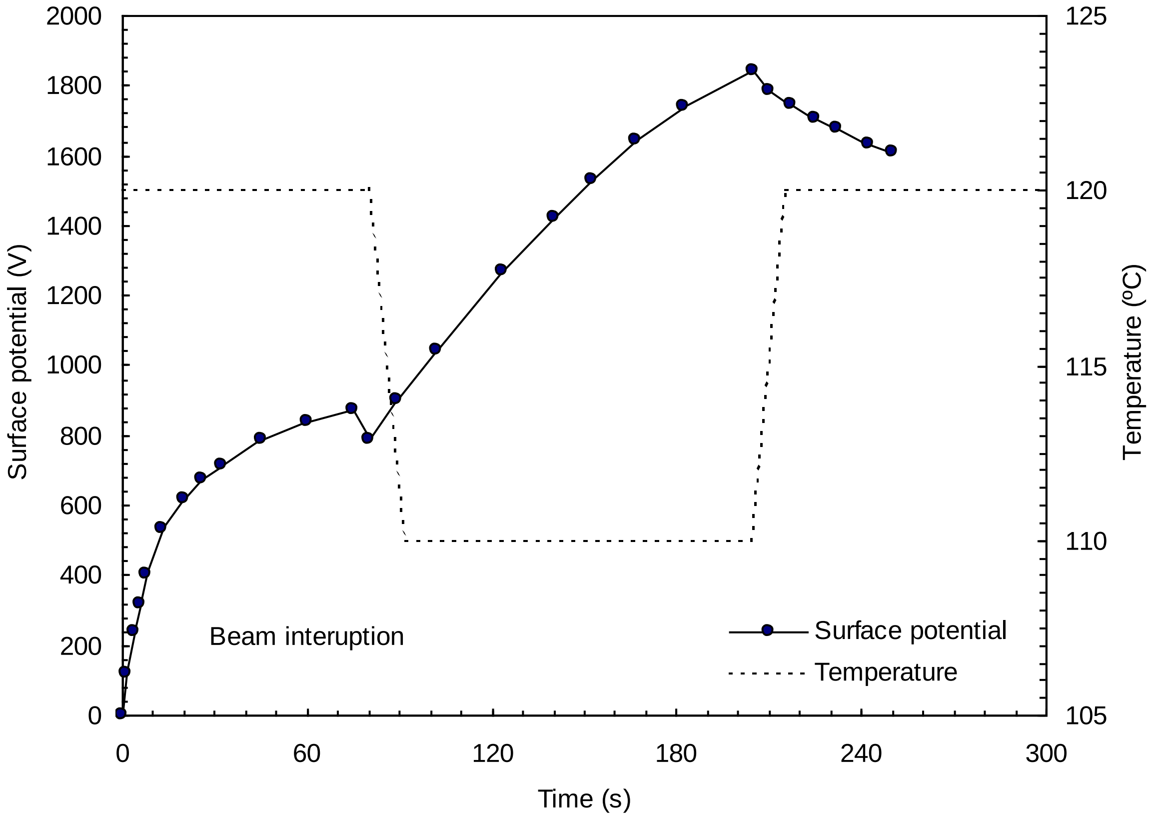
- High temperature suppresses charging effect
- Low temperature conductivity can be very small indeed

E_A=1.0eV for polythene

E_A=1.7eV for PMMA

Illustration of temperature effects





Changes of temperature greatly affect the internal charging process

Radiation induced conductivity

Ionising dose leads to generation of additional charge carriers

Can be due to primary particles or secondary (bremsstrahlung)

$$\sigma = \sigma_0 + k_p \dot{D}^{\Delta}$$

Where σ_0 is the dark conductivity (Ω^{-1}cm^{-1})

k_p is the co-efficient of prompt RIC (Ω^{-1}cm^{-1} rad^{-1} s)

D is ionising dose (rad)

Δ is a dimensionless material dependent exponent (Δ<1)

Δ is typically in range 0.6 to 1.0

RIC not a function of temperature

RIC measurements

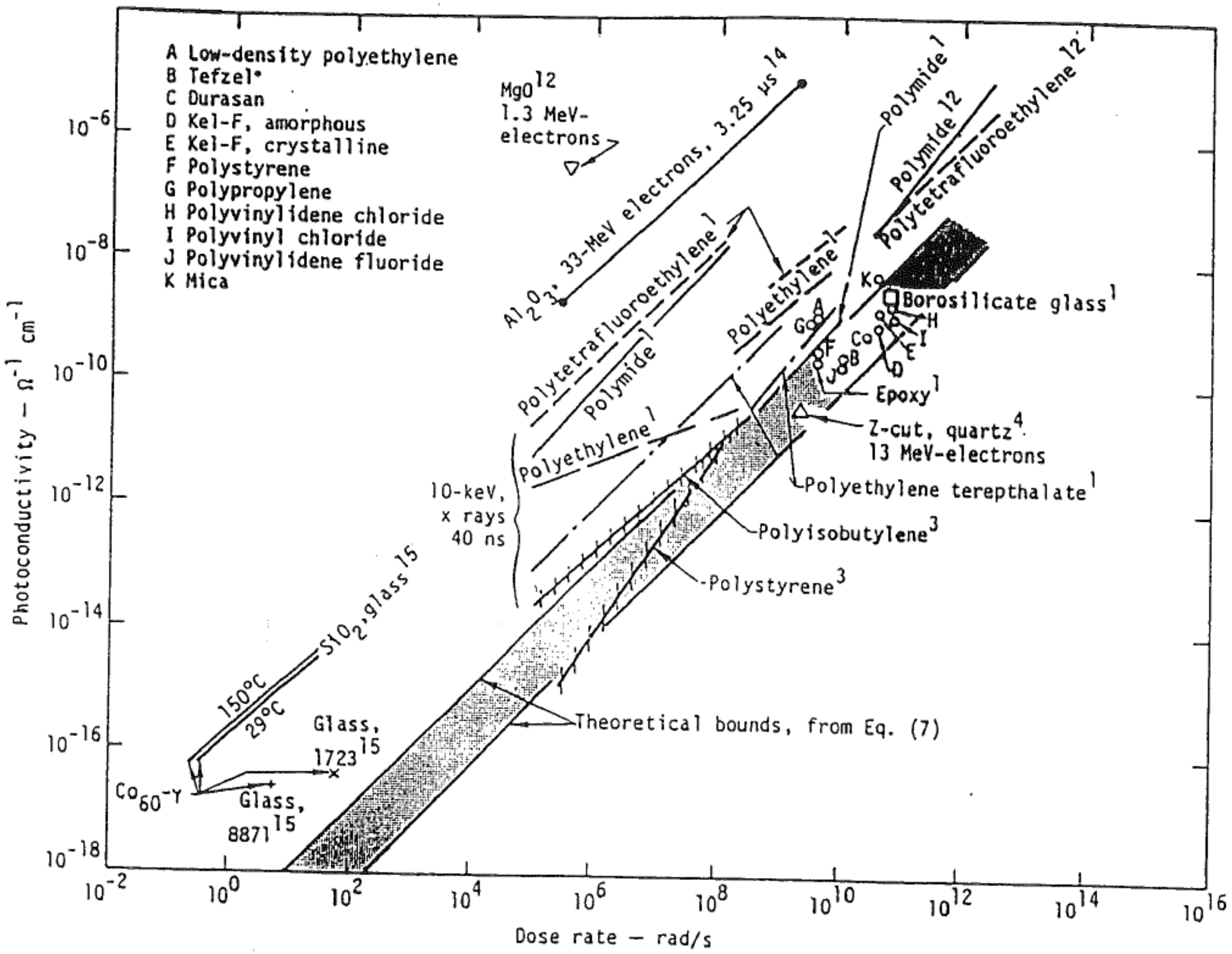


Figure 12. Measurement of dose rate induced conductivity reported by various authors [27]

Delayed conductivity

Transient effects

Conductivity does not reduce to zero instantaneously after irradiation is stopped

Tends to decay more slowly when sample has been irradiated for a long time

Permanent effect

An increase in conductivity dependent on the ionising dose received.

Few reports

Would indicate that charging is less likely as mission proceeds

ESADDC model included this effect but was difficult to get conditions where discharge was likely

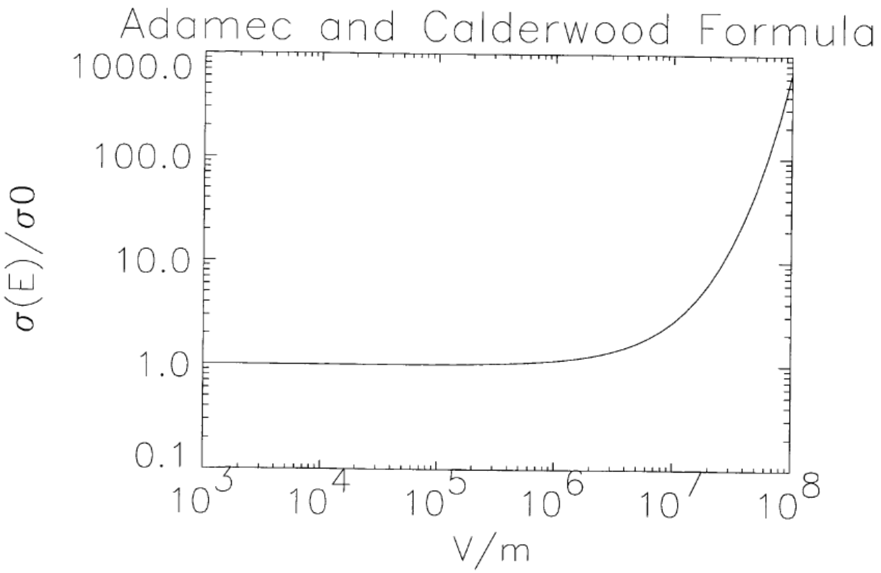
Still a research area since some polymers receive very large doses

Field induced conductivity

Ohmic conductivity breaks down at very high field intensities

$$\sigma(E,T)=\sigma(T)\left(\frac{2+\cosh(\beta_F E^{1/2}/2kT}{3}\right)\left(\frac{2kT}{eE\delta}\sinh\left(\frac{eE\delta}{2kT}\right)\right)$$

where $\beta_F=\sqrt{\frac{e^3}{\pi\varepsilon}}$, e is electron charge, k is the Boltzmann constant, ε is permittivity and δ is an experimentally derived jump distance of 10 an



Dielectric breakdown

Electrical breakdown – avalanche effect caused by high fields (>10^6 V)

- Free charge carriers are accelerated
- Lichtenberg figures generated

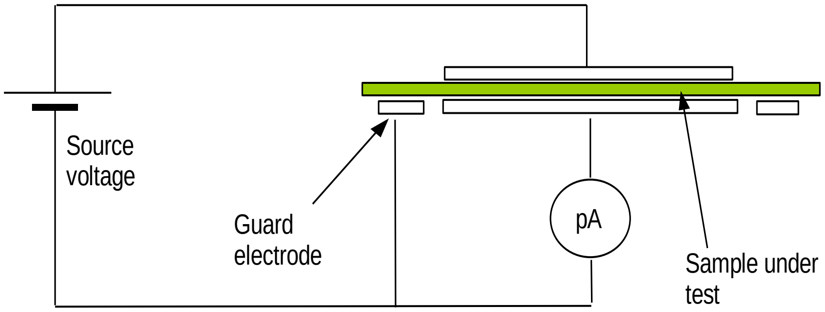
Deep dielectric discharge produces Lichtenberg figures in transparent materials

Inter-electrode breakdown topically at >3×10^7 Vm^{-1}

For internal charging, inferred that similar thresholds apply but difficult to confirm

Threshold typically taken as 1×10^7 Vm^{-1} and preferred to keep electric fields below 1×10^6 Vm^{-1} for safety

Measuring polymer conductivity



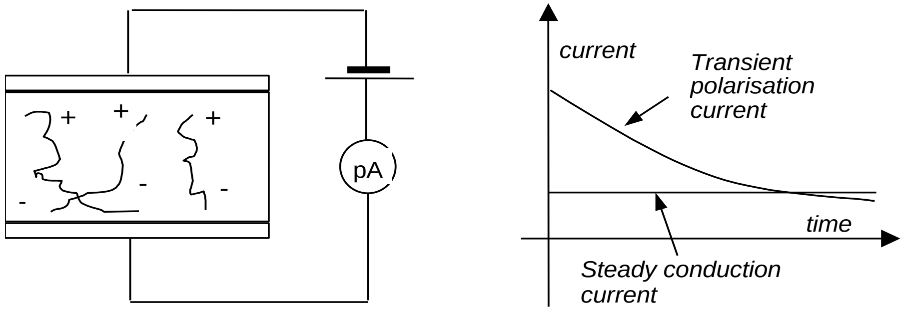


Fig. 2 Long-term polarisation of dielectrics

Beware of typical conductivities quoted by manufacturers

Measurements of dielectric conductivity typically quoted are usually after 60s of current flow

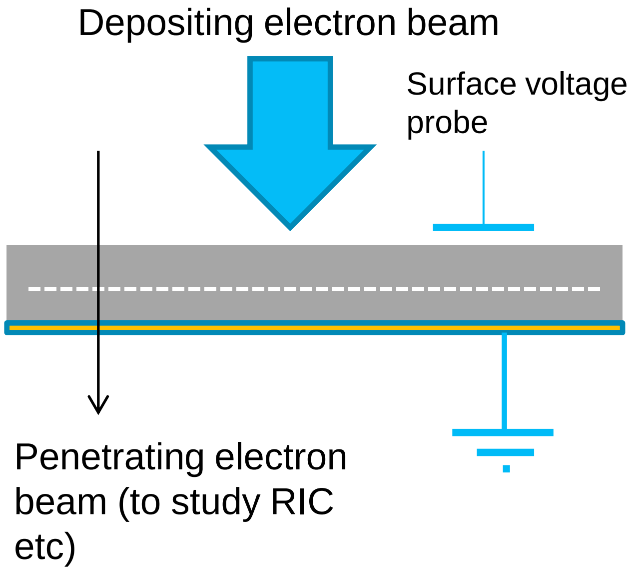
Current measured will decay over time due to polarisation (capacitive charging)

For internal charging, post-polarisation current is more relevant

Measuring conductivities and polymer parameters

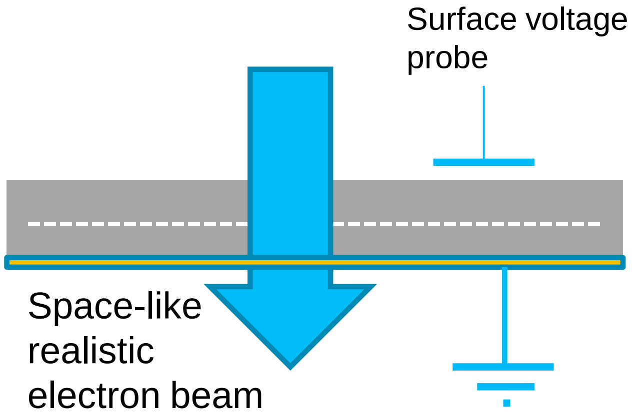
Electron beam method (parameter selective)

- Deposit charge into material and monitor its decay
- RIC can be measured by monitoring rate of decay under fully penetrating beam (e.g. electrons)



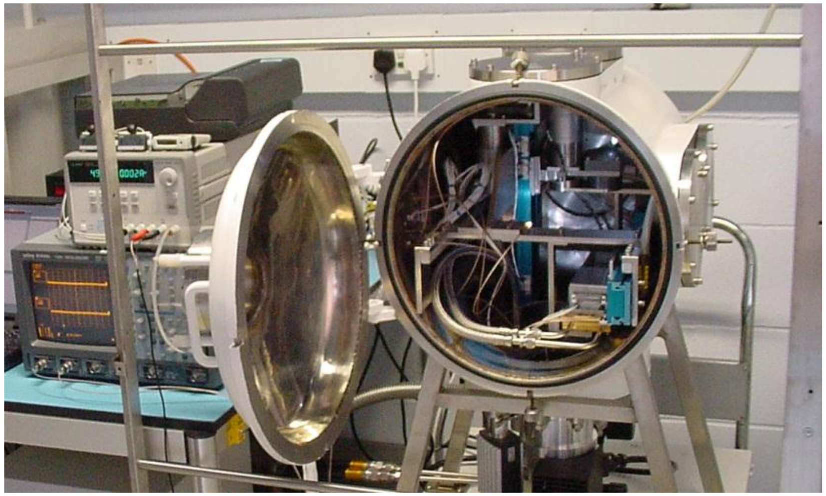
Realistic continuous irradiations (multi-parameter measurements)

- Irradiate under various permutations of environmental conditions (high flux, low flux, high temp. low temp., high RIC, low RIC etc..)
- Creates set of simultaneous equations to solve
- Extract parameters using fitting algorithm

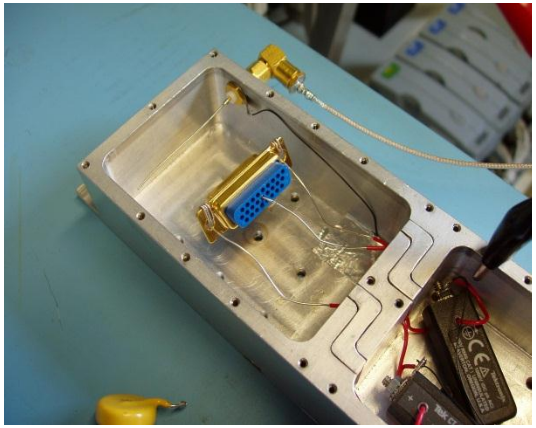


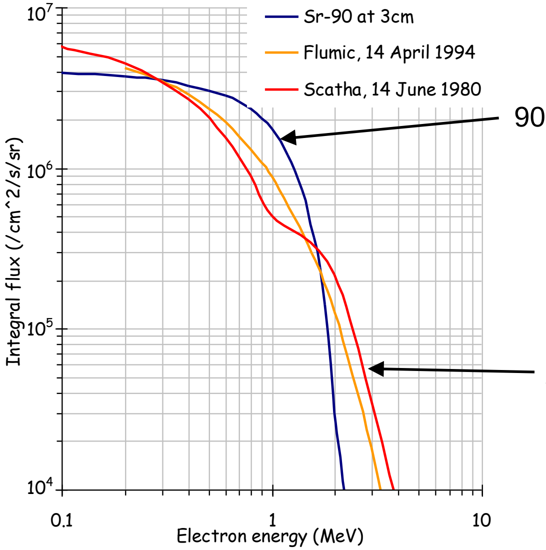
Realistic Electron Environment Facility

- Sr-90 beta source, 3 GBq
- High–Vacuum
- Thermal control for sample
- Well matched to GEO spectrum and intensity
- Long test are possible (weeks……months)



- Testing of components for major satellite projects
  - E.g. Galileo





^{90}Sr spectrum

space spectra

Fluence / current threshold

Unfortunately it is not always easy to obtain necessary materials parameters

0.1 pA cm^{-2} has been established empirically as a 'general' charging

threshold for safe use of dielectrics (or 2×10^{10} electrons / cm^2 over 10 hours appears to be actual threshold)

[Reduced to 0.02 pA cm^{-2} below room temperature in ECSS]

Based on absorbed current (often confused with incident current)

Bodeau has suggested that this level is not always safe and that 0.01 pA cm^{-2} is more suitable

In-orbit measurements of internal charging / discharging

US CRRES mission

- various materials exposed in a GTO orbit (various shielding levels etc) – discharges detected and quantified

‘DDD’ experiment (ESA) – no discharges detected

SURF (STRV and Giove-A)

- measurement of internal charging rate behind shielding

Van Allen probes (RBSP)

- similar to SURF

IDM sample configurations

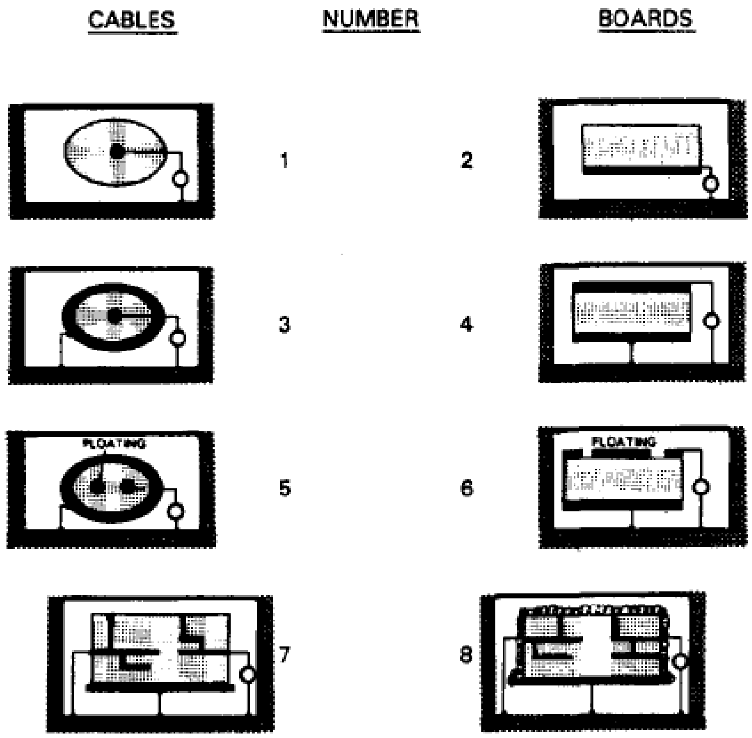


Figure 1

Sample Wiring Configurations. Heavy lines are electrodes, small circles represent the 50 ohm measuring circuit, and the curly line represents leaky paint in configuration 8. Each sample is Faraday shielded from external fields by 0.2 mm aluminum on the top and 0.5 cm aluminum on the sides and bottom of its container. The feed-through [1] to the external detectors is composed of semi-insulating material which does not pulse. It is not shown in order to simplify the drawing.

IDM results

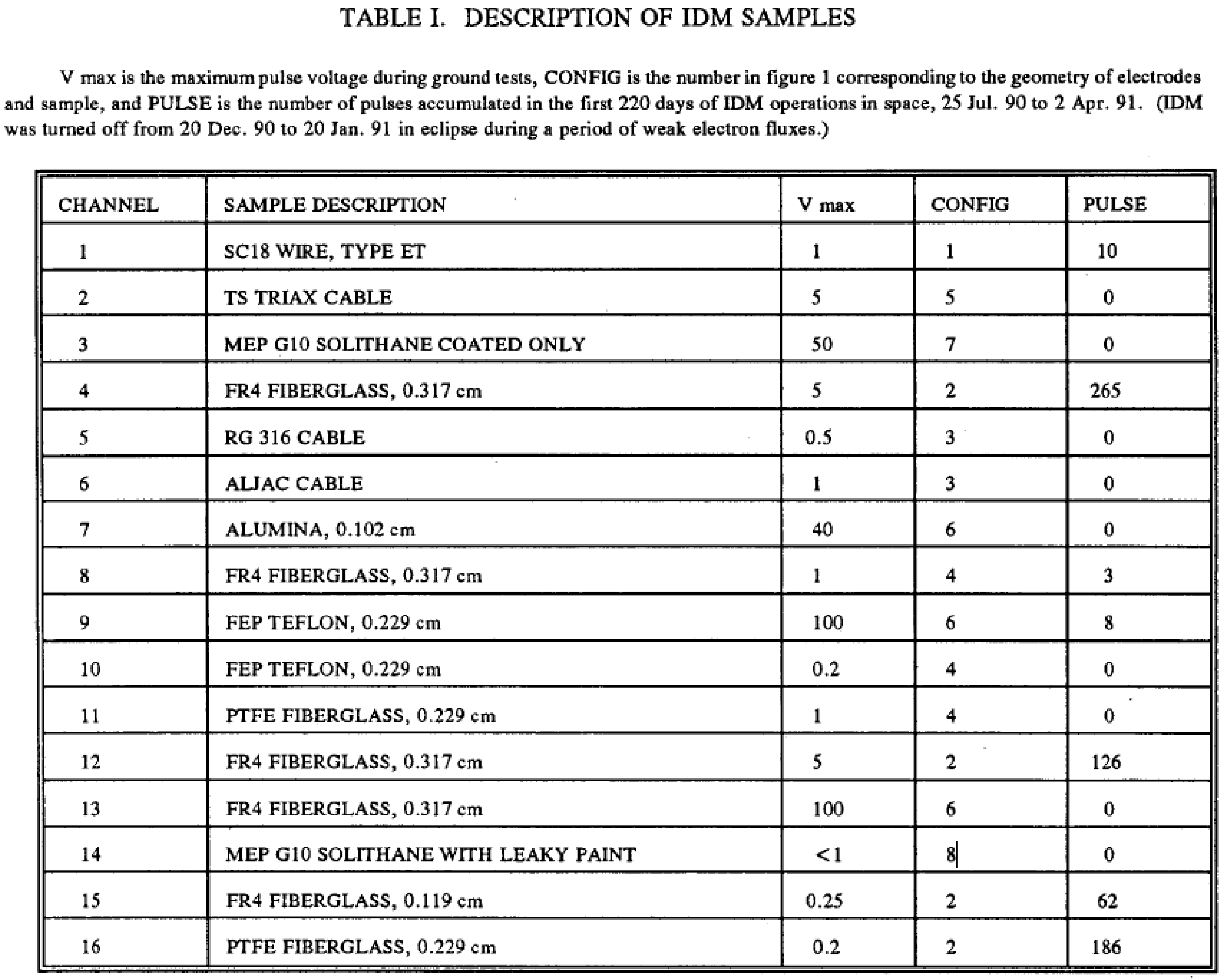


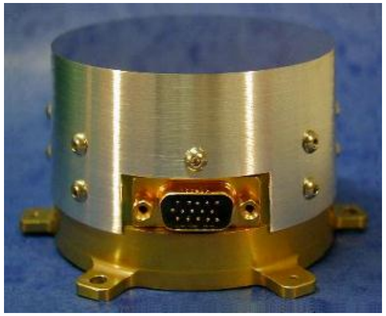
TABLE I. DESCRIPTION OF IDM SAMPLES

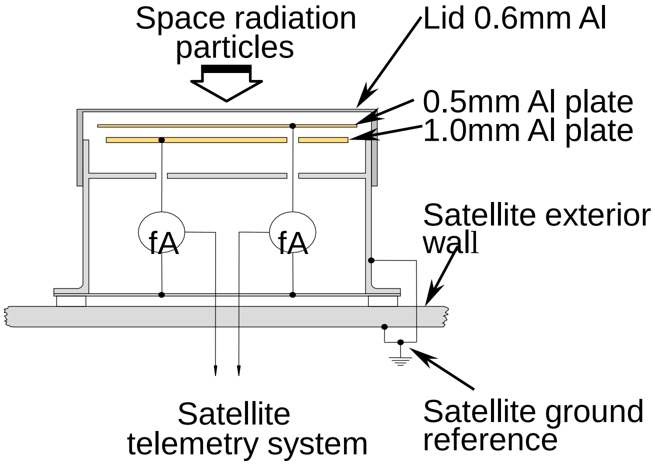
V max is the maximum pulse voltage during ground tests, CONFIG is the number in figure 1 corresponding to the geometry of electrodes and sample, and PULSE is the number of pulses accumulated in the first 220 days of IDM operations in space, 25 Jul. 90 to 2 Apr. 91. (IDM was turned off from 20 Dec. 90 to 20 Jan. 91 in eclipse during a period of weak electron fluxes.)

CHANNEL	SAMPLE DESCRIPTION	V max	CONFIG	PULSE
1	SC18 WIRE, TYPE ET	1	1	10
2	TS TRIAX CABLE	5	5	0
3	MEP G10 SOLITHANE COATED ONLY	50	7	0
4	FR4 FIBERGLASS, 0.317 cm	5	2	265
5	RG 316 CABLE	0.5	3	0
6	ALJAC CABLE	1	3	0
7	ALUMINA, 0.102 cm	40	6	0
8	FR4 FIBERGLASS, 0.317 cm	1	4	3
9	FEP TEFLON, 0.229 cm	100	6	8
10	FEP TEFLON, 0.229 cm	0.2	4	0
11	PTFE FIBERGLASS, 0.229 cm	1	4	0
12	FR4 FIBERGLASS, 0.317 cm	5	2	126
13	FR4 FIBERGLASS, 0.317 cm	100	6	0
14	MEP G10 SOLITHANE WITH LEAKY PAINT	<1	8	0
15	FR4 FIBERGLASS, 0.119 cm	0.25	2	62
16	PTFE FIBERGLASS, 0.229 cm	0.2	2	186

SURF charging current measurements in GTO

- Internal charging current *vs* depth measurement
- Each plate has unique energy response curve so spectrum can be obtained
- Built and flown on STRV1d
- 300g, 0.3W





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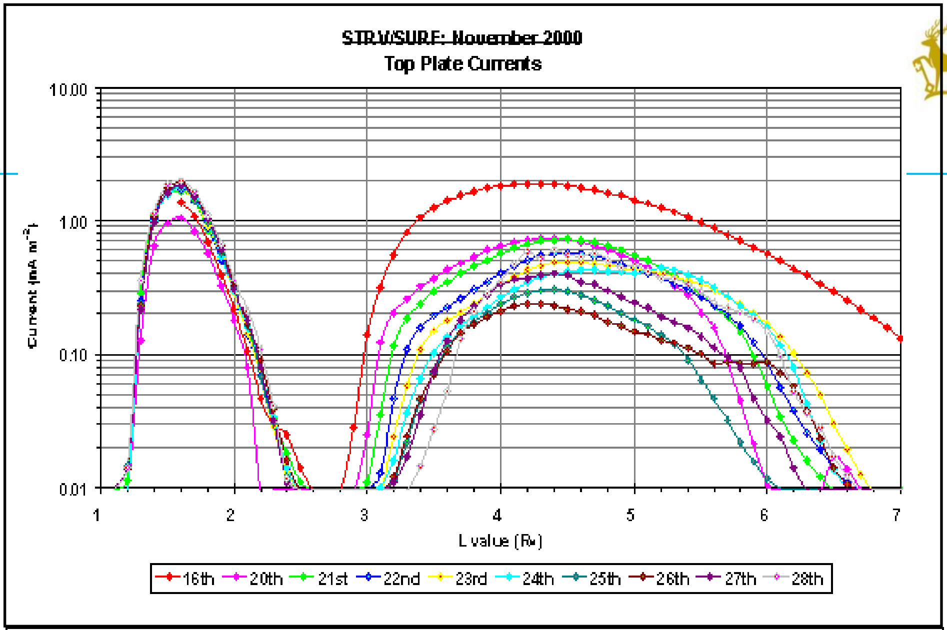
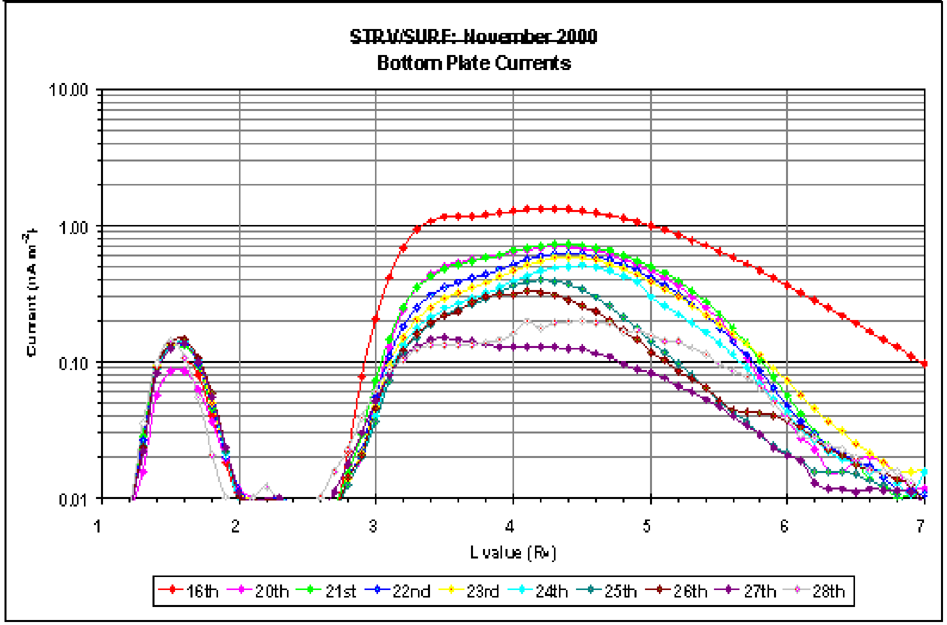
SURF results

- GTO orbit
- 500 x 36,000 km

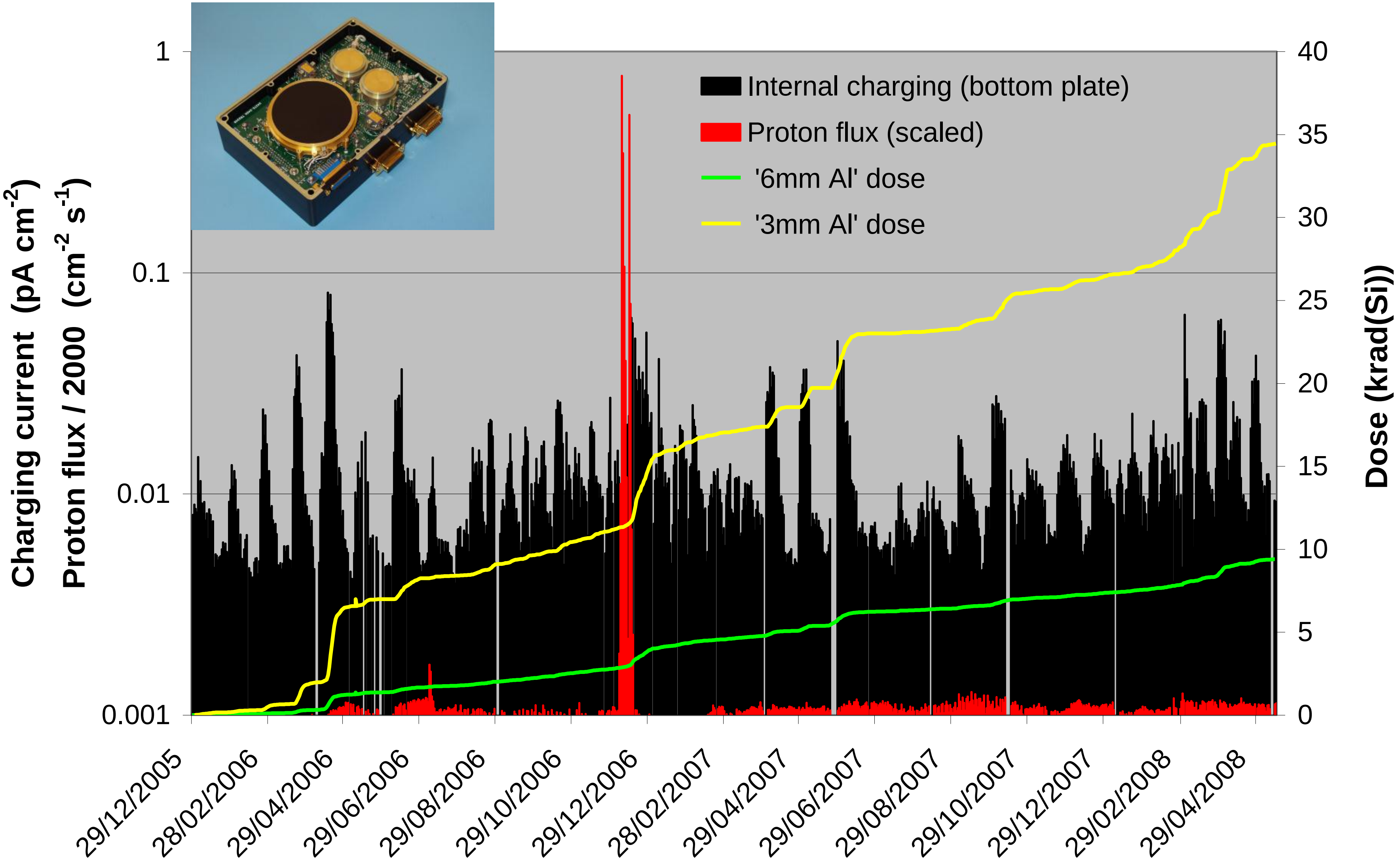


STRV/SURF: November 2000
Top Plate Currents

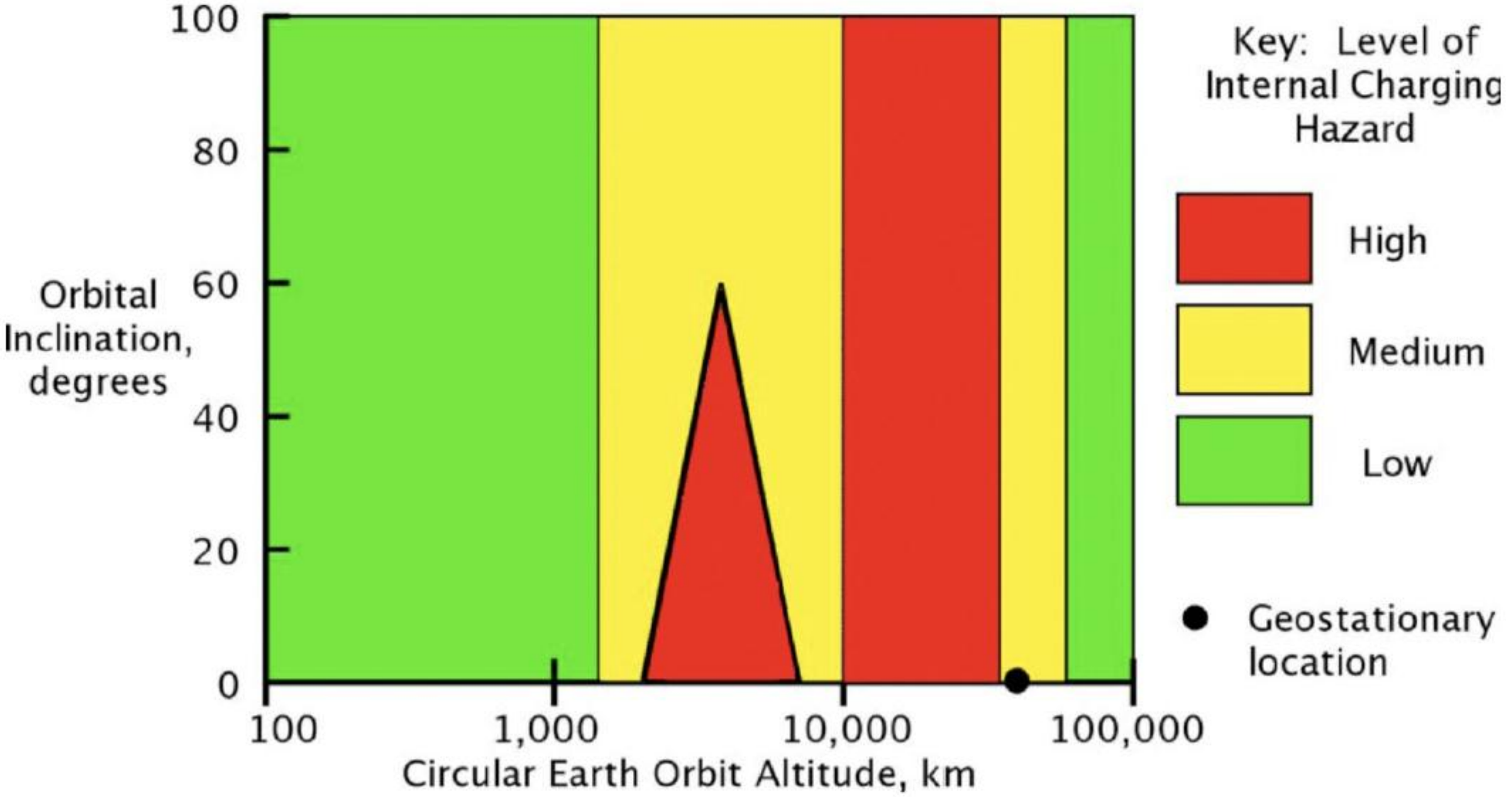


STRV/SURF: November 2000
Bottom Plate Currents

Merlin on Giove-A

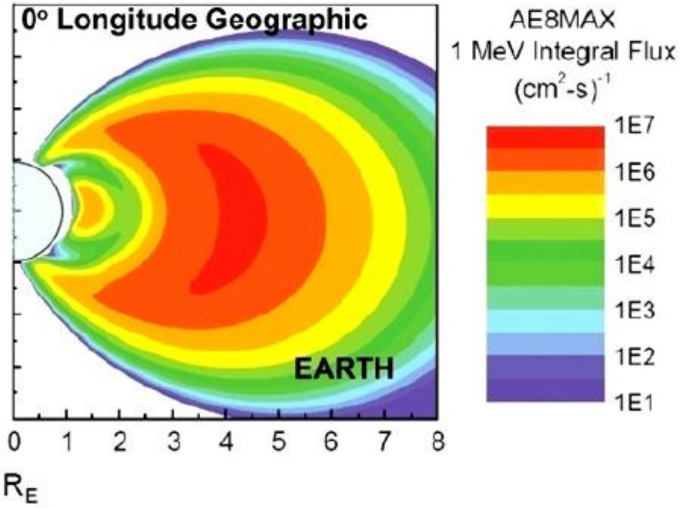


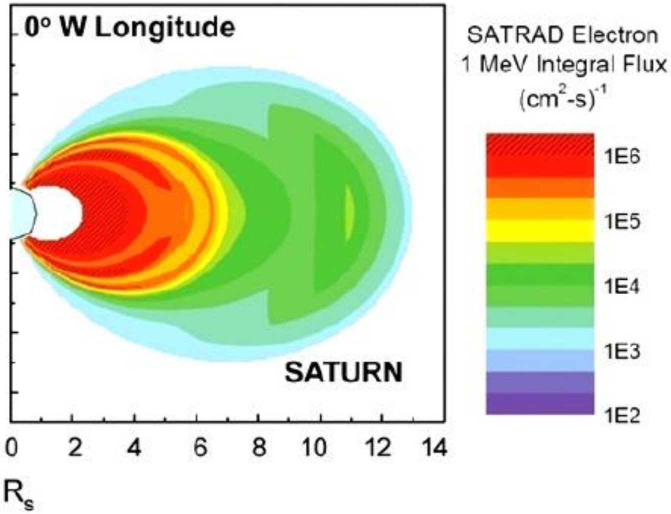
Orbital regimes of concern for internal charging

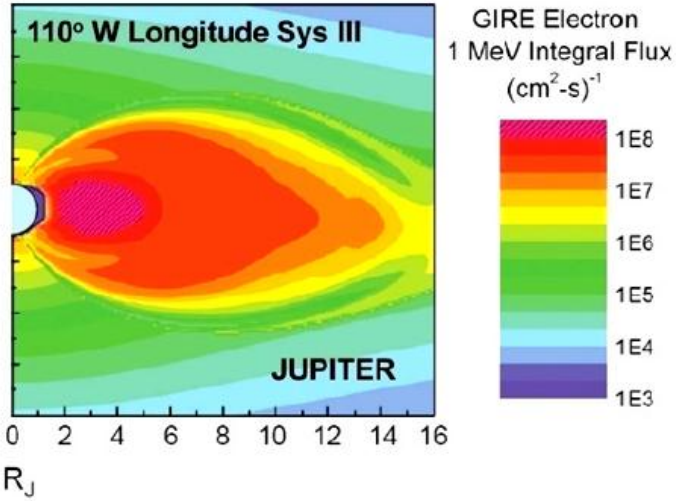


NASA HDBK 40002a

Earth, Jupiter and Saturn electron belts







DICTAT

Dielectric Internal Charging Analysis Tool

Developed around 1999 (ESA funding) to provide a fast analysis tool for engineers

Environment - FLUMIC model (new) - analytical

Electron transport – Weber & Sorensen formulae

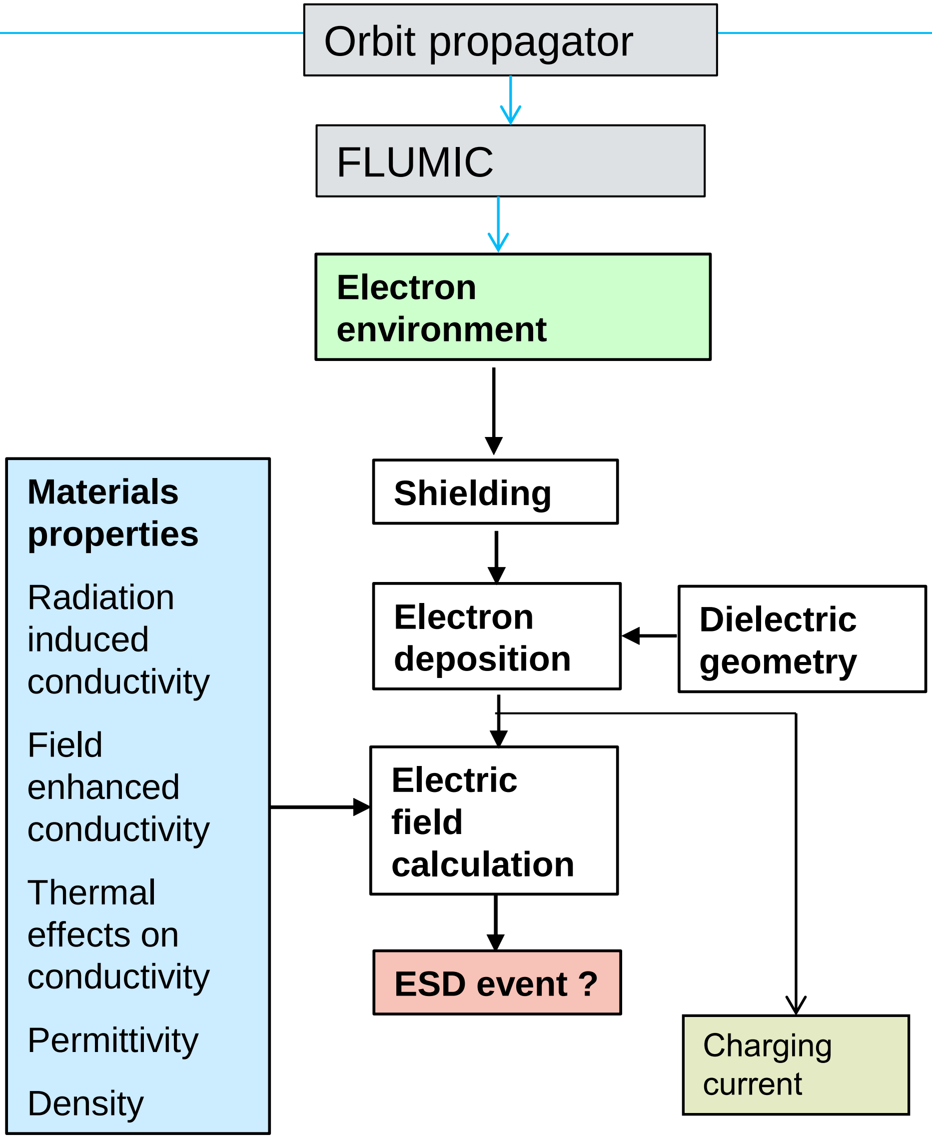
Temperature effects

RIC/FEC

Cable and Flat geometries

Various grounding arrangements

Electric field calculated in ten layers



FLUMIC

- Empirical model developed specifically for internal charging (2000)
- Based mainly on data from SREM and GOES in 1980s and 1990s
- Give ‘worst-case’ 1-day flux envelope as function of:
  - B
  - L
  - fraction of solar cycle
  - fraction of year (seasonal)
- Latest version 3.0

with flux

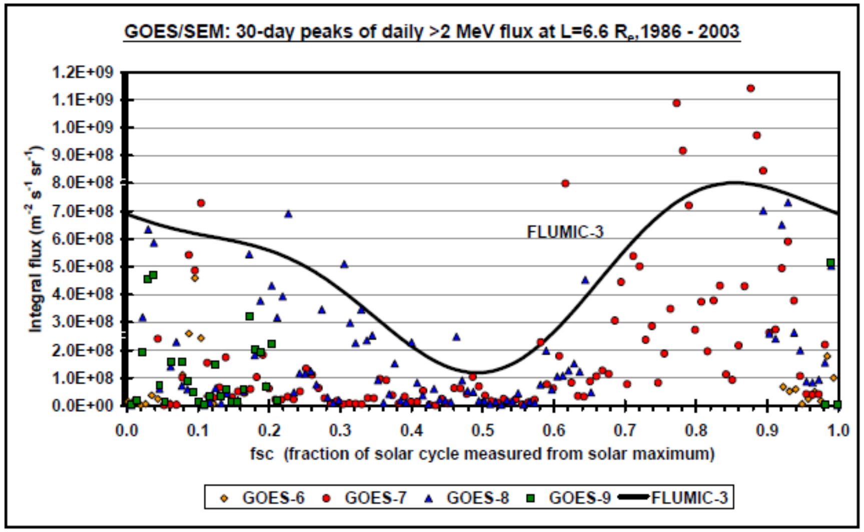
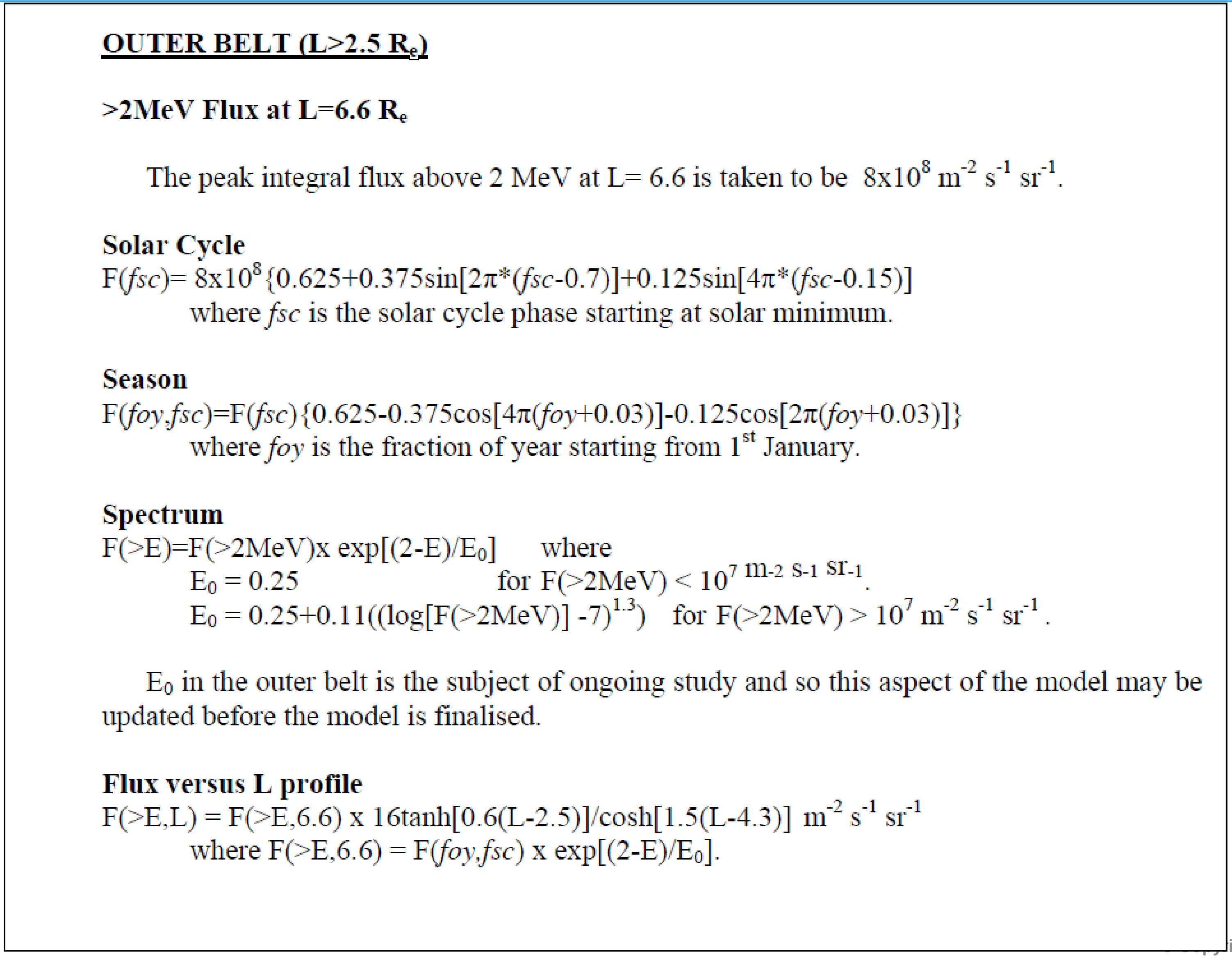


Figure 11. Solar Cycle variation of >2MeV electron flux for 1986-2003, normalised to GOES-7 fluxes at L=6.6, plotted against solar cycle phase (fsc). A curve encompasses almost all the enhancements.

FLUMIC 3 for outer belt



OUTER BELT ($L>2.5\ R_e$)

>2MeV Flux at $L=6.6\ R_e$

The peak integral flux above 2 MeV at L= 6.6 is taken to be $8x10^{8}\ m^{-2}\ s^{-1}\ sr^{-1}$.

Solar Cycle

$F(fsc)= 8x10^{8}\{0.625+0.375\sin[2\pi*(fsc-0.7)]+0.125\sin[4\pi*(fsc-0.15)]$

where *fsc* is the solar cycle phase starting at solar minimum.

Season

$F(foy,fsc)=F(fsc)\{0.625-0.375\cos[4\pi(foy+0.03)]-0.125\cos[2\pi(foy+0.03)]\}$

where *foy* is the fraction of year starting from 1st January.

Spectrum

$F(>E)=F(>2MeV)x\ \exp[(2-E)/E_0]$ where

$E_0 = 0.25$ for $F(>2MeV) < 10^{7}\ m^{-2}\ s^{-1}\ sr^{-1}$.

$E_0 = 0.25+0.11((\log[F(>2MeV)] -7)^{1.3})$ for $F(>2MeV) > 10^{7}\ m^{-2}\ s^{-1}\ sr^{-1}$.

E_0 in the outer belt is the subject of ongoing study and so this aspect of the model may be updated before the model is finalised.

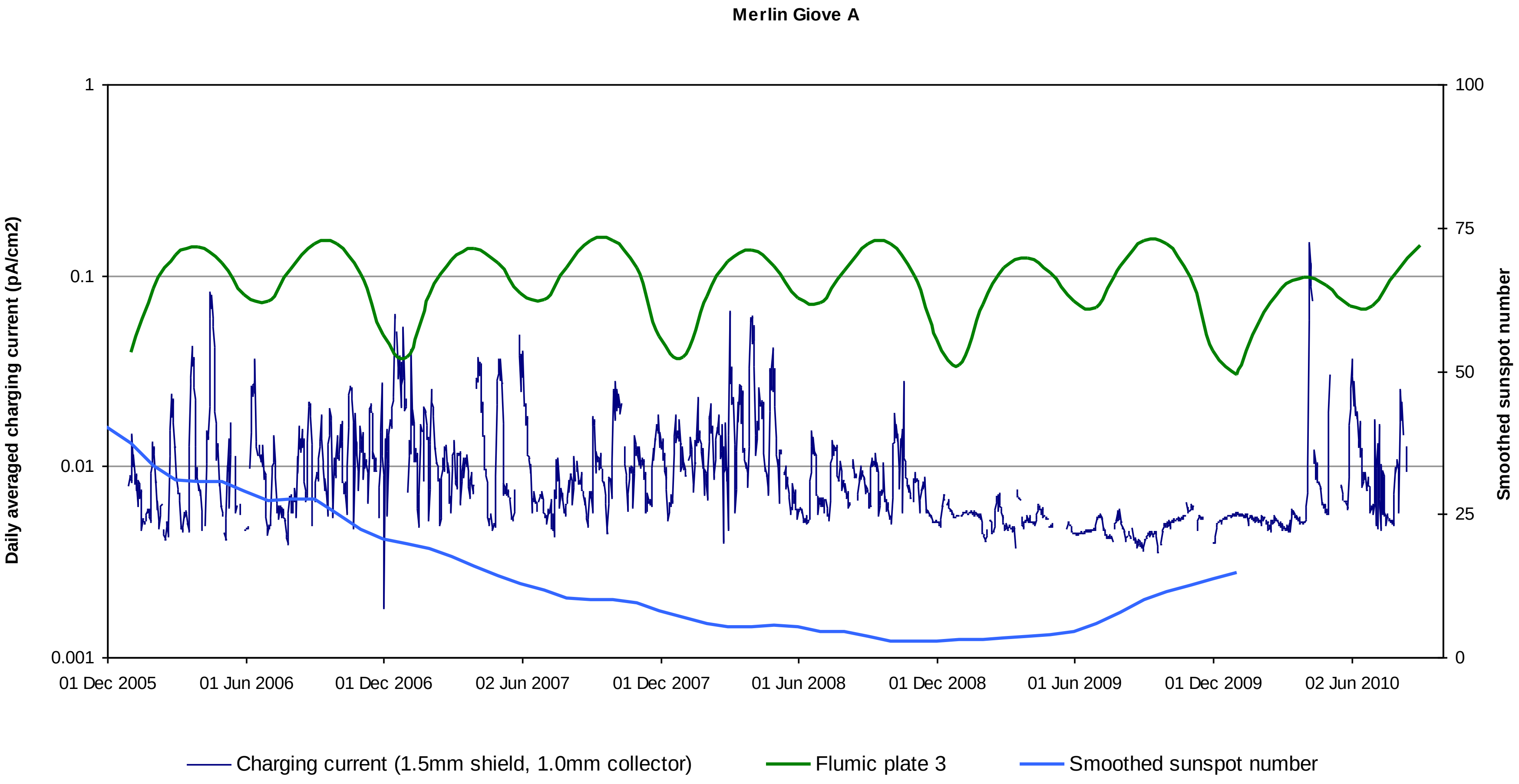
Flux versus L profile

$F(>E,L) = F(>E,6.6)\ x\ 16\tanh[0.6(L-2.5)]/\cosh[1.5(L-4.3)]\ m^{-2}\ s^{-1}\ sr^{-1}$

where $F(>E,6.6) = F(foy,fsc)\ x\ \exp[(2-E)/E_0]$.

Comparison of Giove-A data with DICTAT

1.5mm Al shield, 1.0mmAl collector plate



Internal charging at Jupiter

Copious energetic electrons (up to 100 MeV?)

- Order of magnitude more intense at peak of the belt compared to Earth

Potential for very low temperatures in parts of spacecraft

Hard spectrum leads to increased RIC (good)

Voyager and Galileo suffered upsets anomalies attributed to internal charging

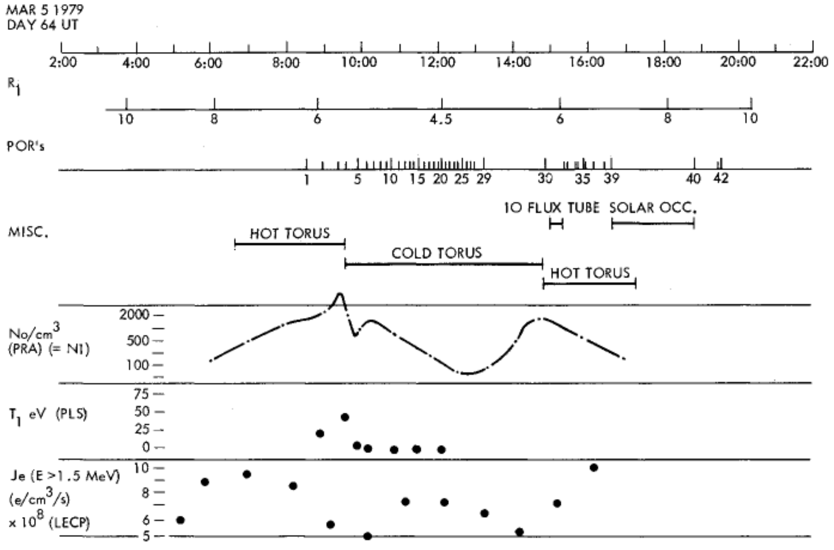
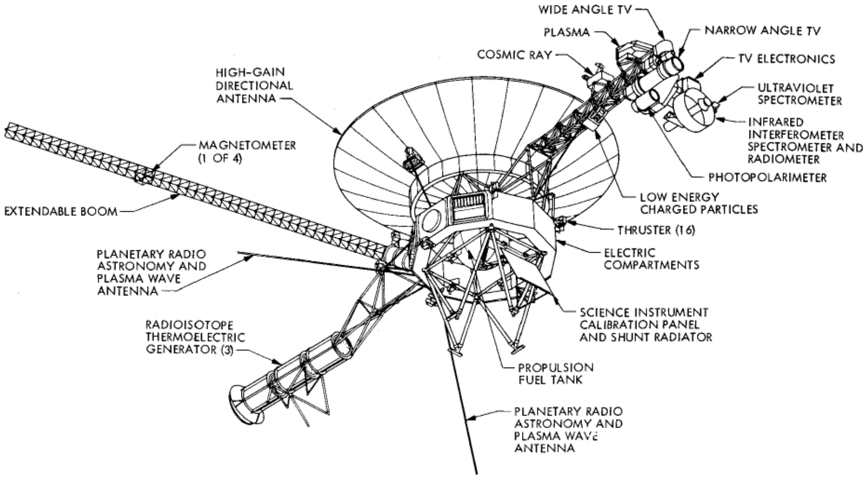


Fig. 4 Timeline showing the PORs and various plasma parameters.



JUICE – the European mission to Jupiter

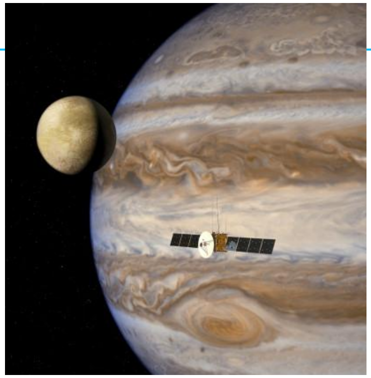
ESA L-class science mission under Cosmic Vision programme

JUICE - Jupiter Icy Moons Explorer

Launch 2022, arrives at Jupiter **2030**

Will spend nearly a year in orbit around Ganymede making remote observations of the surface

Also flypasts of Europa and Callisto



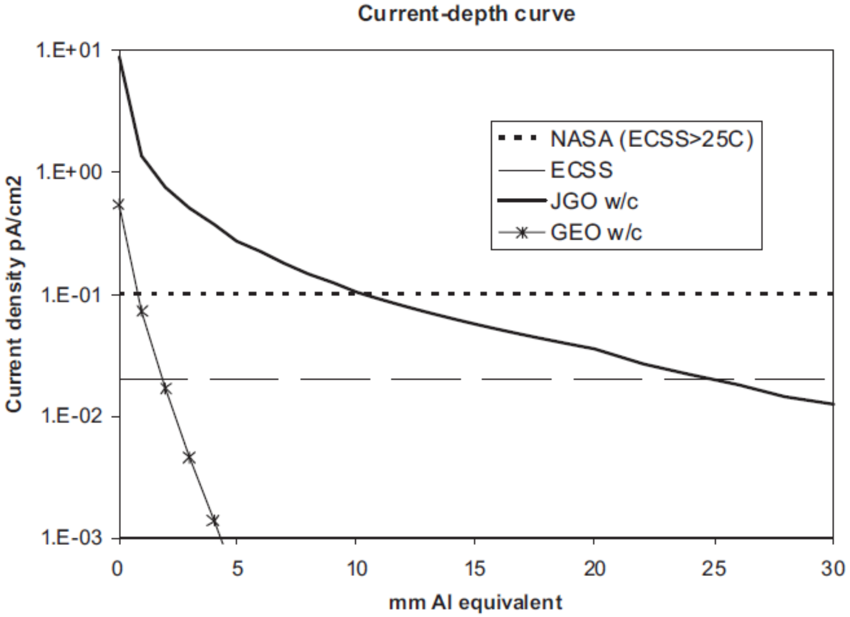


Fig. 1. Charging current versus shielding depth for a planar Aluminium shield as calculated by Mulassis [14]. The FLUMIC model [6] is used to provide a worst case geostationary environment and is compared with a worst-case Jovian environment. Dotted and dashed lines show NASA handbook and ECSS standard critical currents.

DICTATv4 beta

Higher energies

- Weber range formula replaced by Tabata (up to 30MeV)

Improved ‘straggling’ approximation

Non-Al shielding (e.g. Ta)

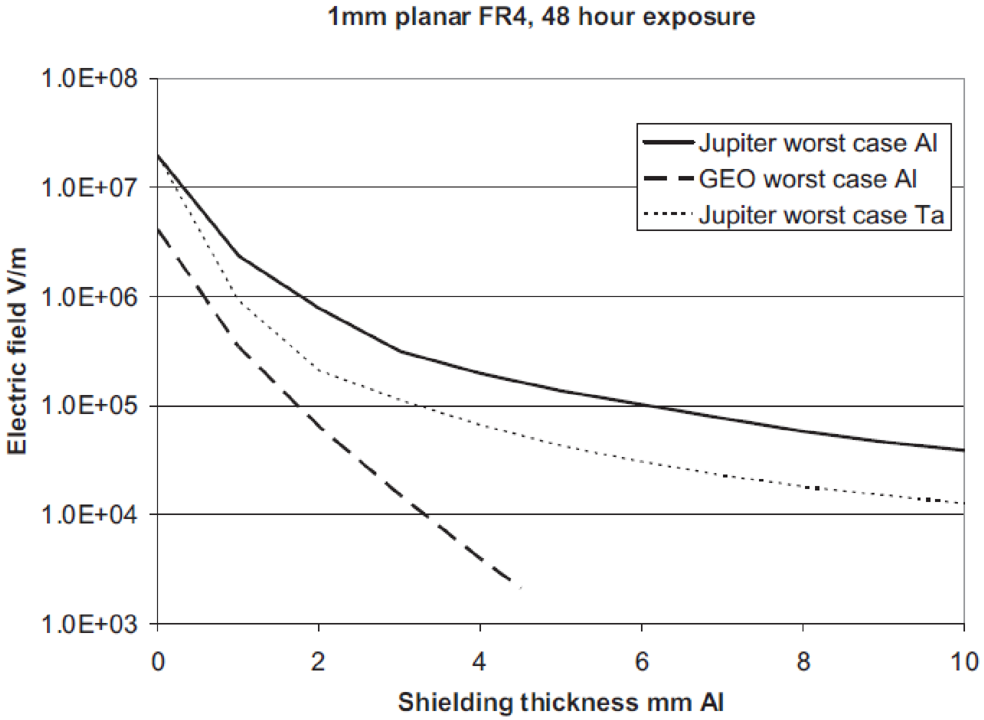


Fig. 9. DICTATv4 calculation of maximum electric field as function of shielding thickness for FR4.

Rodgers et al, IEEE RADECS, 2011

On-going challenges

- Long term behaviour of dielectrics in space
- Some materials may have very long time constants (months, years)
  - 0.01pA cm^{-2} rather than 0.1 pA cm^{-2} safe level?
- In-orbit validations still very sparse
- Extreme space weather (Carrington event)
- 3D modelling
- Discharge trigger events – e.g. cosmic rays?
- Jupiter!

Key references

Standards:

- NASA HDBK 4002A Mitigating In-Space Charging Effects
- ECSS-E-ST-20-06C Spacecraft Charging Standard

Book:

- Guide to Mitigating Spacecraft Charging Effects, H. Garrett and A. Whittlesey, Wiley, 2012