Modeling Electrostatic Fields Generated by Internal Charging of Materials in Space Radiation Environments

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Introduction

Internal (deep dielectric) charging

High energy (>100 keV) electrons penetrate spacecraft walls and accumulate in dielectrics or isolated conductors

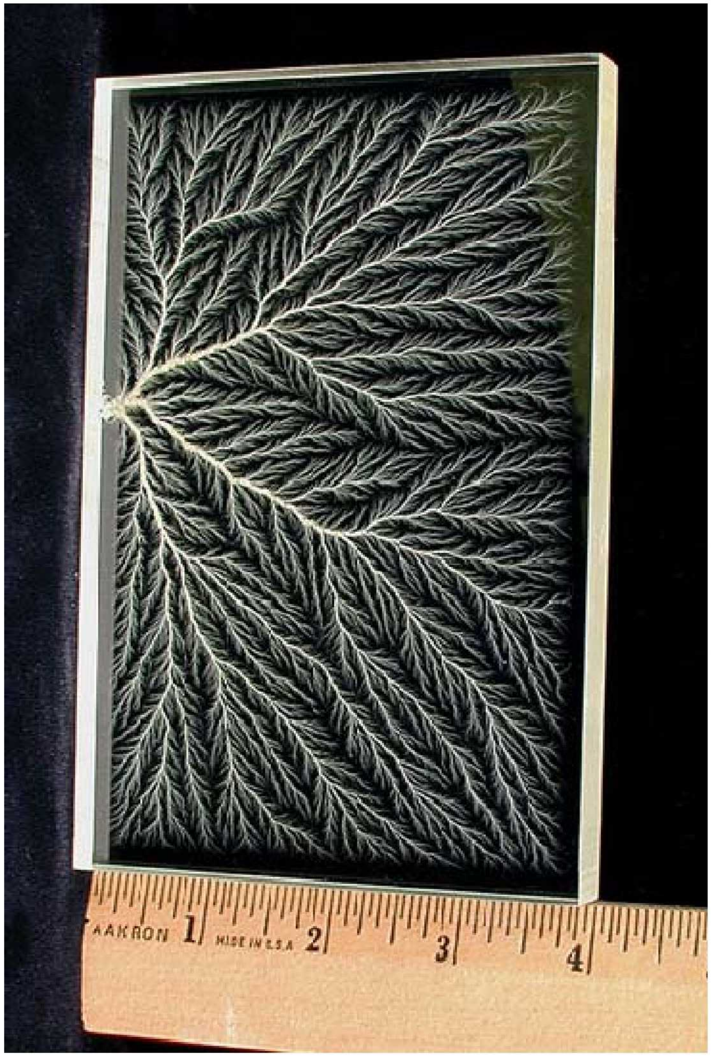
Threat environment is energetic electrons with sufficient flux to charge circuit boards, cable insulation, and ungrounded metal faster than charge can dissipate

Accumulating charge density generates electric fields in excess of breakdown strength resulting in electrostatic discharge

System impact is material damage, discharge currents inside of spacecraft Faraday cage on or near critical circuitry, and RF noise

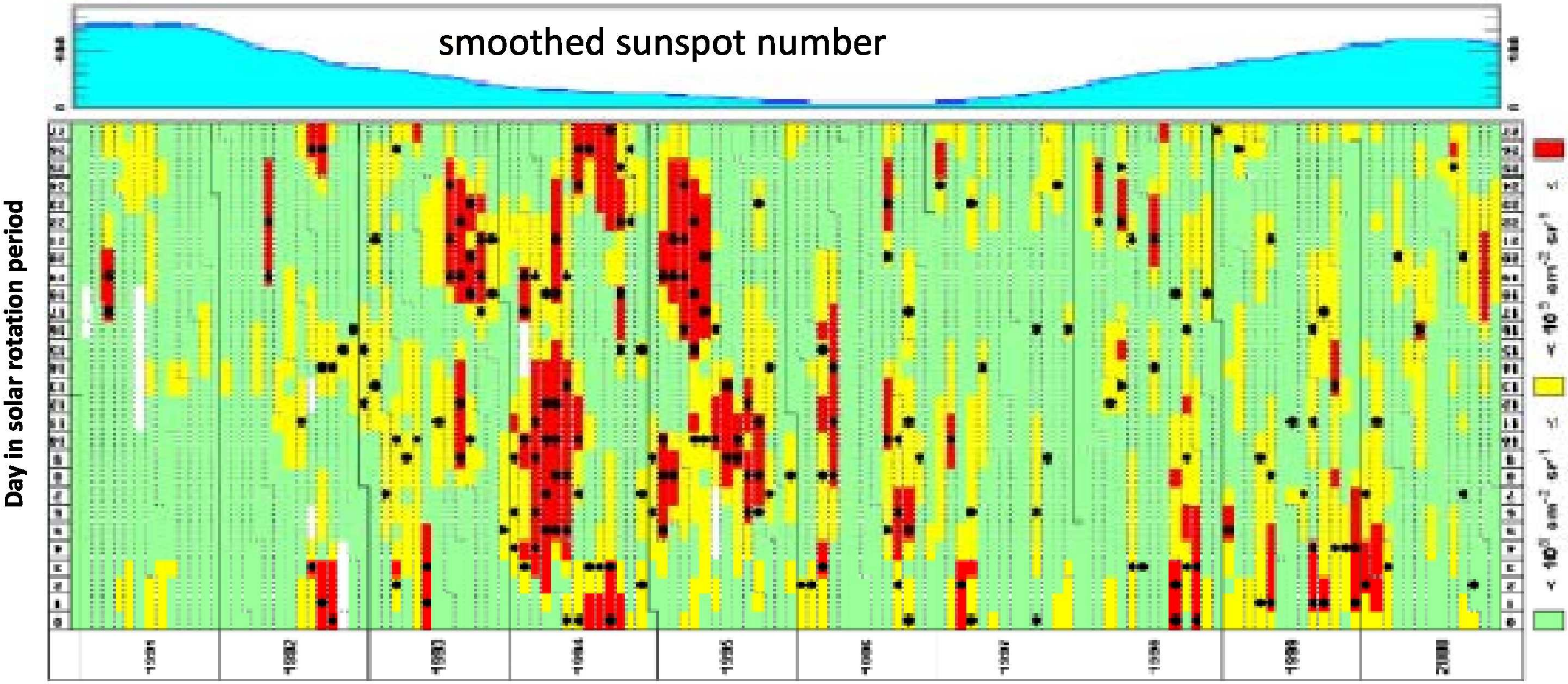
Overview

- Internal charging physics, model formulation
- Examples of two engineering models
  - ESA DICTAT
  - NASA NUMIT
- Other internal charging models



PMMA (acrylic) charged by ~2 to 5 MeV electrons

GOES Solar Cycle 21 Internal Charging Anomalies (GEO)



[*Wrenn et al.* 2002]

- Black: GOES phantom commands

2-day fluence (F2) > 2 MeV electrons

- Red: F2 $\geq 10^9$ e^-/cm^2-sr
- Amber: 10^9 > F2 $\geq 10^8$ e^-/cm^2-sr
- Green: F2 < 10^8 e^-/cm^2-sr
- White: no data

Internal Charging: Physics

$$\nabla \bullet \varepsilon E = \rho$$

$$\varepsilon = \kappa \varepsilon_0$$

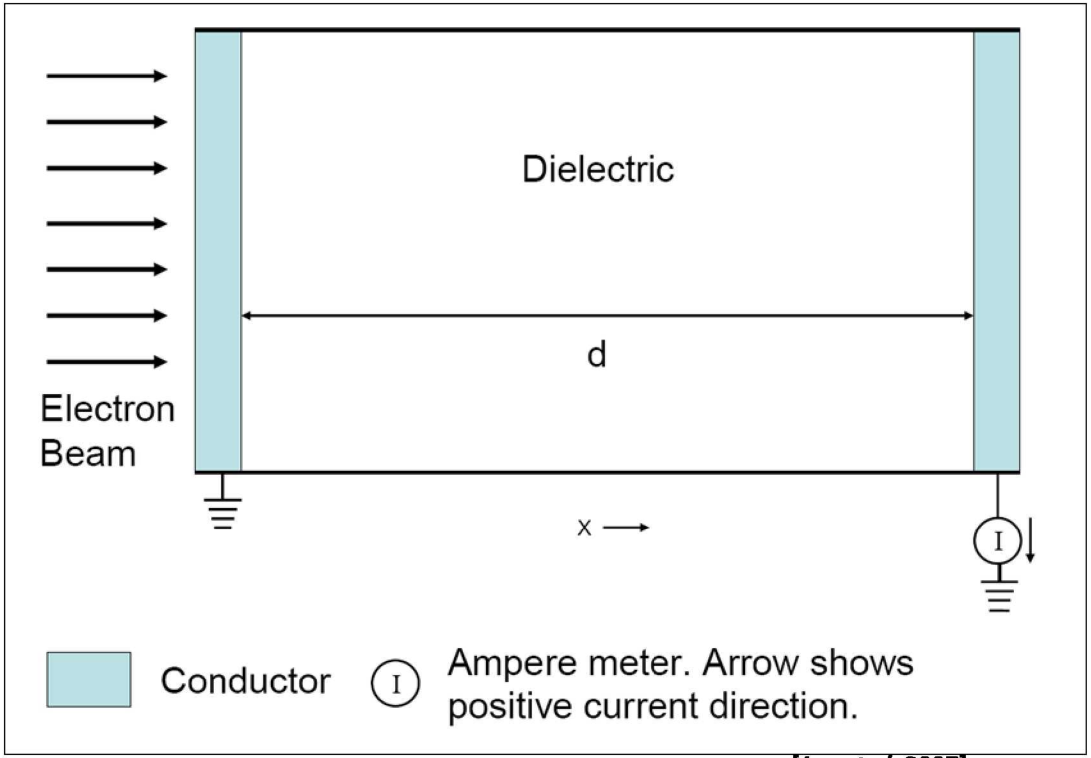
$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$

$$J = J_R + J_C$$

$$J_C = \sigma E$$

$$= \left[\sigma_{dark} + \sigma_{RIC} \right] E$$

$$\sigma_{RIC} = k \left(\frac{d\gamma}{dt} \right)^{\alpha} \qquad 0.5 < \alpha < 1.0$$



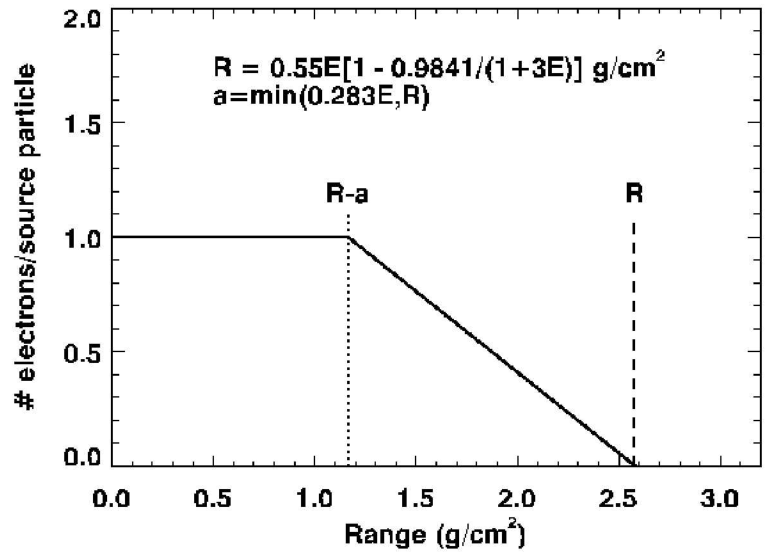
[*Jun et al.* 2007]

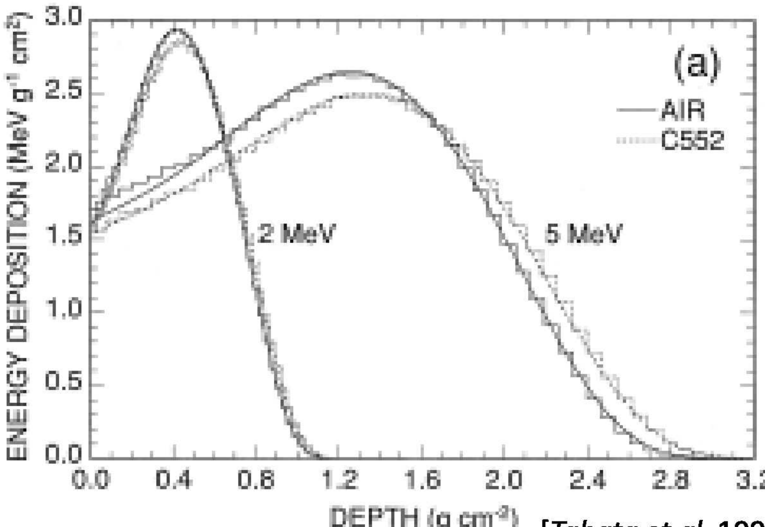
Solution to Poisson, continuity equation involves two problems:

- Radiation (electron) penetration with charge and energy deposition in material
- Electrostatic solution of fields from charge distribution in insulator

Internal Charging: Radiation Transport

- Computation of radiation dose and charge deposition as function of depth requires a radiation transport analysis
- Analytical approximations are used in some codes to avoid time consuming Monte Carlo techniques
- Monte Carlo radiation transport techniques (e.g., ITS, EGS) provide better results
  - Empirical parameterization of Monte Carlo output provides fidelity of Monte Carlo radiation transport results with speed of analytical solution
  - Monte Carlo results are best for general solutions





[*Tabata et al.* 1998]

Internal Charging: Electrostatic Models

- **Generation-Recombination (GR) Model**

Microscopic model explicitly treats the radiation generated charge carrier pairs, field induced drift of carriers, and loss through recombination

$$\epsilon \frac{\partial E}{\partial x} = \rho_+ - \rho_- - \rho_{t-} \quad (4)$$

$$\frac{\partial(\rho_- + \rho_{t-})}{\partial t} = -\frac{\partial J_0}{\partial x} + G - \alpha_f \rho_+ \rho_- - \alpha_t \rho_+ \rho_{t-} + \frac{\partial(\mu_- \rho_- E)}{\partial x} \quad (5)$$

$$\frac{\partial \rho_+}{\partial t} = G - \alpha_f \rho_+ \rho_- - \alpha_t \rho_+ \rho_{t-} - \frac{\partial(\mu_+ \rho_+ E)}{\partial x} \quad (6)$$

$$\frac{\partial \rho_{t-}}{\partial t} = \frac{\rho_-}{\tau_-}\left(1 - \frac{\rho_{t-}}{\rho_m}\right) - \alpha_t \rho_+ \rho_{t-} \quad (7)$$

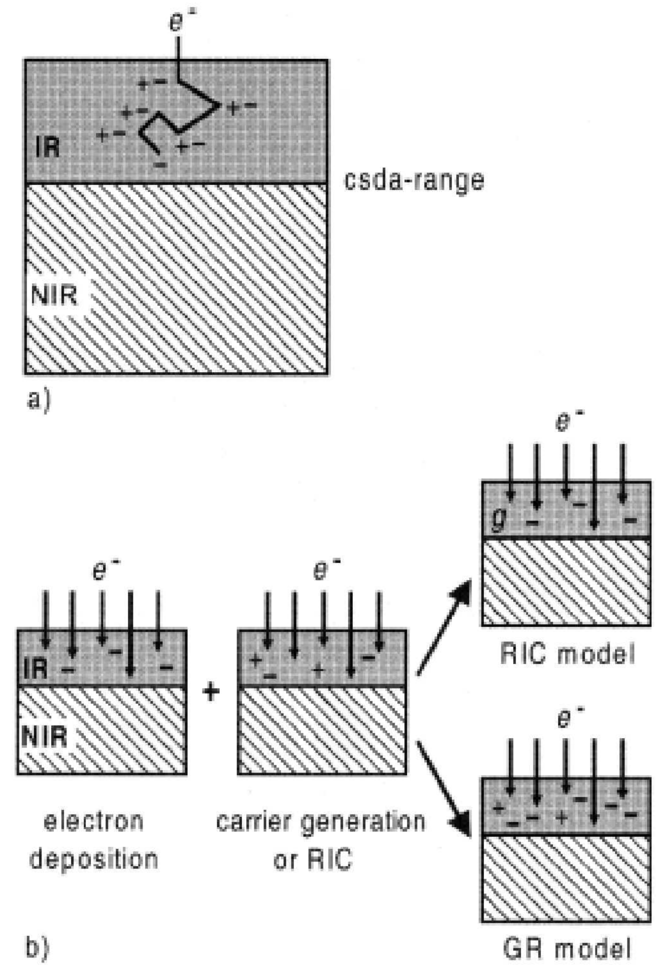
- **Radiation Induced Conductivity (RIC) Model**

Macroscopic model based on empirical relation ship between radiation dose and conductivity

$$\epsilon \frac{\partial E}{\partial x} = -\rho_- - \rho_{t-} \quad (1)$$

$$\frac{\partial(\rho_- + \rho_{t-})}{\partial t} = -\frac{\partial J_0}{\partial x} + \frac{\partial(\mu_- \rho_- E)}{\partial x} + \frac{\partial(gE)}{\partial x} \quad (2)$$

$$\frac{\partial \rho_{t-}}{\partial t} = \frac{\rho_-}{\tau_-}\left(1 - \frac{\rho_{t-}}{\rho_m}\right) \quad (3)$$



[*Sessler et al.* 2004]

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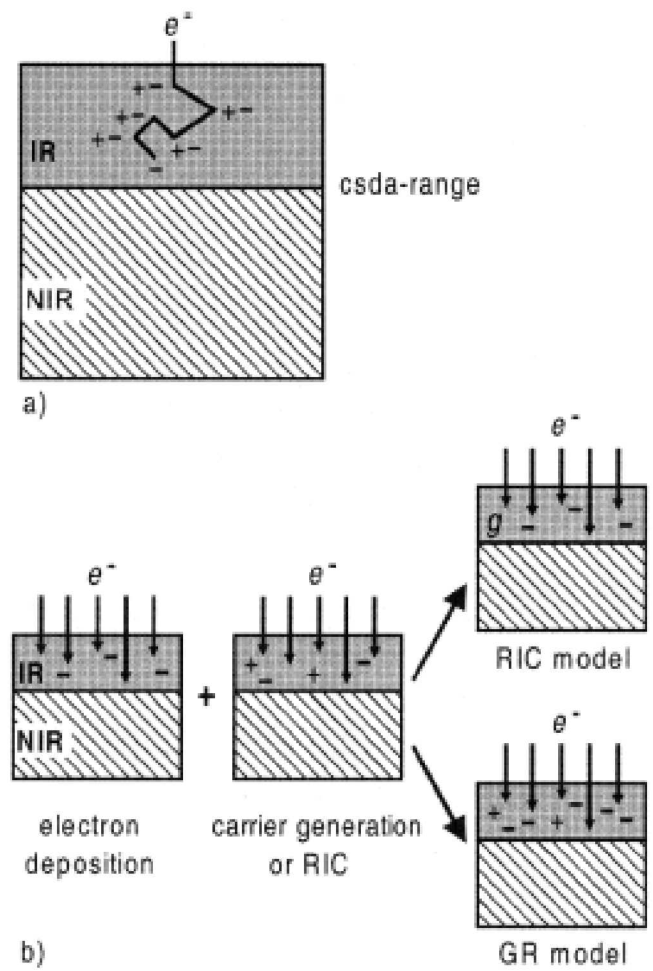
$$\frac{\partial \rho_-}{\partial t} = -\frac{\partial J_0}{\partial x} + \frac{\partial[(\sigma_D + \sigma_{RIC})E]}{\partial x}$$

$$= -\frac{\partial J_0}{\partial x} + \frac{\partial[(\sigma_D + kD^x)E]}{\partial x}$$



[*Sessler et al.* 2004]

DICTAT Internal Charging Code

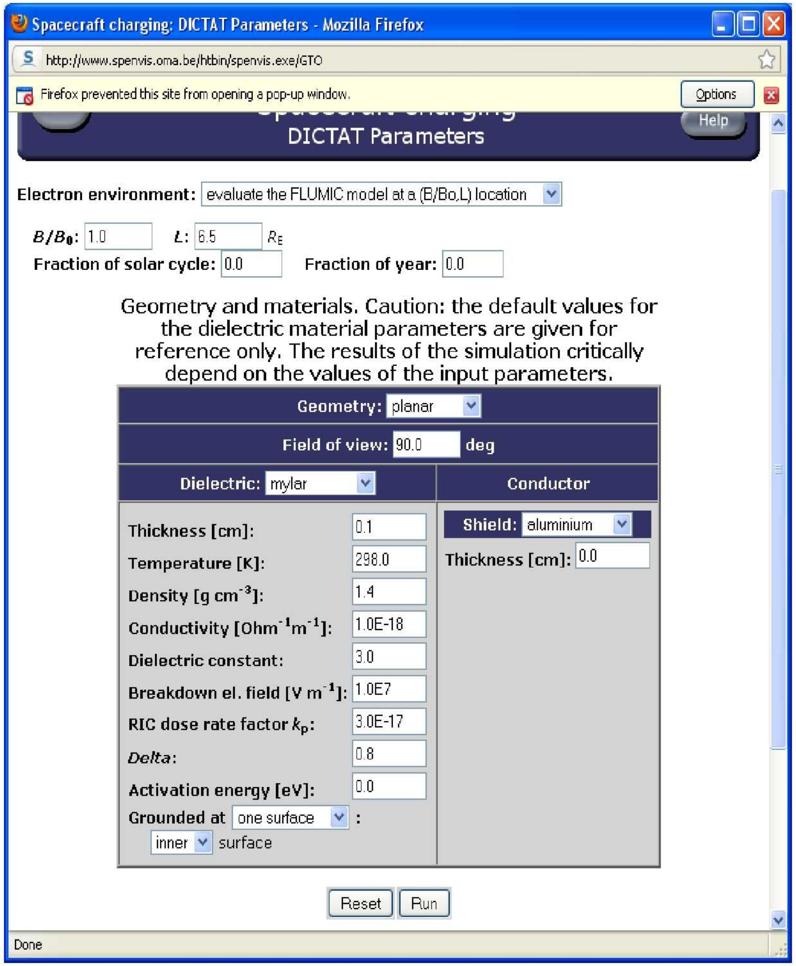
- DICTAT model evaluates possibility of dielectric breakdown of insulating materials due to radiation charging
  - Single material parameterized by electrical conductivity (dark and radiation induced) dielectric constant, density, temperature

Example: 1 mm Mylar exposed to FLUMIC (worst case) GEO electron environment

- **Resistivity 10^{14} Ω-m**
  After 48.0 hours: Charging current= 7.0535E-13 Amps/cm²
  E-max= 6.5170E+05 V/m Voltage= 464.5 volts
  The dielectric IS NOT liable to experience breakdown
  Maximum E lower than Breakdown field= 1.00E+07 V/m

- **Resistivity 10^{16} Ω-m**
  After 48.0 hours: Charging current= 7.0535E-13 Amps/cm²
  E-max= 1.4130E+07 V/m Voltage= 1.1678E+04 volts
  The dielectric IS liable to experience breakdown
  Maximum E higher than Breakdown field= 1.00E+07 V/m

- **Resistivity 10^{18} Ω-m**
  After 48.0 hours: Charging current= 7.0535E-13 Amps/cm²
  E-max= 3.5881E+07 V/m Voltage= 2.8170E+04 volts
  The dielectric IS liable to experience breakdown
  Maximum E higher than Breakdown field= 1.00E+07 V/m

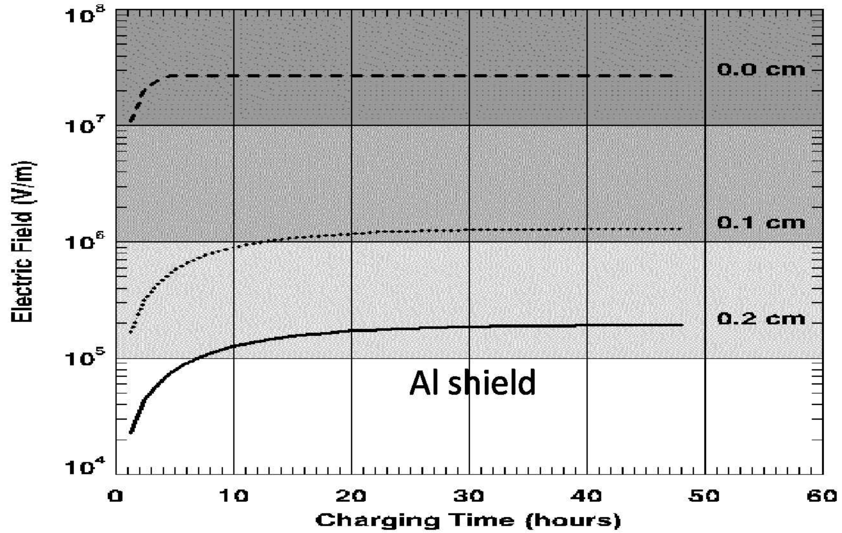


http://www.spenvis.oma.be/

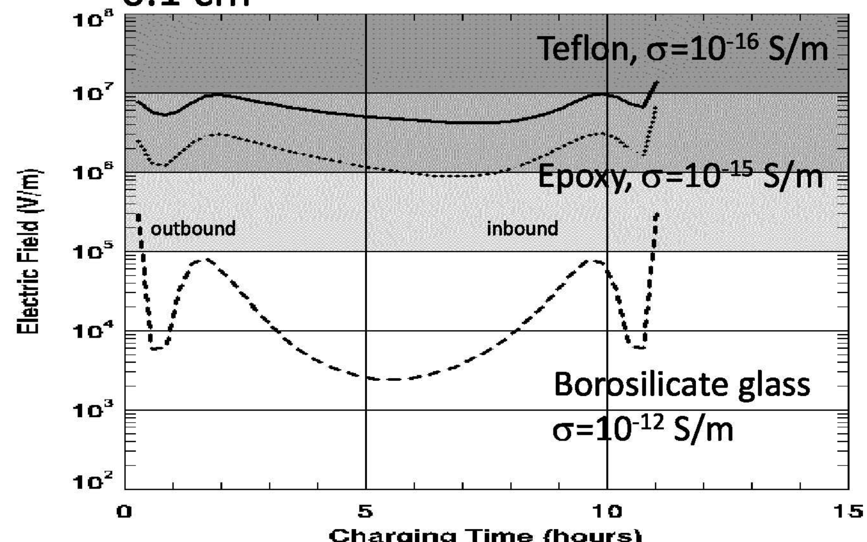
DICTAT Internal Charging Analysis

- Simple first order evaluation of charging along trajectories through Earth's radiation belts using standard trapped radiation models, mitigation of charging by shielding
- 10 mm thick plexiglass shielded by aluminum 0.0 cm to 0.2 cm thick
  - Peak AE-8 GEO radiation flux (constant)
- Three 0.1 materials with conductivity varying from 10^{-16} to 10^{-12} S/m
  - AE-8 solar max electron flux
  - 250 km x 38,226 km x 0° inc, single orbit
- Grey levels indicate relative threat levels for electrostatic discharge assuming materials typically suffer dielectric breakdown at electric fields in the range of 10^6 V/m to 10^7 V/m.

10 cm plexiglass ($\sigma=10^{-15}$ S/m)

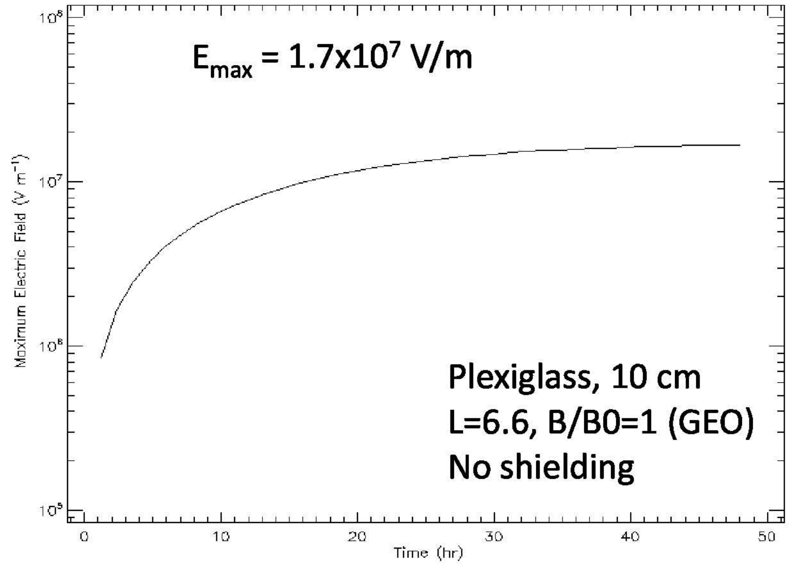


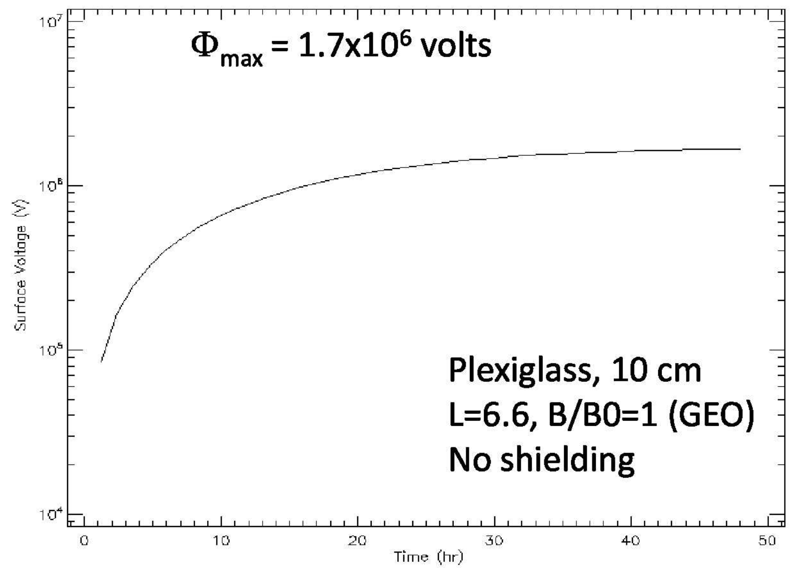
0.1 cm



DICTAT Internal Charging Analysis

- Electric field, surface voltage potential as function of time
- Allows quick screening for materials issues
- Simulation options limited by tool
  - Maximum time (48 hours)
  - Single material
  - Constant flux for user input
  - Radiation belt models for time variations in radiation flux
  - Only maximum E field is reported, no information on electric field as function of depth





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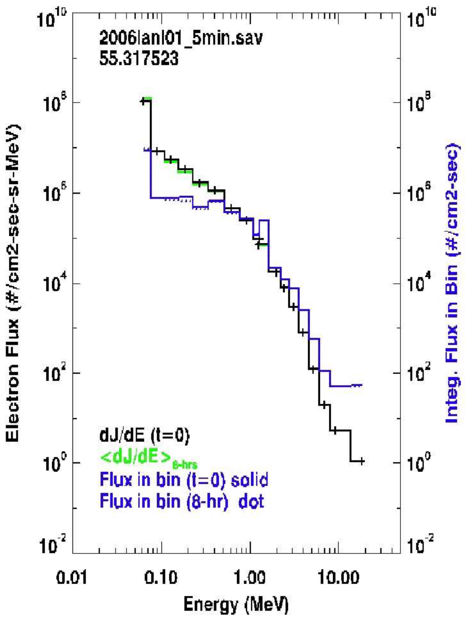
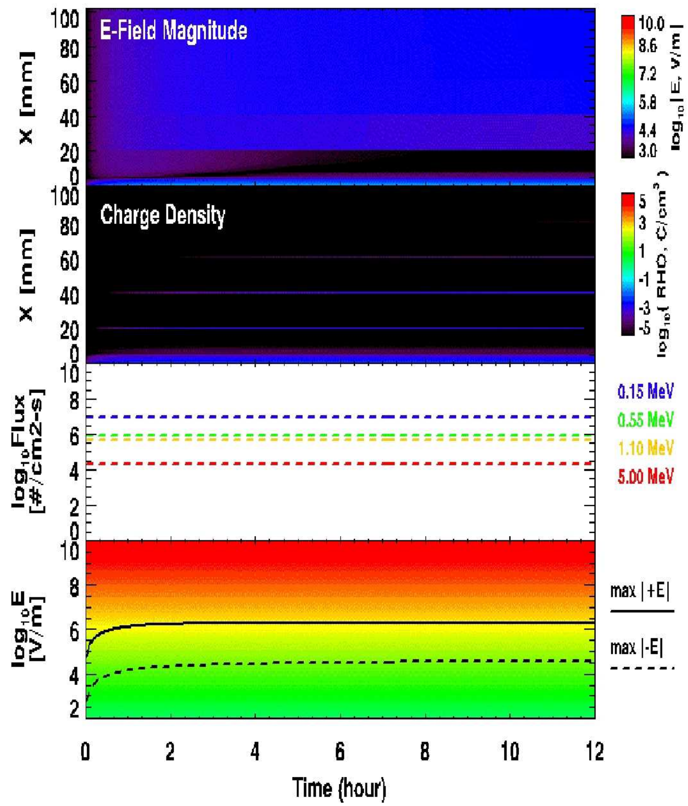
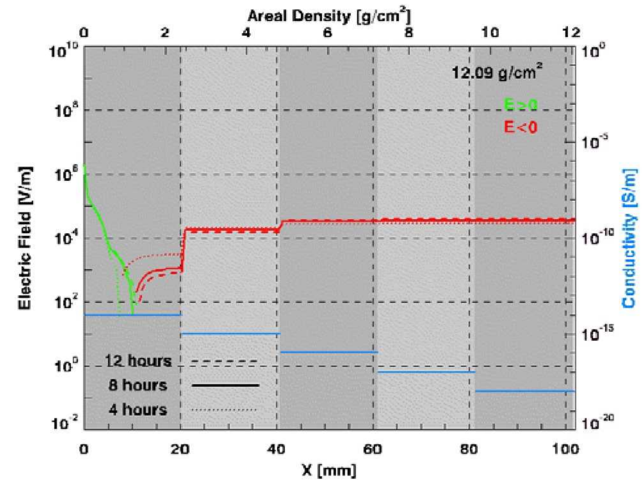
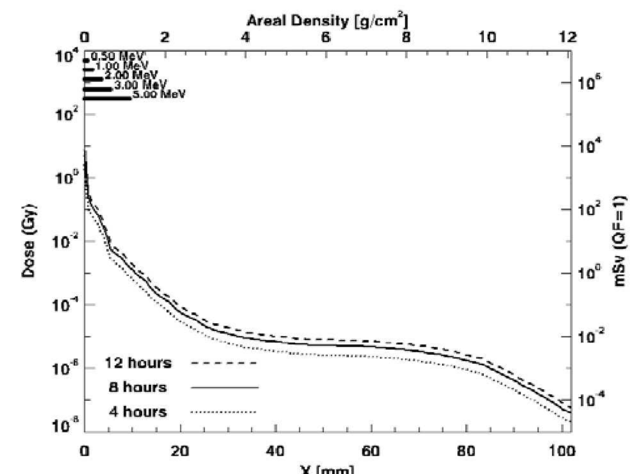
NUMIT (“numerical iteration”) Codes

- Originally developed by A.R. Frederickson et al (AFRL, JPL)
- Tabata algorithm fits to Monte Carlo electron transport code for radiation dose, charge deposition
- Multiple material conductivity, dielectric constant
- Input electron spectrum, monoenergetic beams, fixed flux or time series of arbitrary duration (hours to years)
- Output electric fields, charge density, currents, radiation dose rates as function of depth in material









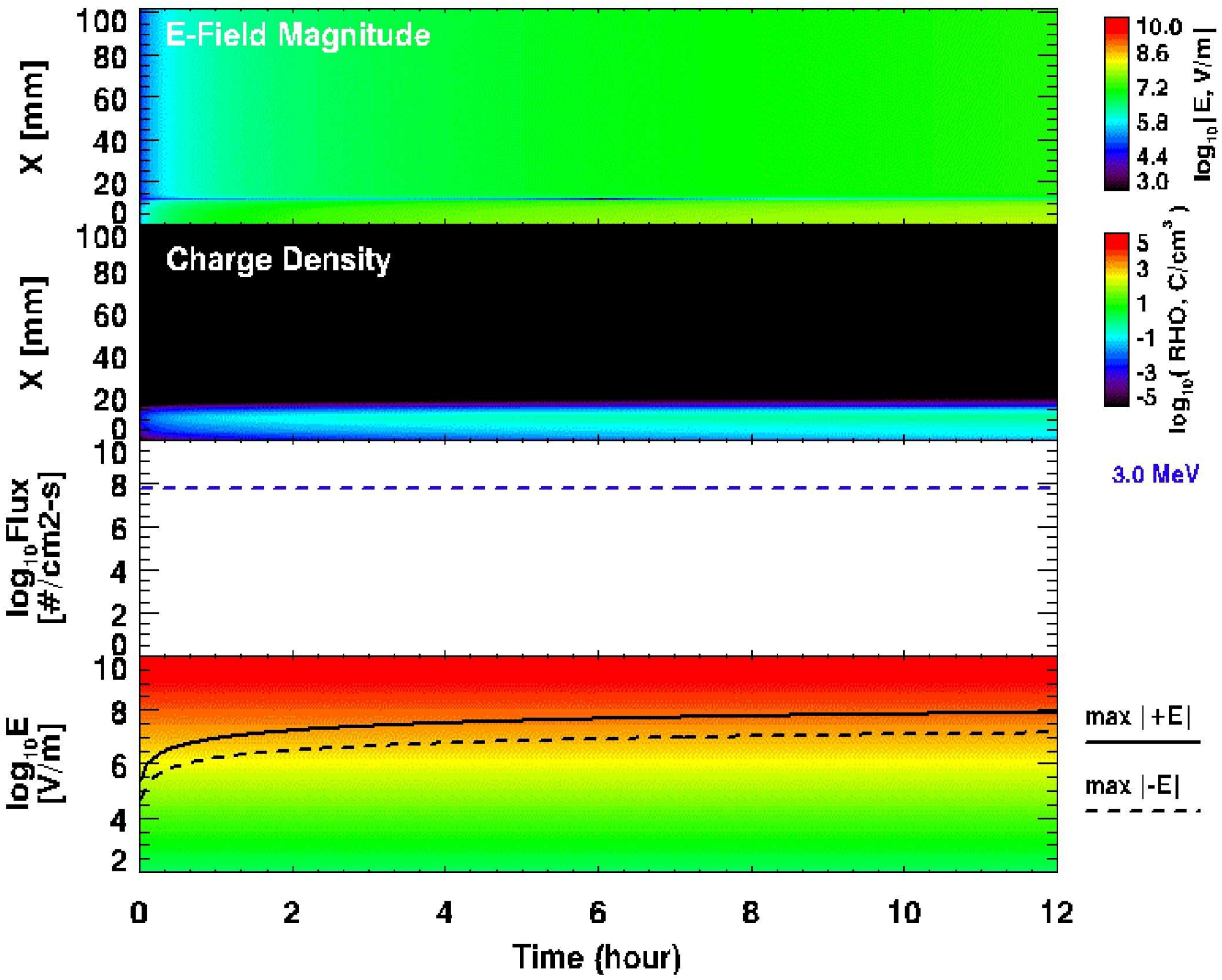
3 MeV electrons on PMMA

Charging beam

- 3 MeV electrons
- 0.01 nA/cm^2

Material

- PMMA (acrylic)
- Z=6, A=12
- ~10 cm thick
- σ ~ 1x10^{-16} S/m
- κ = 3.71
- ρ = 1.19 g/cm^3



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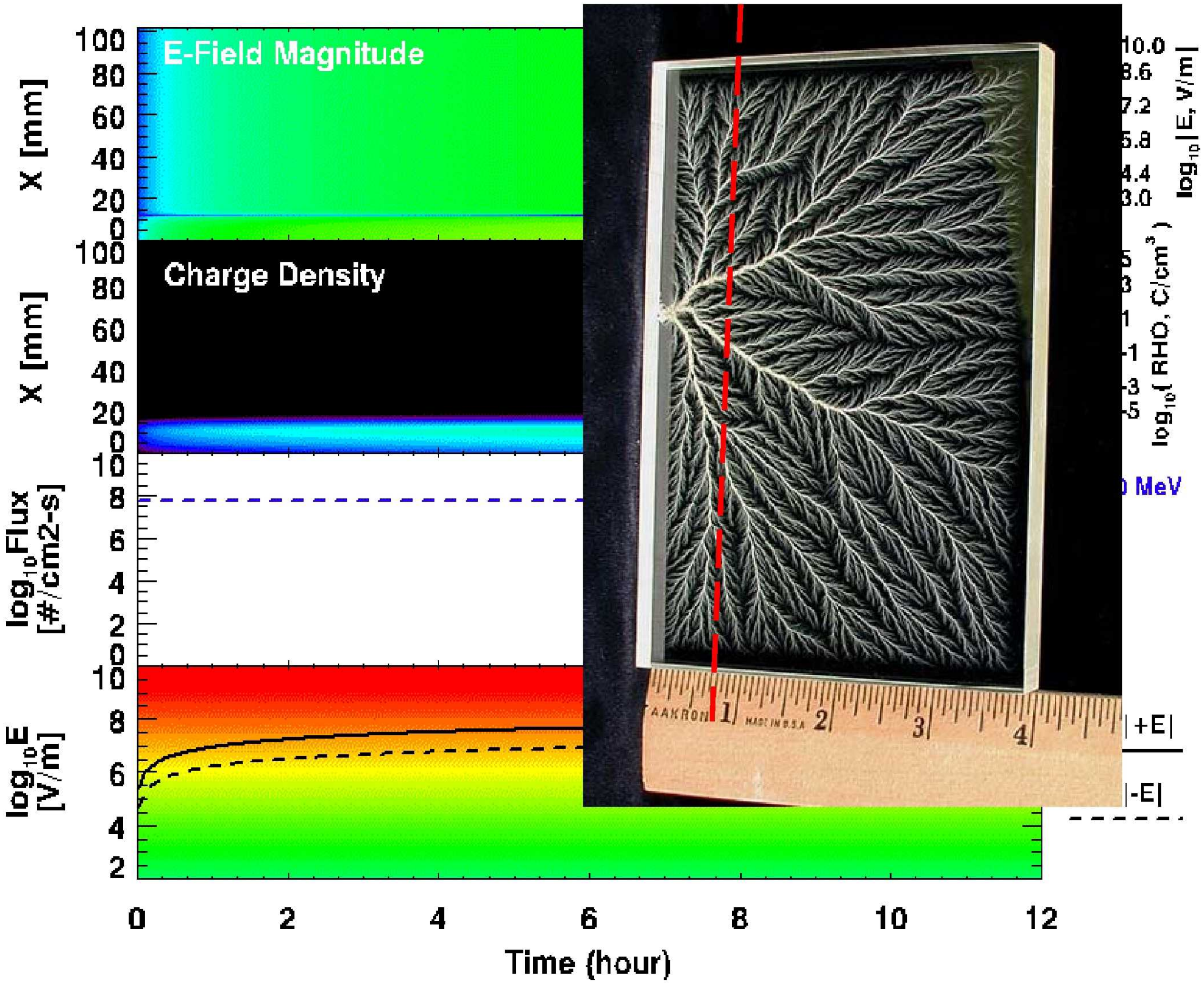

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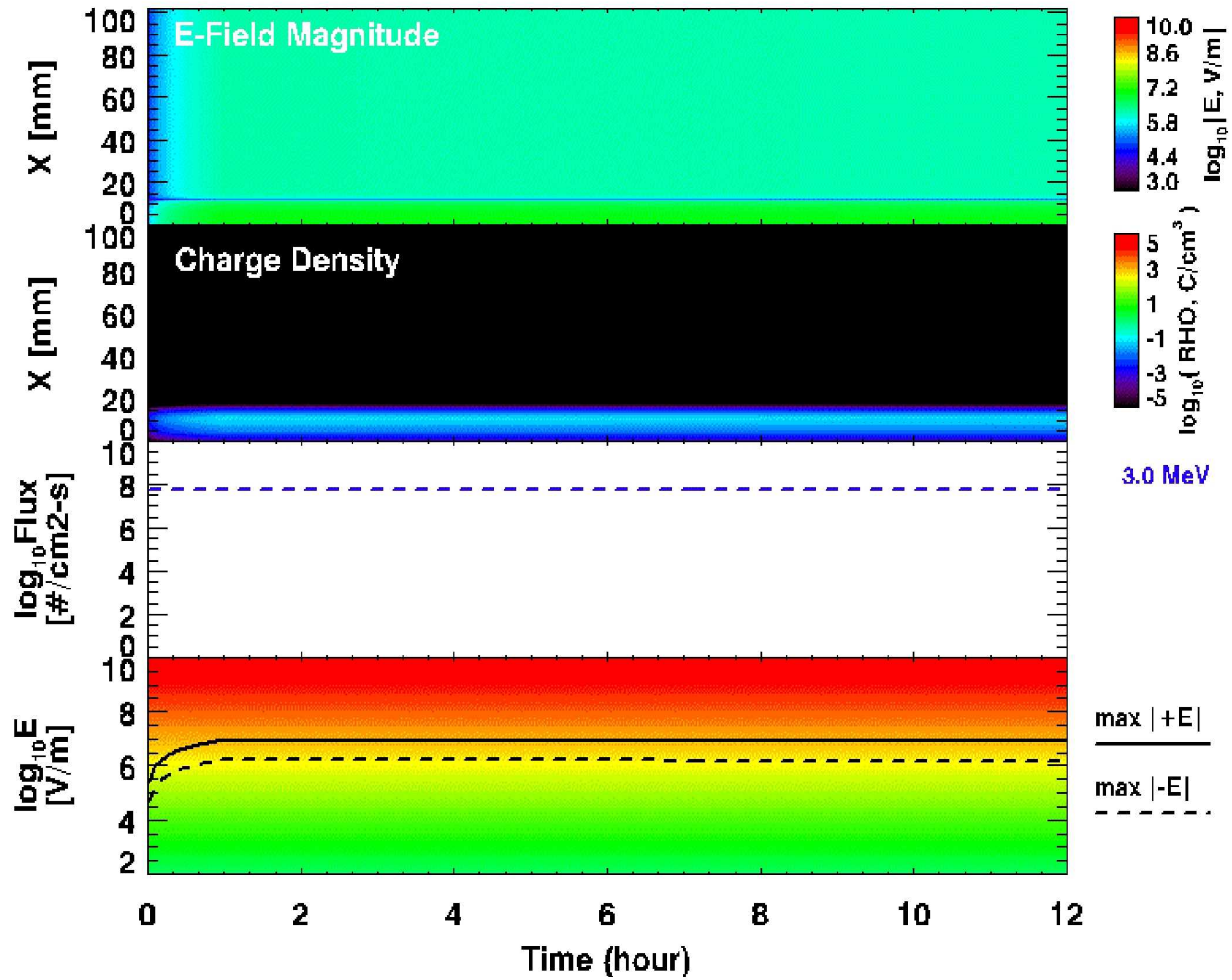
Beam off at 1 hour
No effect since
$\tau \sim \kappa\varepsilon_0/\sigma$=91 hours



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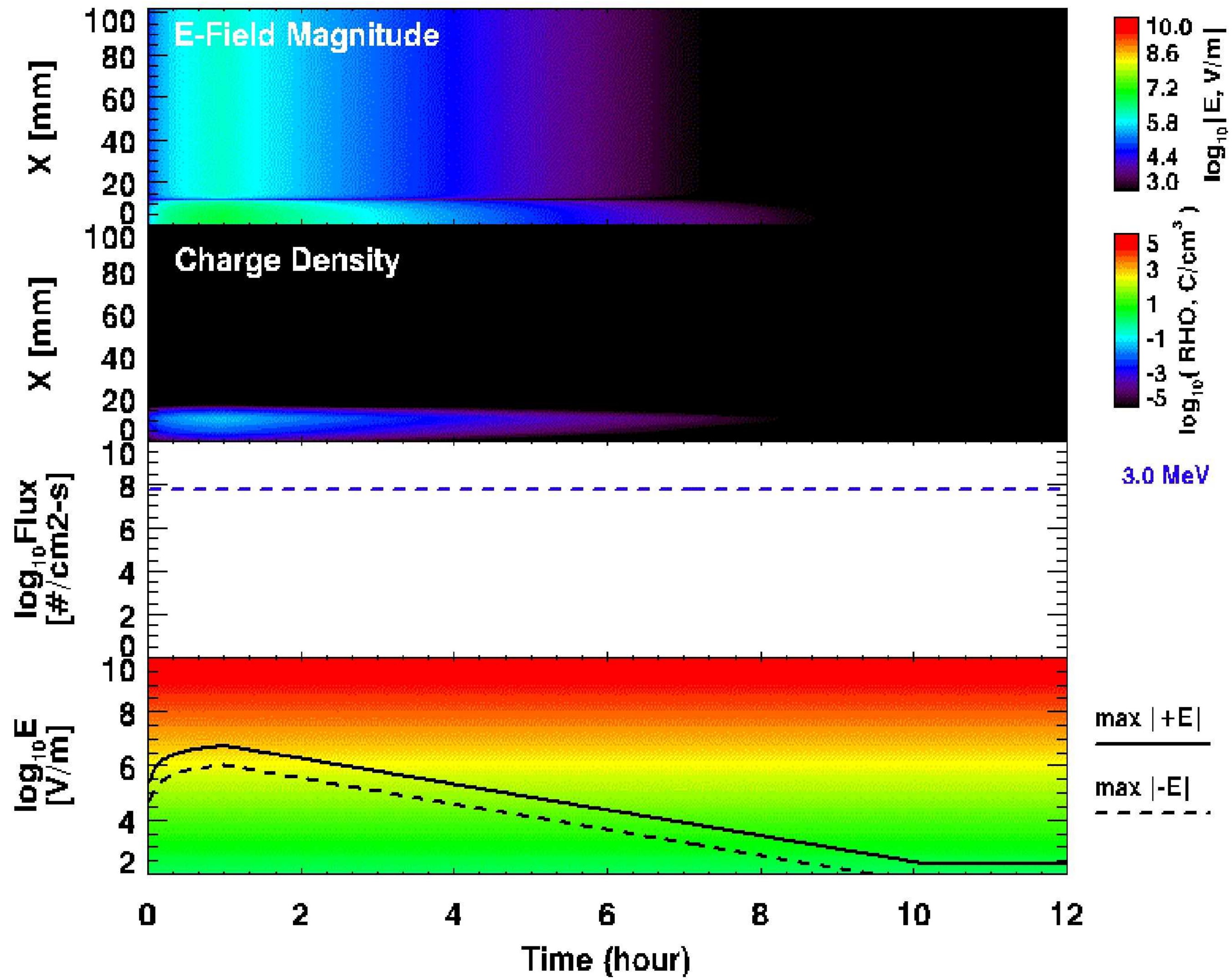
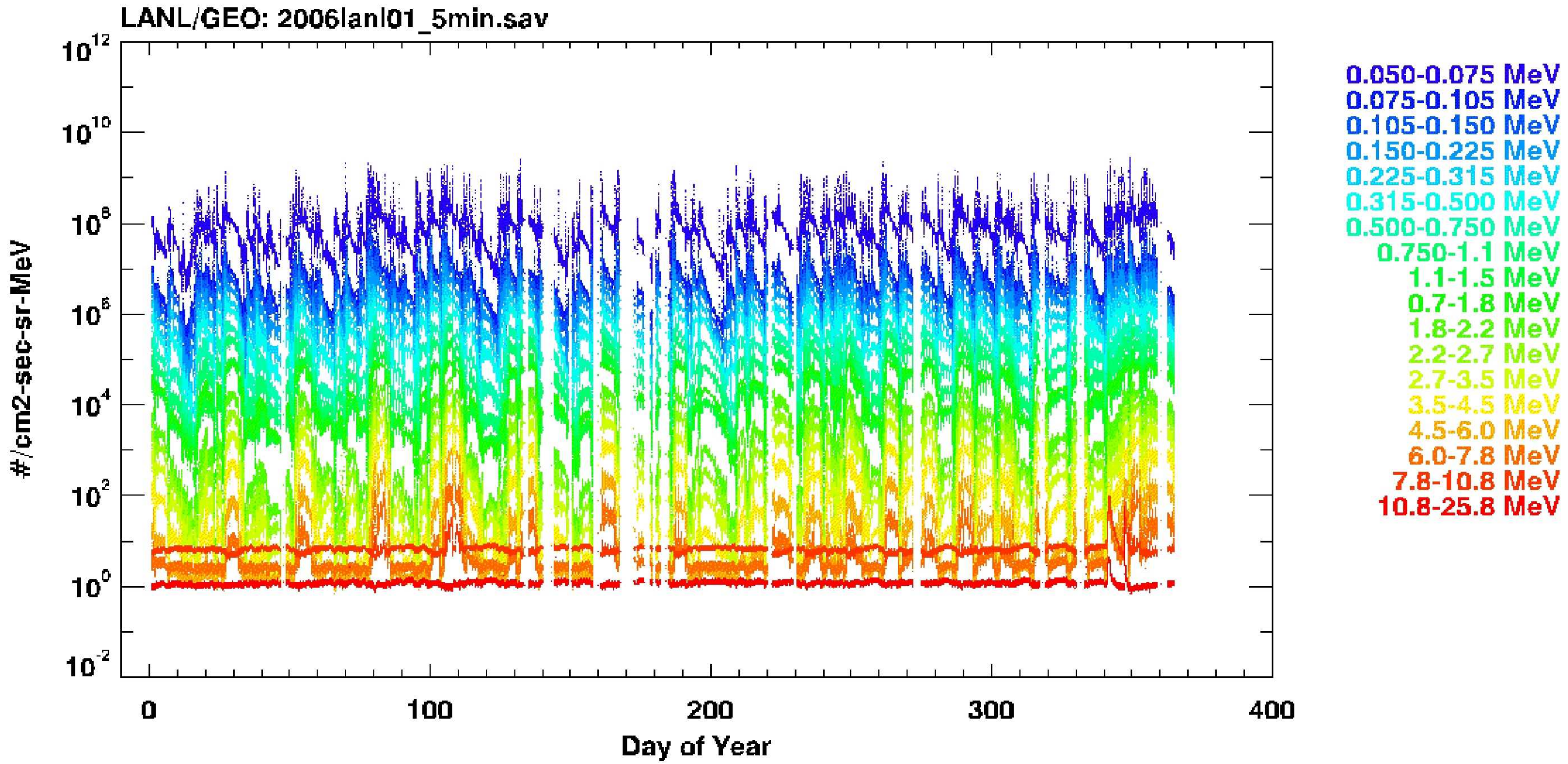


Geostationary Orbit 200 Day Time Series



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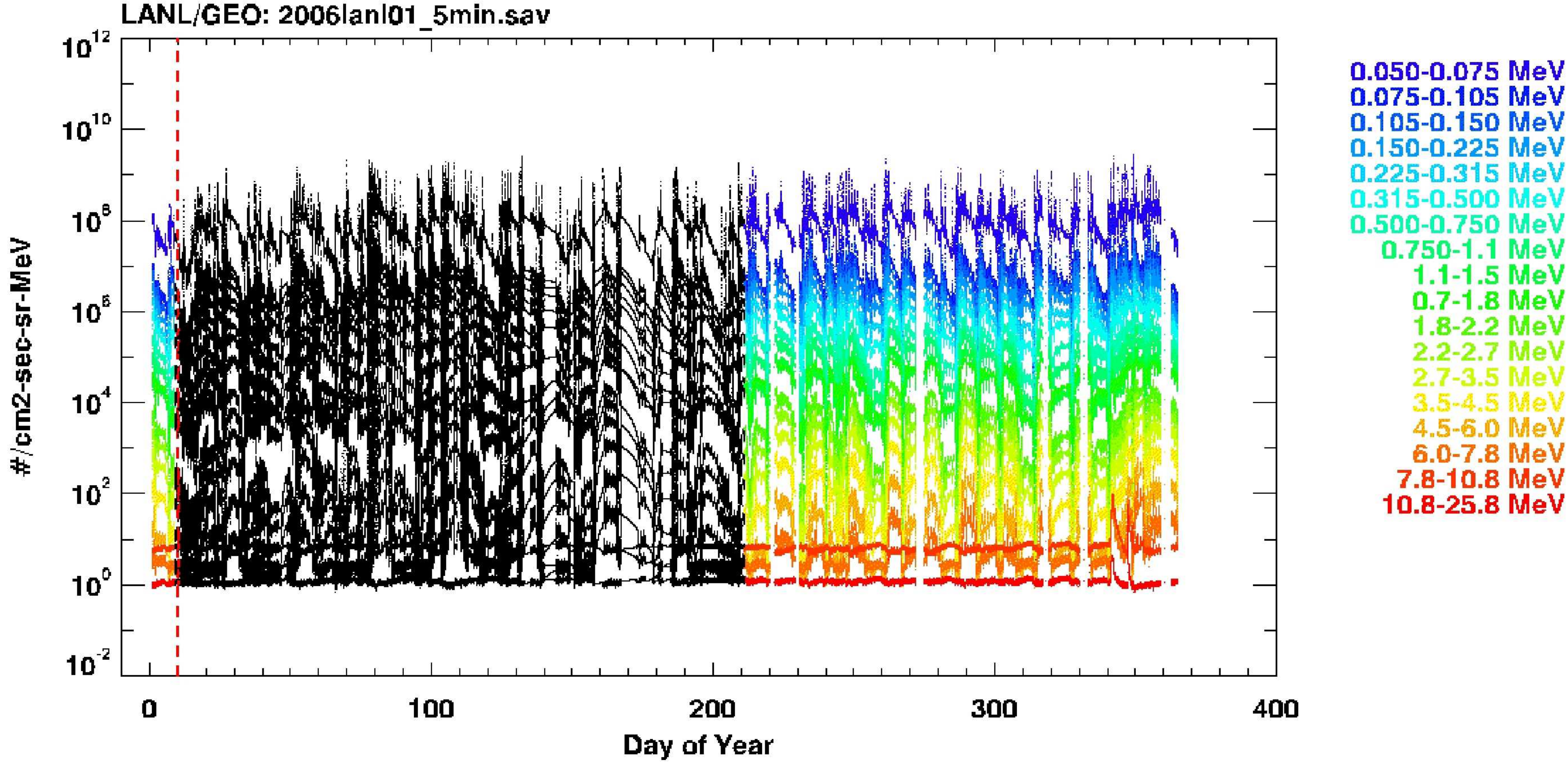


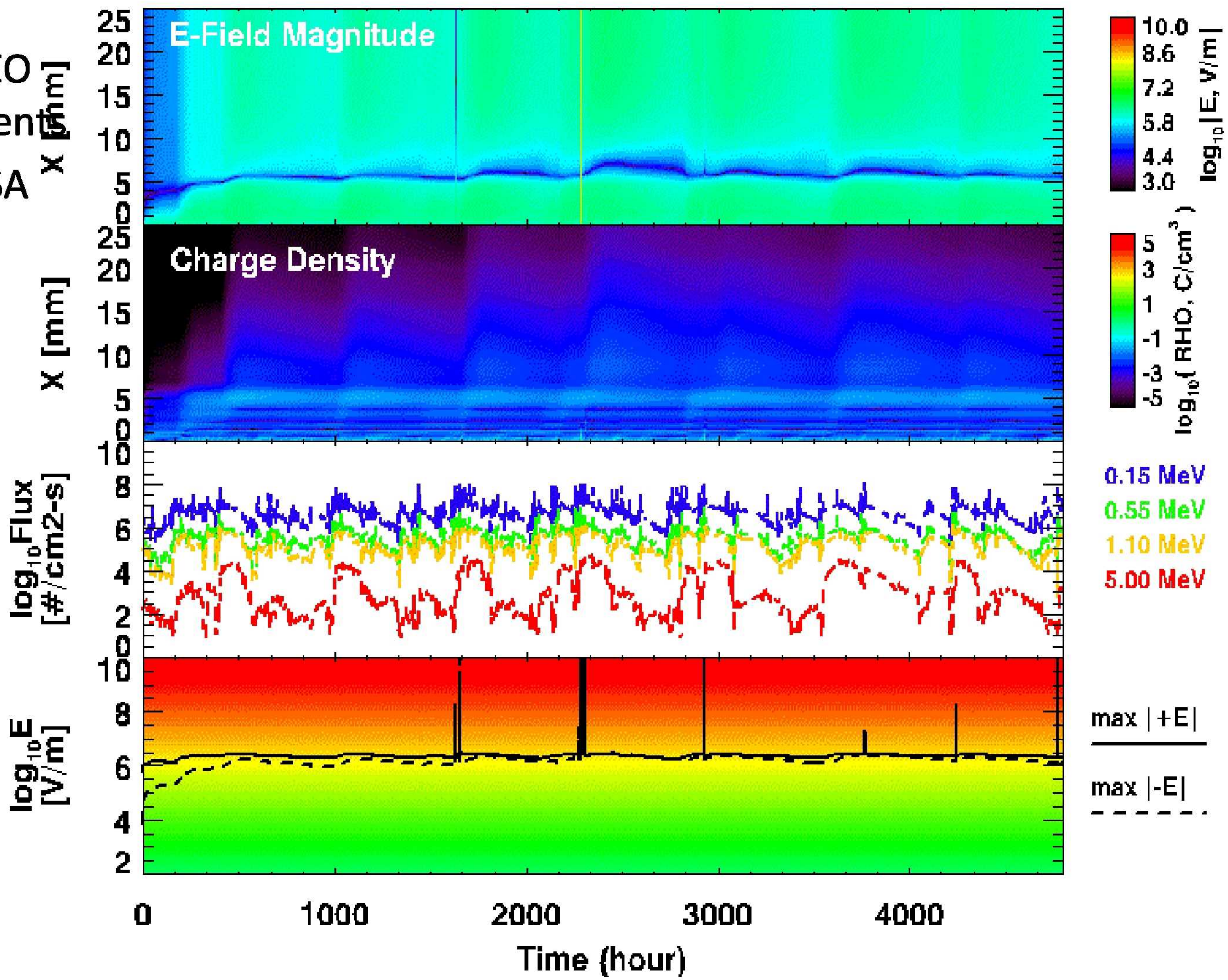
Geostationary Orbit, 200 Days

Charging current

- Energy, flux from GEO electron measurements
- LANL-01A SOPA +ESA

Material

- PMMA
- Z=6, A=12
- ~2.5 cm thick
- σ ~ 1×10^{-17} S/m
- κ = 2.00
- ρ = 1.0 g/cm^3



Internal Charging Codes

Model	Type*	Electron Transport	Features	Reference
NUMIT (original) AFRL, JPL	A, MC	Tabata, Monte Carlo	1-D, single energy, σ(E) models	Frederickson et al., 1974, 1977, 1980, 1983, 1993
NUMIT JPL	A	Tabata	1-D, spectrum, 3 materials	Jun et al. 2008
NUMIT MSFC	A	Tabata	1-D, spectrum, 5 materials	Minow et al. 2007 Jun et al 2008
NUMIT Bethel University, AFRL	A	Tabata	1-D, 1 energy, 3 materials	Beeken and McIver, 2010
NUMIT SAIC	A	Tabata	1-D, spectrum, radiation shield	Davis et al., 2000, 2007
ESA Deep Dielectric Charging Code (ESA-DDC)	MC	Range-energy relationship	1-D, σ(E) models	Soubeyran et al., 1993, 1994
DICTAT	A	Range-energy relationship	1-D, radiation shield, σ(E) models	Rodgers et al. 1999, 2000 , 2003, Sørensen et al. 2000
Moscow State University	MC	GEANT-3	1-D	Mileev and Novikov, 2004
Xi'an Jiaotong University	A	1-D analytical solution	1-D, σ(E) models	Li et al. 2010
Assessment Tool of Internal Charging for Satellites (ATICS)	MC	GEANT-4	1-D panels over a 3-D spacecraft, σ(E) models	Zhong et al., 2007
Multi-Utility Spacecraft Charging Analysis Tool			1-D	Hatta et al. 2009 Cho et al. 2010
JPL	MC	ITS	3-D	Katz and Kim, 2010
Aerospace Corp	MC	GEANT-4	3-D	Lemon et al. 2010

*A = analytical MC = Monte Carlo

Summary

- Internal charging is a risk to spacecraft in energetic electron environments

- DICTAT, NUMIT computational codes are the most widely used engineering tools for evaluating internal charging of insulator materials exposed to these environments

- Engineering tools designed for rapid evaluation of ESD threats, but there is a need for more physics based models for investigating the science of materials interactions with energetic electron environments

- Current tools are limited by the physics included in the models and ease of user implementation….additional development work is needed to improve models