Extending the NUMIT Simulation for Modeling Deep-dielectric Charging in the Space Environment

24 September 2010

Brian Beecken

Jordan McIver

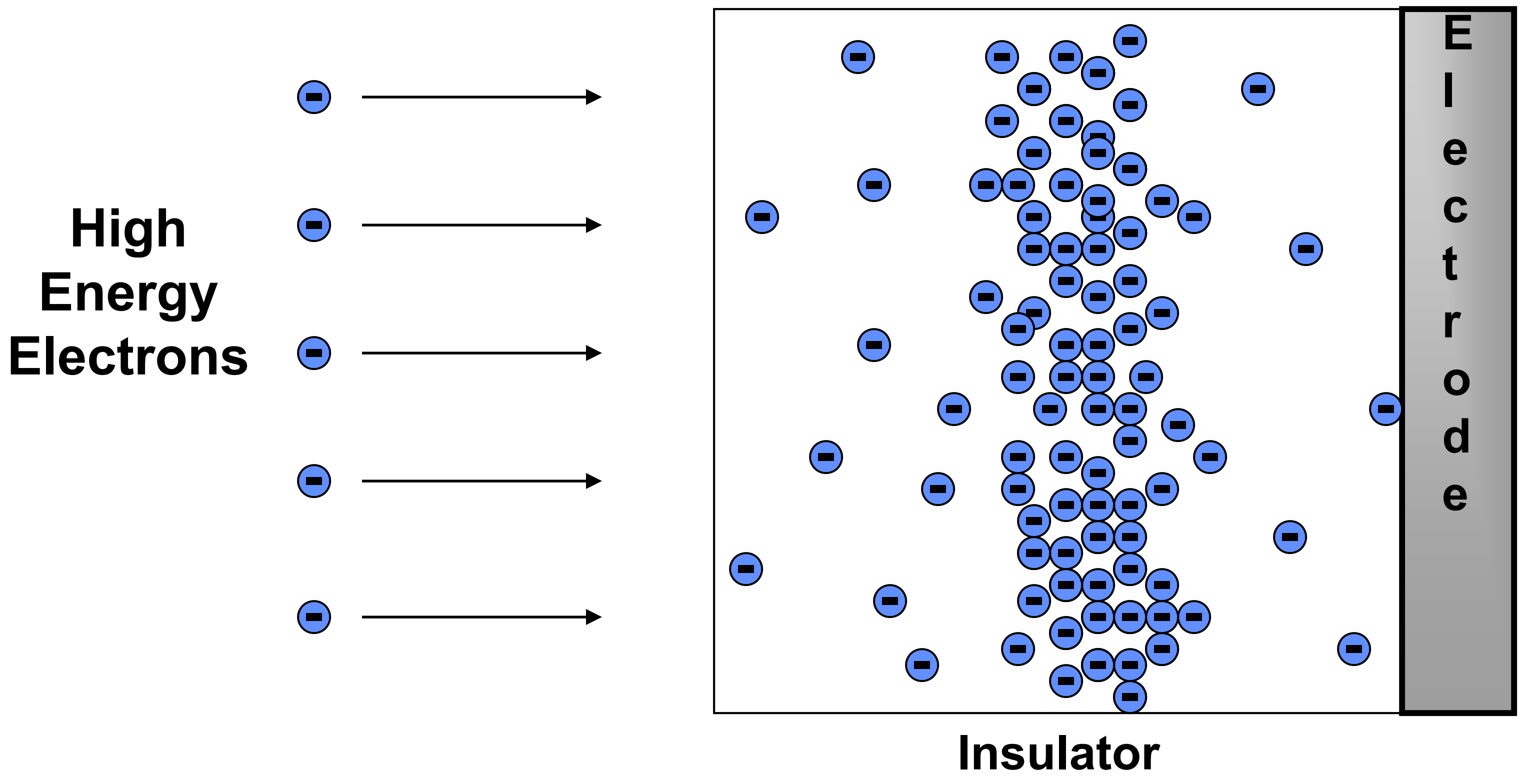
Physics Department, Bethel University, St. Paul, MN

Supported in part by ASEE/AFRL Summer Faculty Fellowship and AFRL/RVBX

Background/Acknowledgements

- **Who is Brian Beecken?**
  - I am *not* a space physicist
  - Chair of a *large* undergraduate physics
  - Research is part-time, with undergraduates
- **How did he get here?**
  - NASA Summer Faculty Fellowship Program at JPL
  - Robb Frederickson introduced me to Spacecraft Charging
  - Two summers working with Robb, the second was on NUMIT
  - David Cooke had interest in NUMIT: 2 summers at AFRL/RVBX

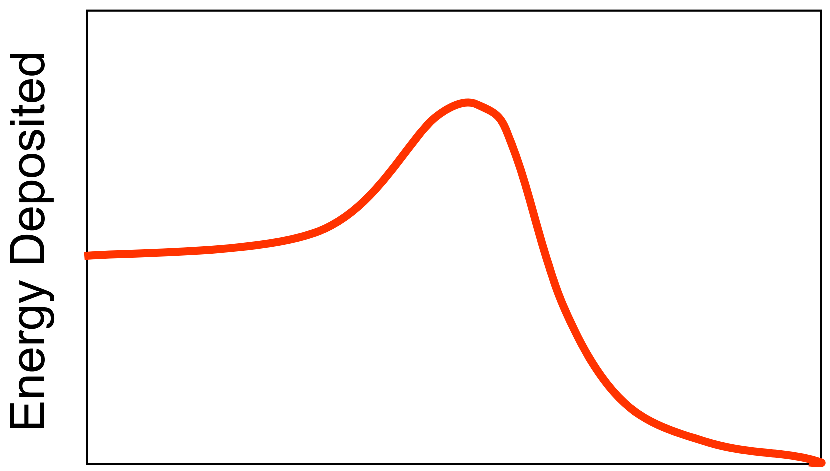
The Deep Charging Problem



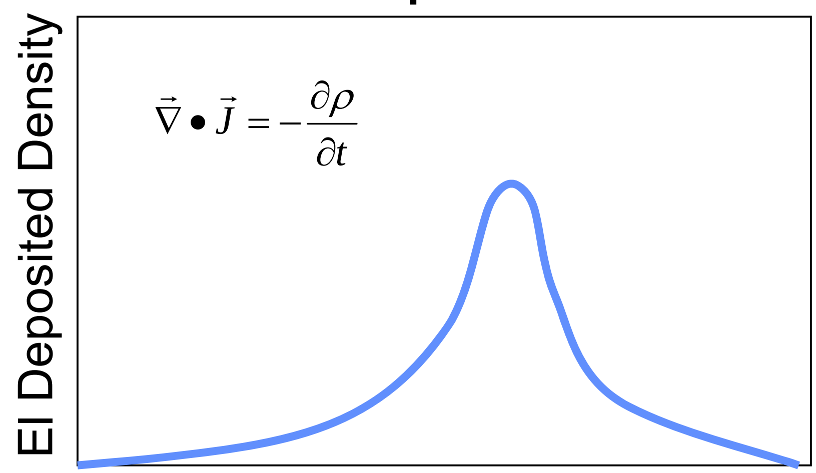
High Energy Electrons are deposited in Insulator

Generalization of Physics

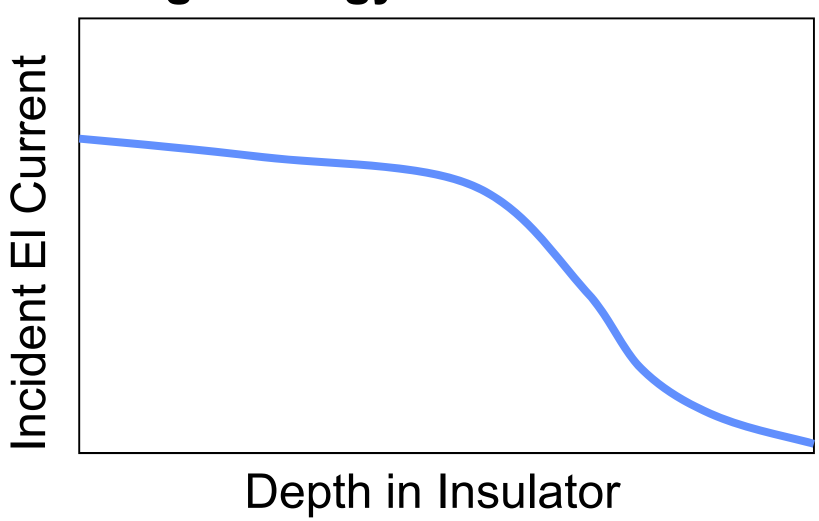
Profile of Deposited Energy



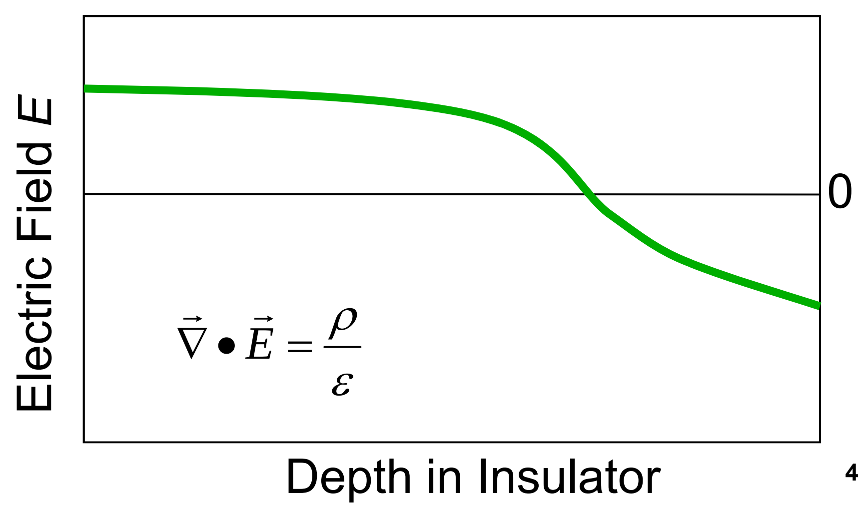
Location of Deposited Electrons



High Energy Electron Current



Resulting Electric Field



Solving Deep Dielectric Charging

- **Is Energy, Flux, or Time best indicator?**
- **Electric Field in Dielectric indicates ESD**
  - **Frederickson compared CRRES data with experiment**
  - **SEE Charging Handbook:**
    - **Pulsing occurs:** **> 10^7 V/m**
    - **Some Pulsing:** **~ 10^6 – 10^7 V/m**
    - **No Pulsing:** **< 10^6 V/m**
- **So E field is Figure of Merit!**
- ***But how do you determine E Field??***

Enter NUMIT

- Developed by Robb Frederickson > 30 yrs ago for use in lab
- NUMIT = NUMerical ITeration
- Electrodynamics used to track charge movement
- FORTRAN program allows input of different parameters:
  - Electron beam energies and current densities
  - Dielectric mass density, strength, and thickness
  - Other initial conditions such as bias voltages
- NUMIT is iterative: charge distribution changes in time and output reflects change
- NUMIT requires two *subroutines* that determine:
  - Energy dose as a function of depth
  - High-energy incident electron current as function of Depth
- Applied successfully in a dozen papers

NUMIT Details

- Dielectric is divided into ~ 100 spatial bins
- As high-energy electron current decreases with depth charge is deposited in bins
- Subroutines required for $J_0(x)$ and $\dot{D}(x)$

Continuity Eq. $$\frac{\partial J(x,t)}{\partial x} = -\frac{\partial \rho(x,t)}{\partial t}$$

Gauss's Law $$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\epsilon}$$

Total Current Eq. $$J(x,t) = J_0(x) + \left[g_0 + k\dot{D}(x)\right] E(x,t),$$

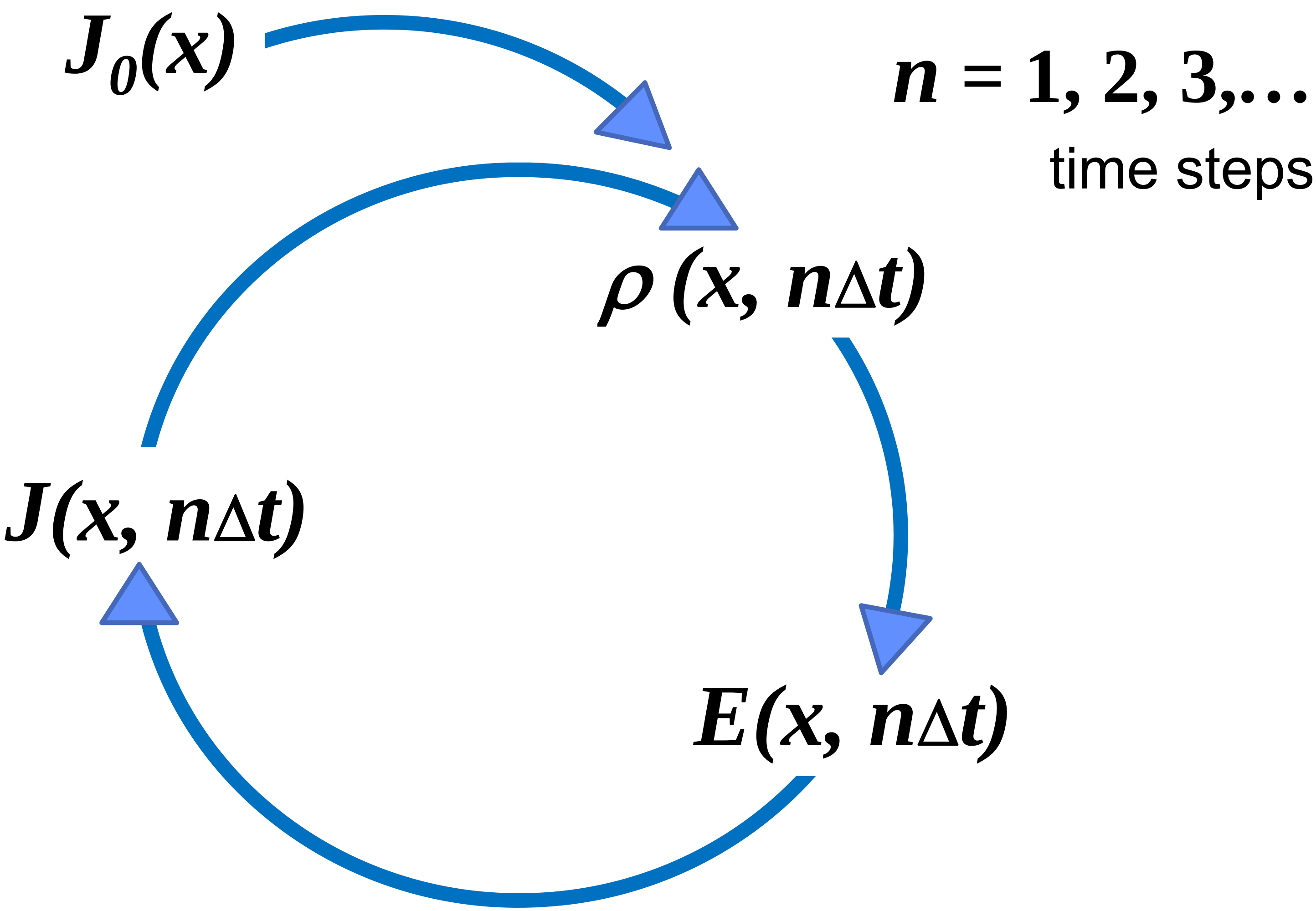
High-energy Electron Current ($J_0(x)$)

Dark Conductivity (g_0)

Coef. of RIC (k)

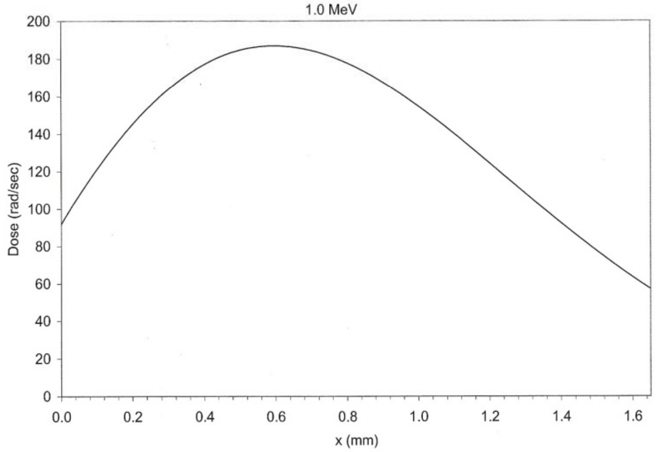
Dose Rate ($\dot{D}(x)$)

NUMIT Algorithm Schematic

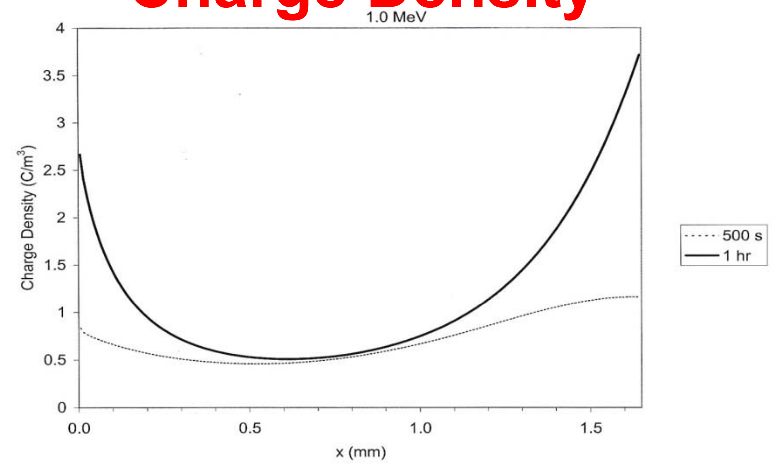


Ex: FR4 Circuit Board

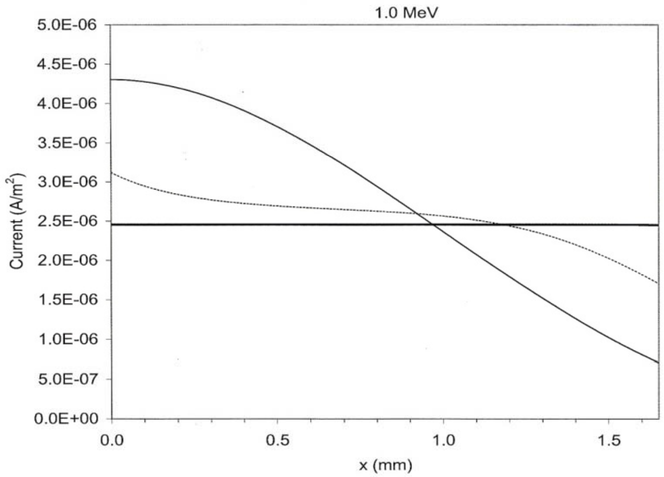
Dose



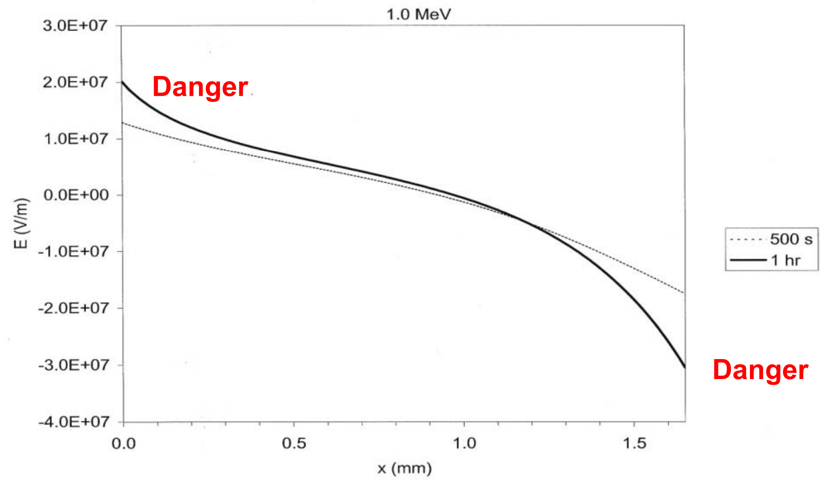
Charge Density



Current



Electric Field



First Subroutine Required

Determination of Dose Rate: *EDEPOS*

- EDEPOS = Energy DEPOSited
- Algorithm (45 lines) compiled by Tabata & Ito, 1974
- Fit to > 20 data sets and > 6 Monte Carlo studies
- Improved fit over earlier one by Kobetich and Katz
- Normally incident mono-energetic electrons 0.1—20 MeV
- Inputs required:
  - Atomic number (or effective Z)
  - Atomic weight
  - Energy of incident electrons
- Output: dose profile $\dot{D}(x)$

2nd Subroutine Required

Determination of High-energy incident electron current

- **Frederickson, Bell, and Beidl, 1995**
- **Took EDEPOS and modified it**
- **Used functions that "crudely" simulate physical process**
- **Result is algorithm that fits data using functions for 5 different fitting parameters and 1 tabulated parameter**
- **Robb had me program his new algorithm in FORTRAN and incorporate it into NUMIT**
- **Output is High-energy electron current $J_0(x)$**

BETHEL UNIVERSITY PHYSICS

NUMIT Limitations

NUMIT was Designed as a Lab Tool

- Dielectric is a large, flat slab
- Incident Electron flux is constant
- Incident Electrons are mono-energetic
- Incident Electrons are perpendicular to surface

For Space Environment Modeling

- Dielectric could be a large, flat slab
- Incident Electron flux must be changing
- Incident Electrons are multi-energetic
- Incident Electrons are isotropic

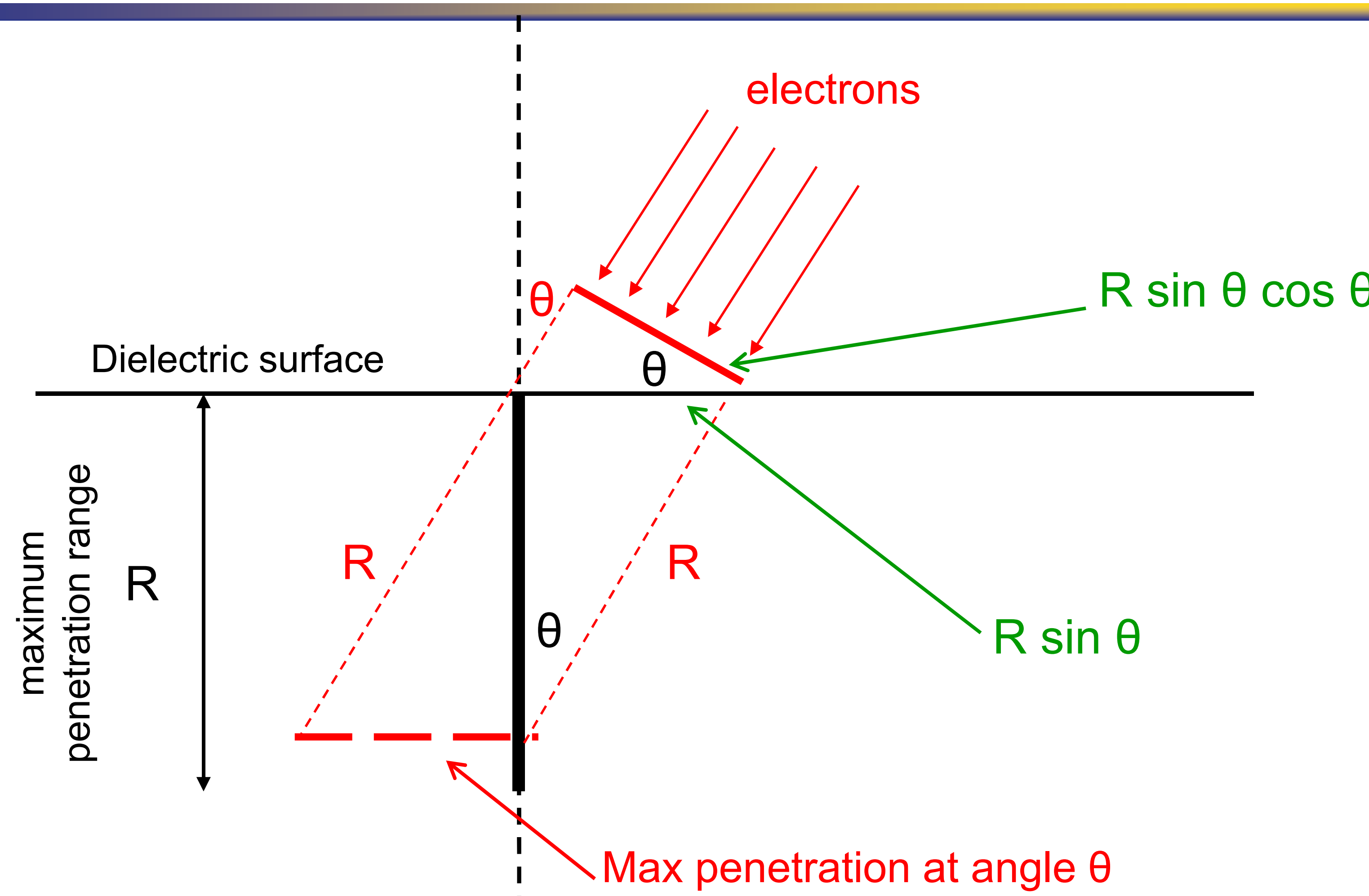
NUMIT must change ⟶ *Subroutines*

NUMIT2

GOAL: utilize analytical approach to model isotropic electron incidence

- **If dielectric modeled is a large, flat slab:**
  - **NUMIT's charge transport modeling can continue in 1D**
  - ***But*, incident electrons *must* be modeled in 3D**
- **Assume dielectric is isotropically homogeneous**
  - **EDEPOS algorithm applies at any angle**
  - **High-energy electron current algorithm $J_0(x)$ also applies**
- **Determine appropriate electron flux as function of angle**

Modeling Isotropic Incidence



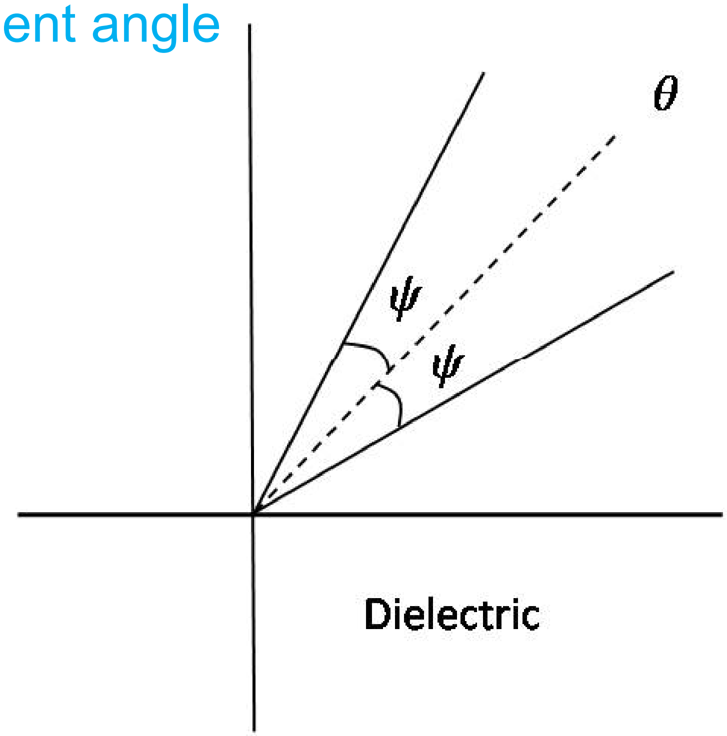
$$I_{\mathrm{tot}} = \int_0^{2\pi} \int_0^{\pi/2} I_o \sin\theta \cos\theta \, R^2 \sin\theta \, d\theta \, d\phi \; = \frac{2}{3}\pi R^2 I_o$$

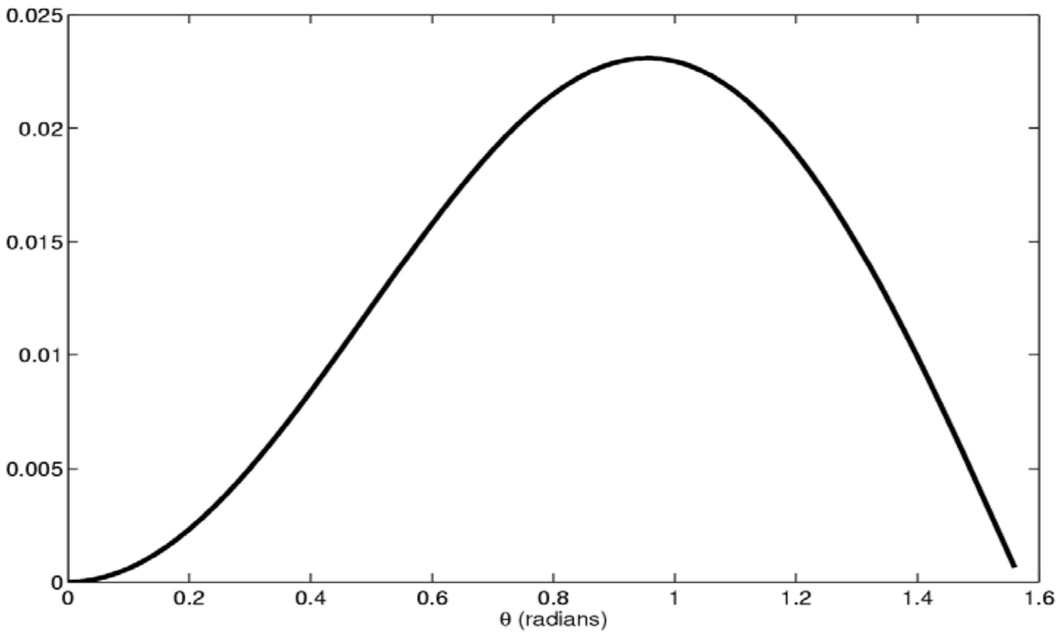
Angular Bins

- Flux and penetration depth depend on incident angle
- Must have "angular bins" for model

$$I_{\text{bin}} = \int_0^{2\pi} \int_{\theta-\psi}^{\theta+\psi} I_o \sin\theta \cos\theta \, R^2 \sin\theta \, d\theta \, d\phi$$

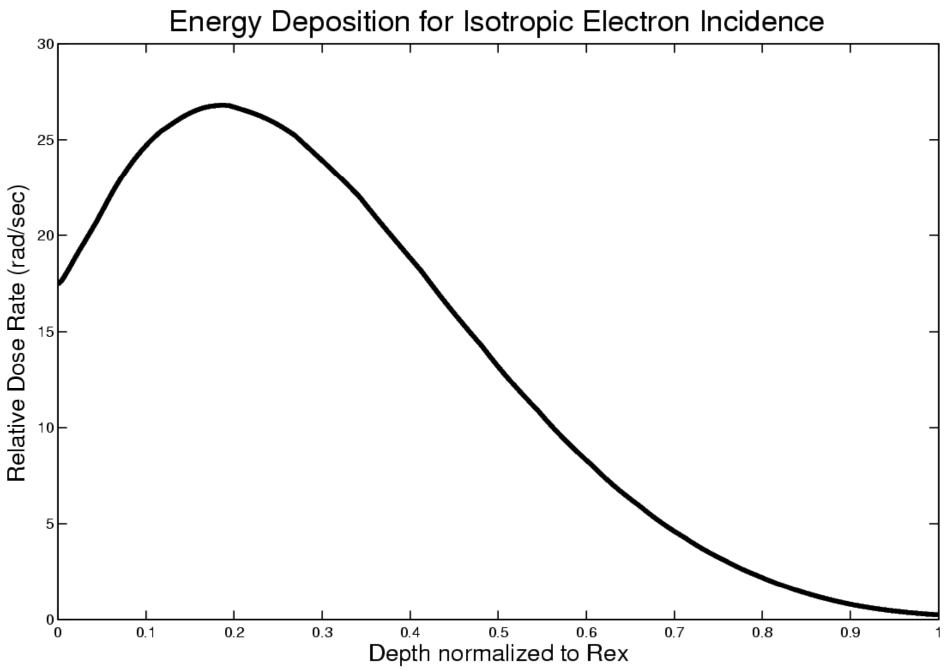
$$= \frac{2}{3}\pi R^2 I_o \left[\sin^3(\theta+\psi) - \sin^3(\theta-\psi)\right]$$





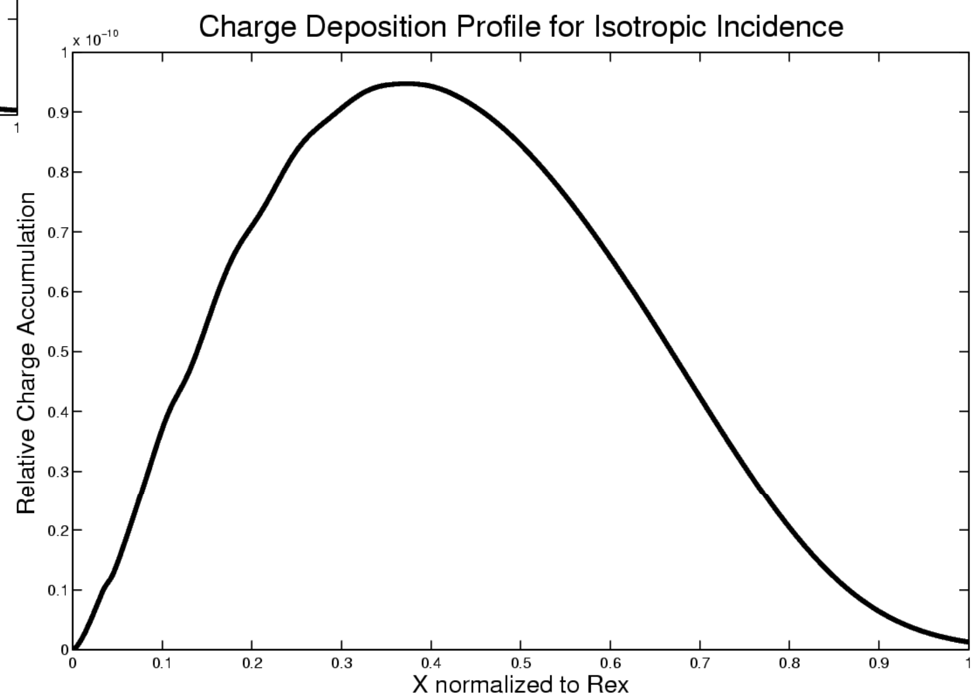
If electrons were incident on a flat disc, this graph would be symmetric

Isotropic Incidence Results



Energy deposition peak broadens slightly and moves towards surface

Electron deposition peak broadens significantly and moves towards surface



Model is for 0.5 MeV electrons incident on carbon

Applying NUMIT2 to S/C Charging

- **NUMIT was intended to guide thinking about experiments and data → modifications necessary**
- **Subroutines must be changed:**

  Normal Incidence → Isotropic electrons

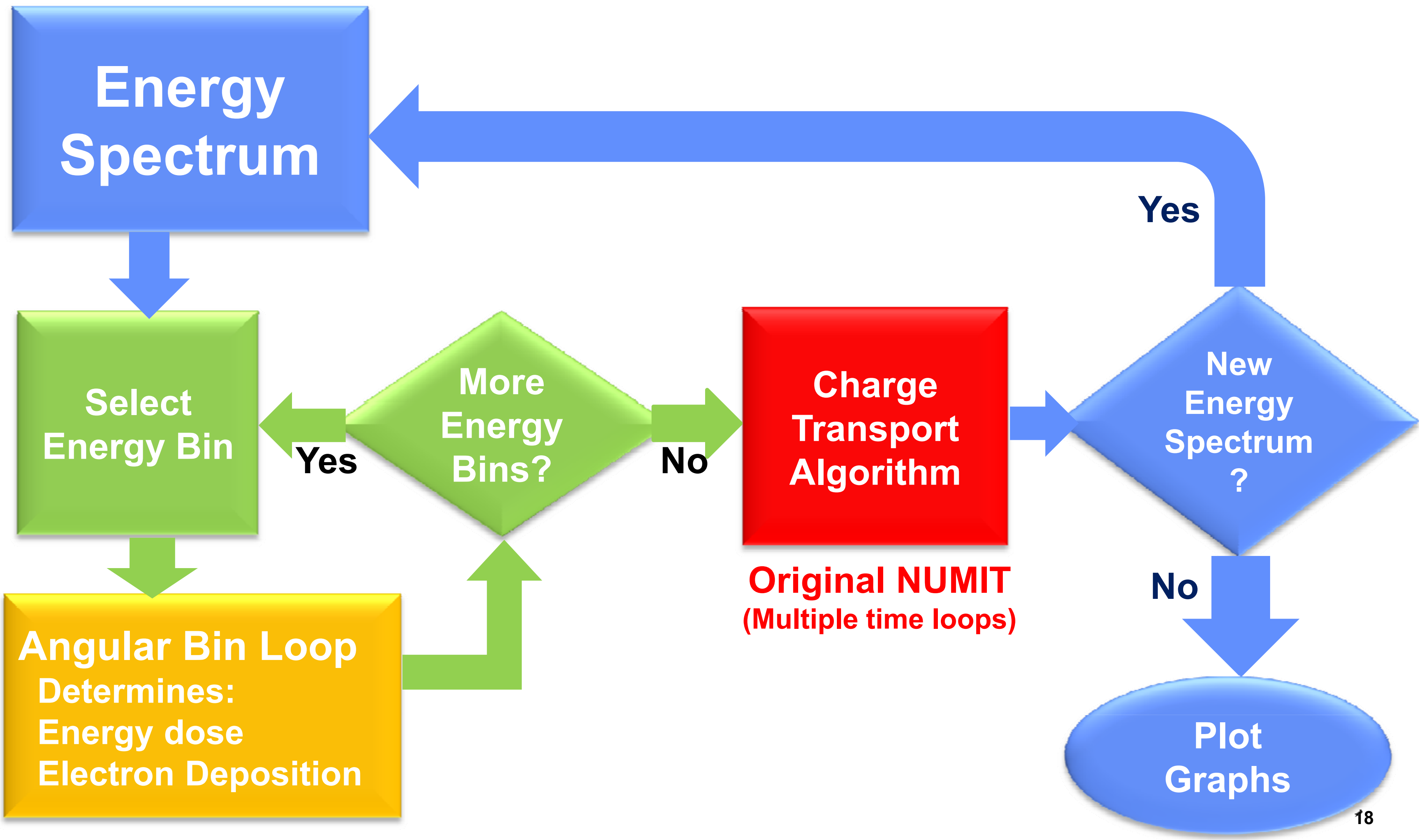
- **Other enhancements allow application to Spacecraft:**

  Mono-energetic → Energy spectrum

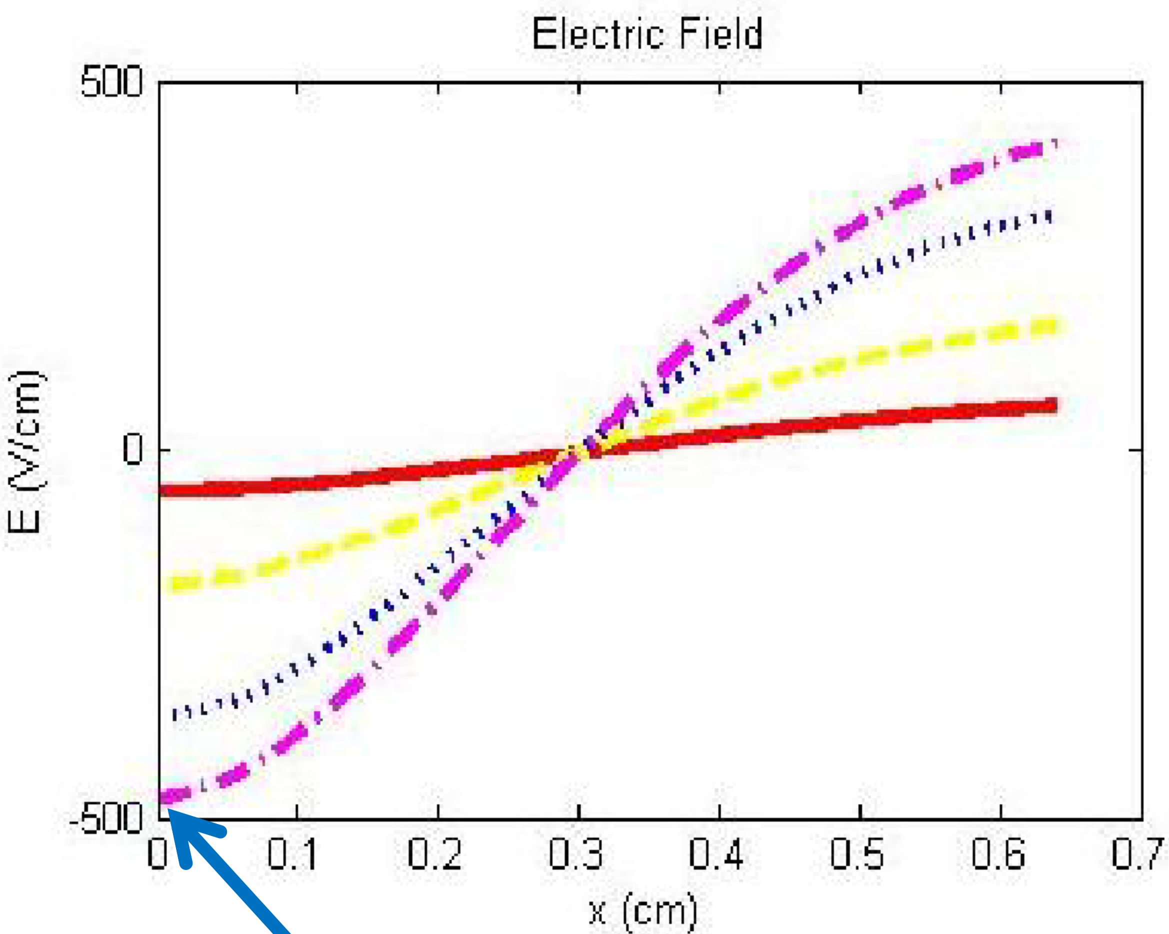
  Constant energy → Time-dependent spectrum

- **These changes have been made: NUMIT → NUMIT2**

NUMIT2


Energy Spectrum
Select Energy Bin
Yes
More Energy Bins?
No
Charge Transport Algorithm
Original NUMIT
(Multiple time loops)
New Energy Spectrum ?
Yes
No
Angular Bin Loop
Determines:
Energy dose
Electron Deposition
Plot Graphs

NUMIT2 Simulation Results



Non-conductive Al

CRRES Environment

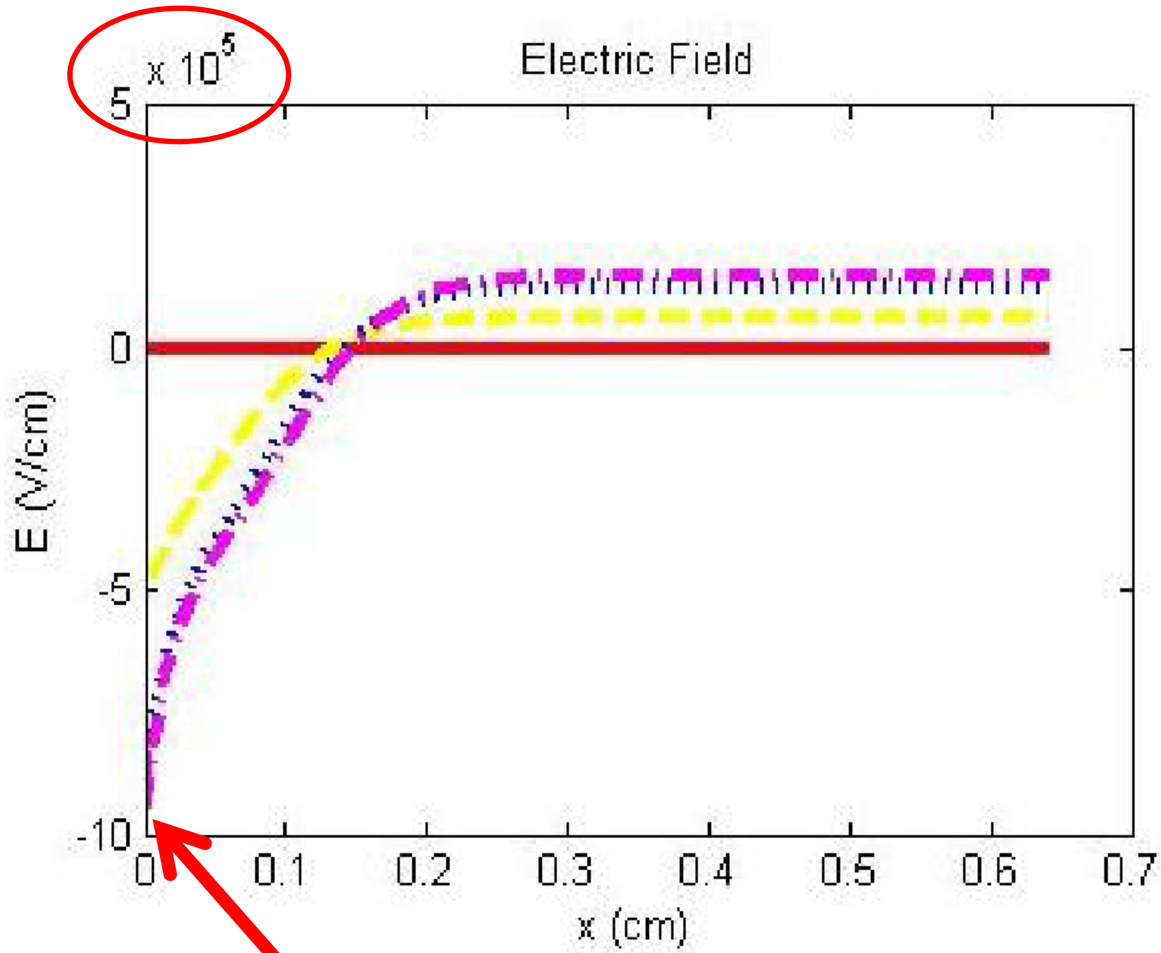
3 Energy Spectrums

4—6 MeV

Plotted
8,000 sec
9,500 sec
10,500 sec
12,000 sec

$5 \times 10^4\ \mathrm{V/m}$ **Far short of Pulsing Threshold**

NUMIT2 Simulation Results



$10 \times 10^7\ \mathrm{V/m}$ **Exceeds Pulsing Threshold!**

Non-conductive Al

CRRES Environment

2 Energy Spectrums

4—6 MeV

3rd Energy Spectrum

1.0—1.8 MeV

<u>Plotted</u>
8,000 sec
9,500 sec
10,500 sec
12,000 sec

Summary

- **NUMIT2 Changes**
  - Isotropic Electron Flux
  - Multi-energetic electrons
  - Flux changes with time
- **NUMIT2 Results**
  - Reasonable
  - Surprising
  - High Energy then Low Energy generates large enough electric fields to cause pulsing!
- **Work to be Done**
  - Electron backscatter
  - Low energy (< 100 keV) incident electrons
  - Time-delayed RIC
  - Run simulations with realistic environments