A 3-D Model of Circuit Board Internal Electrostatic Charging

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Jet Propulsion Laboratory
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Pasadena, California

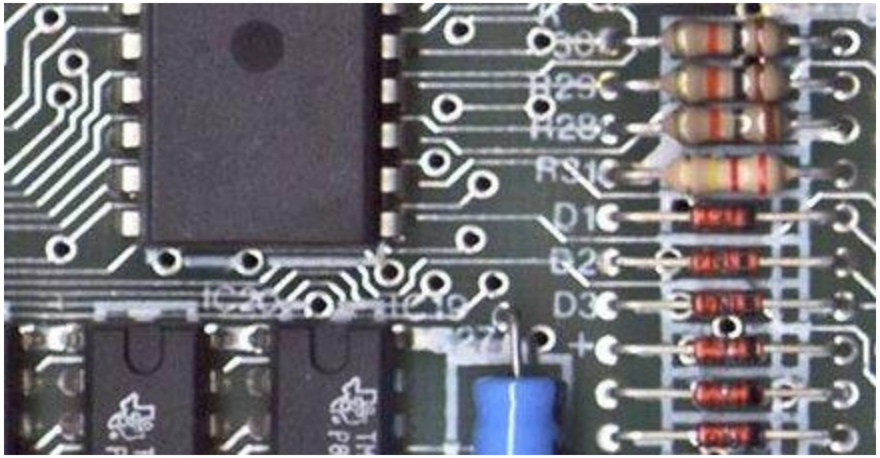
A 3-D Model of Circuit Board Internal Electrostatic Charging

- Purpose:

  Calculate potentials, energy storage, and discharge characteristics due to ungrounded metal traces on circuit boards exposed to the Jupiter Europa Orbiter (JEO) concept radiation environment for future use in deriving IESD design guidelines

- Approach:

  Calculate potentials and charge distribution due to penetrating electrons including conduction and plasma arc currents.



Top view of a typical circuit board showing dielectric board material (green), metal traces (silver), and assorted circuit components

Jupiter Europa Orbiter (JEO) Concept

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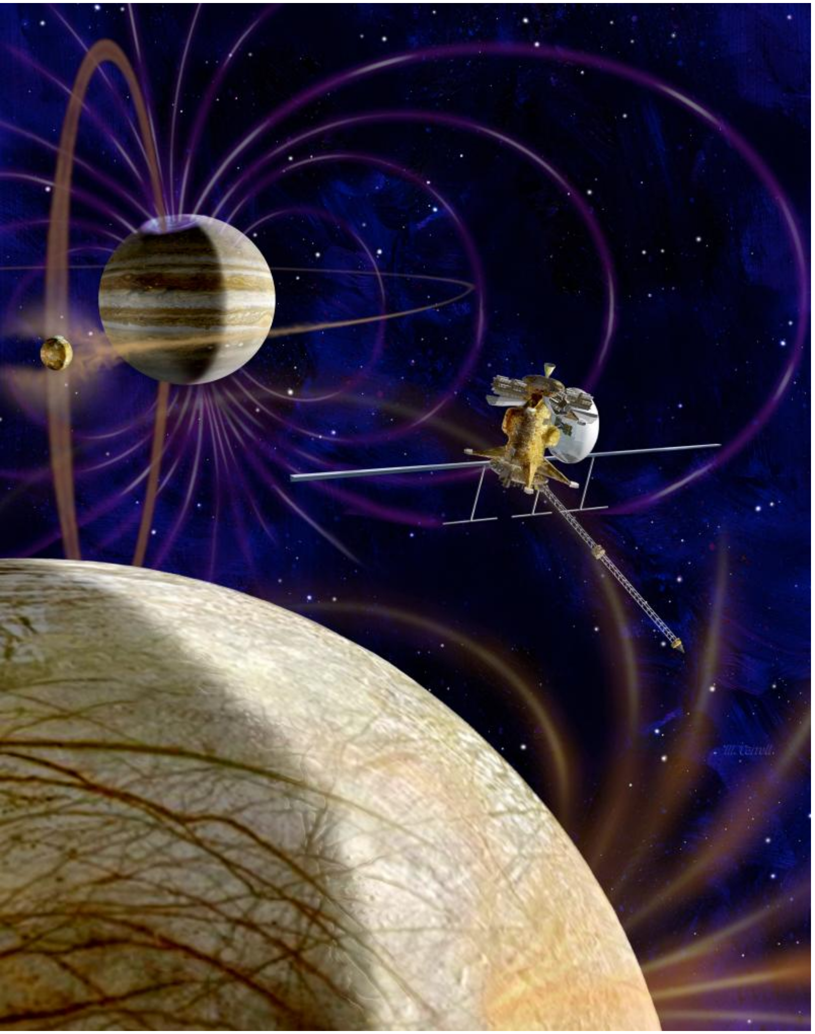

- **JEO is the NASA element of the Europa Jupiter System Mission**

  It is designed to follow-up on the major discoveries of the Galileo and Voyager missions at Europa, especially its ocean. JEO would be built to withstand the intense radiation in Europa orbit, and would consist of an orbiter with 11 science instruments designed for extensive mapping of Europa. On the way to Europa, JEO would tour the Jovian system and make routine and frequent observations of Jupiter, its satellites and its environment.

- **Science Overview**

  Within the context of the EJSM themes and objectives, JEO would focus on its sub-goal: Explore Europa to investigate its habitability. While the primary focus of JEO is to orbit Europa, the science return encompasses the entire Jovian system, especially as is relevant to Europa's potential habitability. JEO uniquely includes flybys of Io and Europa, and includes flybys of Ganymede and Callisto, along with ~ 2.5 years observing Jupiter's atmosphere, magnetosphere, and rings.

- **Mission Overview**

  JEO would launch in February 2020 on an Atlas V 551 and, using a ballistic trajectory with Venus-Earth-Earth gravity assists (VEEGA), arriving at Jupiter in December 2025. Jupiter Orbit Insertion (JOI) begins a 30 month Jovian system tour followed by a 9 month science mapping phase after Europa Orbit Insertion (EOI) in July 2028. The orbiter would ultimately impact the surface of Europa after succumbing to radiation damage or running out of orbit maintenance fuel.

from the JPL Outer Planet Flagship Mission website: opfm.jpl.nasa.gov

Galileo Project Generated Data on Circuit Board IESD

- Paper published 27 years ago
  - Philip L. Leung, Gregory H. Plamp, and Paul A. Robinson, Jr., "Galileo Internal Electrostatic Discharge. Program", Space Environmental Interactions Technology 1983, NASA Conference Publication 2359, AFGL-TR-0018, pp 423-425
- Data
  - Charged circuit boards using high energy electrons generated in JPL's Dynamitron facility
  - Circuit boards had grounded and ungrounded metalized traces
  - Measured characteristics of pulses carried by grounded leads
- Concerns
  - Mono energetic, high current environment
  - Currents measured in leads, not on the boards
- Plan to extrapolate results to JEO
  - Environment including shielding
  - Circuit board geometry
  - Proximity to ground plane

Code Test Cases Based on Galileo ESD Paper

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- Experimental Setup

Stainless steel (diffuser)	75 micron
Aluminum plate (plasma current collector)	50 micron
Cu 2 oz/ft^2	68 micron
FR4 board thickness	1.6 mm

- Electron Beam

Energy	0.85 – 1.75 MeV
Current Density	4 – 26 pA/cm^2

- Results (measured across 50 Ω resistor to ground)

Small amplitude transients early	(<1 V, < 20ns)
After 2-4 hrs larger transients	(>5 V)

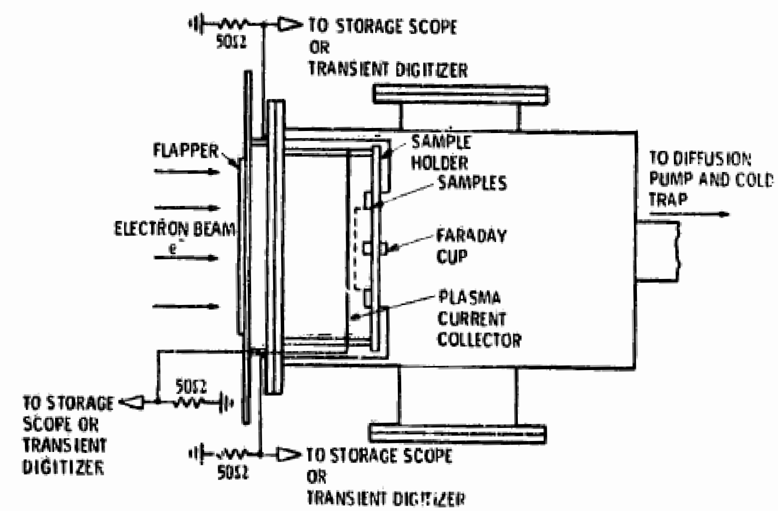

Figure 1. - Target chamber and fixtures.

GALILEO INTERNAL ELECTROSTATIC DISCHARGE PROGRAM*

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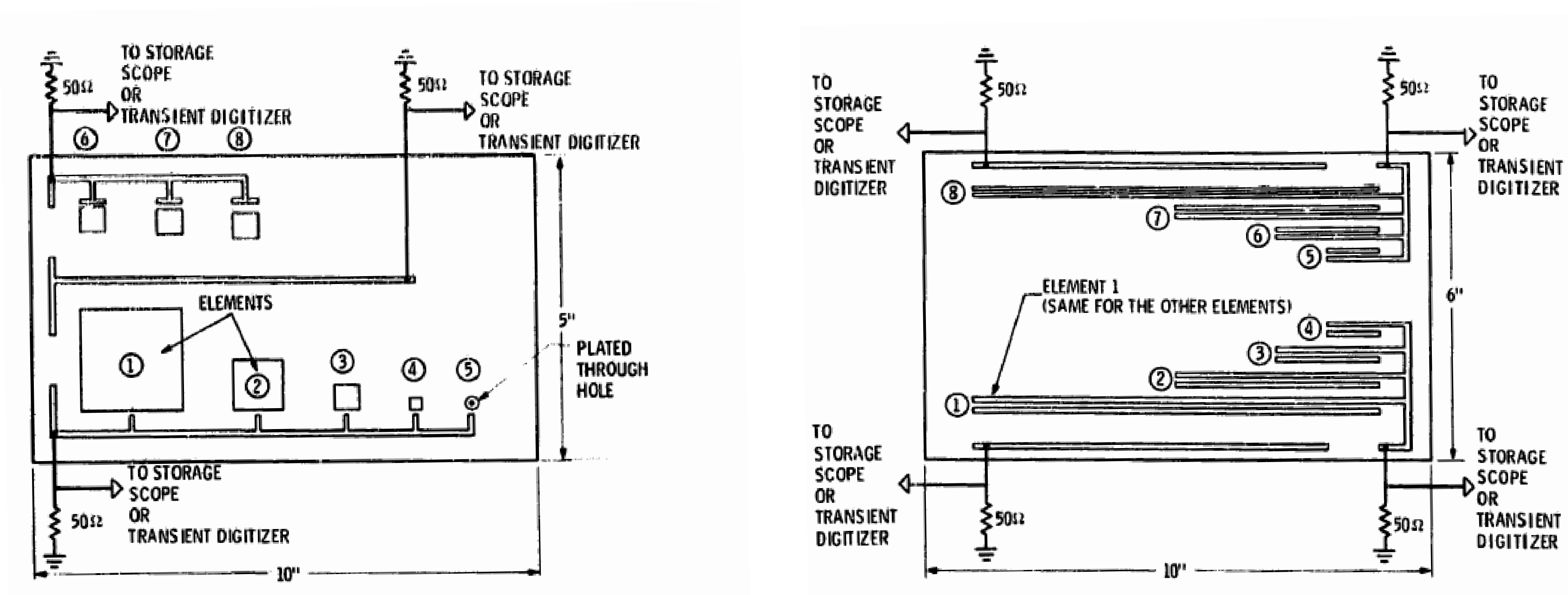
Circuit Board Layouts in the Galileo Tests



(a) Board A.

(b) Board B.

What Happens During a Discharge

- Discharge creates a local plasma
- Only a small amount of charge is affected if plasma is contained inside the dielectric (Grounded Surface)
- Charge from large areas can contribute if plasma cloud can propagate in space (Floating dielectric surface)
- In either case, current appears on nearby conductors due to the redistribution of image charges

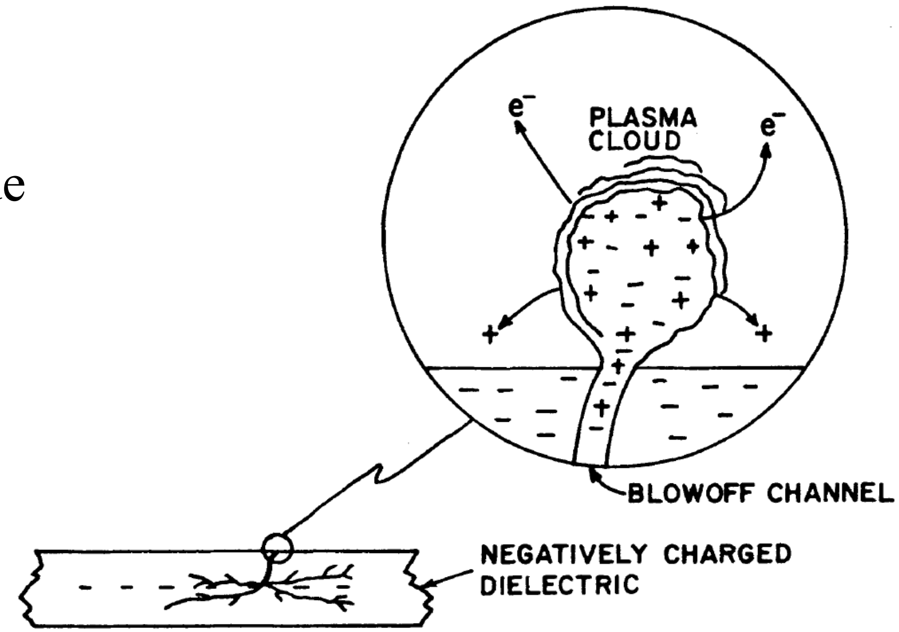


Fig. 5: Plasma cloud in the vacuum associated with discharge pulse and its tree.

A. R. Frederickson, “Electric Discharge Pulses In Irradiated Solid Dielectrics In Space”, IEEE Transactions on Electrical Insulation Vol. EI-18 No.35 June 1983, 337

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Smaller Pulses: Electron Flow to Ground

- Beam electrons charge "element" negative
- Arc makes low impedance path between "element" and nearby trace
- Small pulse involves electrons flowing from the "element" to the nearby trace
- Negative voltage indicates electrons flowing through the resistor to ground

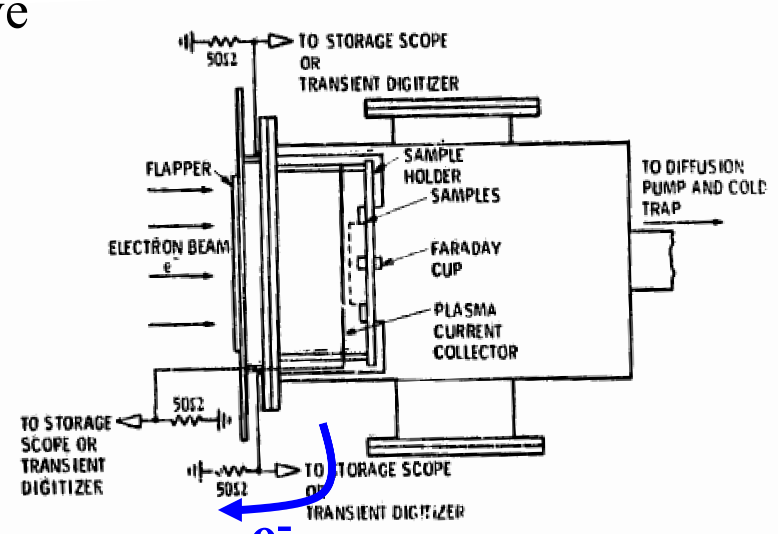


Figure 1. – Target chamber and fixtures.

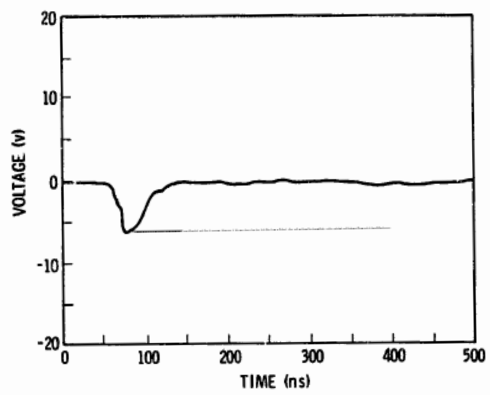
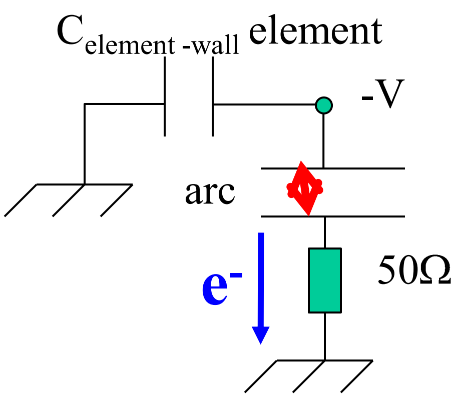


Figure 3. – An intermediate discharge pulse observed during electron beam irradiation of circuit boards with floating circuit trace. Detector is a nearby grounded trace.



Larger Pulses: Electrons Flow to Plasma Current Collector

- Plasma Cloud Discharges negative dielectric
- Electrons trapped in dielectric flow to ground through Plasma Current Collector Resistor resistors (negative voltage)

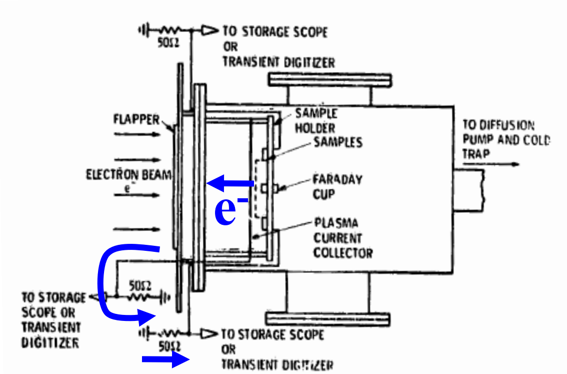
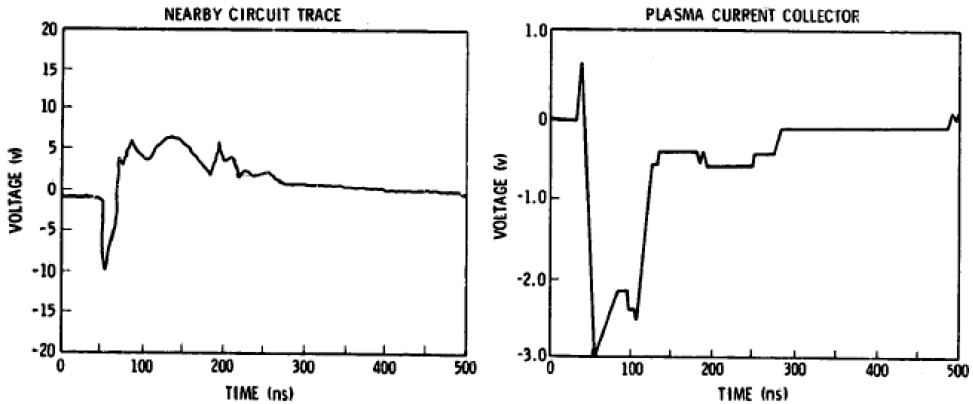
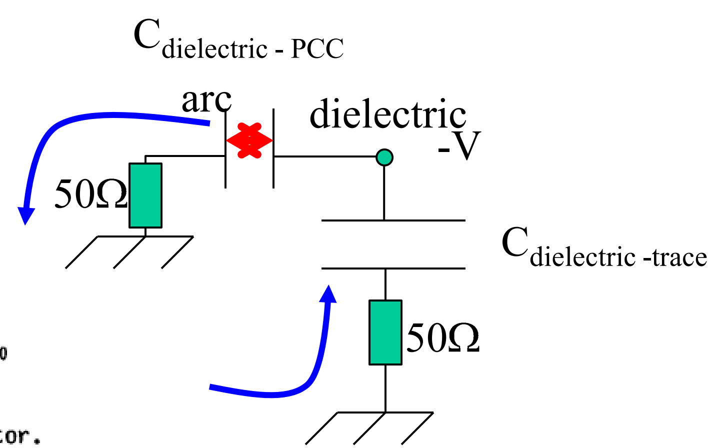


Figure 1. – Target chamber and fixtures.



(a) Detector, nearby grounded trace. (b) Detector, plasma current detector.

Figure 4. – Large discharge pulse observed during electron beam irradiation of circuit board with floating traces.



Previous 1-D IESD Codes

- NUMIT (NUMerical InTegration) code
  - Developed by A. R. Frederickson
  - Developed by AFRL & later maintained by NASA
  - Documented in Insoo Jun, Henry B. Garrett, Wousik Kim, Joseph I. Minow, "Review of an Internal Charging Code, NUMIT", IEEE Transactions On Plasma Science, Vol. 36, No. 5, October 2008, p. 2467-2472
  - 1-D charging calculations also in 1-D slab geometry
  - Allows only a single shield material, aluminum, and a single dielectric layer.
  - Uses analytical fits to published Monte Carlo electron deposition profiles to model the energetic particle transport. T
    - limits accuracy, especially for the substantial shielding required in harsh radiation environments such as Jupiter, and in multilayer components, such as circuit boards, where charge buildup frequently occurs at material interfaces.
  - SAIC group developed a Java version of NUMIT that also handles 1-D cylindrical geometry.
    - Code is part of NASA's Space Environment Effects Interactive Charging Handbook, and is limited to Earth orbiting spacecraft.
    - The cylindrical capability enables the modeling of coaxial cables, but only for the special case of omni-directional, isotropic radiation, and not for the mono-energetic, single direction beams used in laboratory testing.
    - JPL has a version of the SAIC code that allows user defined spectra, such as Jupiter radiation belt models, but only in the steady state limit.
- DICTAT (DERA Internal Charging Threat Assessment Tool)
  - D.J. Rodgers, K.A. Ryden, G.L. Wrenn, P.M. Latham, J. Sørensen, L. Levy,"An Engineering Tool for the Prediction of Internal Dielectric Charging", 6th Spacecraft Charging Technology Conference,, September 2000, pp. 125-130
  - Developed for ESTEC by DERA and ONERA/DESP
  - 1-D slab and cylindrical geometries
  - Very similar to NUMIT, but for electron transport. DICTAT adds a finite width to a simple, algebraic, electron range formula and ignores angular scattering, backscatter, secondary electrons, photon electrons
  - Incorporated into European Space Agency (ESA) Space Environment Information System (SPENVIS)

CB_IESD Code Designed to Extrapolate Lab Data to Jupiter Radiation Environment

- Geometry
  - 3-D Cartesian
  - Test chamber
  - Single circuit board
  - Traces
    - two or more
    - grounded and floating
- Charge deposition from 1-D Monte Carlo electron transport calculations using TIGER
- Calculations of time dependent potentials from Poisson's equation (spacecharge) and Ohm's law (conduction)
- Boundary Conditions on traces
  - Fixed potential (e. g. grounded)
  - Floating Potential - Total charge
  - Traces assumed to be thin compared with circuit board
- Output
  - Electric potentials, fields, and charges on traces

Circuit Board IESD Equations

- Basic equations: charge continuity, Ohm's law and Poisson's equation

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \mathbf{j} = \dot{\rho}$$ Charge continuity

$$\mathbf{j} = \sigma \mathbf{E} = -\sigma \nabla \phi \qquad \sigma = \sigma_0 + k_p D^{\Delta}$$ Ohm's Law with Dose Enhanced Conductivity

$$\nabla \bullet \varepsilon \nabla \phi = -\rho \qquad \varepsilon \Rightarrow \kappa \varepsilon_0$$ Poisson's equation

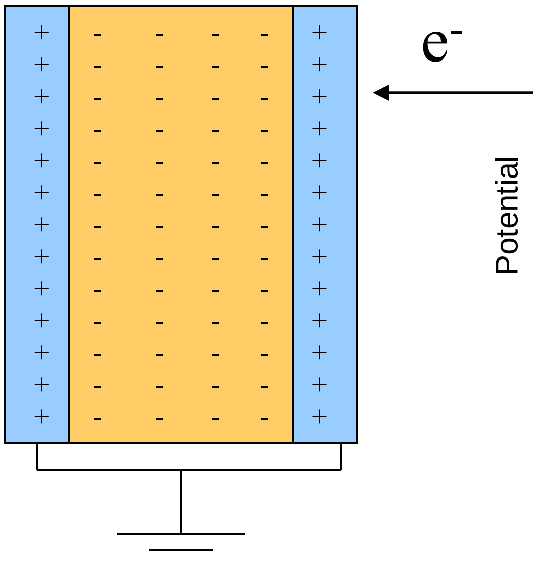
- Can be combined into a single equation
  - Useful in 1-D codes
  - Less practical for 3-D code because the boundary conditions become too complex
  - Used to compare timescales

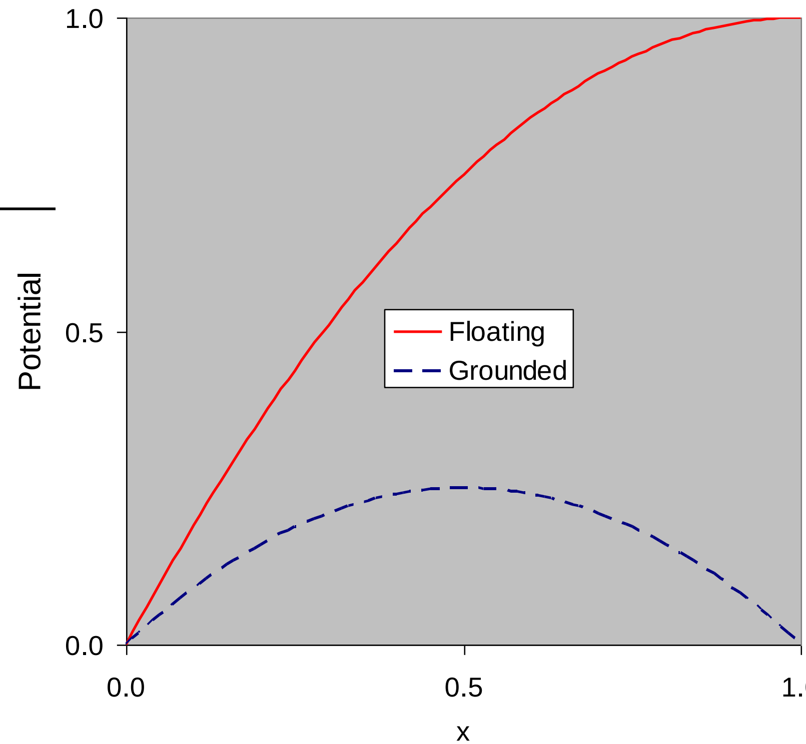
$$\boxed{\frac{\partial}{\partial t} \nabla \bullet (\varepsilon \nabla \phi) + \nabla \bullet (\sigma \nabla \phi) = -\dot{\rho}}$$

1-D Physical Picture

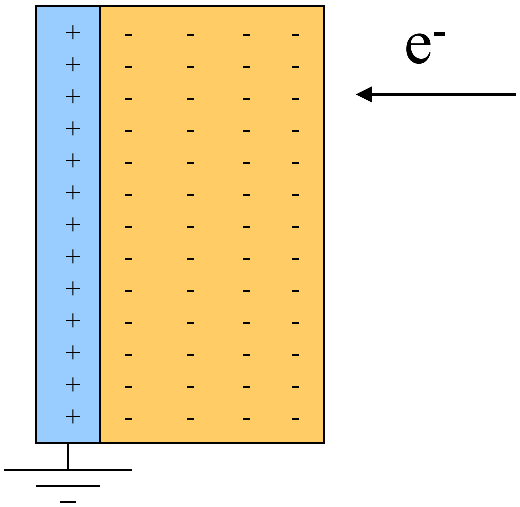
- Environment deposits charge and enhances conductivity
  - Electrons from the environment are deposited in the dielectric
  - Electrons from the material are promoted into the conduction band
- Grounded conducting external layer reduces charging
  - Electric field reduced by a factor of 2
  - Peak potential reduced by a factor of 4

Both Surfaces Grounded





Floating Surface



1-D Analytical Solution for Uniform Charging

- Charge deposition and conductivity independent of position or time

$$\kappa\varepsilon_0 \frac{\partial^2}{\partial x^2}\frac{\partial \phi}{\partial t} + \sigma \frac{\partial^2 \phi}{\partial x^2} = -\dot{q}$$

Grounded Surfaces

$$\phi(x,t) = \frac{\dot{q}\ell^2}{2\sigma}\frac{x}{\ell}\left(1-\frac{x}{\ell}\right)\left(1-e^{-\frac{\sigma t}{\kappa\varepsilon_0}}\right)$$

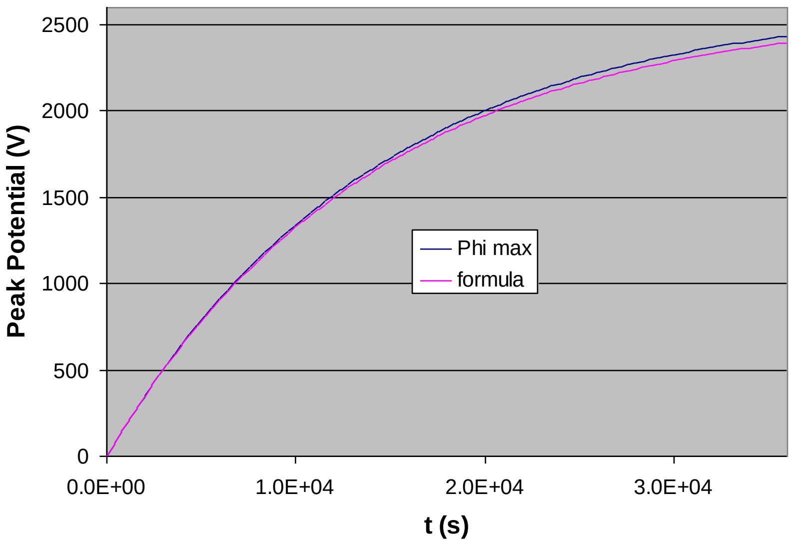
$$\phi_{\max} = \frac{\dot{q}\ell^2}{8\sigma}$$

$$\dot{\phi}_{\max} = \frac{\dot{q}\ell^2}{8\kappa\varepsilon_0}$$

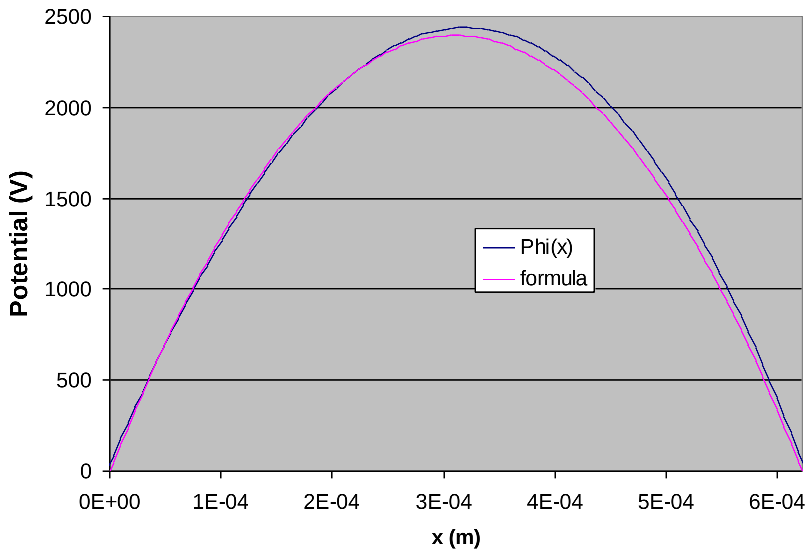
$$\tau_0 = \frac{\kappa\varepsilon_0}{\sigma}$$

$$E_{\max} = 4\frac{\phi_{\max}}{\ell}$$

Analytical formula quite accurate for hard spectra
Coaxial results close to those for slab geometry

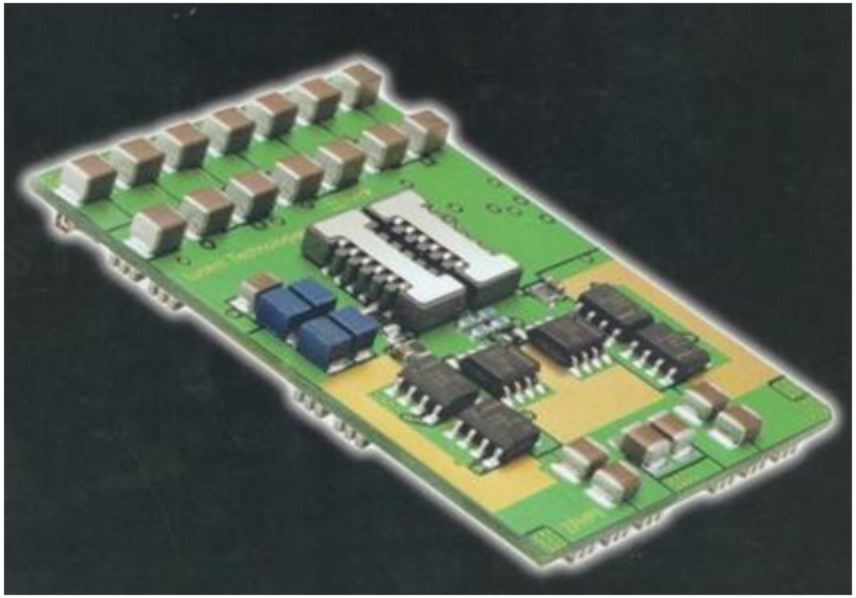


Formula for uniform deposition in cable inner dielectric compared with potential calculations using spatially dependent deposition and dose



Physical Geometry

- Calculation of a thin circuit board with one or more grounded metal traces and a single ungrounded area of metallization. The circuit board is suspended inside a grounded metal chamber.



Finite Difference Scheme For Spatial Potentials

- Basic equation in 1-D $\kappa\varepsilon_0 \Rightarrow \varepsilon$

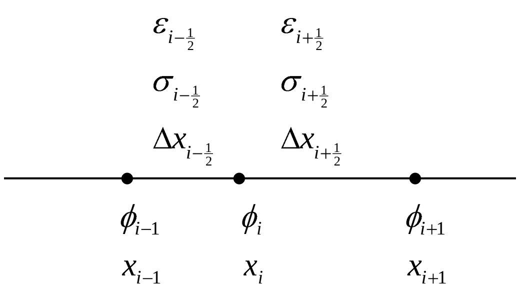
$$\frac{\partial}{\partial x}\varepsilon\frac{\partial\phi}{\partial x} = -\rho$$

- Finite difference formulation

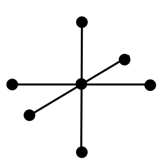
$$\Delta x_{i+\frac{1}{2}} \equiv x_{i+1} - x_i$$

$$\Delta x_i \equiv \tfrac{1}{2}(x_{i+1} - x_{i-1})$$

$$\frac{1}{\Delta x_i}\left(\varepsilon_{i+\frac{1}{2}}\frac{\phi_{i+1}-\phi_i}{\Delta x_{i+\frac{1}{2}}} - \varepsilon_{i-\frac{1}{2}}\frac{\phi_i-\phi_{i-1}}{\Delta x_{i-\frac{1}{2}}}\right) = -\rho_i$$



- Standard 7 point difference operator in 3-D



Time Dependent Solution

- Time derivative of the potentials
- Assume exponential time dependence

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\sigma E) = \dot{\rho}$$

$$\phi(t) \approx (1 - e^{-t/\tau})\phi_0$$

$$\frac{\partial}{\partial t}\nabla \bullet (\varepsilon \nabla \phi) + \nabla \bullet (\sigma \nabla \phi) = 0$$

$$\tau \approx \frac{\varepsilon}{\sigma} \approx \frac{10^{-11}}{10^{-16}} \approx 10^5\, s$$

- Since the conduction timescale is so long, conduction is treated explicitly

$$\frac{V_i}{\Delta t}\left(\rho_i^{t+1} - \rho_i^t\right) = V_i\,\dot{\rho}_i^{t+1} + A_x\left(\sigma_{i+\frac{1}{2}}\frac{\phi_{i+1}^t - \phi_i^t}{\Delta x_{i+\frac{1}{2}}} + \sigma_{i-\frac{1}{2}}\frac{\phi_{i-1}^t - \phi_i^t}{\Delta x_{i-\frac{1}{2}}}\right)$$

$$V_i = \Delta x \Delta y \Delta z$$

$$A_x = \Delta y \Delta z$$

$$\Delta x = \Delta x_{i+\frac{1}{2}} = \Delta x_{i-\frac{1}{2}}$$

$$\rho_i^{t+1} = \rho_i^t + \Delta t \dot{\rho}_i^{t+1} + \frac{\Delta t}{\Delta x^2}\left(\sigma_{i+\frac{1}{2}}(\phi_{i+1}^t - \phi_i^t) + \sigma_{i-\frac{1}{2}}(\phi_{i-1}^t - \phi_{i+1}^t)\right)$$

Finding Floating Potential in Time

- Numerically calculate derivatives of charge and current with respect to floating potential

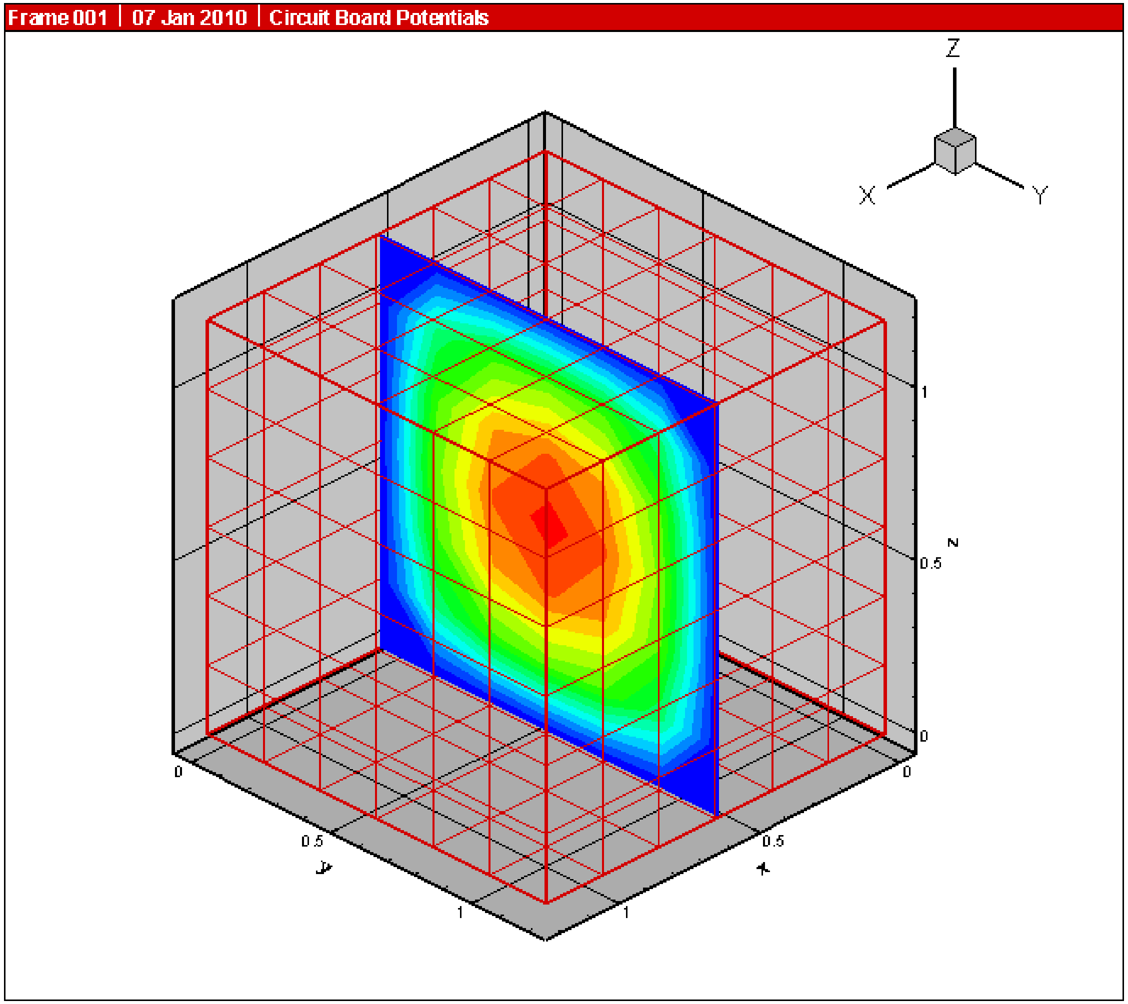
$$V^t = V_0 + \Delta V$$
$$Q^t = Q^{t-1} + \Delta t\ (I^t + \dot{Q})$$
$$\frac{dI}{dV} \approx \frac{I_1 - I_0}{V_1 - V_0}$$
$$\frac{dQ}{dV} \approx \frac{Q_1 - Q_0}{V_1 - V_0}$$
$$I^t = I_0 + \Delta V \frac{dI}{dV}$$
$$Q^t \approx Q_0 + \Delta V \frac{dQ}{dV} = Q^{t-1} + \Delta t\ (I_0 + \Delta V \frac{dI}{dV} + \dot{Q})$$
$$\Delta V \left(\frac{dQ}{dV} - \Delta t \frac{dI}{dV} \right) = Q^{t-1} - Q_0 + \Delta t (I_0 + \dot{Q})$$

- Floating Potential solved for implicitly

$$\Delta V = \frac{Q^{t-1} - Q_0 + \Delta t (I_0 + \dot{Q})}{\left(\frac{dQ}{dV} - \Delta t \frac{dI}{dV} \right)}$$
$$I^t = I_0 + \Delta V \frac{dI}{dV}$$
$$Q^t = Q^{t-1} + \Delta t\ (I_f^t + \dot{Q})$$

First Test Case

- Solution of simplified Poisson's equation in a unit cube



$$\varepsilon = 1$$

$$\rho = 1$$

$$\ell = w = h = 1$$

$$\nabla \bullet (\nabla \phi) = -1$$

Non-Uniform Meshing

- Second order accurate calculation of electric fields at Circuit Board surfaces require equal zone sizes across interface.
  - Integral of electric fields used to determine charge on grounded metal and potential of floating metal
  - Accuracy effects the usefulness of the calculations

$$\Delta x_1 = d$$

$$\sum_{i=1,n} \Delta x_i = \ell$$

$$\Delta x_{i+1} = \alpha \, \Delta x_i$$

$$\sum_{i=1,n} \Delta x_i = \Delta x_1 \sum_{i=1,n} \alpha^{i-1}$$

$$= \Delta x_1 \frac{\alpha^n - 1}{\alpha - 1}$$

$$\frac{\alpha^n - 1}{\alpha - 1} = \frac{\ell}{\Delta x_1}$$

$$\alpha_{i+1} = \left(\frac{\ell(\alpha_i - 1)}{\Delta x_1} + 1 \right)^{1/n}$$

Analytical Test Case

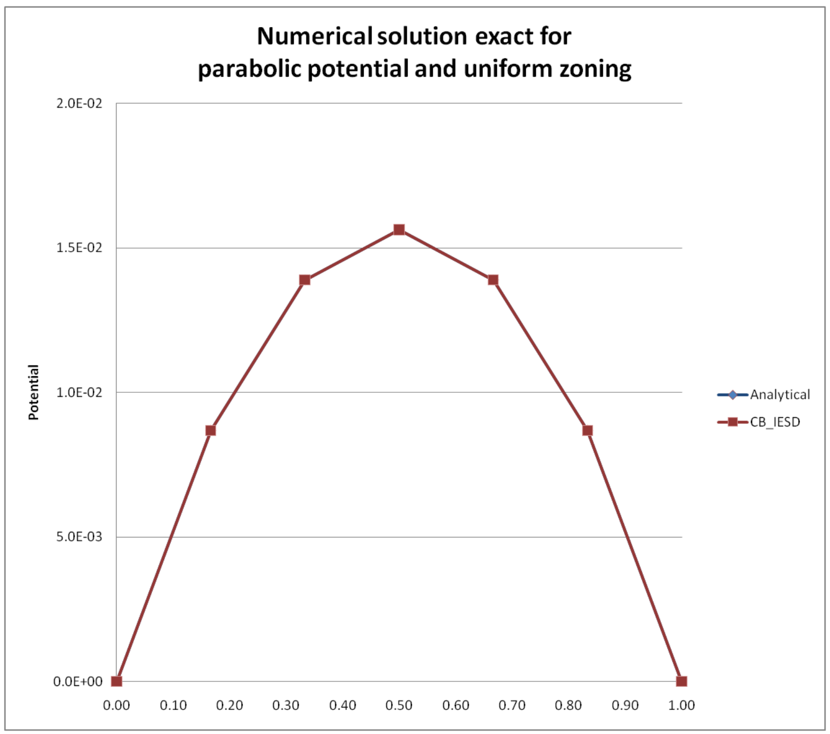
- Test Case Solution is assumed to be a product of parabolas

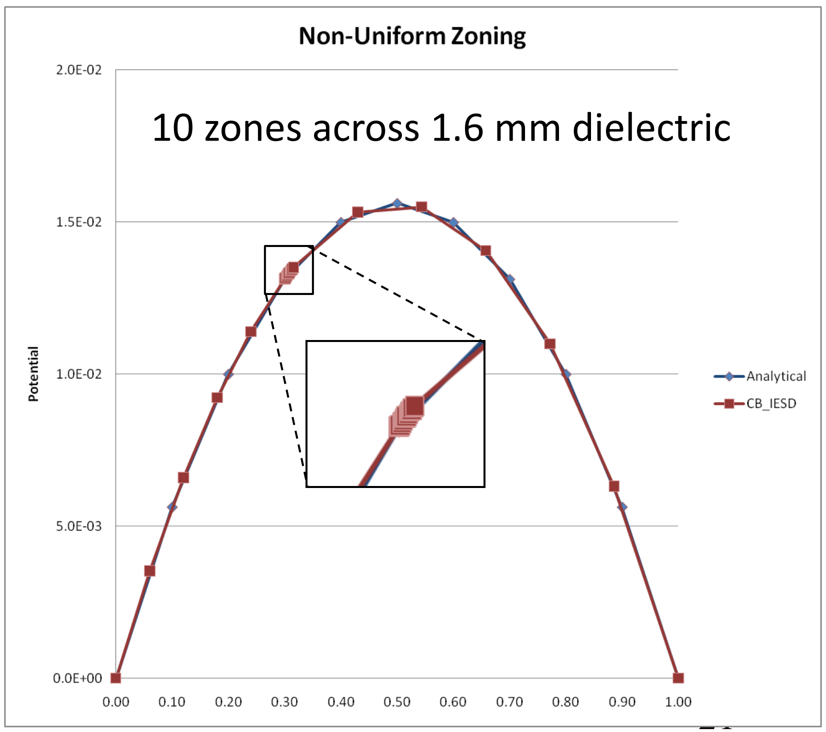
  This determines the right hand side

$$\phi(x,y,z) = xyz(1-x)(1-y)(1-z)$$

$$\frac{\partial^2 \phi}{\partial x^2} = -2yz(1-y)(1-z)$$

$$\nabla \bullet (\nabla \phi) = -2yz(1-y)(1-z) - 2xz(1-x)(1-z) - 2xy(1-x)(1-y)$$

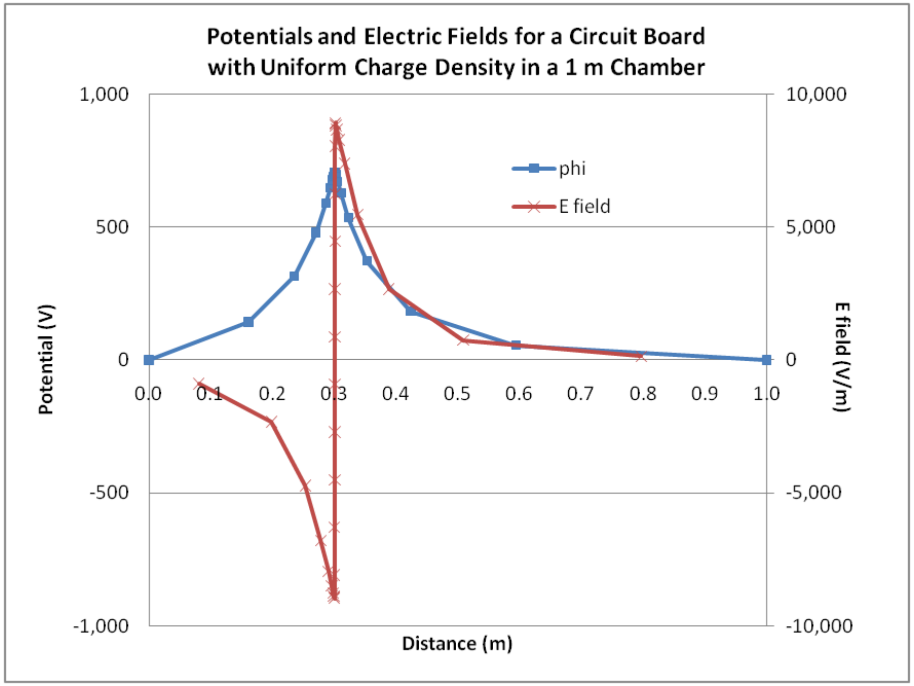


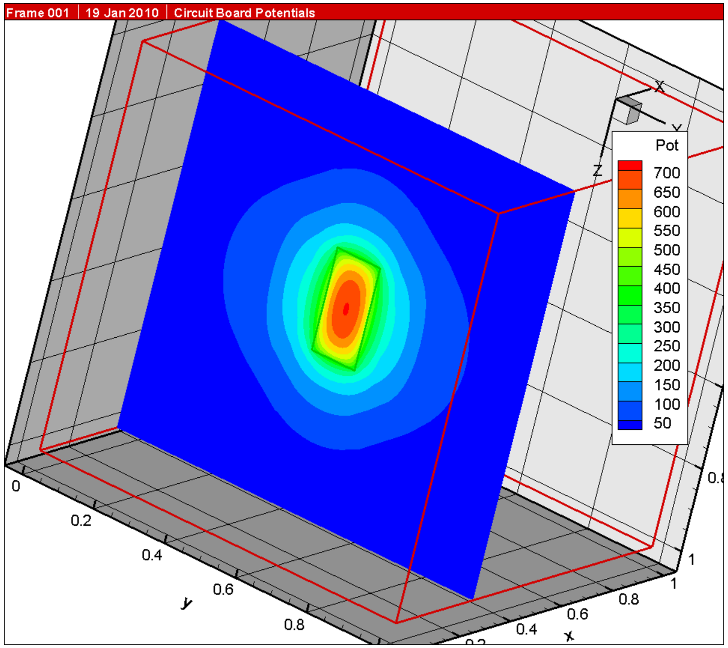


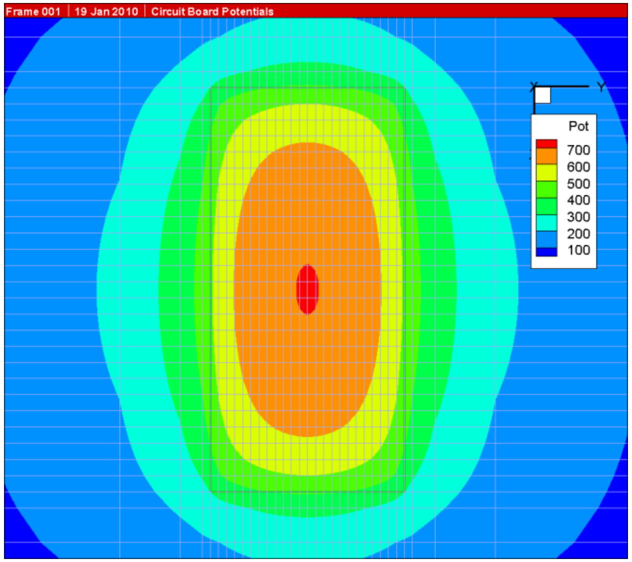
Tests with Charge Deposition in Dielectric

- Uniform charge density

$$h = 1.6\times10^{-3}\ m$$
$$\rho = 10^{-4}\ C\,m^{-3}$$
$$\kappa = 1$$
$$\Delta E = \frac{\rho h}{\kappa\varepsilon_0} = 1.81\times10^{4}\ V\,m^{-1}$$
$$\Delta E_{code} = 1.79\times10^{4}\ V\,m^{-1}$$







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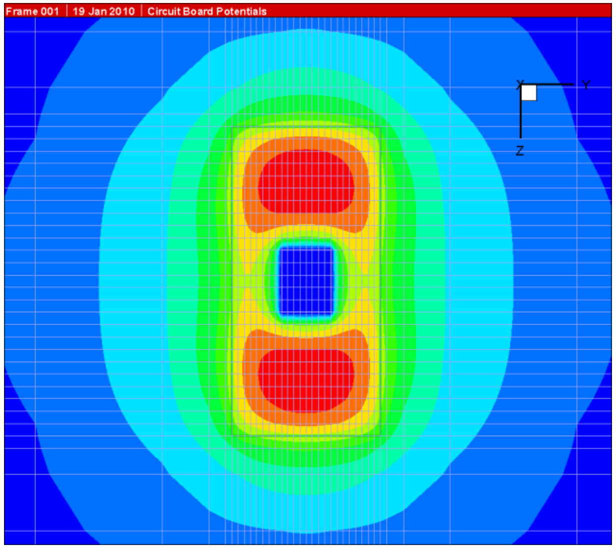
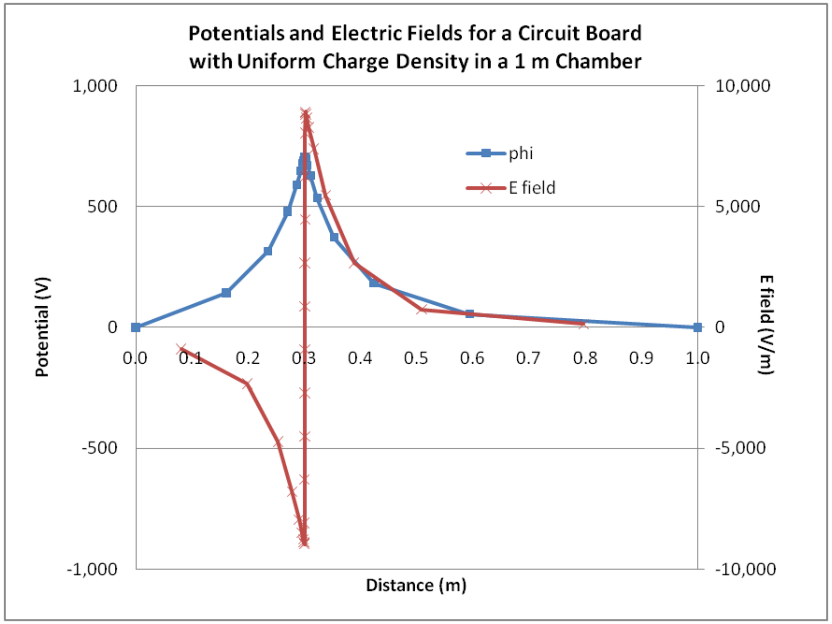
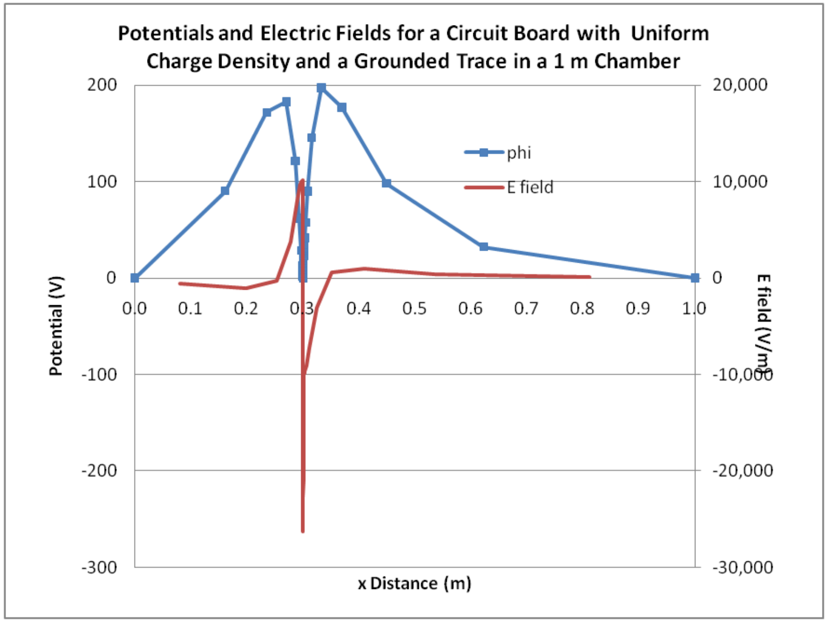
Tests with a Grounded Trace

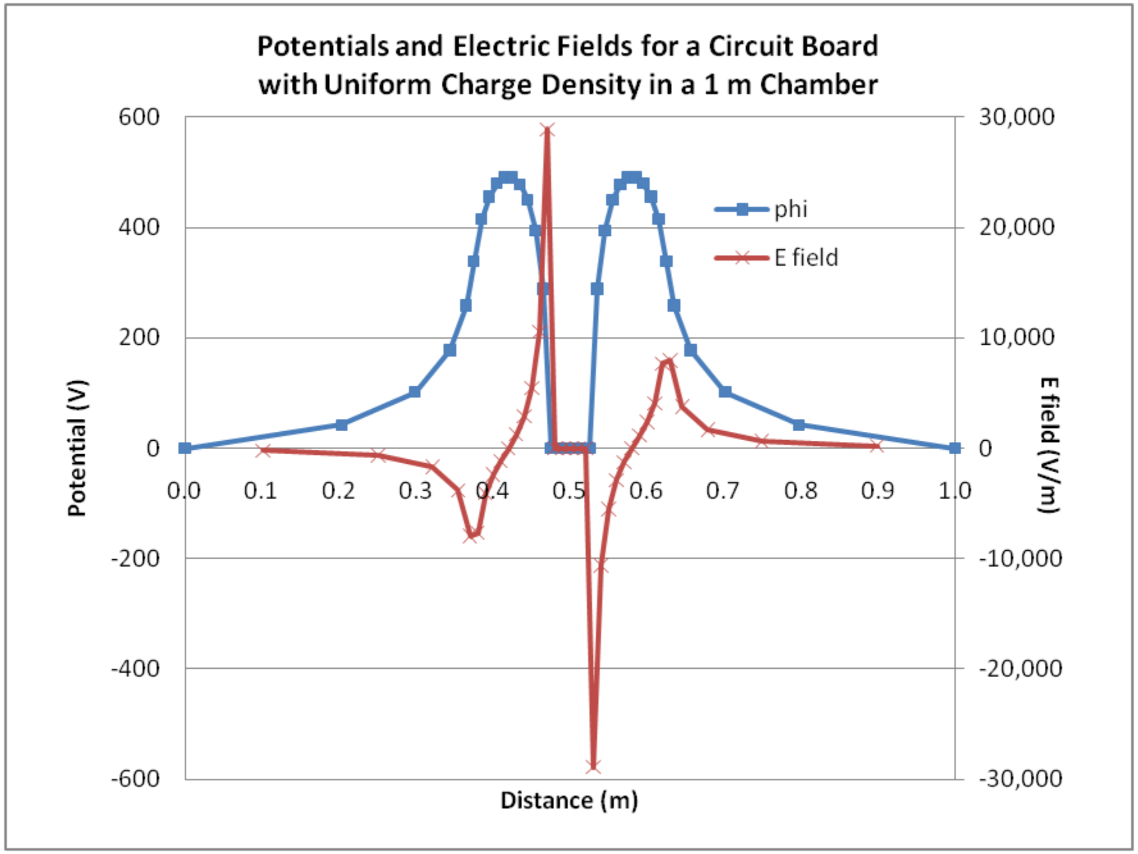
- Grounded trace amplifies Electric fields
  - ΔE_{charge} =18,000 V/m
  - ΔE_{plate} =36,500 V/m
- Field polarity changes
  - Positive image charge on the plate
  - Potential has a saddle point in front of plate







Potentials Along Board with Trace



Test of Finite Kappa & Q_{trace}

- Potential difference between CB surface and CB max Error ~ 3%

$$\Delta\phi_{\kappa=1}^{CB} = 3.60V$$
$$\Delta\phi_{\kappa=3.5}^{CB} = 1.005V$$
$$\frac{\Delta\phi_{\kappa=1}^{CB}}{\Delta\phi_{\kappa=3.5}^{CB}} = 3.58$$

- Parallel plate capacitor – accuracy ~4%

  part could be fringing fields

  Center Efield error < 1%

$$h = 1.6\times10^{-3}\ m$$
$$\rho = 10^{-4}\ C\,m^{-3}$$
$$w = 0.12\ m$$
$$\ell = 0.25m$$
$$Q = 4.80\times10^{-9}\ C$$
$$\frac{Q}{2} = 2.40\times10^{-9}\ C$$
$$\frac{Q_{code}}{2} = 2.07\times10^{-9}\ C\quad 1^{st}\ order$$
$$\frac{Q_{code}}{2} = 2.30\times10^{-9}\ C\quad 2^{nd}\ order$$

$$h = 1.6\times10^{-3}\ m$$
$$\rho = 10^{-4}\ C\,m^{-3}$$
$$\kappa = 3.5$$
$$E_{trace} = \frac{1}{2}\times\frac{\rho h}{\kappa\varepsilon_0} = 2.58\times10^{3}\ V\,m^{-1}$$
$$\Delta E_{code} = 2.32\times10^{3}\ V\,m^{-1}\quad 1^{st}\ order$$
$$\Delta E_{code} = 2.58\times10^{3}\ V\,m^{-1}\quad 2^{nd}\ order$$

Test of Finite Conductivity

- Parallel plate conduction test

  Charge on Traces -5.83028E-07 5.86843E-07

  Current to Traces 1.87500E+04 -1.87500E+04

  Area of Traces 3.00000E-02 3.00000E-02

$$h = 1.6\times10^{-3}\ m$$

$$\sigma = 1\ \Omega^{-1}\, m^{-1}$$

$$\Delta\phi = 1000V$$

$$E_{trace} = \frac{\Delta\phi}{h} = \frac{1000}{1.6\times10^{-3}} = 6.25\times10^{5}\, V\, m^{-1}$$

$$j = \sigma\, E = 6.25\times10^{5}\ A m^{-2}$$

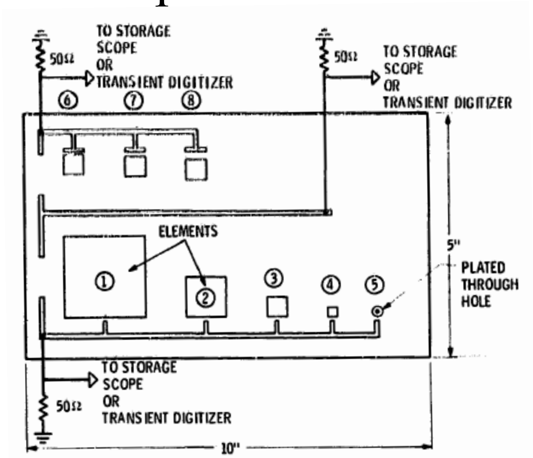
$$A = \ell \times w = 0.25\times0.12 = .03m^{2}$$

$$I = A\, j = 1.875\times10^{4}\ Amps$$

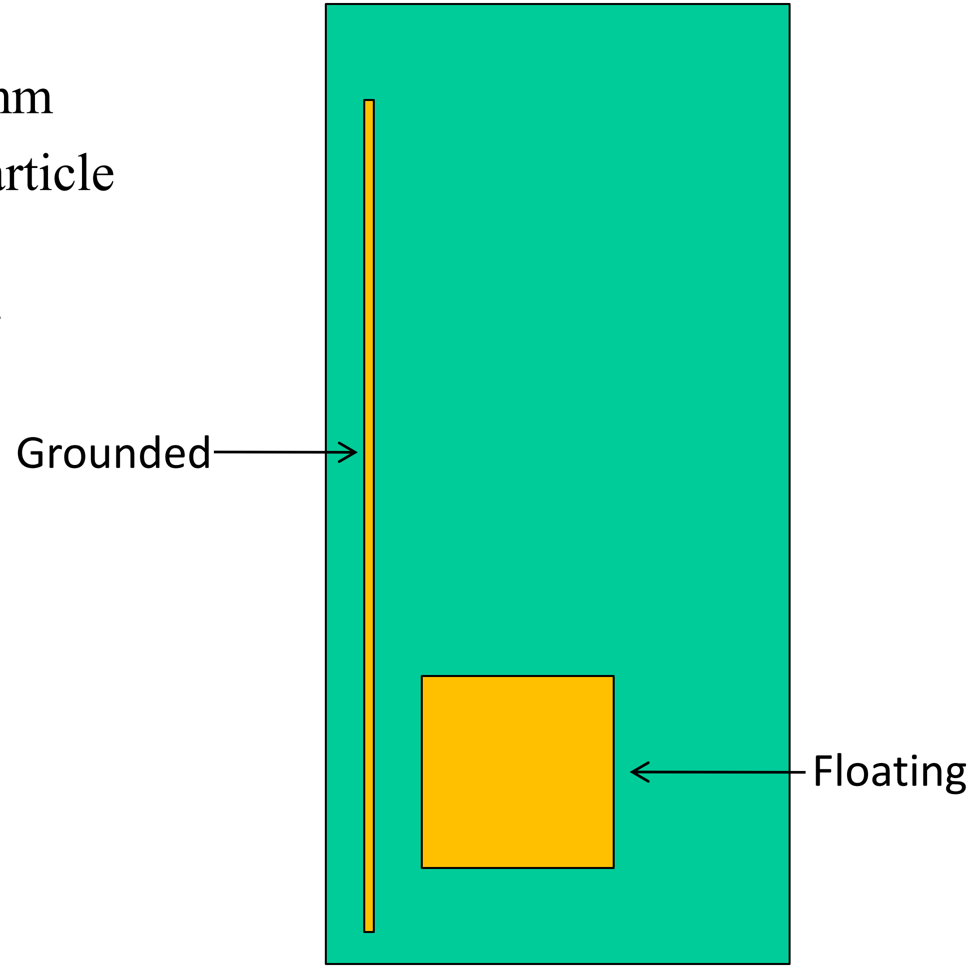
$$I_{code} = 1.875\times10^{4}\ Amps$$

Test Case: Circuit Board with 2 Traces

- Circuit board 12cm x 25cm x 1.6mm
- Similar dimensions to Leung test article
- Floating 5cm x 5cm trace
  - Located (2.5cm,2.5cm) from corner
- Ground trace 20cm x 0.5cm
  - Located (1cm,1cm) from corner
- No Ground plane



(a) Board A.

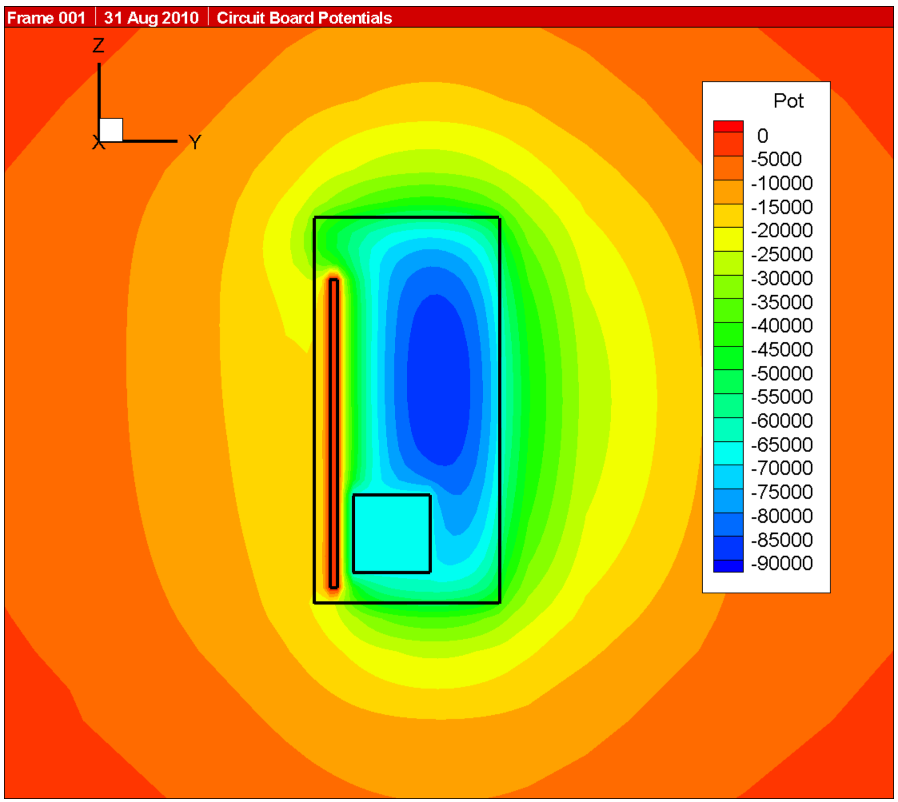


Test Case Circuit Board has Large Areas of Dielectric and no Ground Plane

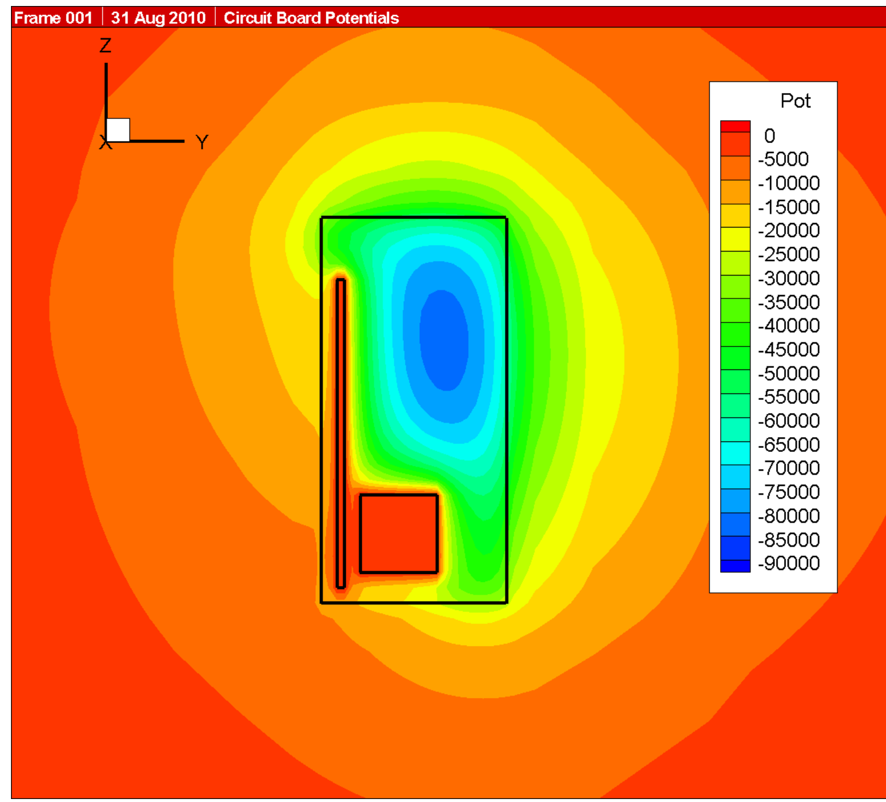
30 Minute Charging Test Case

- Arc Discharge Module calculates flow of image charges assuming the floating metal connects to ground
- Arc module has no mechanism for releasing charge store in the dielectric
- 1 hour min charging at 4 picoamp/cm^2
- Floating potential 67 kV

Beam Current Density (A/m2) 4.00000E-08
Phi Max -9.00E+04
it, t, Vf, Qf, dQ 1 1800.0 -67082.3 -2.503E-08 -1.032E-15
it, t, Vf, Qf, Curr 0 0.0 0.0 0.000E+00 0.000E+00
it, t, Vf, Qf, Curr 1 1800.0 -67082.3 -2.503E-08 -1.536E-13
Arc to ground on trace 2
Charge on Traces 9.83345E-08 1.22306E-07
Arc image charge flow 1.473322E-07
after arc Phi Max -8.30E+04



Fully charged



Floating element grounded

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CB_IESD Calculations Show Additional Grounded Metallization Reduces Peak Potentials and Fields

- Electron Beam Charging
  - 850 keV
  - 4 picoamp/m^2
  - 30 min charging

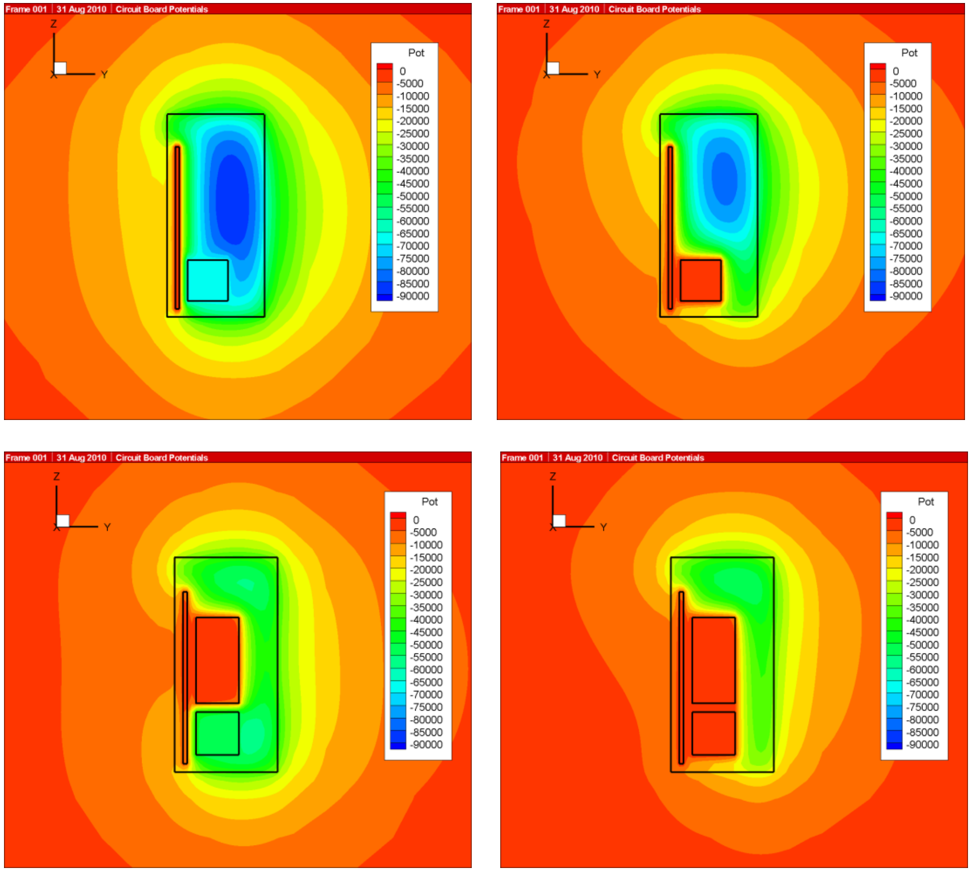
- Floating Metal with Strip
  - Metal Floating Potential -67 kV
  - Arc image charge flow 1.5E-07 C
  - Peak Potential in Dielectric -90 kV

```
Beam Current Density (A/m2)   4.00000E-08
  Phi Max    -6.08E+04
 it, t, Vf, Qf, dQ     1      1800.0    -55587.8  -2.505E-08  -3.026E-16
 it, t, Vf, Qf, Curr    0         0.0          0.0   0.000E+00   0.000E+00
 it, t, Vf, Qf, Curr    1      1800.0    -55587.8  -2.505E-08  -1.654E-13
Arc to ground on trace            2
 Charge on Traces    6.59049E-08  1.04179E-07  1.94866E-07
Arc image charge flow 1.292264E-07
 after arc Phi Max    -5.72E+04
```

- Floating Metal Large Grounded Metallization
  - Metal Floating Potential -56 V
  - Arc image charge flow 1.3E-07
  - Peak Potential in Dielectric -61 kV

Potentials in Dielectric Reduced by 32%

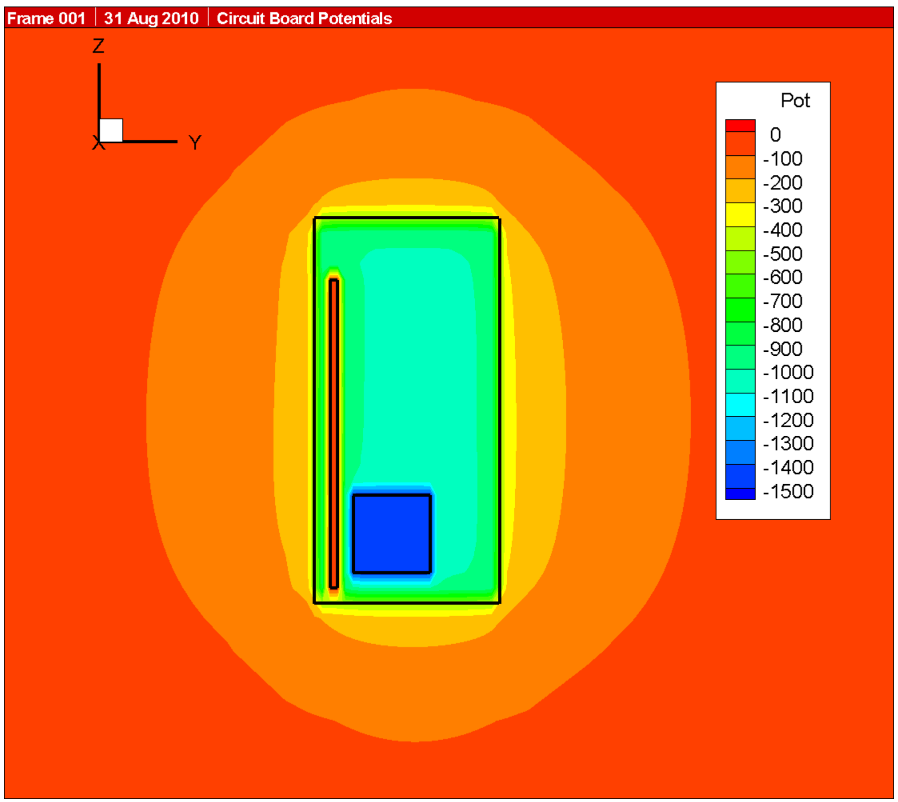
Fully Charged | After Arc

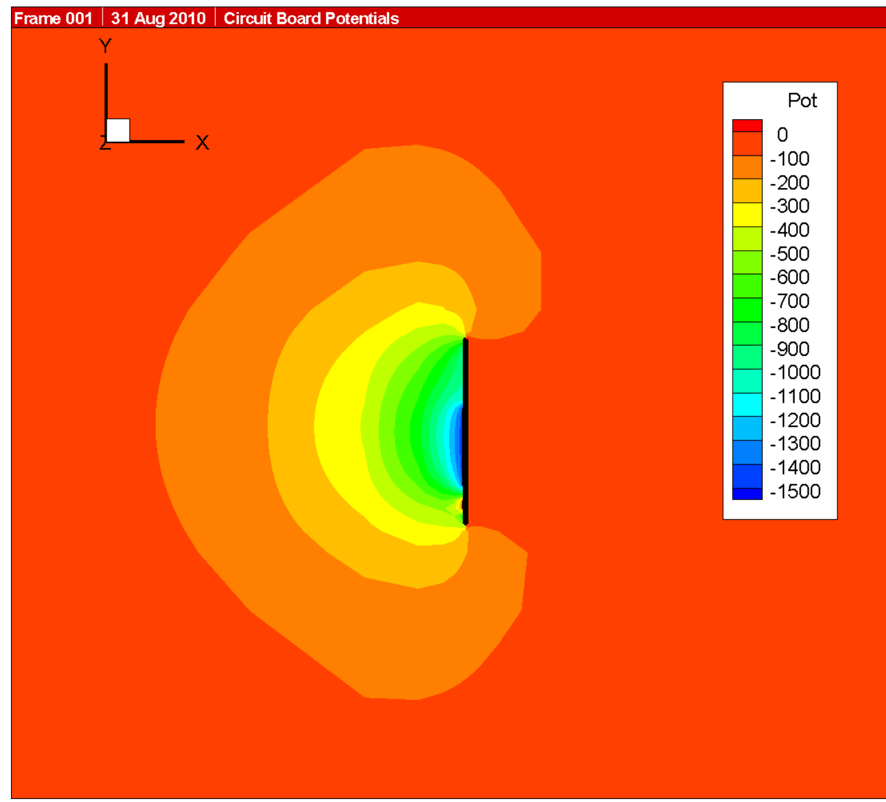


Ground Plane Reduces Charging by 97%

- Floating Potential -1500 V
- Same as 1-D calculation

Beam Current Density (A/m2) 4.00000E-08
Phi Max -1.49E+03
it, t, Vf, Qf, dQ 1 1800.0 -1488.7 -2.430E-08 4.195E-17
it, t, Vf, Qf, Curr 0 0.0 0.0 0.000E+00 0.000E+00
it, t, Vf, Qf, Curr 1 1800.0 -1488.7 -2.430E-08 2.484E-13
Arc to ground on trace 2
Charge on Traces 2.13102E-08 5.01517E-08 6.76596E-07
Arc image charge flow 7.445453E-08
after arc Phi Max -1.01E+03





A 3-D Model of Circuit Board Internal Electrostatic Charging

Conclusions

- CB_IESD code can resolve circuit board lateral and internal dimensions
  - 2nd order accurate algorithms
  - Verified by comparison with analytical solutions
- Calculations performed for geometry similar to pre-Galileo circuit board IESD tests
  - Sparsely populated circuit board
  - Only one floating trace
- Results show that 3-D potentials in general much larger than those predicted by 1-D models
- CB_IESD code will be used to help determine design guidelines and to extrapolate laboratory test results to expected Jupiter radiation belt environments