ON THE POSSIBILITY THAT A GROUNDED SLAB OF HIGHLY RESISTIVE DIELECTRIC MATERIAL WILL DETERIORATE IN A CHARGING ENVIRONMENT DUE TO THE ENERGY RELEASED BY ELECTROSTATIC DISCHARGES

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Objectives

- **A modeling experiment aimed at getting a better understanding of the impacts of different grounding configurations on ESD rates (or the absence thereof) for high-bulk-resistivity dielectrics placed in a charging environment.**

- **An attempt to capture as much fidelity of cause-and-effect as possible with a minimum of mathematical complexity and modeling detail, and in a way that is analytically tractable.**

- **Use creative mathematical modeling techniques to *emulate* some aspects of dielectric charging that normally require the use of sophisticated computer models.**

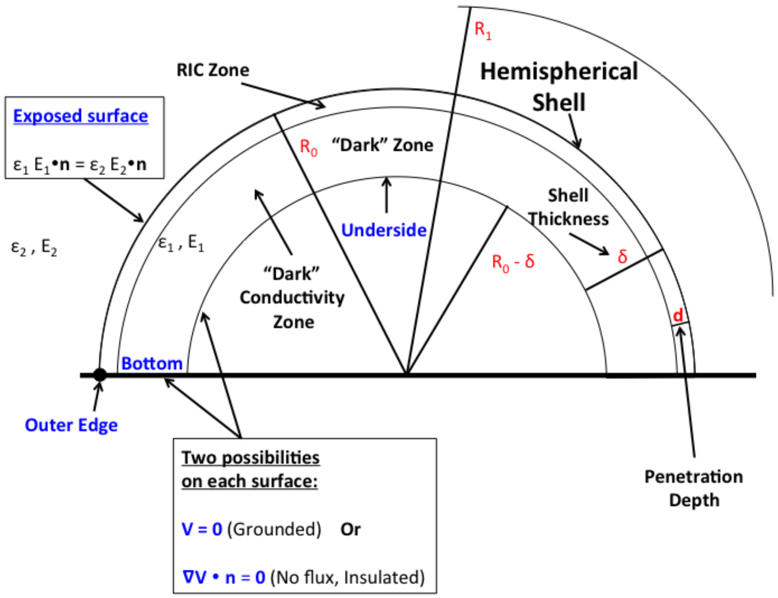
- **The physics modeled includes (a) Poisson's equation, (b) the charge continuity equation, (c) Ohm's law, (d) the dependence of the charging current density on the potential at the dielectric surface, and (e) radiation-induced conductivity (RIC).**

The Physical Situation

- **Instead of a rectangular slab of dielectric in a charging environment, which has *five* exposed surfaces, we chose a hemispherical shell which only has *one* exposed surface.**

- **The dielectric sits on a substrate, parts of which may be either grounded or insulated.**

- **The figure below illustrates the basic geometric parameters.**



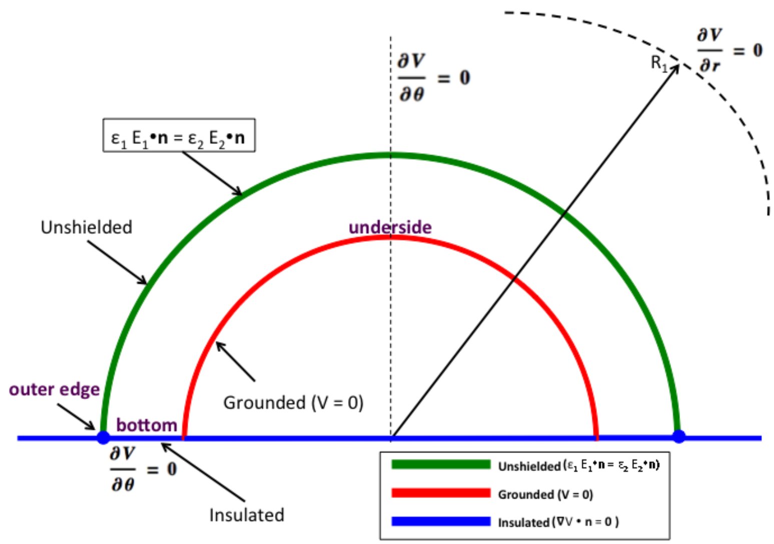
So for purposes of analysis we'll actually have three zones:

(1) The "dark" conductivity zone, which goes from the underside of the shell to the edge of the penetration depth,

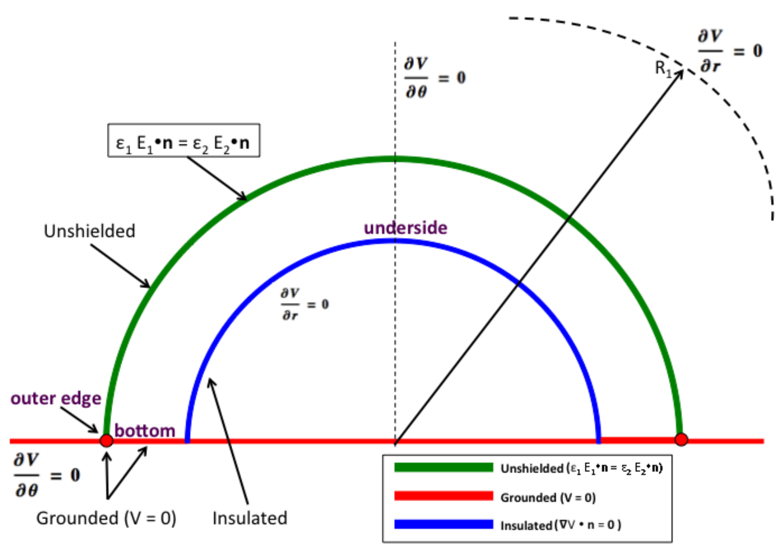
(2) The RIC zone, which extends from the outer surface of the dielectric down to the electron penetration depth, and

(3) The outer zone, which extends from the surface of the dielectric out to some radius R_1, which may actually be infinity.

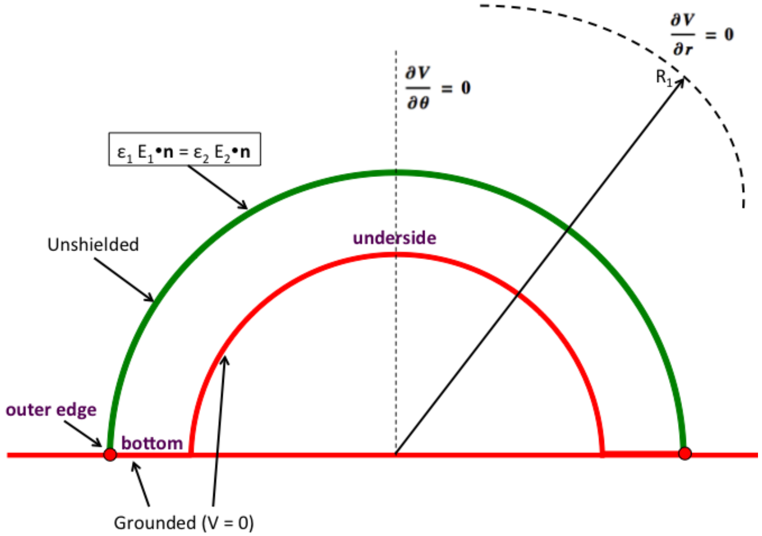
The figures below illustrate several possible grounding configurations:



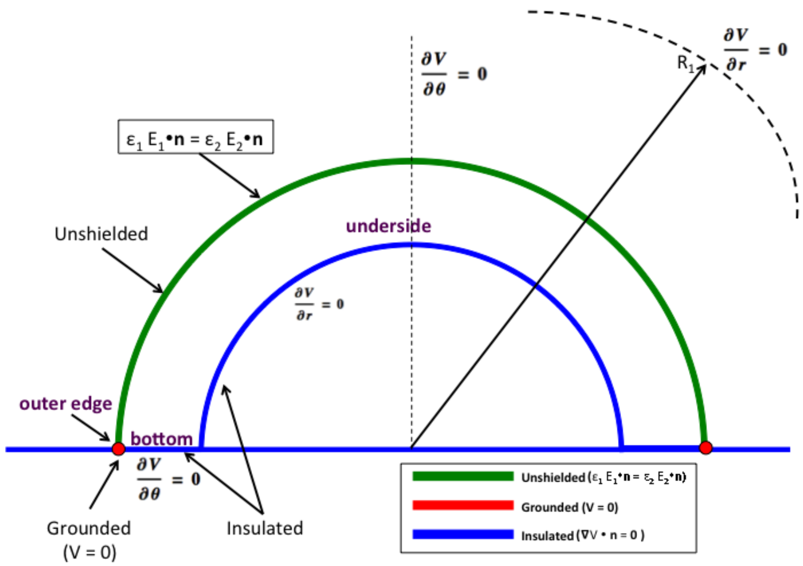
Case 1: *Only underside is grounded*



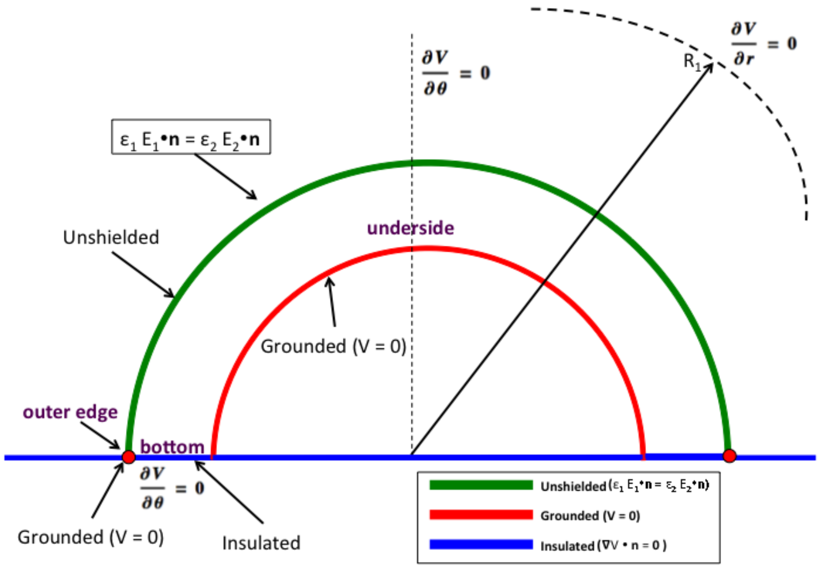
Case 2: *Entire bottom is grounded*



Case 3: ***Entire bottom and underside are grounded***



Case 4: ***Only outer edge is grounded***



Case 5: ***Outer edge and underside are grounded***

The dielectric charging equations

These are from [6] and [7]:

$\nabla \bullet \epsilon \nabla V = -\rho$ (Poisson's equation)

$\partial_t \rho + \nabla \bullet (j + J_R) = 0$ (Charge continuity)

$j = \sigma E$ (Ohm's law)

$\sigma = \sigma_0 + k_P \dot{D}^{\Delta}$ (Radiation-induced conductivity [RIC])

$J_R = J_0\, e^{-\frac{\Delta V}{V_P}} \simeq J_0\, (1 - \frac{V[R_0,\theta]}{V_P})$ (Incident particle flux/current density)

Where V is the potential, E is the electric field, ρ is the charge density, σ is the conductivity, σ_0 is the dark or intrinsic conductivity, ϵ is the permittivity, $\dot{D}$ is the dose rate, k_P is the RIC coefficient and J_0 is the ambient electron current density.

Inside the electron penetration depth, the conductivity is greatly enhanced by the incident radiation, typically by many orders of magnitude. Outside this very thin

layer the conductivity becomes the intrinsic or “dark” conductivity.

In [6] it is pointed out that $-\nabla \cdot J_R$ = the charge deposition rate (often denoted by the symbol $\dot{\rho}$)

Modeling Approach

Explore several ideas:

- The presence of a radiation dose rate is much more important than the details of dose vs. depth.

- The presence of a RIC region (where the conductivity is many orders of magnitude greater than the dark conductivity) is much more important than the details of how this RIC conductivity varies with depth into the material

- The details of the spatial variation of the incident current density inside the penetration depth (and the resulting charge deposition rate that it produces) are much less important than the fact that (a) charge is being deposited inside the material, (b) the magnitude of the incident current density on the surface of

the dielectric depends on the potential at the dielectric surface, and (c) this current density goes to zero at the penetration depth.

- Since our goal is to explore and get better insight into understand cause-and effect relationships, rather than to precisely calculate what will happen on a spacecraft headed for a planetary mission, for example, we have considerably more liberty and flexibility in choosing geometries, boundary conditions, and initial conditions than we would otherwise.

- The art here is to find a way to exploit this freedom in a way that makes the problem analytically tractable while preserving the essence of the cause-and-effect mechanisms involved, so that we can get the maximum of insight and clarity without excessive mathematical complexity.

Mathematical Approach

- Set up the equations for each of the three zones (different conductivities, different permittivities, different particle fluxes)

- Take the Laplace transform of equations with respect to time. This introduces the initial charge density in a very explicit way. Since we are assuming a steady-state dose rate, this implies a non-zero initial charge density.

- Use the Laplace-transformed equations to eliminate the charge density and get a single equation for the potential in each region.

- Simplification: Express the initial charge density in terms of the first two even Legendre functions of Cos[θ], with coefficients that depend on r. For Case 1 (insulated at the bottom), the charge density is expected to be greater at $\theta = \frac{\pi}{2}$ than at $\theta = 0$.

- Express the potential and charge density (in each zone) in terms of the first two even Legendre functions with coefficients that depend on r.

- Substitute these expressions into the equations to get ordinary differential equations for the coefficients of the Legendre functions. These differential equations

(and their solutions) will also contain the solutions evaluated at R_0 (from the equation for the incident particle flux). From the general solutions one can algebraically solve for these values of the coefficients at R_0 and substitute them back into the solution.

- Each of the r-dependent coefficients of the Legendre functions will also contain two arbitrary constants that will be determined from the boundary conditions. The algebra for doing this is VERY involved.

- There is a jump in the normal electric field at the RIC-Outer interface due to the change in permittivity: $\epsilon_{\text{RIC}} E_{\text{RIC}} = \epsilon_{\text{Out}} E_{\text{Out}}$.

- There is a much bigger jump in the electric field at the Dark-RIC interface due to the jump in conductivity across this interface. This comes from integrating the charge continuity equation across this boundary.

- Note also that the $\epsilon_{\text{RIC}} E_{\text{RIC}} = \epsilon_{\text{Dark}} E_{\text{Dark}}$ means that $E_{\text{Dark}} = \frac{\epsilon_{\text{RIC}}}{\epsilon_{\text{Dark}}} \times E_{\text{RIC}}$, and since the ratio of the conductivities is on the order of 10^{10} - 10^{15}or so, this produces a potentially very large jump in field gradient across the Dark-RIC interface.

Insights

- **When the bottom is insulated, as in Case1, the E-field is mostly radial, and high-E-fields are produced at the Dark-RIC interface on the Dark side.**

- **When all or part of the bottom is grounded (as in Cases 2 - 5), the RIC zone acts like a conductive coating connected to ground, and so the E-field will be much smaller and mostly in the angular direction, with a minimal radial component.**

- **Nevertheless, due to the potentially large field magnification at the RIC-Dark boundary, the use of conductive coatings for ESD mitigation (for example) needs to be carefully analyzed, as even small radial field components can get magnified by many orders of magnitude.**

- **The large jump in conductivity in the RIC zone can lead to extremely large voltage gradients in the Dark zone, very likely exceeding the breakdown field strength for the dielectric.**

- **There are processes operating at two very different time constants: the vary fast RIC time-constant, and the much slower Dark time constant. These can also lead to rapidly changing voltage gradients near the Dark-RIC interface.**

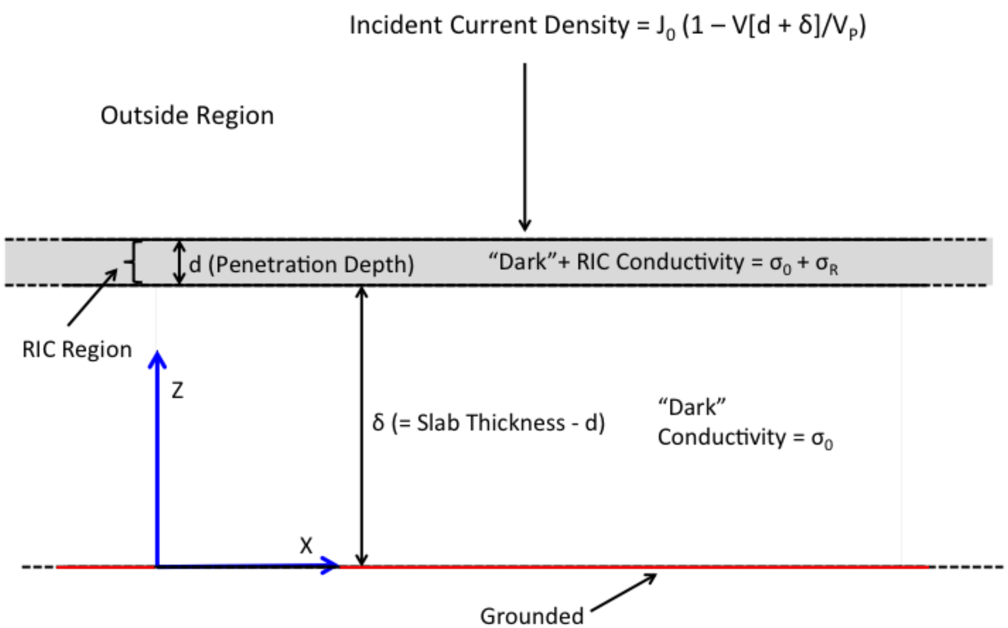
• The algebra required to carry out an analytical solution is excessive, even with a powerful symbolic manipulation capability such as *Mathematica*.

• We do not yet have reliable numerical results at this time.

• The very narrow RIC zone (penetration depths are on the order of microns), the very short RIC time constants, and the potentially very steep voltage gradients pose significant computational challenges for numerical techniques such as the finite-element method.

Additional Insights

A geometry that is simpler than the hemispherical geometry investigated above, and that still yields considerable physical insight, is a simple infinitely long slab of dielectric in a charging environment, as illustrated in the figure below. The advantage of this geometry is that it is one-dimensional, thereby simplifying the mathematics considerably:

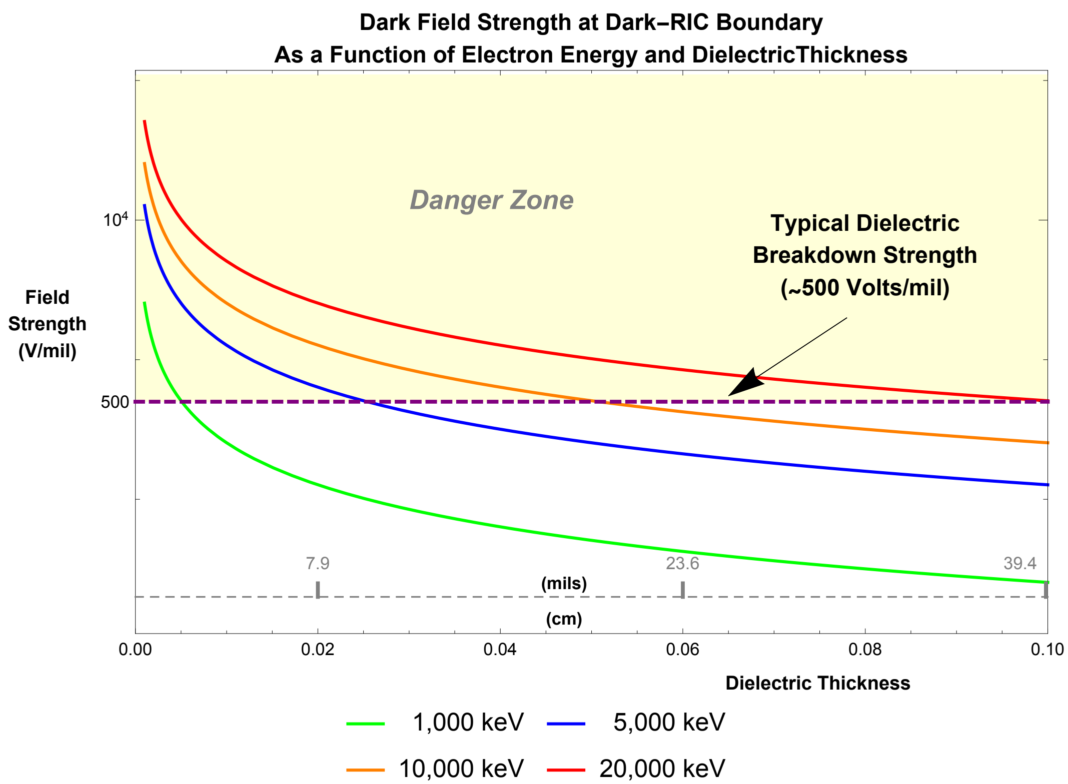


Here, the largest potential gradient (i.e., electric field) occurs in the Dark region at the Dark-RIC interface, due to the large jump in conductivity from the Dark to the RIC regions. The time-dependent solution can be worked out analytically and is fairly complicated, but the steady-state component of this solution, assuming no initial charge density in either the Dark or Outside regions, reduces to a constant potential gradient throughout the Dark region, and is given to a very high degree of approximation by

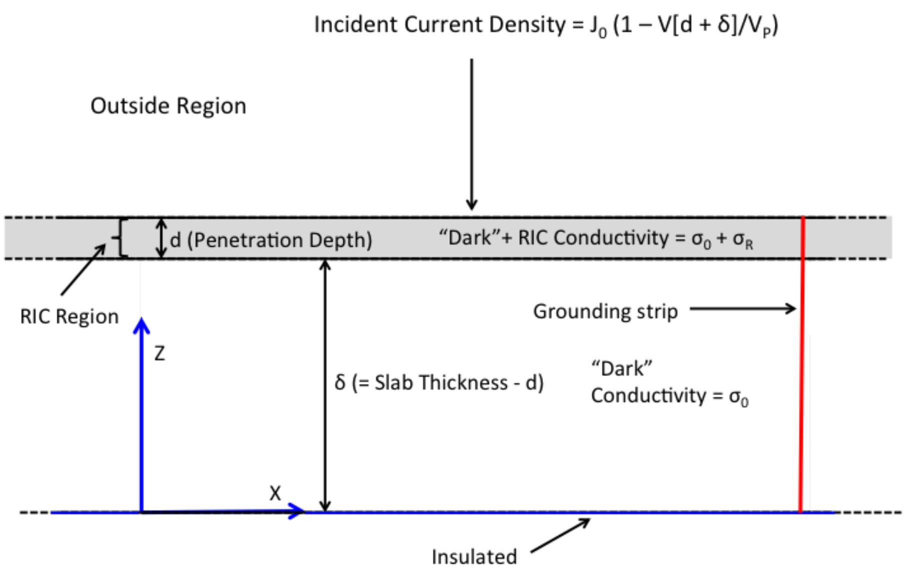
$$V'[z] = \frac{V_P}{\delta},$$

where δ is the thickness of the dielectric slab (minus the penetration depth, typically on the order of microns), as indicated in the figure above, and V_P is the plasma potential. For example, for 10 KeV electrons and a dielectric slab of thickness 0.5 millimeter, the potential gradient or field strength is 508 $\frac{\text{Volts}}{\text{mil}}$, which is typically the breakdown field strength of Kapton.

The plot below shows the field strength as a function of both dielectric slab thickness and electron energy. Dielectric breakdown can be expected to occur for points above the purple 500 Volts/mil line.



We anticipate that the insertion of a grounding strip, as shown in red in the figure below, coupled with an insulated underside, will greatly reduce the field strength at the Dark-RIC boundary, since the electrons will for the most part be able to flow to ground through the high-conductivity RIC region, thereby largely avoiding the high-resistivity Dark region.



We have not yet completed this analysis, but the cause-and effect mechanisms involved seem fairly intuitive once one understands what is happening in the grounded case.

This also has implications for very thin conductive surface coatings, such as coatings on solar cell cover glass, where the conductive coating acts in essentially the same manner as the highly conductive material in the RIC region. Since cover glass thickness is typically on the order of a few mils, the above plot shows that even with low-energy electrons the field strength will be far above the breakdown level. What this says is that if the conductive coating is not grounded, then

the field amplification effect caused by the large jump in conductivity from the Dark to the RIC regions will lead to continuous dielectric breakdown and surface degradation. The introduction of micro cracks in the top layer will reduce the amount of light reaching the sensitive region of the solar cells, thereby compromising the efficiency of solar power generation. On the other hand, if the coating is grounded, then the fields experienced inside the dielectric are reduced significantly.

References

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6. Kim, W., Katz, I, Green, N.W., & Jun, I., "An internal electrostatic charging test of circuit boards under electron beam," RADECS 2011 Summary.