Modeling Multipactor in Dielectric Loaded Accelerators

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High-Gradient Structures, AAC 2006

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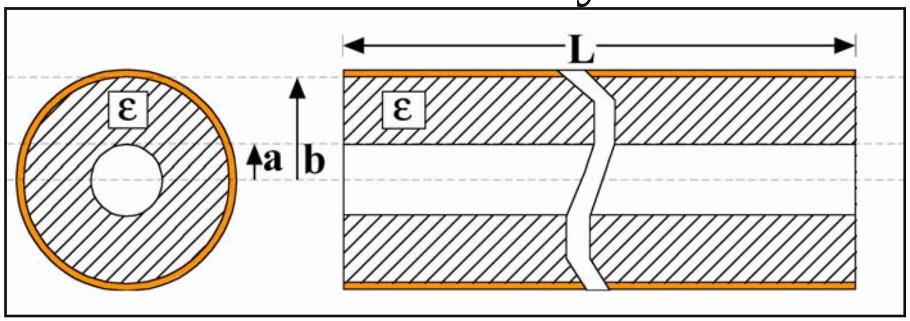
In collaboration with Steven H. Gold, NRL

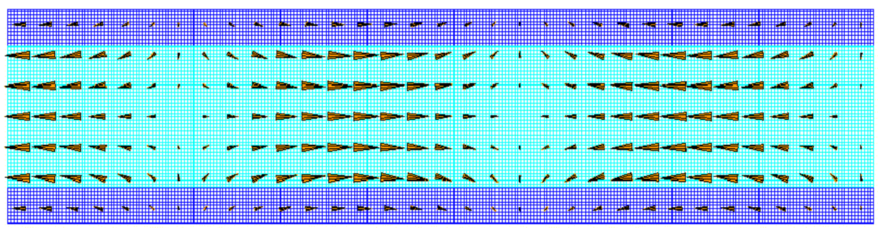
Externally RF Driven DLA Structures

- ANL, NRL, SLAC Collaboration

Geometry



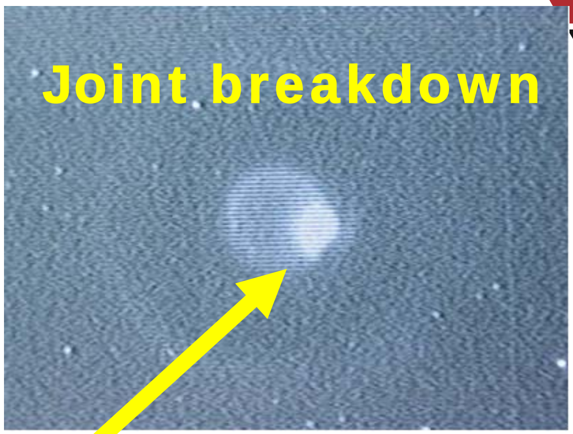
Electric Field Vectors (TM_{01})



- **Program Goals**
  - DLA Structure Development
  - DLA High Power RF Testing

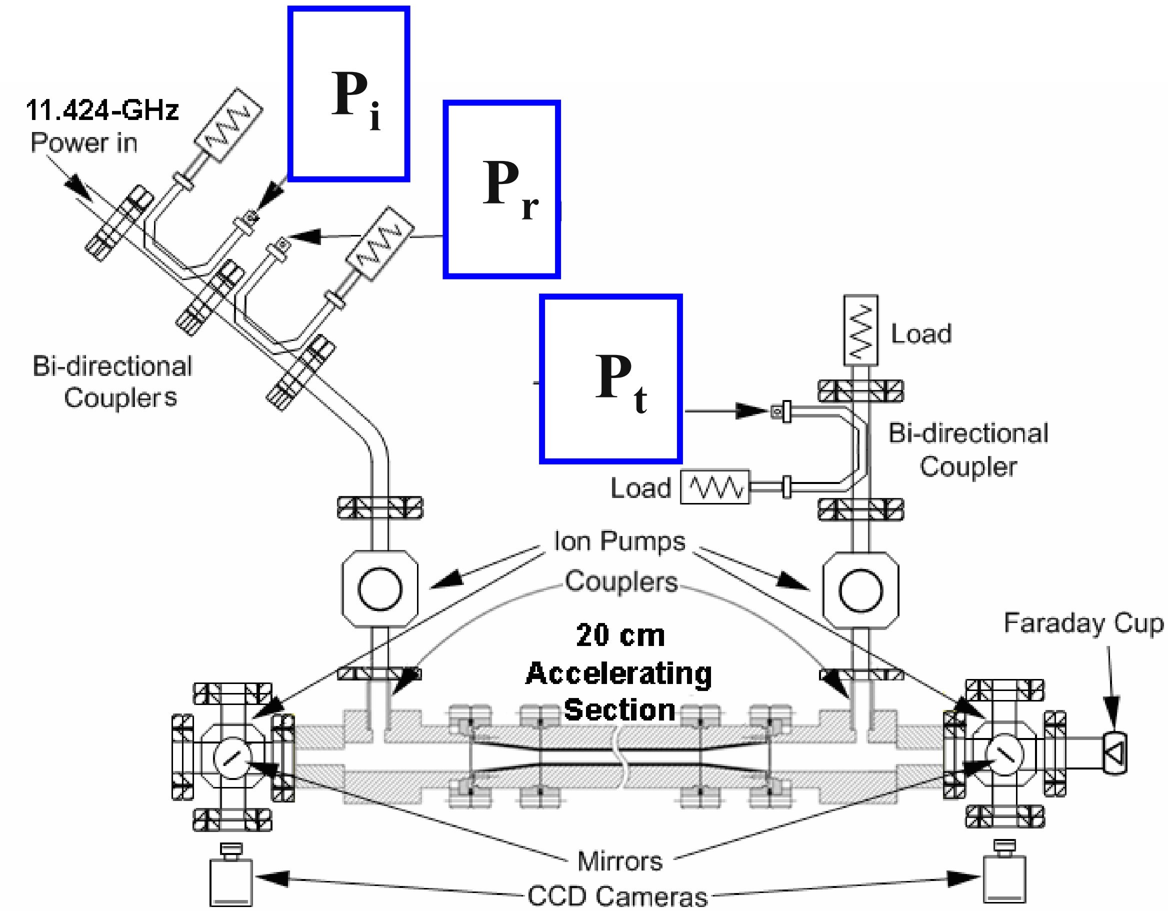
High Power Tests : Major Results

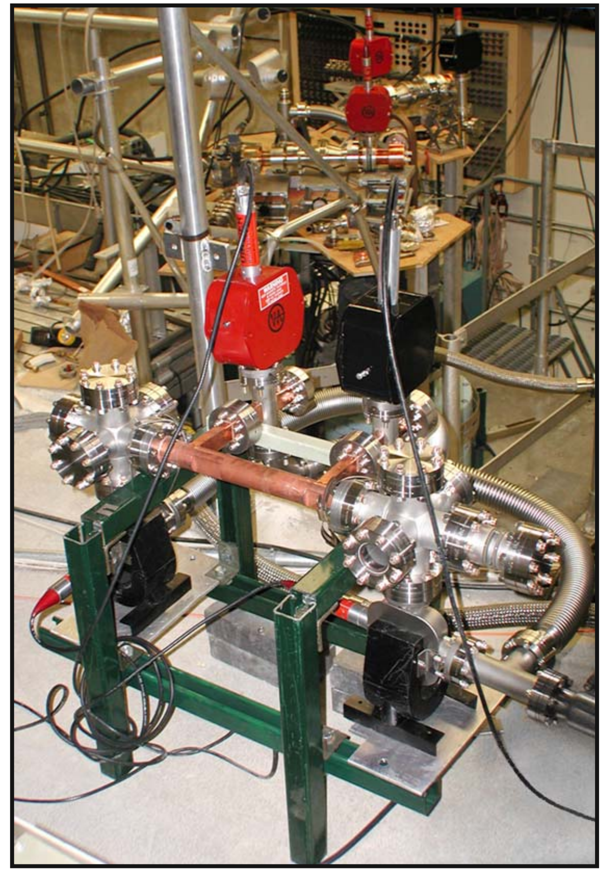
- **Experimental**
  - No breakdown in the bulk dielectric (E_{acc} ~8 MV/m)
  - Good vacuum properties
  - Breakdown in Coupler → *cured*
  - Breakdown in gap at dielectric joint
  - Multipactoring



- **Theoretical**
  - Developed new structures based on fundamental understanding of the issues.
  - A simple theory of single-surface multipactor (very different from RF windows: resonant vs. non-resonant)

High Power Tests at the NRL Magnicon Facility





Experimental Setup

Argonne
NATIONAL LABORATORY

Experimental Observation of Multipactor and a Model of Single Surface Multipactor

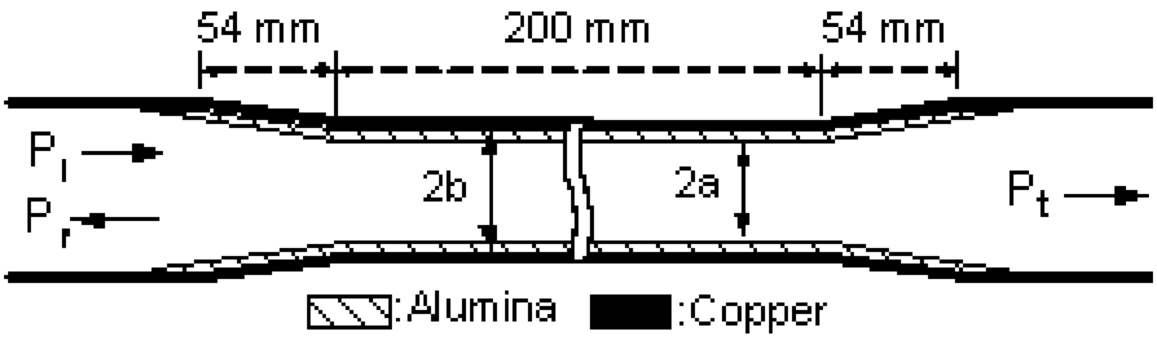
A Brief Review

THE UNIVERSITY OF CHICAGO

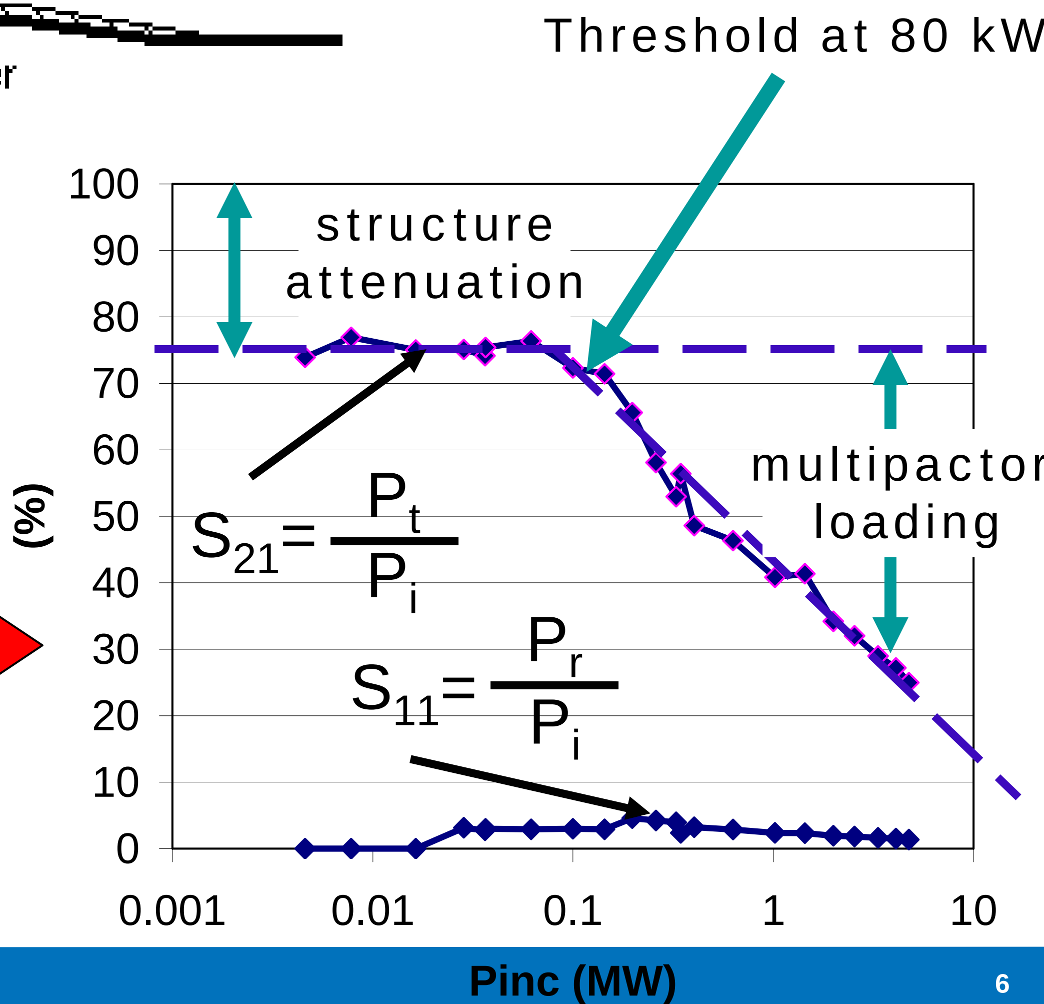
Office of Science
U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by The University of Chicago

Multipactor Induced RF Loading

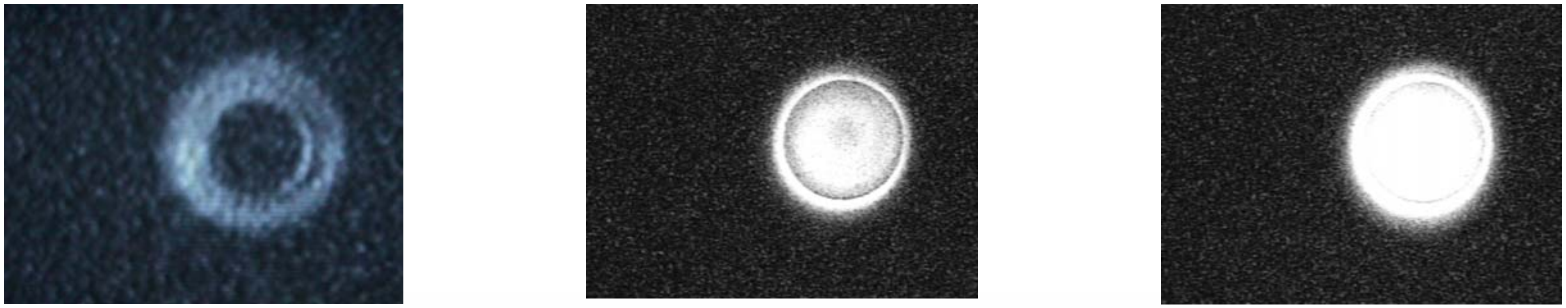


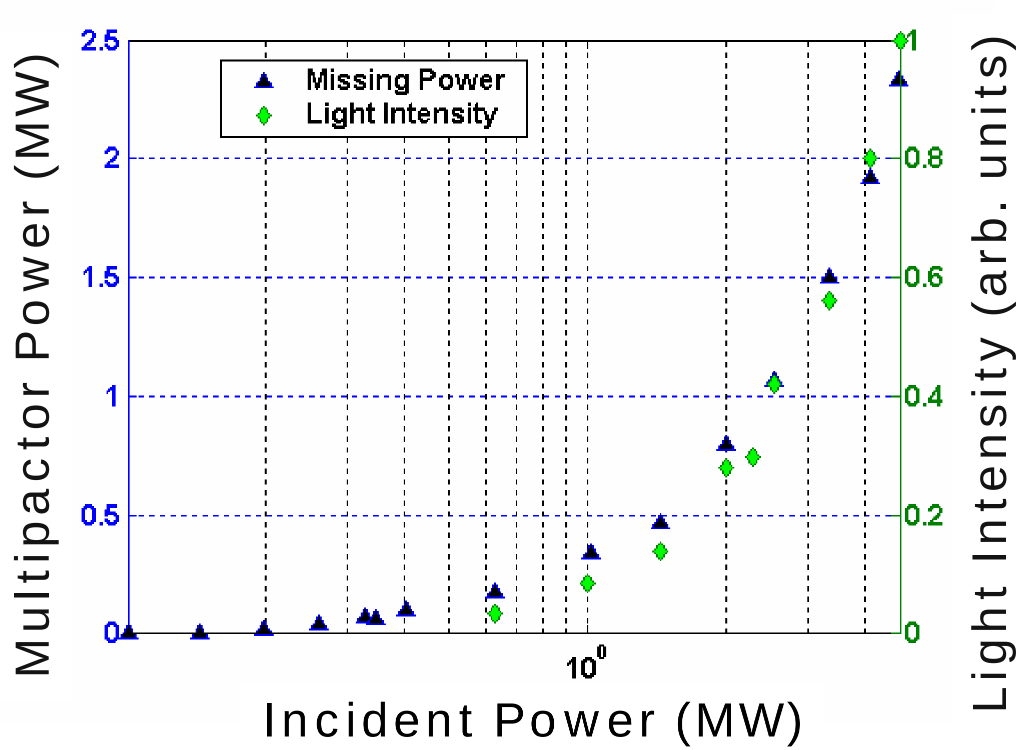
First observed in Alumina DLA structure



Multipactor Induced RF Light Emission

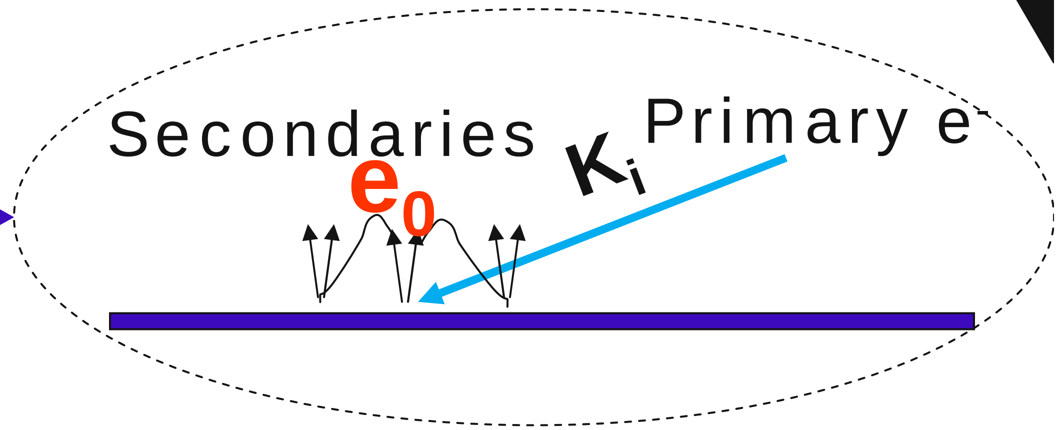
Increasing Power →

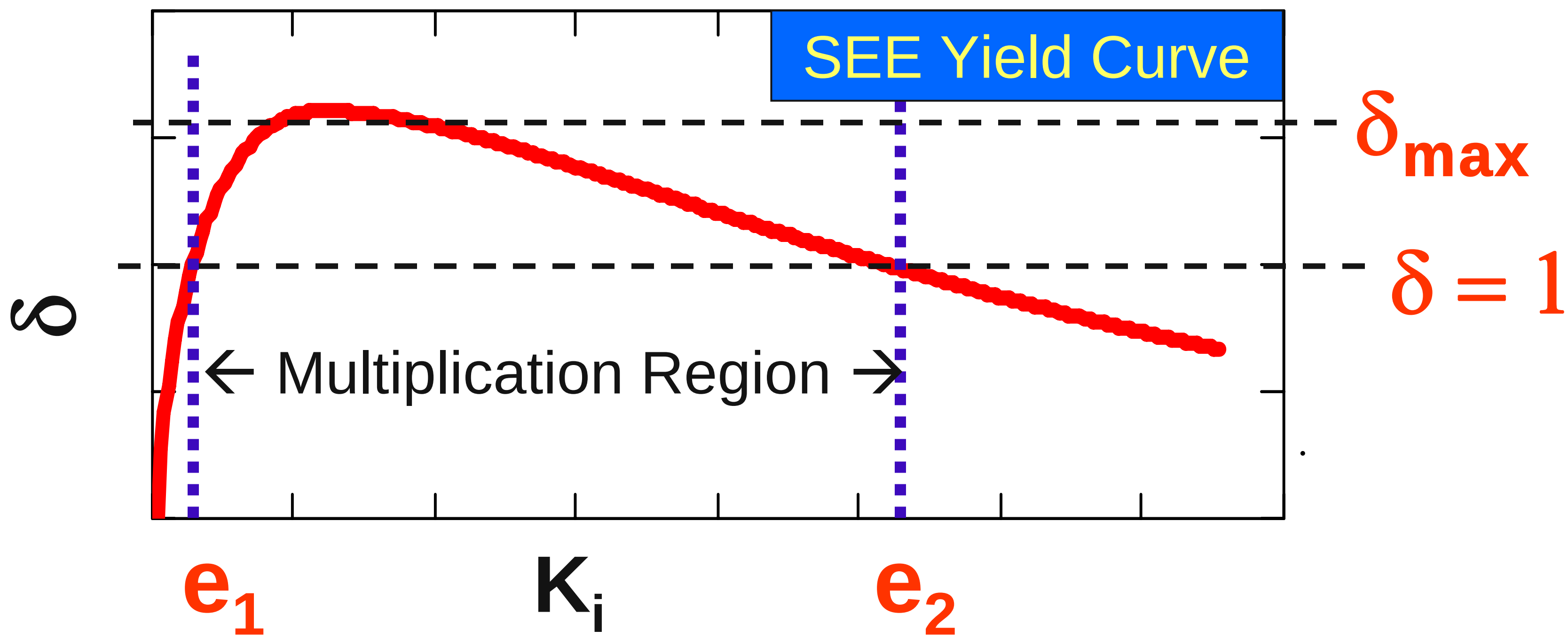




A Very Brief Summary of Single Surface Multipactor

Secondary
Electron Emission
Avalanche



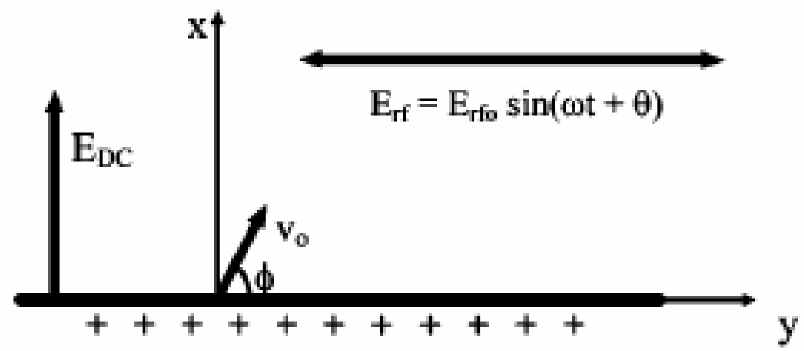


Recall:
Multipactor on an dialectic RF window

Simulation Model†

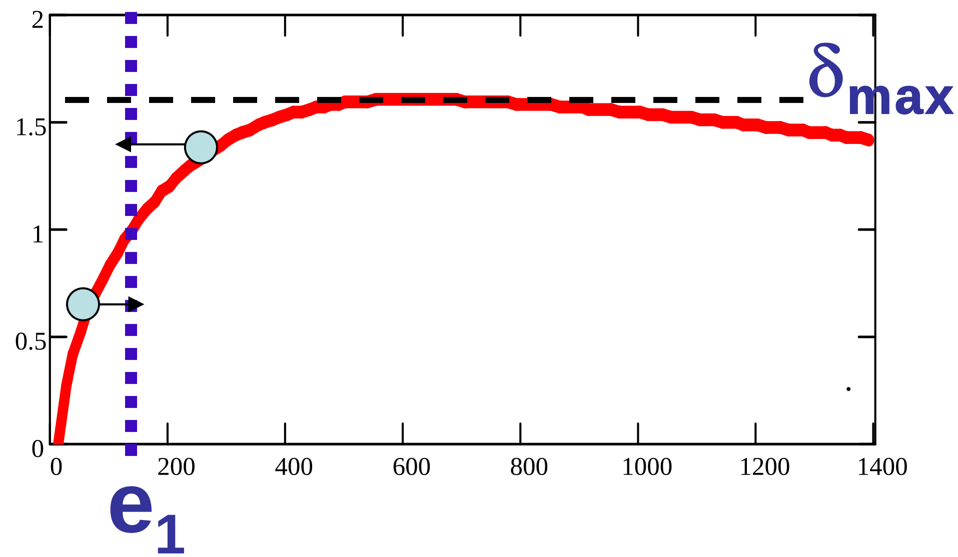
1. E_{RF}, parallel to surface

2. E_{DC} (from surface charge + space charge)



Simulation Results

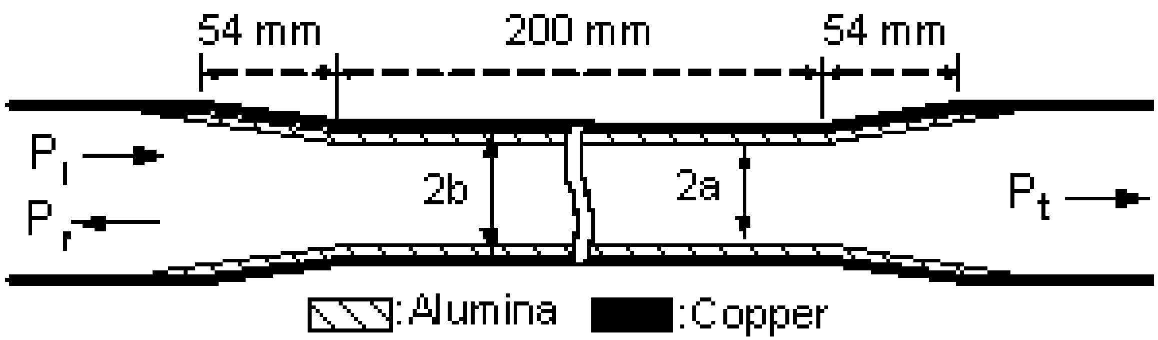
1. **Non-resonant Saturation**
   - $E_{DC} \propto N_e$
   - $\tau_h \propto 1/E_{DC}$ ($\tau_h << \tau_{RF}$)
   - $K_i = e_1$
   - $E_{DC} \sim 0.3 E_{RF}$
2. **RF loading due to Multipactor**
   - $P_m = N_e K_i / \tau_h \sim 0.01 P_{inc}$

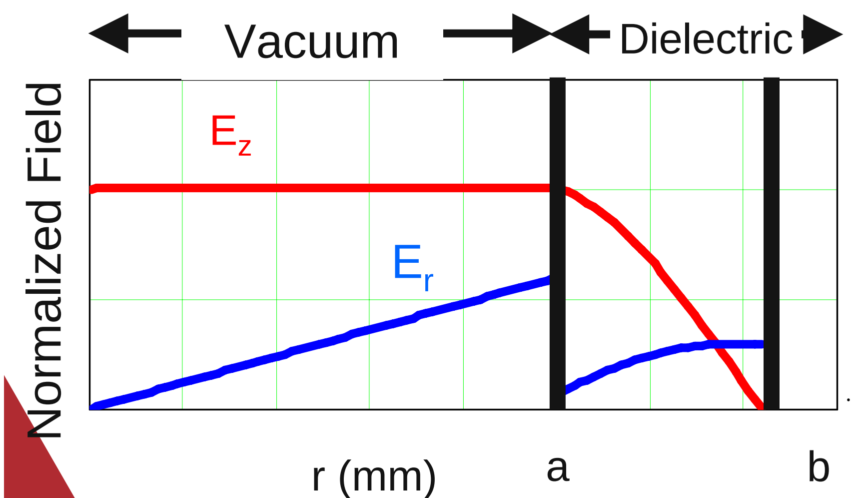


A Model of Single Surface Multipactor†

(1) S.E.E. → e_0, e_1 & K_i (ignores e_2 & $\delta>1$)

(2) particle tracking in r-z using E_z, E_r (ignores H_ϕ)





$$E_z = E_{RF} I_0(k_r r)\cos(\omega t - k_z z)$$

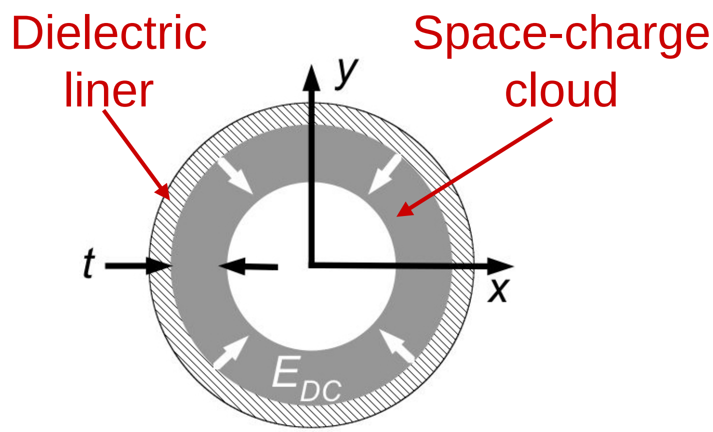
$$E_r = E_{RF}\left(\frac{k_z}{k_r}\right) I_1(k_r r)\sin(\omega t - k_z z)$$

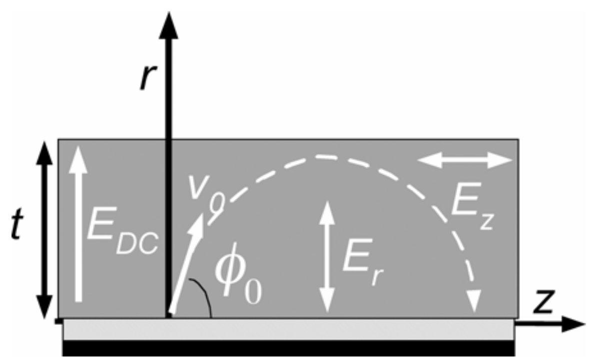
$$H_\varphi = E_r / Z_{TM}$$

r < a

2D Model:
Multipactor in a DLA Accelerator

(3) Space Charge Cloud, E_{dc} (at saturation, ignores dynamics)





$$v_0 = \sqrt{2e_0/m_e} \quad \textbf{(I.C.)}$$

ϕ_0 = emission angle
e_0 = emission energy

→ Putting it all together

$$m\ddot{r} = -eE_{dc} - eE_{z0}\left(\frac{\pi a}{\lambda_z}\right)\sin\left(\omega t - k_z z + \theta\right)$$

$$m\ddot{z} = -eE_{z0}\cos\left(\omega t - k_z z + \theta\right)$$

$$P_m = N K_i / \tau$$

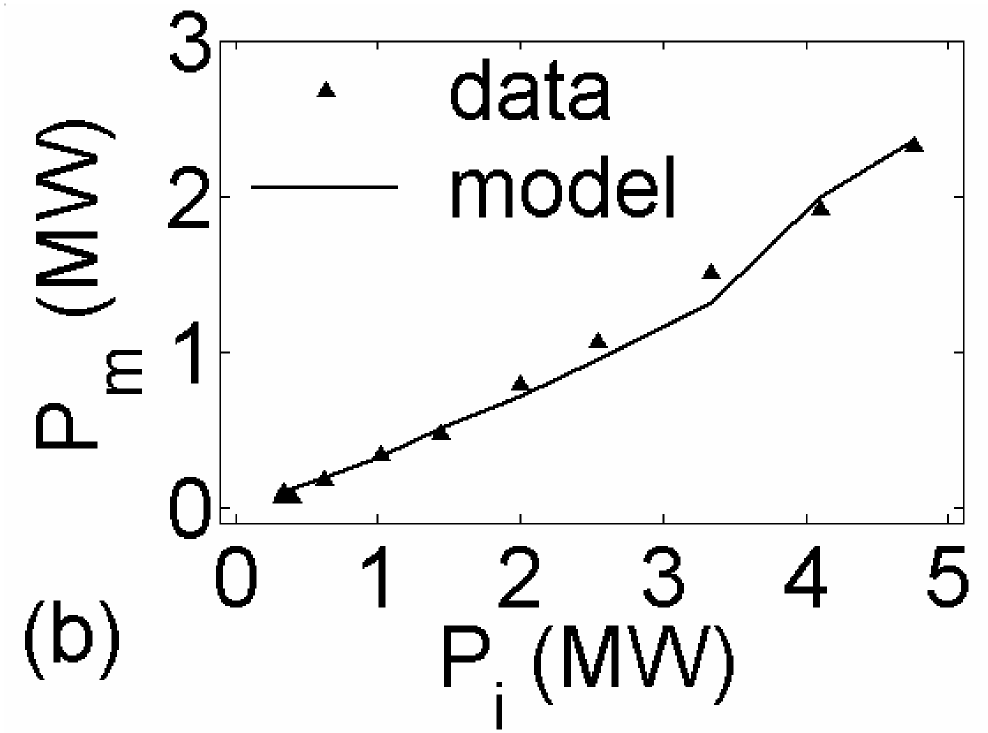
→ Find the Multipactor Power

1. Increase Edc (N) until all trajectories stop
2. Find K_i at saturation
3. $\tau = T_{RF}$

Comparison of Multipactor Model and Experiment

Excellent Agreement

$$P_m = N K_i / \tau$$



Fit Parameters

e_0 = 2 eV
e_1 = 60 eV
L = 250 mm

Saturation →
E_{DC}/E_{z0} ~30%

Observation of Multipactor in Recent High Power Tests
&
A 1D Theory of Single Surface Multipactor

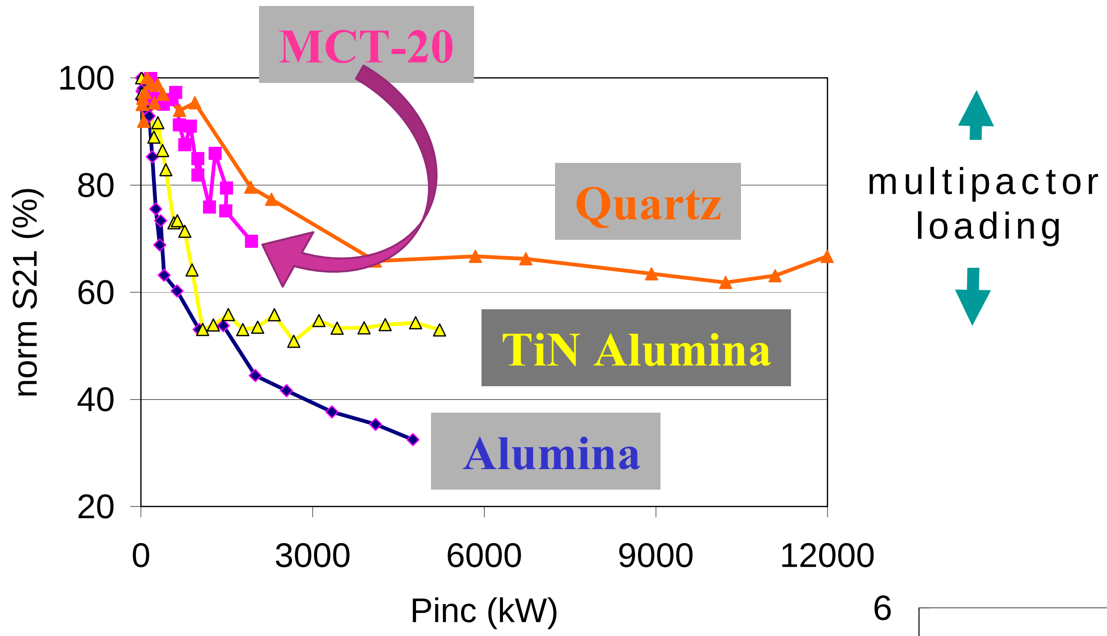
A U.S. Department of Energy laboratory
managed by The University of Chicago

DLA Structures Tested at NRL

Material	Al_2O_3 †	$Mg_xCa_{1-x}TiO_3$	SiO_2
Dielectric constant	9.4	20	3.78
Loss tangent	2×10^{-4}	3×10^{-4}	2×10^{-5}
Inner radius	5 mm	3 mm	8.971 mm
Outer radius	7.185 mm	4.567 mm	12.079 mm
R/Q	6.9 kΩ/m	8.8 kΩ/m	3.6 kΩ/m
Group velocity	0.134*c*	0.057*c*	0.38*c*
RF power for 1MV/m gradient	80 kW	27 kW	439 kW
Demonstrated Gradient	8 MV/m	7.2 MV/m	5 MV/m
Principal Problem	Multipactor	Breakdown at joints	Multipactor

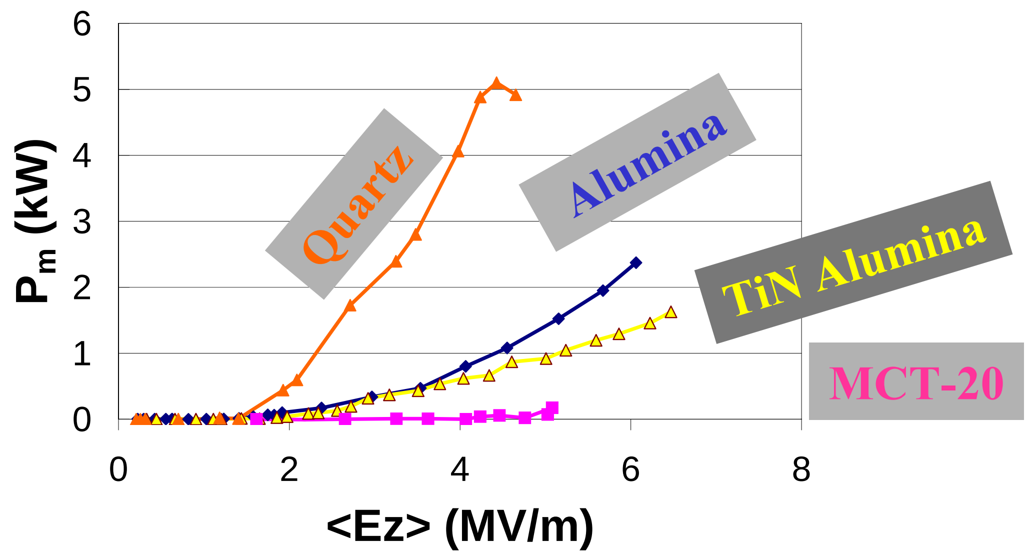
† Both non-coated and TiN coated

Comparison of multipactor-induced RF loading for the different structures.



Raw data

Corrected for shunt impedance, and length



Whys→
- Power Level?
- Saturation?

What are the possible explanations?

1. **Material properties:**
   - Secondary Emission: e_0, e_1, e_2, δ_{max}
   - Permittivity:
     1. $\varepsilon_{alumina}=9.8$,
     2. $\varepsilon_{mct}=20$,
     3. $\varepsilon_{quartz}=3.78$
2. **Geometrical**
   - Alumina: a=5 mm, b= 7.185 mm, L=308 mm
   - MCT: a= 3 mm, b= 4.567 mm, L=197 mm
   - Quartz: a= 8.9 mm, b= 4.567 mm, L=195 mm

→ *Use a 1D theory to answer this …*

1D Theory of Single Surface Multipactor

1. Ignore z motion → and integrate to find expressions for v(t) & r(t)

$$m\ddot{r} = -eE_{DC} - eE_{z0}\left(\frac{\pi a}{\lambda_z}\right)\sin(\omega t + \theta)$$

$$v_0 = \sqrt{2e_0/m_e} \qquad \textbf{(I.C.)}$$

2. e^- take exactly 1 RF period to return to the surface

$$r(t = T_{rf}) = 0 \rightarrow E_{DC} = \frac{m\omega}{e\pi}v_0 - \frac{a}{\lambda_z}E_{z0}\cos(\theta)$$

3. Last Trajectory at Saturation →

$$\theta = \pi$$

Simplifications (from 2D)

1. e1 < Ki < e2
2. Ignore z motion (OK)
3. Saturation only
4. No multihops

Multipactor induced power loss

$$P_m = N K_i / \tau$$

$$eN = 2\pi a \varepsilon_0 E_{DC} L$$

$$\tau = T_{rf}$$

$$K_i = \frac{1}{2} m v_r^2 = \frac{1}{2} m \left(v_{r0} - \frac{eT_{rf}}{m} E_{DC} \right)^2$$

Power Scaling (ignore e_0) →

$$E_{DC} \propto E_r$$

$$E_r = \frac{\pi a}{\lambda_z} E_z$$

$$P_m = N K / \tau \propto E_r^3$$

$$P_m = N K / \tau \propto a^4$$

Trouble for all DLA with large normal E field !!

→cylindrical

→planar

KEY → Multipactor in DLA dominated by E_r

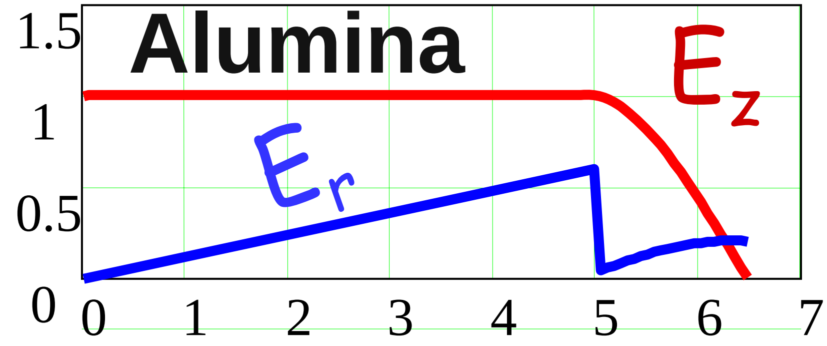
Er to Ez ratio depends on a

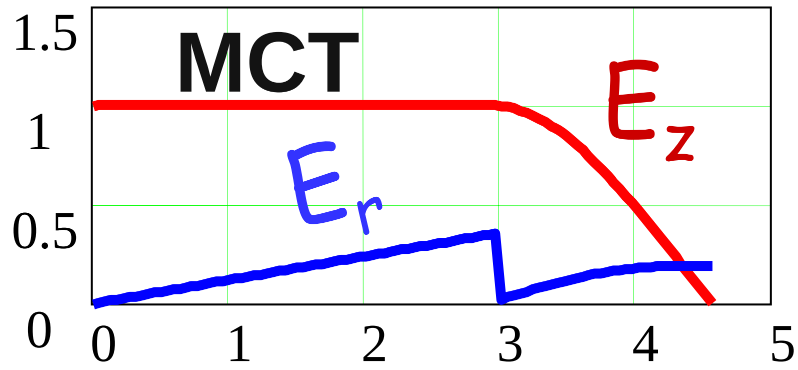
$$\frac{E_r}{E_z} = \frac{\pi a}{\lambda_z} =$$

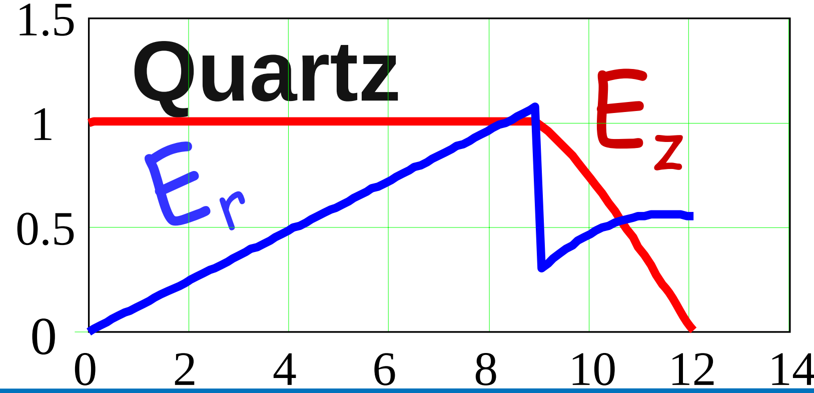
0.60 (alumina)

0.36 (MCT)

1.08 (Quartz)







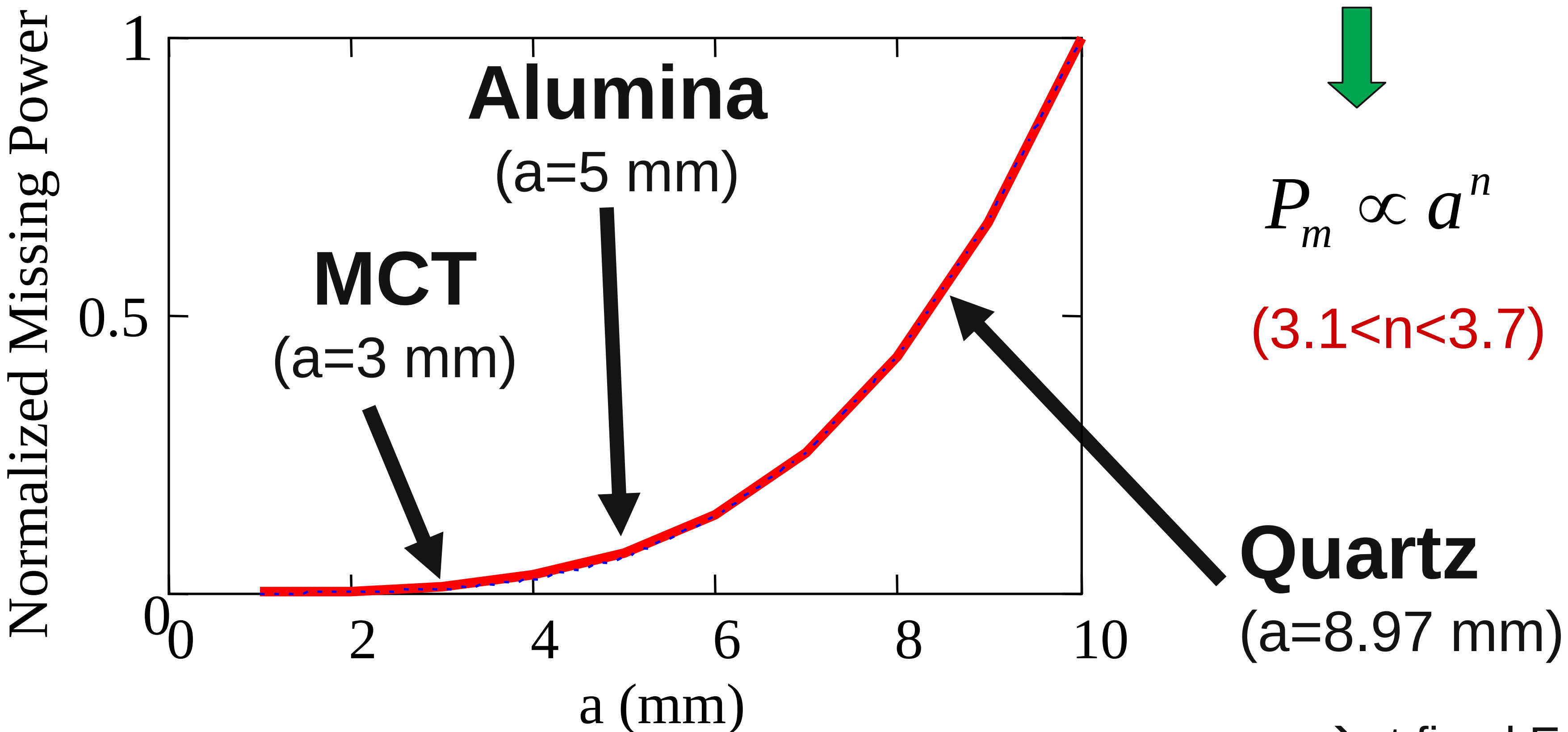
Multipactor Induced Power Absorption as a function of radius a

Ignoring e0 → $P_m = NK/\tau \propto a^4$ → Including e0

↓

$P_m \propto a^n$

(3.1<n<3.7)

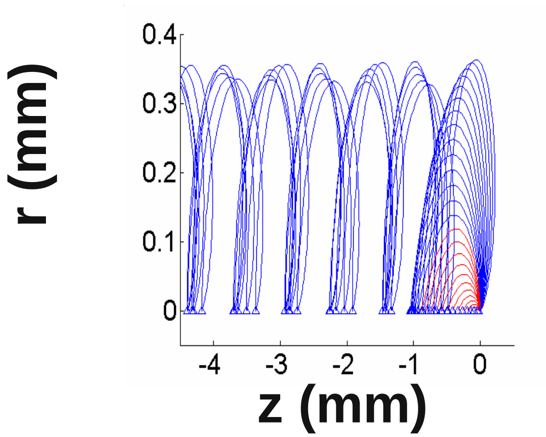


→at fixed Ez

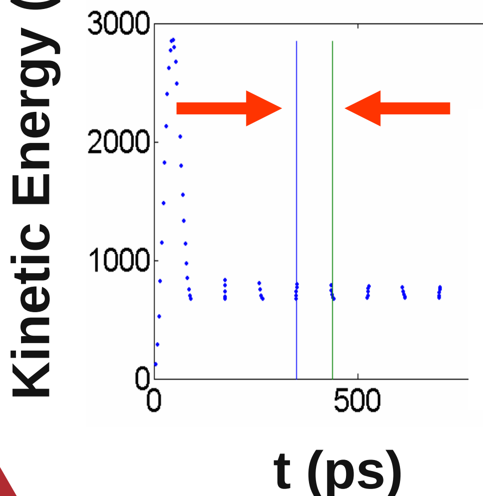
Single hop and Multihop Trajectories

1D Theory and/or e_0=0eV

single hop trajectories



Kinetic Energy of Impact



$\tau = T_{RF}$

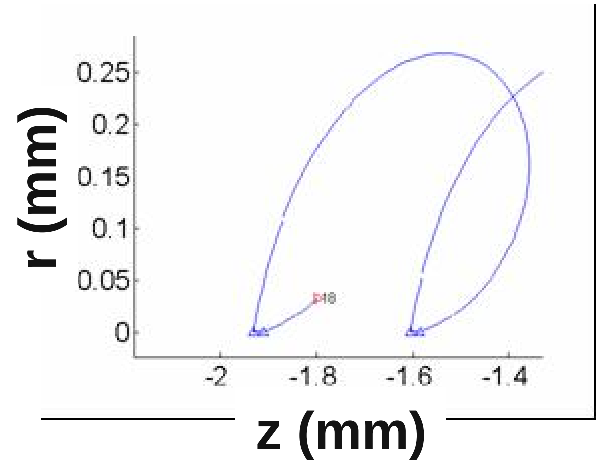
E_{RF}=6 MV/m

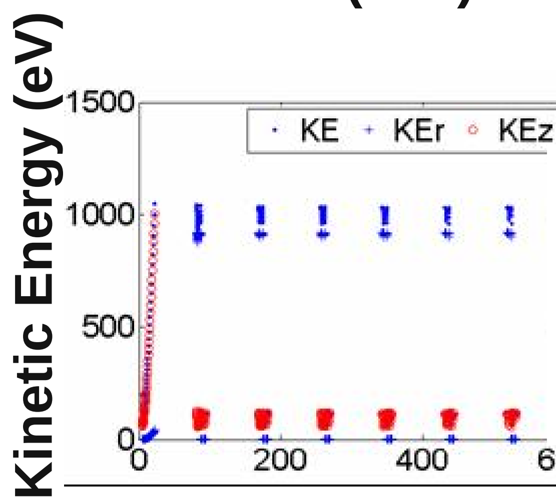
E_{DC}=1.1 MV/m

K_i = 0.8 keV

2D Model & $e_0 \neq$ 0eV

Multi-hop trajectories





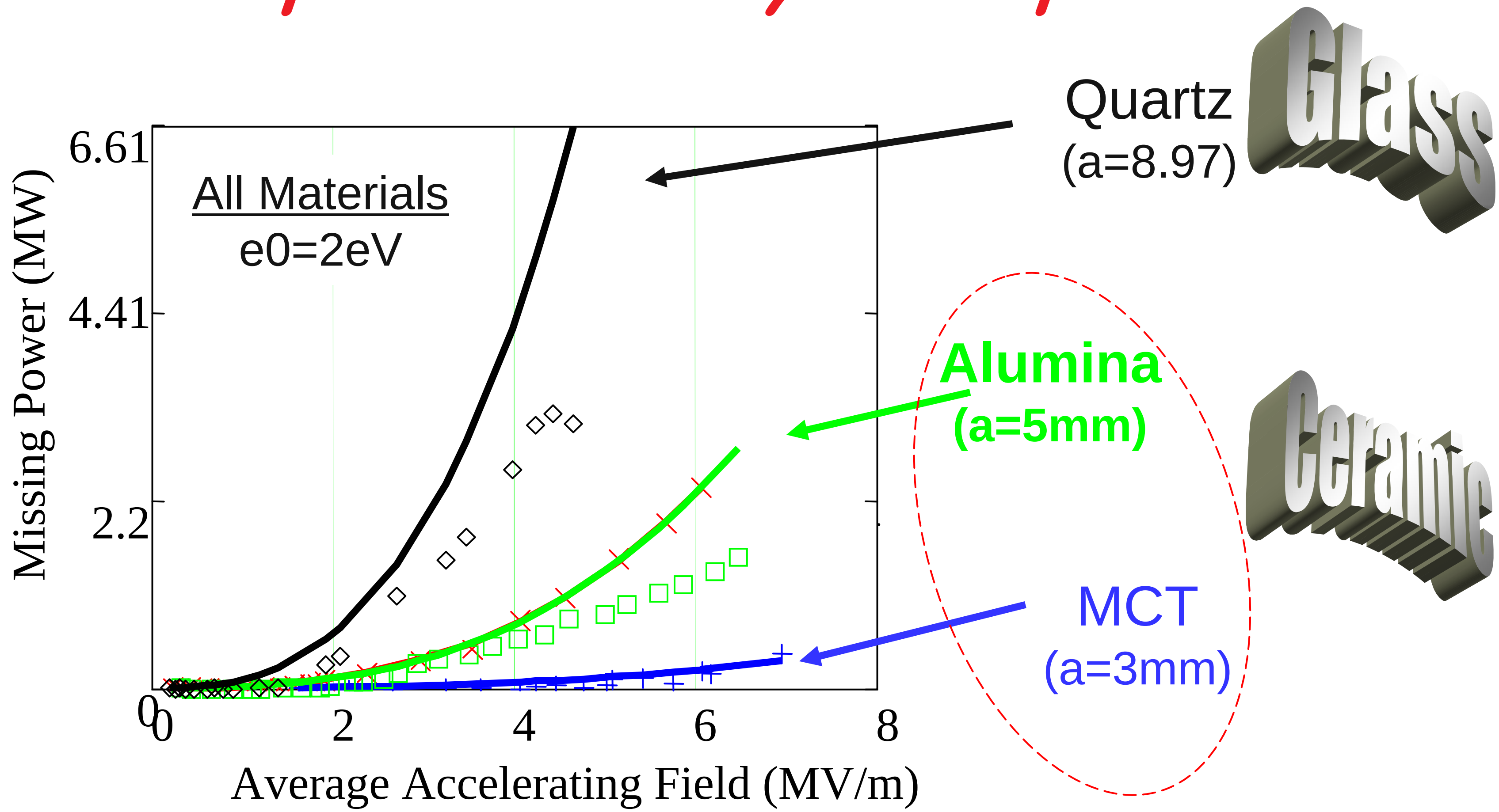
$\tau = T_{RF}$

E_{RF}=6 MV/m

E_{DC}=1.3 MV/m

K_i = 1.1 keV

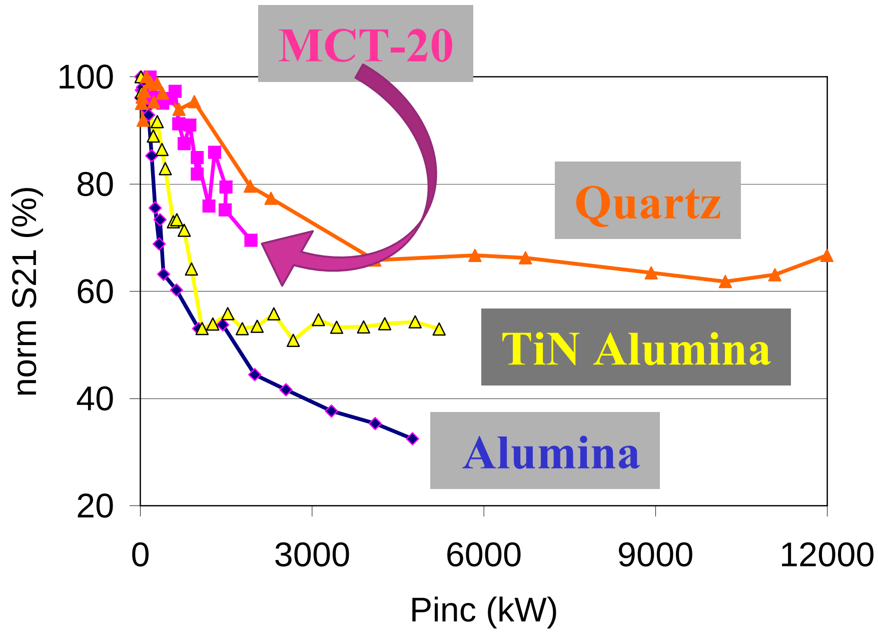
Comparison of 1D Multipactor Theory to Experiment

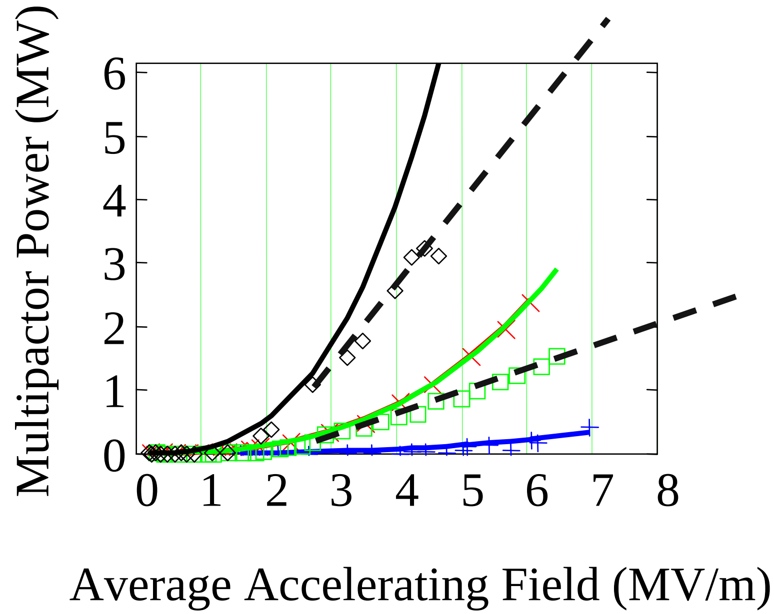


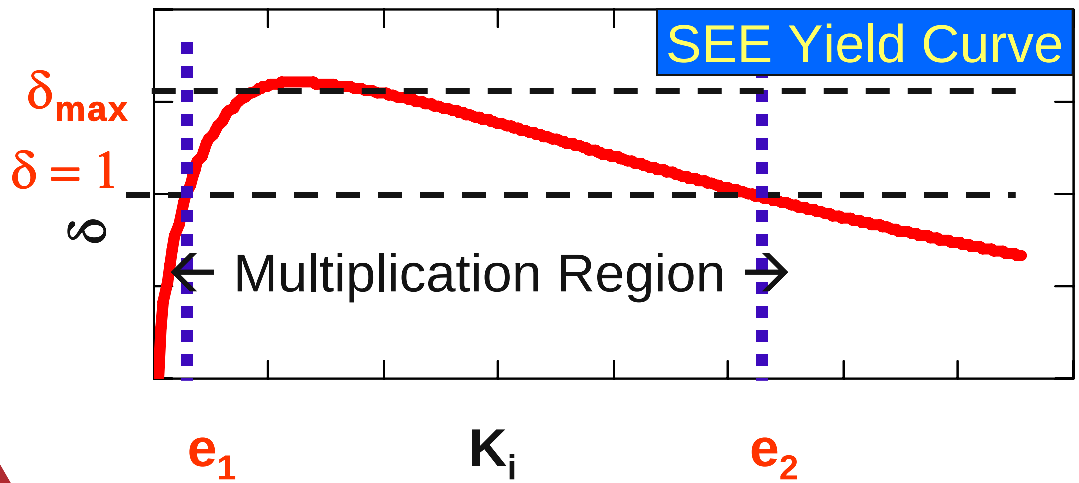
Geometry effects alone gets ~right magnitude
... but some features still depend on material

*Scaled Edc by 1.25 to get quantitative agreement (multihop)

Can we explain 'saturation' (slope change)? …back to 2D numerical model



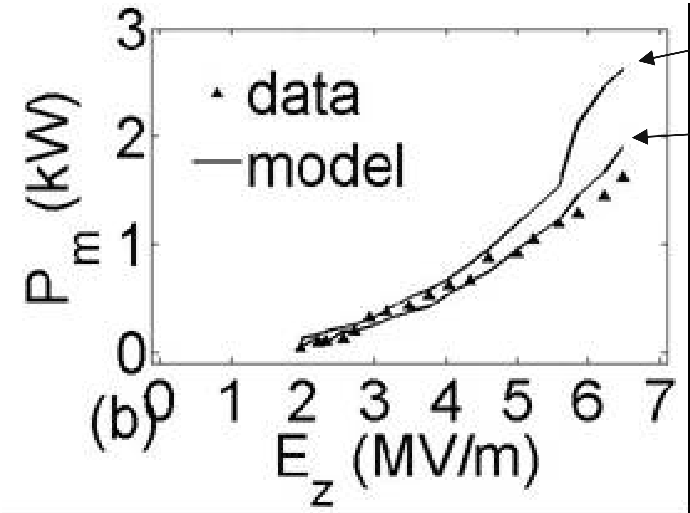




MCT & Alumina → ceramics

Quartz and TiN coated → Different e_0, e_1, e_2??

First attempts at fitting the TiN coated Alumina data

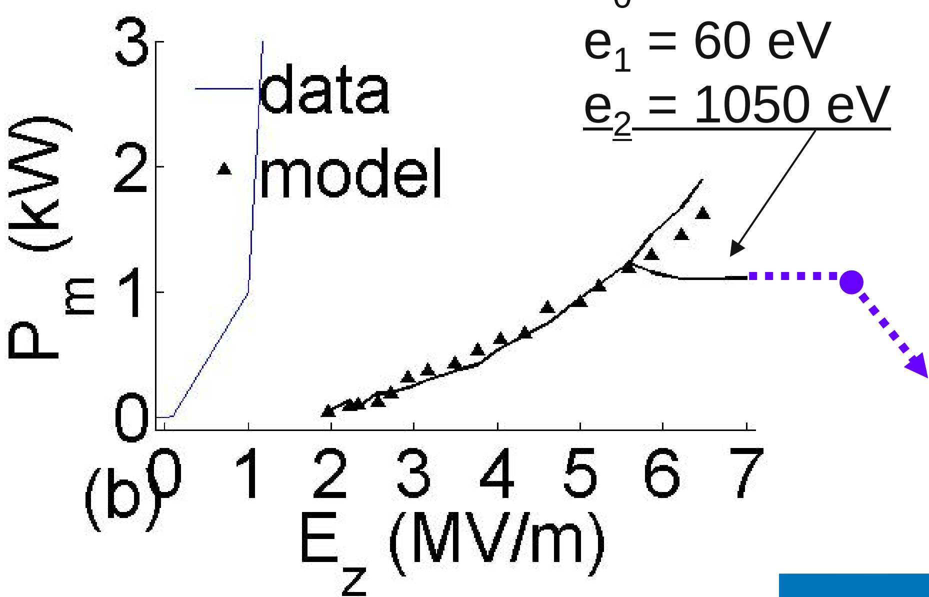


e_0= 2 eV (3 hops)

e_0= 1 eV (2 hops)

Best explanation so far → lowered emission energy, but still below e_2

e_0= 1 eV
e_1 = 60 eV
e_2 = 1050 eV



First attempt at adding e_2 to the model (preliminary)

- e2 caps K_impact
- ERF 5.86 → 7.00
- EDC 1.32 → 1.30
- new phase range: 15 → 30

→Multipactor RF loading is Capped
→May roll over

Future Direction of Multipactor Modeling in DLA Structure

FUTURE:
Modeling multipactor in the DLA structures

1. Test model predictions against experiment
   1. Geometric Parameters
      1. Multipactor scaling with length, '*L*':
      2. Multipactor scaling with inner radius, '*a*':
   2. Material Parameters:
      1. Bulk Materials: Make DLA structures with the same geometry ('*a*' and '*L*');
      2. Coatings: coating thickness (10 nm – 200 nm), coating materials (TiN, indium tin oxide (ITO), etc. coating techniques (ALD, sputtering, etc.)
2. Set up an S.E.E. measurement lab (or find a vendor.)
3. Extend Numerical Model & Theory
   1. **Scaling with length (L), frequency (f), pulse length (τ)**
   2. **Include second cross-over energy (e_2) and δ, ρealistic emission distribution (e_0)**
   3. …

Conclusions on DLA Multipactor Modeling (Preliminary and otherwise)

- Simple models explain most of the experimental features (but better theoretical models are in development)
  - Strong Multipactor in the DLA due to strong normal E-field (Should affect planar DLA too)
  - The difference in multipactor-induced power loss is primarily due to the different inner radius, *a*; secondarily due to materials.
- Continue to study how to suppress multipactor
- Does multipactor roll off at higher Er (Ki > e2)?

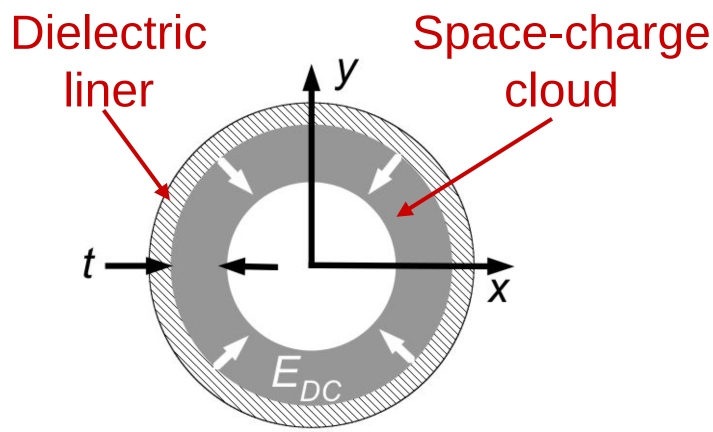
EXTRAS

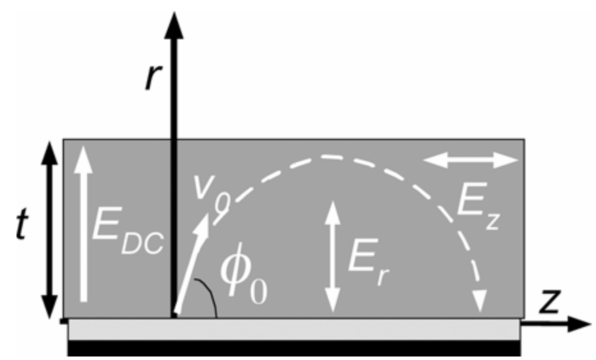
(extra) Multipactor suppression

- **Using one or more of the following methods to attempt to suppress multipactor**
  - Static Magnetic or Electric field
  - Short Pulse (τ) wakefield
  - Different ceramics with low SEE properties
  - Jump over the SEE regime
  - Low SEE coatings (TiN)
  - **Smaller inner radius to wavelength ratio: a/λ_z**

(extras) 2D Model details

(3) Space Charge Cloud, E_{dc} (at saturation, ignores dynamics)





$$v_0 = \sqrt{2e_0/m_e}$$

ϕ_0 = emission angle

e_0 = emission energy

2-D Equations of Motion

$$m\ddot{r} = -eE_{DC} - eE_{RF}\left(\frac{\pi a}{\lambda_z}\right)\sin(\omega t - k_z z + \theta)$$

$$m\ddot{z} = -eE_{RF}\cos(\omega t - k_z z + \theta)$$

λ_z = 2.6 cm; a = 5 mm; θ = emission phase

Simplifying Assumptions

- **Secondary electron emission is normal and monoenergetic ($\phi_0 = \pi/2$, e_0 = const.)**
- **Space charge field E_{DC} calculated from total electrons in cloud (N_e)**
- **Launch electrons with all emission phases ($0^0 < \theta < 360^0$), continue when secondary coefficient is >1 and emission phase is favorable**
- **Space charge increases until only resonant trajectory remains**