Multipactor Discharge in the Parallel-Plate Geometry with Two-Frequency RF Fields and Space-Charge Effects

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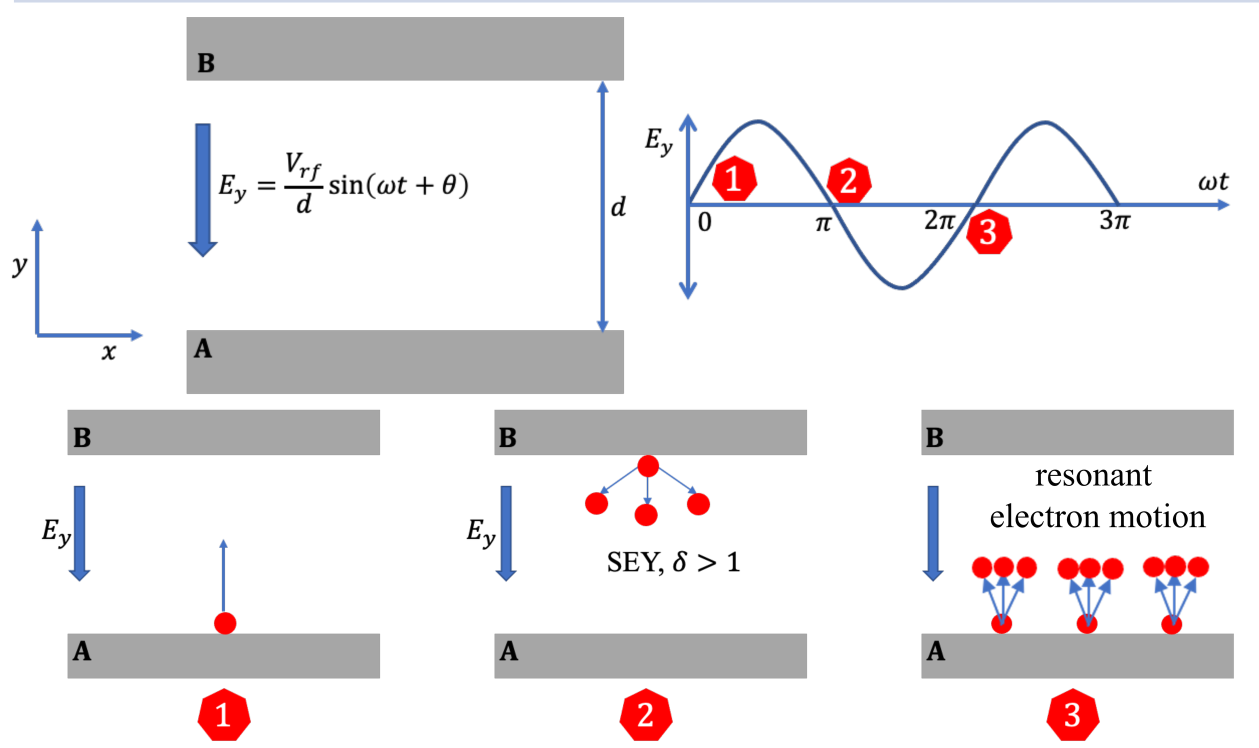
Motivation

- Multipactor [1,2] is a nonlinear phenomenon in which an electron avalanche driven by a high frequency rf field sustains itself by an exponential charge growth through secondary electron emission from a metallic or dielectric surface.
- Multipactor causes breakdown of dielectric windows, erosion of metallic structures, melting of internal components etc.
- Two-frequency RF operation significantly changes multipactor dynamics [2,3]
- Space-charge effects [3,4,5] play an important role in multipactor discharge, yet they are largely unexplored in existing literature

Resonant multipactor in parallel plate geometry

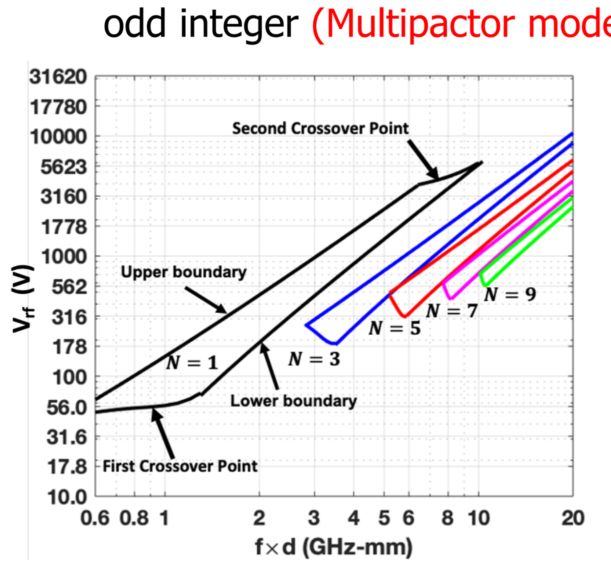


Conditions for successful two-surface multipactor development [1]:

- Secondary Electron Yield (SEY), $\delta > 1$
- $\omega, d, E_y \rightarrow$ must give rise to resonant electron motion

Multipactor susceptibility chart: 1D analytical model

- Resonance condition → electrons impact the opposing surface near the time the electric field changes direction
- Simplified Assumption → $y = d$ at $\omega t = N\pi + \theta \rightarrow N$ = positive odd integer (Multipactor mode) [1]



$$V_{rf} = \frac{m}{e}\frac{\omega d(\omega d - v_0 N\pi)}{N\pi cos\theta + 2sin\theta}$$

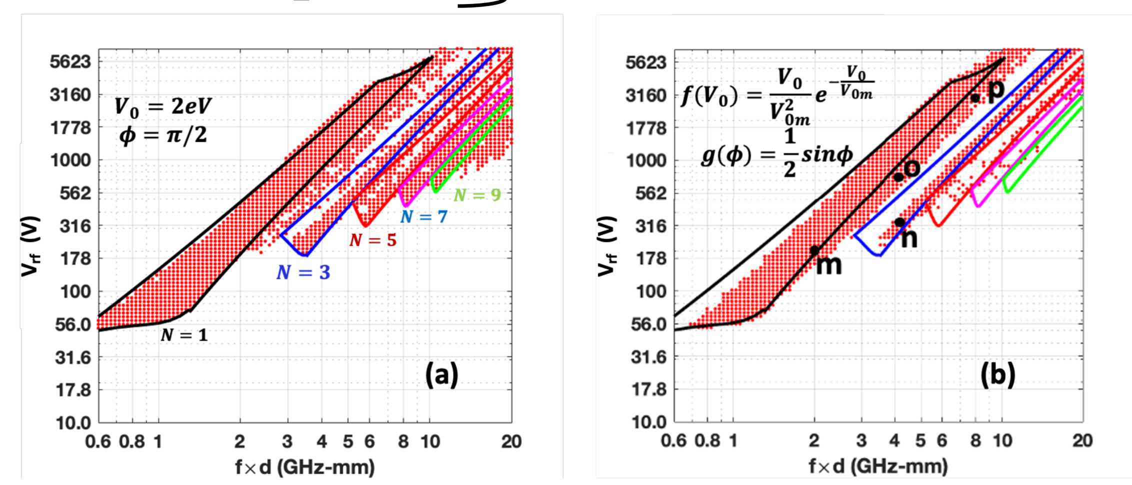
V_{rf} = peak RF voltage
ω = angular frequency
f = RF frequency
d = gap distance
v_0 = electron emission velocity
θ = RF phase at electron emission
N = multipactor mode (RF half cycles required for electron to traverse the gap distance)

2D Monte-Carlo (MC) Simulation

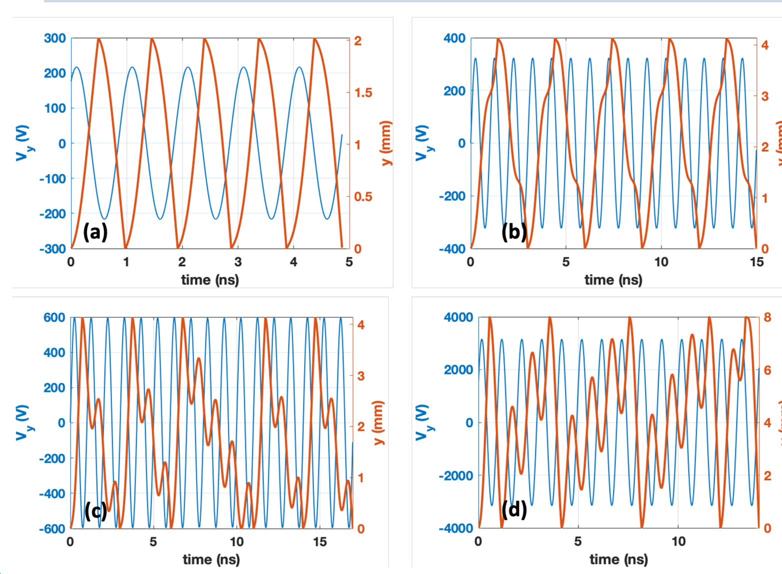
- Grid search in the (V_{rf}, fd) parameter space to identify parameter combinations that lead to multipactor discharge
- Distributions of random emission energy & angle [6]-

$$f(E_0) = \frac{E_0}{E_{0m}^2} e^{-\left(\frac{E_0}{E_{0m}}\right)}, \quad g(\phi) = \frac{1}{2} sin\phi$$

E_0= random emission energy
E_{0m}= peak of the distribution of emission energies

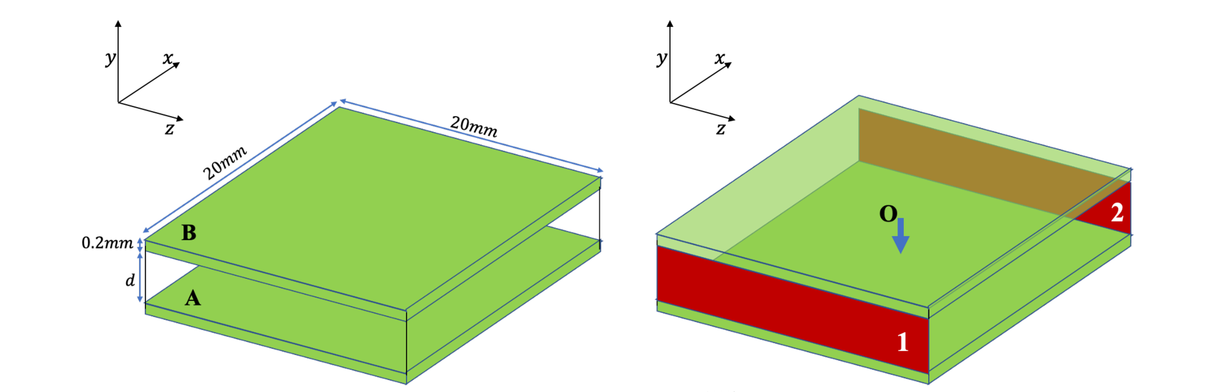


Multipacting Particle Trajectory: MC model

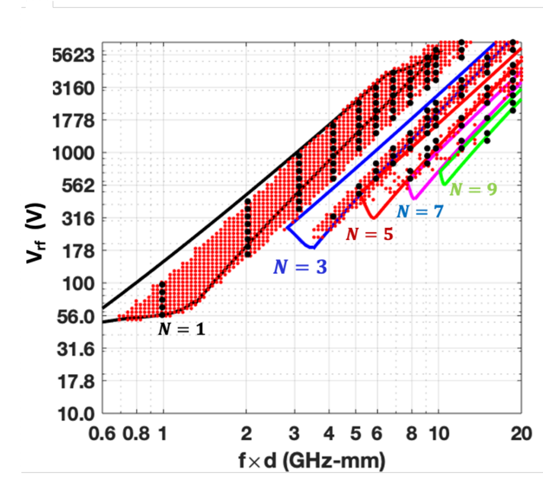


- Transit time from bottom plate to top plate (τ_{AB}) = Transit time from top plate to bottom plate (τ_{BA}) → Single multipactor mode (a,b) → points m, n in the susceptibility chart
- $\tau_{AB} \neq \tau_{BA}$ → mixed multipactor mode (c,d) → points o, p in the susceptibility chart

3D Electromagnetic CST Simulation [7]

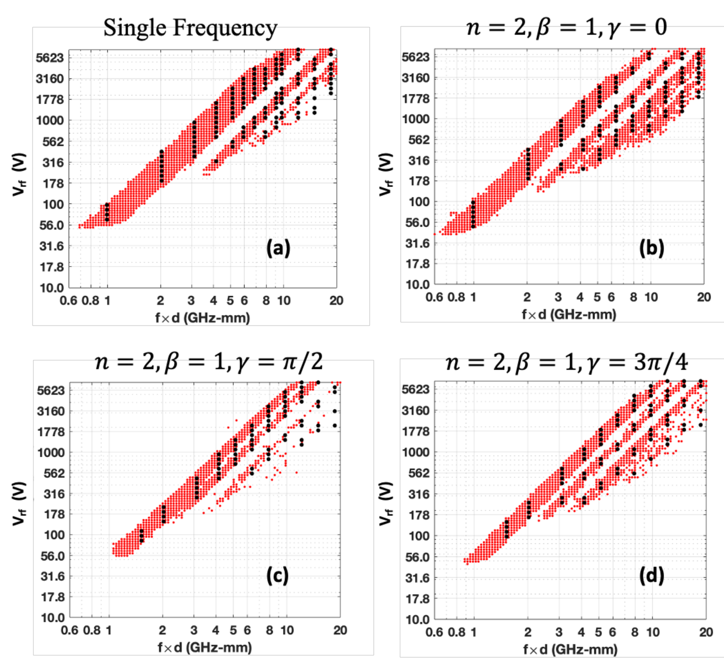


- **A, B** → Parallel metal plates (*Cu*)
- **1, 2** → Waveguide ports
- **O** → Electron source
- Emission energy: gamma distribution
- Emission angle distribution:
  Azimuthal → uniformly distributed
  Polar → $f(\theta) = cos\theta, \theta \in [0, \pi/2]$



Two-frequency RF operation: multipactor reduction

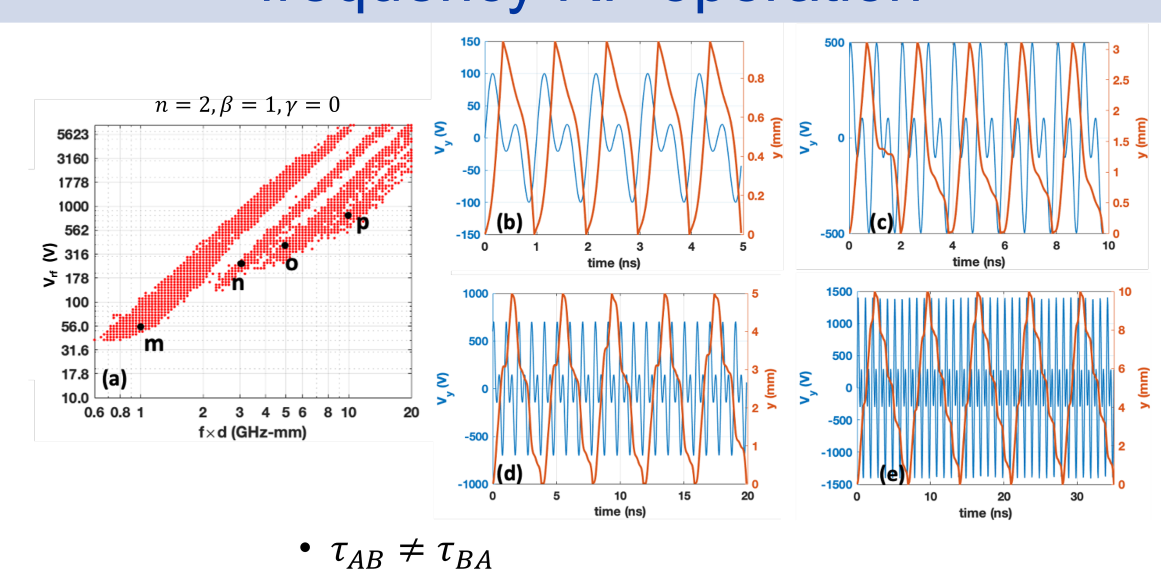
RF Field $\rightarrow \vec{E}_y = [\vec{E}_{rf}\sin(\omega t + \theta) + \beta\vec{E}_{rf}\sin(n(\omega t + \theta) + \gamma)]$



β = relative strength of the 2nd carrier mode
n = frequency ratio between the two carrier modes (need NOT be an integer)
γ = relative phase of the 2nd carrier mode

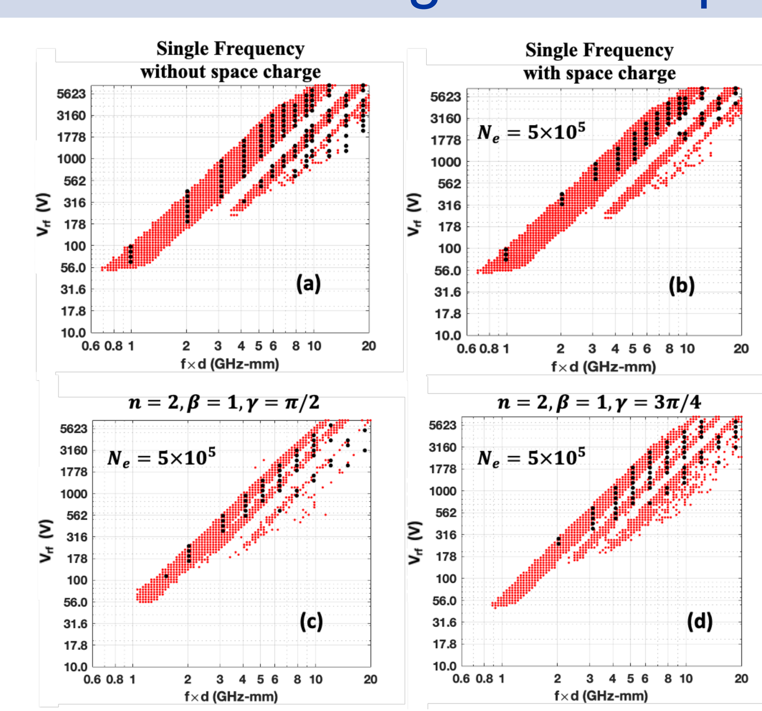
- Susceptibility is sensitive to the relative phase γ of the second carrier mode
- Multipactor reduction [2,3]

Novel mixed multipactor modes with two-frequency RF operation



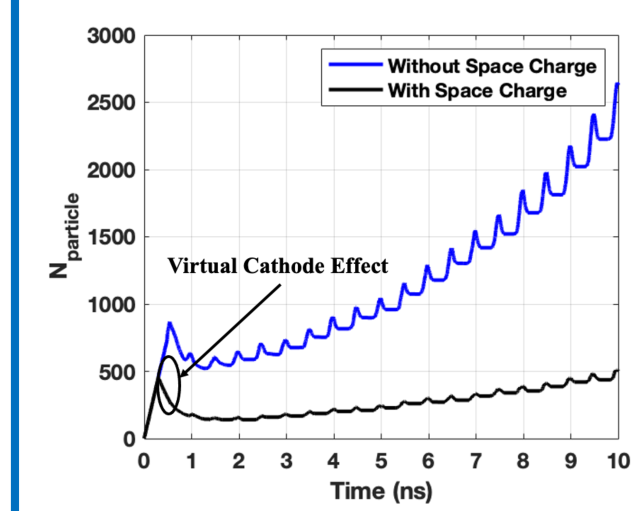
- $\tau_{AB} \neq \tau_{BA}$
- $\tau_{AB} + \tau_{BA} = \tau_{round}$ = constant

CST simulation with Space charge effects: Shrinking of susceptibility bands



- Susceptibility bands shrink due to effects introduced by accumulated space charge in the planar gap [5]
- Important to choose sufficient electron-to-computer particle ratio (N_e) in CST simulation to observe space-charge effects

Which space-charge effects are in play?



- Virtual cathode effect [4] → space charge accumulated in the planar gap reduces further electron emission from the surface
- Disruption of resonant electron motion
- Reduced impact energy of primary electrons → reduced secondary electron yield (SEY)
- Reduced electron growth rate over a long period of time [3]

Conclusion

- Shrinkage of multipactor susceptibility regions observed for different configurations of two-frequency rf operation
- Regions of different multipactor modes observed in the susceptibility chart for multipactor modes under two-frequency operation
- Space charge significantly changes the time dependent physics of multipactor discharge
- Electron growth rate over a long period of time lowered with space charge because of the virtual cathode effect, disruption of the resonant electron motion, and reduced SEY due to the reduced impact energy of primary electrons
- Susceptibility bands in the multipactor susceptibility chart shrink in the presence of space charge

Future Work

- The effect of non-integer frequency separation on two-frequency rf field induced two-surface multipactor
- Two-frequency rf induced two-surface multipactor in other geometries (microstrip, circular, and co-axial waveguides)
- Study of multi-carrier rf operation, including non-sinusoidal waves

Reference

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