Time-Dependent Physics of Single-Surface Multipactor with Dual-Tone RF Carriers

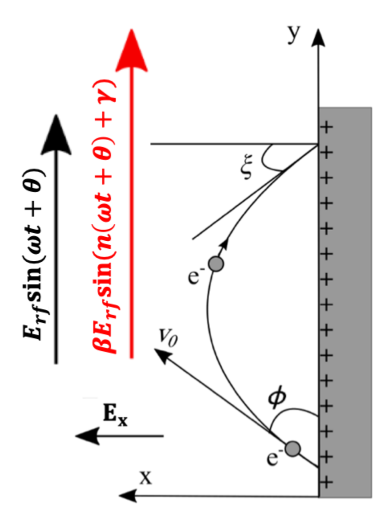
Asif Iqbal[a], Patrick Y. Wong[a], John Verboncoeur[a,b], and Peng Zhang[a]

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, and perforation of vacuum walls, etc.
- Study of the time-dependent physics [3] offers a better understanding of the multipactor dynamics.

Dual tone single surface multipactor

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



- β = relative strength of the 2[nd] carrier mode
- γ = relative phase of the 2[nd] carrier mode
- n = frequency ratio between the two carrier modes (need NOT be an integer)
- ϕ = initial angle of electron flight
- v_0 = initial velocity
- ξ = impact angle
- E_x = normal electric field

Monte Carlo Simulation

Distributions of random emission energy & angle [4, 5]-

$$f(E_0) = \frac{E_0}{E_{0m}^2} e^{-\left(\frac{E_0}{E_{0m}}\right)}$$

$$g(\phi) = \frac{1}{2}\sin\phi$$

E_0 = random emission energy

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

The Force Law

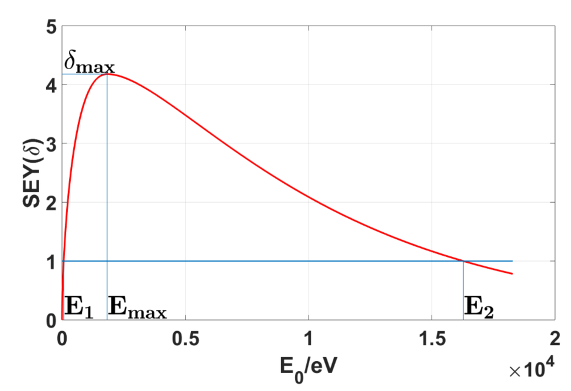
$$m\frac{\partial\vec{v}}{\partial t} = -|e|\left[\vec{E}_{rf}\sin(\omega t+\theta) + \beta\vec{E}_{rf}\sin(n\omega t+\theta+\gamma) + \vec{E}_x\right]$$

$$\begin{cases} v_x = -\dfrac{|e|}{m}E_x t + v_0\sin\phi \\ v_y = \dfrac{|e|}{m\omega}E_{rf}\left\{\cos(\omega t+\theta) - \cos\theta + \dfrac{\beta}{n}[\cos(n\omega t+\theta+\gamma) - \cos(\theta+\gamma)]\right\} + v_0\cos\phi \end{cases}$$

$$\begin{cases} x = -\dfrac{|e|}{2m}E_x t^2 + v_0 t\sin\phi + x_0 \\ y = \dfrac{|e|}{m\omega}E_{rf}\left\{\dfrac{1}{\omega}\sin(\omega t+\theta) - t\cos\theta + \dfrac{\beta}{n}\left[\dfrac{1}{n\omega}\sin(n(\omega t+\theta)+\gamma) - t\cos(n\theta+\gamma)\right]\right\} + v_0 t\cos\phi + y_0 \end{cases}$$

Secondary Electron Yield (SEY)

- Secondary electron yield (δ) depends on primary electrons' impact energy and impact angle [6].



- E_1 = first crossover point
- E_2 = second crossover point
- Impact energy between E_1 and E_2 → $SEY > 1$ → charge growth
- SEY model used: Vaughan's model [6]

Vaughan's Model of SEY [6]

$$\delta = \delta_{max}(we^{1-w})^k, w \le 3.6$$

$$\delta = \delta_{max}(1.125/w^{0.35}), w > 3.6$$

$$k = \begin{cases} 0.56, & w < 1 \\ 0.25, & 1 \le w \le 3.6 \end{cases}$$

$$w = E_i/E_{max}$$

$$E_{max} = E_{max0}\left(1 + \frac{K_{sE}\xi^2}{2\pi}\right)$$

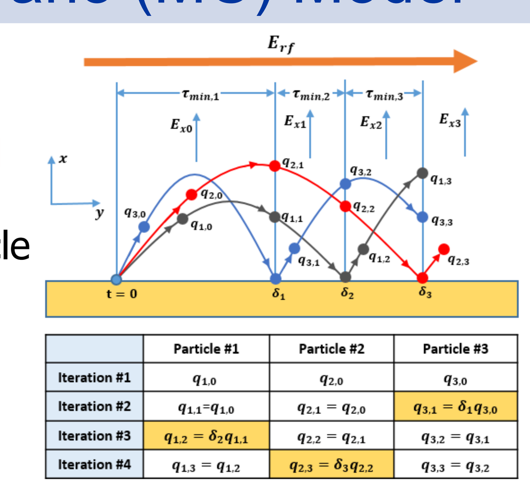
$$\delta_{max} = \delta_{max0}\left(1 + \frac{K_{s\delta}\xi^2}{2\pi}\right)$$

- E_{max0} = impact energy for δ_{max0}
- δ_{max0} = maximum yield at impact angle $\xi = 0$
- E_i = impact energy of macroparticle
- k_{sE}, $k_{s\delta}$ = surface smoothness factors ($k_{sE} = k_{s\delta} = 1$ used)

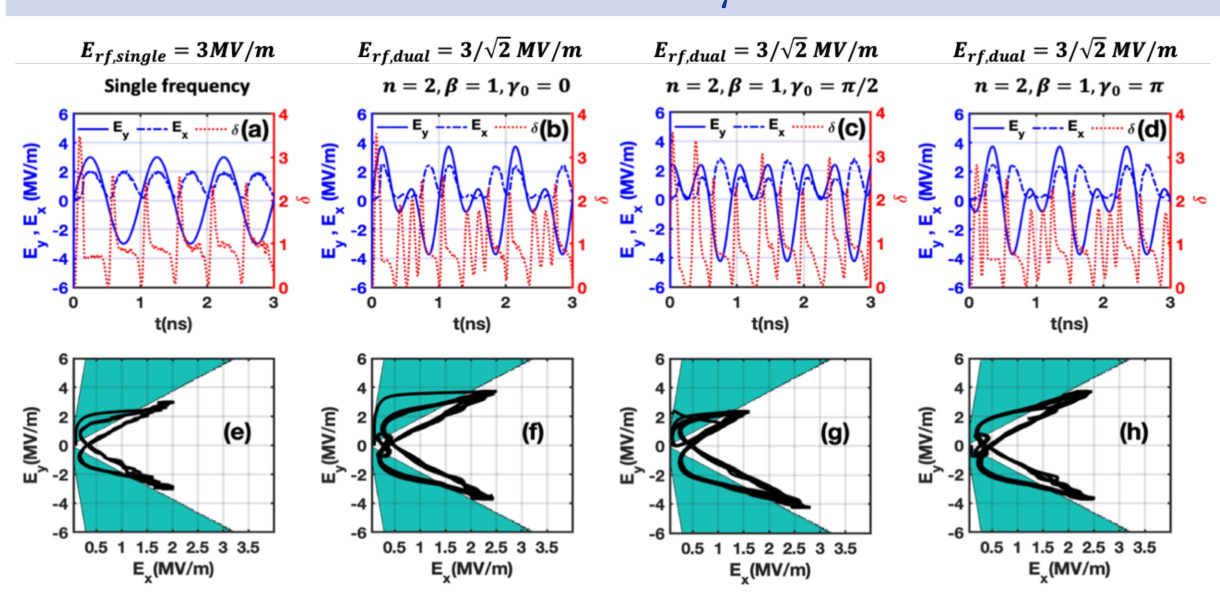
Multiparticle Monte Carlo (MC) Model

Multiparticle MC model [7]-

- large number of macroparticles
- number of macroparticles kept fixed ($N = 200$)
- charge in the impacting macroparticle changed and normal electric field updated at each impact
- time intervals between subsequent bounces of particles on the surface calculated exactly



Temporal study of dual tone multipactor
- effect of γ



Temporal study of dual tone multipactor
- effect of γ

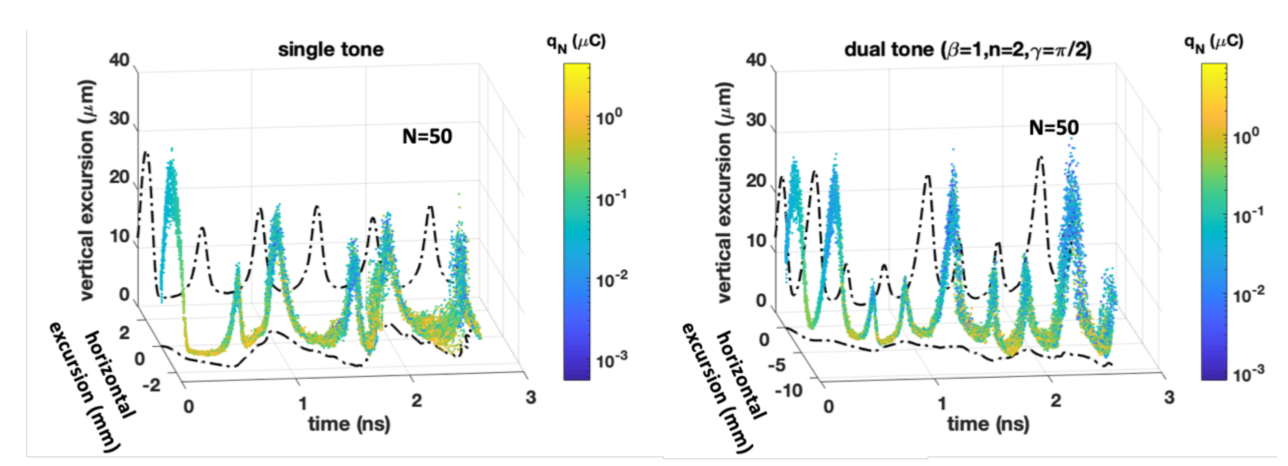
- Single Frequency → E_x and δ oscillates at twice the rf frequency [3]
- $n = 2, \beta = 1, \gamma = 0, \pi$ → E_x and δ oscillates at four times the rf frequency [7]
- $n = 2, \beta = 1, \gamma = \pi/2$ → E_x and δ oscillates at three times the rf frequency

Temporal study of dual tone multipactor
-Time spent by E_x in small and large loops

RF field configuration		Time spent (ns) in growth (decay) regime		Time averaged normal electric field $E_x(MV/m)$
		in large loops	in small loops	
Single tone		0.2 (0.8)	0 (0)	0.9
Dual tone	$n = 2, \beta = 1, \gamma_0 = 0$	0.13 (0.54)	0.17 (0.16)	0.756
	$n = 2, \beta = 1, \gamma_0 = \pi/2$	0.08 (0.25)	0.21 (0.46)	0.775
	$n = 2, \beta = 1, \gamma_0 = \pi$	0.13 (0.54)	0.17 (0.16)	0.7501

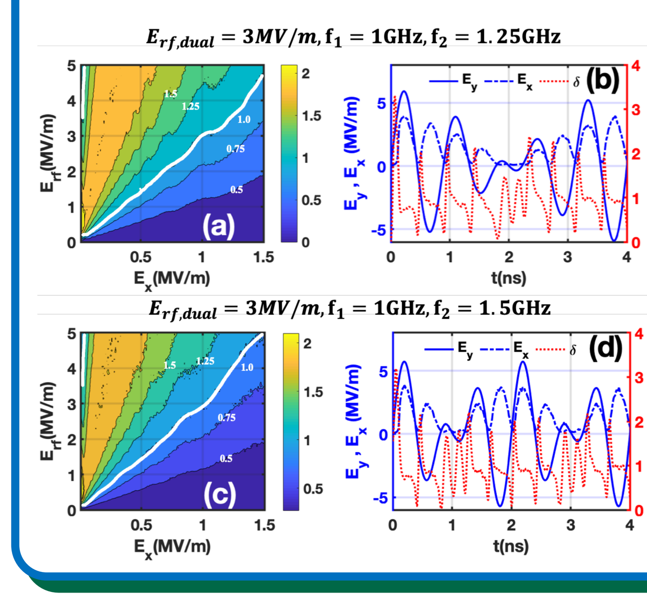
- Dual tone operation→
  - growth time in small loops > growth time in large loops
  - growth rate in small loops < growth rate in large loops
  - lower electron population for a longer duration during an rf period [7]
  - Time averaged normal electric field E_x (multipactor strength) reduced with the same rf power as the single tone case

Temporal study of dual tone multipactor
- analyzing macroparticle trajectories



- Single tone operation → the rf field has periodic symmetry in positive and negative directions along the surface → negligible time averaged horizontal displacement of macroparticles
- Dual tone operation → the rf field may not have periodic symmetry in positive and negative directions along the surface → significant time averaged horizontal displacement of macroparticles
- Can be useful for cleaning a given location in a structure to reduce further susceptibility to multipactor, or for directing multipacting electrons to a specific desirable location in the geometry

Temporal study of dual tone multipactor
- effect of n



- Susceptibility boundary relatively insensitive to the frequency ratio, n, for $n = 1.25, 1.5$
- Temporal profile of E_x significantly changes with respect to n
- Beat waves are produced in the temporal profiles of E_x
- Frequency domain analysis required to resolve the frequency components of E_x

Conclusion

- For dual tone operation of the rf electric field, the normal electric field oscillates at higher frequency than that for the single tone operation of the rf electric field.
- The time averaged normal electric field E_x (corresponding to multipactor strength) is decreased compared to the single tone operation for the dual- tone case with total rf power equal to the single tone case.
- Non-integer frequency ratio between the two carrier modes produces beat wave pattern in the temporal profile of the normal electric field.
- Multipactor particle trajectories can be controlled by controlling parameters n, β, and γ of the second carrier mode.

Future Work

- Frequency domain analysis of the dual tone single surface multipactor
- Temporal study for different non-sinusoidal rf waveshapes
- Study of multi-frequency operation

Reference

1. P.T. Farnsworth, J. Frankl. Inst. **218**, 411 (1934).
2. Asif Iqbal, John Verboncoeur, and Peng Zhang, Phys. Plasmas **25**, 043501 2018.
3. H.C. Kim and J.P. Verboncoeur, Phys. Plasmas **12**, 123504 (2005).
4. R.A. Kishek and Y.Y. Lau, Phys. Rev. Lett. **80**, 193 (1998).
5. P. Zhang, Y. Y. Lau, M. Franzi and R. M. Gilgenbach, Phys. Plasmas **18**, 053508 (2011).
6. R.M. Vaughan, IEEE Trans. Electron Devices **40**, 830 (1993).
7. A. Iqbal, J. Verboncoeur, and P. Zhang, Phys. Plasmas **26**, 024503 (2019).

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(a) Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
(b) Department of Computational Mathematics, Science and Engineering, Michigan State University, East Lansing, MI 48824, USA

Email: {iqbalas3, wongpat3, johnv, pz}@egr.msu.edu