

Influence of Finite Velocity Spread on Hybrid-Resonance Modes of Two-Sided Multipactor

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Abstract

Hybrid-resonance modes in multipactor breakdown is studied within a simple plane-parallel model using both an analytical approach and numerical simulations. Particular attention is given to effects of a spread in the initial velocities of secondary emitted electrons and it is shown this leads to either a suppression of the hybrid resonance modes or to an overlapping and merging of many hybrid-resonance modes. Numerical simulations show that the outcome depends crucially on the value of the secondary emission yield. The obtained results are consistent with experiments, which have demonstrated a wider region of multipactor breakdown than predicted by the commonly accepted theory.

The phenomenon of electron multipactor is considered as one of the main reasons for vacuum breakdown in high power microwave devices. It has been studied theoretically during more than 50 years see e.g. [1]. Generally, the theoretical predictions are in good agreement with experimental results. However, more detailed comparisons demonstrate some discrepancies between theory and experiment. Therefore so far there is no single, commonly accepted picture concerning the structure of multipactor zones in parameter space. Whereas some authors consider the zones to be overlapping others have a quite opposite view assuming well separated zones. Detailed analysis has been undertaken to clarify this point and its results are presented below. In particular a consistent discrepancy has been found between results of numerical simulations and predictions of commonly accepted theories of the resonance multipactor. This discrepancy can be understood by taking into account the excitation of hybrid multipactor modes, originally pointed out by Sombrin [2] and later analyzed by Gilardini [3]. As shown in this paper, there are even more complicated hybrid modes than those predicted by Gilardini. These modes are very sensitive to a spread of the initial velocity of the secondary electrons and the value of the secondary emission yield. When the secondary emission yield is high enough, the zones of hybrid modes overlap even for relatively small velocity spread. In fact, under realistic conditions one can expect overlapping of all multipactor zones in this case. At the same time the hybrid modes are completely suppressed by a velocity spread if the secondary emission yield is less than some threshold value (higher than unity). In the latter case only the classical resonant multipactor modes with well separated zones are possible.

Within the simple theory for two-sided multipactor, electrons are assumed to oscillate between two parallel plates separated by a distance L . These oscillations are driven by a spatially homogeneous RF electric field directed perpendicular to the plates and varying harmonically in time as $E = E_0 \sin \omega t$. The impact of an electron with the plates is assumed to result in production of secondary electrons. The production yield depends on the impact energy of the primary electron. Specifically, in order to release more than one secondary electron, the impact velocity, U , of the primary electron must lie within a definite interval $V_1 < U < V_2$ where the characteristic velocities, V_1 and V_2 are determined by the properties of the material of the plates. It is assumed that all secondary electrons start with the same initial velocity V_0 . In this case the motion of an electron can be described by the equations:

$$v = v_0 + \cos \varphi_1 - \cos \varphi \quad x = (\varphi - \varphi_1)(v_0 + \cos \varphi_1) + \sin \varphi_1 - \sin \varphi \quad (1)$$

where v is the electron velocity normalized to the amplitude of the electron velocity oscillations in the RF field $V_\omega = \frac{eE_0}{m\omega}$, $v_0 = V_0/V_\omega$, x is the electron coordinate normalized to V_ω/ω , $\varphi = \omega t$ is the instantaneous phase of the RF field, $\varphi_1 = \omega t_1$, where t_1 denotes the initial time when the electron starts from the plate with the coordinate $x = 0$. When the starting phase φ_1 belongs to a certain favorable interval (which depends on the parameters $\lambda = \omega L/V_\omega$ and v_0), the electron will arrive to the second plate with an impact phase ψ_1 , which is determined by the smallest root (that exceeds φ_1) of the transcendental equation

$$\lambda = (\psi_1 - \varphi_1)(v_0 + \cos \varphi_1) + \sin \varphi_1 - \sin \psi_1 \quad (2)$$

The motion of the corresponding secondary electron is still described by equation (1), however for another starting phase $\varphi_2 = \psi_1 - \pi k_1$ (here k_1 is an odd number and $-\pi < \varphi_2 < \pi$). This secondary electron will arrive at the opposite plate with some impact phase ψ_2 , provided its starting phase belongs to the favorable interval. Thus every electron trajectory generates a sequence of starting phases φ_r ($r = 1, 2, \dots$) corresponding to the odd numbers k_r :

$$\lambda = (\pi k_r + \varphi_{r+1} - \varphi_r)(v_0 + \cos \varphi_r) + \sin \varphi_r + \sin \varphi_{r+1} \quad (3)$$

This sequence can be infinite or finite if the last starting phase is unfavourable for electrons to go away from the plate of birth. Obviously, the multipactor development requires the existence of an electron trajectory with an infinite sequence of starting phases. Specifically any periodic sequence (with $\varphi_{p+1} = \varphi_1$ and $k_{p+1} = k_p$) is infinite and could give rise to multipaction. The simplest case is the ordinary resonance when all φ_r and k_r are the same, i.e. the corresponding sequence has a period, $p = 1$. Most researchers restrict themselves to an analysis of this simplest case only. The multipactor modes analyzed by Gilardini correspond to period $p = 2$. However, analysis and numerical simulations show that modes with a period $p > 2$ are also possible.

For given value of the parameter λ any mode of such type is completely characterized by certain finite series of odd numbers k_1, k_2, \dots, k_p , which play the same role as the single odd number k in the case of the ordinary resonance. To some extent, one can treat these modes as a combination of ordinary resonances of different orders and we suggest to call them hybrid resonance modes. For any possible hybrid mode, a series of starting phases $\varphi_1, \varphi_2, \dots, \varphi_p$ is determined by the roots of a set of transcendental equations (4)

with $r = 1, 2, \dots, p$, and $\varphi_{p+1} = \varphi_1$. Choosing index 1 to denote the minimum value among φ_r , one can illustrate the occurrence of such modes in the plane λ vs φ_1 (see Fig. 1).

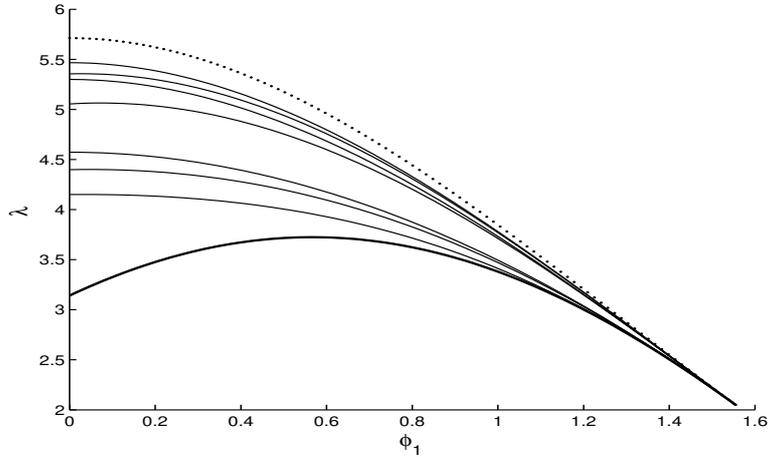


Figure 1: Examples of the resonance curves in the plane λ vs. φ_1 (here $\varphi_1 = \min \varphi_r$) for some sequences k_1, k_2, \dots, k_p and zero initial velocity $V_0 = 0$. The lowest curve corresponds to the ordinary resonance of the first order ($p = 1, k_1 \equiv k = 1$). The higher lines correspond to $k_1 = k_2 = k_3 = 1, k_4 = 3$; $k_1 = k_2 = 1, k_3 = 3$; $k_1 = k_2 = 1, k_3 = 101$; $k_1 = 1, k_2 = 3$; $k_1 = 1, k_2 = 3, k_3 = 101$; $k_1 = 1, k_2 = 5$; $k_1 = 1, k_2 = 5, k_3 = 101$ respectively. The dotted line corresponds to the upper boundary of the region filled by hybrid resonance modes with $k_1 = 1$.

In the case of $V_0 = 0$ the parameters of the particular hybrid modes with $p = 2$ can be expressed in explicit form. For the general case, it is possible to state that in the plane λ vs φ_1 , an infinite number of hybrid modes forms a series of separated bands accompanying each ordinary resonance curve as shown in Fig.1. The lower boundary of each band corresponds to the ordinary resonance mode $\lambda = \pi k(v_0 + \cos \varphi_1) + 2 \sin \varphi_1$ and the upper boundary of each band can be expressed as $\lambda = (\pi k + \pi/2 - \varphi_1)(v_0 + \cos \varphi_1) + 1 + \sin \varphi_1$

A necessary condition for the first starting phase is caused by the requirement that the electron will not return to the plate of birth due to the retarding action of the RF field. When $v_0 \ll 1$ (which is typical for multipactor), this condition can be expressed approximately as the inequality: $-\sqrt{8v_0/3} < \varphi_1 < v_0 + \pi/2$. Within most theories the stability of the resonance mode with respect to deviations of the first starting phase is considered as an important condition for the realization of this multipactor mode. For any hybrid resonance mode this condition can be generalized and together with the previous requirement it results in relatively narrow, well separated bands of the parameter λ associated with these modes. The corresponding bands of hybrid modes are much more narrow. In particular, at $v_0 = 0$ the hybrid mode with $p = 2, k_1 = 1, k_2 = 3$ is the most stable one, however its bandwidth of stability is less than 0.01 ($\Delta\lambda_{1,3} \approx 0.008$). On the other hand there is an infinite number of hybrid modes within every finite interval of the parameter λ near each zone of the ordinary resonance mode.

The simple multipactor theory does not take into account the spread of the initial velocity of the secondary electrons that exists in any experiment. This spread is known to give rise to two important effects. First, it disturbs the resonance between the electron

and the field oscillations and thereby results in losses of electrons. Second, it promotes overlapping of different resonance bands provided that the secondary emission is high enough. Estimates show that hybrid resonance modes should be considerably blurred by any realistic velocity spread. At the same time, the effect of velocity spread should not significantly disturb the first resonance mode of multipactor. To confirm these assumptions we have carried out detailed numerical simulations of the problem with different values of the velocity spread. To understand more clearly the role of the secondary emission rate we assumed a step-function dependence of the emission yield σ on the impact electron velocity, i.e. $\sigma = \sigma_m = \text{constant}$, if $U > V_1$ and $\sigma = 0$. Within our series of calculations, the ratio V_ω/V_1 was set equal to the constant value 1.5 and the spread of initial velocities of the secondary electrons was approximated by a Maxwellian distribution function, $F(V) \propto \exp[-V^2/(2V_T^2)]$ with varying value of the thermal velocity V_T .

For small values of V_T , we found from 3 to 4 separated multipactor zones depending on the value of σ_m . In principle, the first and the last zones could be correlated with the first and second zones of the ordinary resonances. Other zones lie in the region of hybrid modes and are associated with excitation of different hybrid modes only. It should be noted that the higher boundary of the first zone lies in the region of hybrid modes. This demonstrates clearly the overlapping between the first ordinary resonance and the neighboring hybrid modes which becomes more pronounced with increasing σ_m . For higher values of V_T , two separated multipactor zones have been found and only within the range $2 < \lambda < 10$. However the first zone has considerably higher bandwidth compared to the zone of the first ordinary resonance. For $\sigma_m = 2$ this zone includes the whole region of the hybrid modes.

The classical experiment [4] demonstrated the existence of a separate first zone of multipactor. However the width of the observed zone was found to be larger than predicted by the theory of the ordinary resonance mode. The above results can explain this discrepancy. A plane parallel model of multipactor has been studied in detail using both an analytical approach and numerical simulations. An infinite number of new multipactor modes have been found. The new modes are associated with hybrid resonances of the multipactor. The corresponding zones fill certain regions in parameter space between the well known resonant zones. The results of numerical simulations demonstrate that even a relatively small spread of initial electron velocities significantly affects the structure of the multipactor zones. The latter are very sensitive to the value of the secondary emission yield. This implies that a detailed chart of the multipactor zones cannot be given based on a theory, which assumes only one fixed value of the electron initial velocity. In fact, it is absolutely necessary to take into account the actual spread of the secondary electrons over initial velocities in order to obtain reliable predictions. Such an analysis requires extensive numerical simulations.

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