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Microwave Breakdown in RF Devices

D. Anderson[1], M. Buyanova[2], D. S. Dorozhkina[2], U. Jordan[1], M. Lisak[1], I. Nefedov[3], T. Olsson [4], J. Puech[5], V. Semenov[2], I. Shereshevskii[5], R. Udiljak[1]

[1] *Depart. Radio and Space Science, Chalmers Univ. of Tech., 41296 Göteborg, Sweden*

[2] *Institute of Applied Physics, 603950 Nizhny Novgorod, Russia*

[3]*Institute for Physics of Microstructures, 603950 Nizhny Novgorod, Russia*

[4] *Powerwave Technologies Sweden AB, 187 80 Täby, Sweden*

[5]*Centre National d'Etudes Spatiales, 31401 Toulouse, France*

Introduction

Microwave breakdown in RF equipment is a serious problem in many different applications. The basic physics involved in the microwave-induced breakdown process is well-known; a rapid growth in time of the free electron density in the device, when the ionization rate caused by microwave accelerated free electrons hitting neutral gas particles (corona) or device walls (multipactor) exceeds the rate of electron losses. The concomitantly increasing plasma density eventually changes the transmission properties in the device and significantly interferes with normal operation characteristics. The consequences range from increased noise levels and link budget degradation in rf communication systems to catastrophic damage in high power microwave systems like accelerators and systems for microwave heating of fusion plasmas.

Although a strong effort has been made over many years to understand the phenomenon, microwave breakdown remains a serious concern, partly because the technical development in microwave applications constantly leads to increasing power densities as well as to new situations where the established theory is not applicable. The aim of this contribution is to give a general presentation of the field of microwave-induced breakdown in gases and in vacuum and to summarize results of recent research and development work that has been carried out during recent years involving Chalmers University of Technology in Gothenburg, Sweden, Institute of Applied Physics in Nizhny Novgorod, Russia, Centre National d'Etudes Spatiale in Toulouse, France, and Powerwave Technologies, Täby, Sweden. This work involves theoretical and numerical analysis of breakdown phenomena, as well as experimental investigations. The applications range from space-borne rf equipment for communication purposes to high power microwave transmission in wave guides and through wave guide windows. Particular topics are: breakdown in situations involving microwave fields that are strongly inhomogeneous in space or time, importance of the statistical properties of the electron background density for breakdown initiation of short microwave pulses, and breakdown at low, but finite, gas pressures where breakdown occurs as a combination of both corona and multipactor processes.

Corona breakdown

When a microwave propagates in a gas, it may affect the density of free electrons in the gas by causing ionization and/or attachment when electrons accelerated by the rf field collide with neutral particles. The density of free electrons, $n(\mathbf{r},t)$, in a gas of finite pressure, p, is determined by the continuity equation for the electron fluid, [1]

$$\frac{\partial n}{\partial t} = \nabla\cdot(D\nabla n) + \nu_i n - \nu_a n + S \tag{1}$$

where D is the diffusion constant, ν_i and ν_a are the ionization and attachment frequencies respectively, and S denotes a source of electrons. Eq.(1) is to be solved under the boundary condition that $n(\mathbf{r},t)$ vanishes on the boundary on the volume considered. Whereas D and ν_a depend primarily only on gas pressure, ν_i in addition to pressure, depends also strongly on the magnitude of the electric field, E, a dependence that is often approximated as $\nu_i \propto E^{\beta}$, where β is a parameter that depends on the gas. For the simplest geometry of two parallel plates and a homogeneous rf electric field, the continuity equation can be simplified to

$$\frac{dn}{dt} = -\frac{D}{L_e^2}n + \nu_i n - \nu_a n + S \equiv \nu_{\text{net}}(p,L_e,E)n + S \tag{2}$$

where the diffusion length, L_e, is directly related to the distance between the plates, L, (in fact $L_e = L/\pi$) and $\nu_{\text{net}}(p,L_e,E) = \nu_i(p,E) - \nu_D(p,L_e) - \nu_a(p)$ is the net ionization frequency due to the competition between ionization and the two loss mechanisms - attachment and diffusion out of the breakdown region ($\nu_D \equiv D/L_e^2$). The solution of Eq.(2) grows exponentially in time if $\nu_{\text{net}} > 0$ - corona breakdown - and the breakdown condition is taken as $\nu_{\text{net}}(p,L_e,E_b) = 0 \;\rightarrow\; E_b = E_b(p,L_e)$. Typically the breakdown electric field, E_b, increases for increasing high pressures and for decreasing low pressures leading to the characteristic U-shaped form of the so called Paschen curve for $E_b = E_b(p,L_e)$. If the wave is assumed to have a finite pulse length (τ_p) and constant amplitude, the breakdown condition given above is necessary but not sufficient, the electron density must have time to grow to high enough values in order to affect the microwave propagation properties. Usually it is assumed that 20 exponentiations are enough and the dynamic breakdown condition is taken as $\nu_{\text{net}}(p,L_e,E_b)\tau_p = 20$ implying that $E_b = E_b(p,L_e,\tau_p)$.

Although microwave breakdown under the above simple conditions involving microwave fields that are homogeneous in space and constant in time is rather well understood, realistic situations in present day applications involve a number of complications. Of particular importance are factors due to (i) inhomogeneous electric fields, e.g. caused by mode structure or by sharp corners and wedges, (ii) non-stationary microwave fields, e.g. caused by multi-carrier operation scenarii, and (iii) stochastic effects in breakdown initiation due to the naturally occurring small values of S, which leads to the so called waiting time problem where the breakdown threshold is observed to vary significantly from pulse to pulse. Different problems associated with these effects have been analyzed in the references given in [2].

Multipactor

The breakdown rf field due to corona breakdown increases monotonously as the pressure decreases. However, as gas pressure decreases, the mean free path between collisions between electrons and neutral particles increases and ultimately becomes of the order of the characteristic device length. Electrons will then collide primarily with the walls of the device and may, provided their energy is large enough, knock out secondary electrons from the walls. If such collisions are frequent enough and the concomitant secondary electron emission coefficient, σ, is larger than unity, an avalanche-like increase of the free electron density will occur - multipactor breakdown. For the simplest geometry of two parallel plates and a homogeneous electric field directed perpendicular to the plates, the equation of electron motion is simply $m\ddot{x} = -eE_0 \sin(\omega t)$, which is easily solved for arbitrary initial conditions to find the electron trajectory between the plates. Breakdown occurs provided the following two conditions are fulfilled: (i) The transit time between the plates is equal to an odd number of half rf periods (resonance condition) and (ii) The electron impact energy, W_{impact}, is in the energy range where $\sigma(W_{\mathrm{impact}}) > 1$. The dynamic multipactor breakdown condition is conceptually the same as for the corona case - 20 gap crossings are assumed to be enough to reach a breakdown plasma density that causes significant effects on the wave propagation. It is clear that although there are a number of similarities between the corona and multipactor phenomena, there are also crucial differences, primarily due to the resonant nature of the multipactor effect, which leads to the appearance of so called resonance bands in the parameter space spanned by the voltage between the plates and the product of wave frequency and plate separation.

However, results obtained assuming constant amplitude signals and the simple parallel plate geometry cannot safely be applied to more realistic situations involving inhomogeneous field and/or complicated time variations. Extensive studies have been made of a number of important effects relevant to modern applications. Of particular importance are studies of (i) electron trajectories more complicated than the simple resonance ones, e.g. the so called hybrid and multiphase modes, and influence of finite velocity of secondary emitted electrons, (ii) the possibility of multipactor initiation when the rf field is parallel to the surface (as e.g. at dielectric windows), and (iii) multipactor in inhomogeneous rf fields (as e.g. in waveguides) where the ponderomotive force on the electrons tends to push them out of the breakdown region, leading to enhanced breakdown thresholds, (iv) effects of time varying rf power as e.g. in multicarrier operation, and (v) effect of finite gas pressure on multipactor initiation. Examples of such studies are given in Ref. [3].

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