SATURATION OF A ONE-SIDED MULTIPACTOR IN A DECELERATING ELECTROSTATIC FIELD

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We analyze the saturation mechanism of a vacuum resonance microwave discharge (multipactor) where the decelerating electrostatic field returns electrons to the secondary-emission multiplying surface. It is found that the Coulomb defocusing of electron bunches prevails over their microwave focusing (toward the resonance phase of the field) in the stationary state, making it possible to extract superfluous secondary electrons when the electron bunches are reproduced on the discharge surface. Using this model, we determine the main characteristics of this multipactor, such as the magnitude and phase disposition of the resonant electron bunch. An explanation of the increase in the discharge power with increase in the secondary-emission coefficient is given.

A secondary-emission resonance microwave discharge (SERMD), or a multipactor [1, 2], initiates breakdowns in a variety of high-power microwave vacuum electronic facilities [2, 3]. In particular, relativistic Čerenkov oscillators are very sensitive to the SERMD localized near one of the walls (one-sided discharge) [3, 4], where electrons move along a strong magnetostatic field under the action of the microwave field and decelerating electric field of the main electron beam in the device. The conditions for reducing the problem to the well-known analysis of a one-sided multipactor [1, 5] were determined in [6] for the initial stage of discharge. The breakdown time [4] depends on discharge characteristics at the saturation stage where the microwave focusing and Coulomb defocusing effects of the oscillating electron bunch ensure its exact reproduction when it comes to the surface due to the secondary emission. In the present paper, we propose an analytical model and calculate the characteristics of a saturated multipactor in a decelerating electric field. The method is similar to that proposed in [7] where the observed characteristics of the multipactor [8] were explained for the magnetostatic field parallel to the discharge surface.

1. This analysis is based on the one-dimensional model of electrons moving near the plane surface \(x = 0\) (the applicability limits of this model are shown below). The motion of electrons with charge \(-e\) and mass \(m\) under the action of the electric field \(E = E_0 (-E_1 \sin \omega t + E_0)\), which is the superposition of microwave and decelerating static fields, is described by the equation

\[
\frac{d^2x}{dt^2} = \frac{e}{m} (E_1 \sin \omega t - E_0).
\]

Disregarding the initial velocity of the electrons (their average emission energy is about 3 eV and is much smaller than their characteristic kinetic energy in the discharge), we present the solution in a convenient form:

\[
\begin{align*}
\dot{a} &= \cos T_0 - \cos T - \varepsilon (T - T_0) \equiv \cos T_0 \cdot (1 - \cos \tau) + \sin T_0 \cdot \sin \tau - \varepsilon \tau, \\
\dot{x} &= \cos T_0 \cdot (T - T_0) + \sin T_0 \cdot \sin T - \frac{\varepsilon}{2} (T - T_0)^2 \equiv \cos T_0 \cdot (\tau - \sin \tau) + \sin T_0 \cdot (1 - \cos \tau) - \frac{\varepsilon}{2} \tau^2,
\end{align*}
\]

where $T = \omega t$, $T_0 = \omega t_0$, and $\tau = T - T_0$ are the dimensionless time, the injection time, and the transit time of the electrons, $\varepsilon = E_0 / E_1$, and $a = eE_1 / (m\omega^2)$ is the spatial scale of oscillations; the dot denotes the derivative with respect to $T$.

2. As long as the interaction of electrons is negligible, the discharge undergoes an avalanche stage if the secondary-emission coefficient $\sigma > 1$. The avalanche is created by resonant electrons whose total time of transit before they return to the surface $x = 0$ is a multiple of the microwave field period $\tau = 2\pi k$, where $k$ is the multiplicity of the resonance, or the number of the discharge area. For the resonant phase $T_{br}$, it follows from (2) that

$$\cos T_{br} = \varepsilon \pi k.$$  \hspace{1cm} (3)

The typical trajectory of a resonant electron is shown by a dashed line between the boundaries of a saturated bunch shown by solid lines in Fig. 1 (see the text below).

According to relations (2) and (3), the rate of surface bombardment by electrons amounts to

$$\dot{x}_b = -2a \cos T_{br}.$$  \hspace{1cm} (4)

The focusing takes place if $|\dot{T}_b| \leq 1$ under the condition $(T_b - T_{br}) = 2\pi k$. Then, according to Eqs. (4) and (3),

$$(\frac{\partial T_b}{\partial T_0})_{T_0=T_{br}} = 1 - \frac{\sin T_{br}}{\varepsilon} = 1 - \pi k \tan T_{br} < 0,$$  \hspace{1cm} (5)

we find that the minimum resonant phase (for the perfect focusing) is given by $T_{br}^{\min} = \frac{\pi}{2} \arctan(1/\pi k)$ in the maximum decelerating field where $\varepsilon_{\max} = (1 + \pi^2 k^2)^{-1/2}$. With the decrease in deceleration, the resonant phase increases, impairing the focusing and letting the later injected electrons be first on the surface. The focusing disappears at the phase stability boundary $T_{br}^{\max}$ where the left-hand side of (5) is $-1$, i.e., $T_{br}^{\max} = \arctan(2/\pi k)$ and $\varepsilon_{\max} = (4 + \pi^2 k^2)^{-1/2}$. The boundaries between the areas of resonant motion are presented in Table 1. It is seen that the discharge can only develop in moderate decelerating fields $E_0 \leq 0.3E_1$ and that decelerating fields decrease with increase in the area number $k$. The areas themselves rapidly shrink with increase in $k$, leaving wide gaps with respect to $\varepsilon$. Thus, we have given the well-known statements [1, 5] required for the further analysis and presented them in convenient terms.

3. If the secondary-emission coefficient $\sigma > 1$, then the discharge can also take place for a certain microwave defocusing (for the unstable phase $T_{br}$) when the multiplication of electrons during the interaction of the electron bunch with the discharge surface exceeds their loss due to scattering. Hence, the lower boundary $\varepsilon_{\min}$ of the area of resonant motion can roughly be estimated from the relationships

$$(\frac{\partial T_b}{\partial T_0})_{T_0=T_{br}} = 1 - \pi k \tan T_{br} = -\sigma, \quad T_{br}^{\max} = \arctan \frac{1 + \sigma}{\pi k}, \quad \varepsilon_{\min} = [(1 + \sigma)^2 + \pi^2 k^2]^{-1/2}.$$  \hspace{1cm} (6)

Taking account of this possible defocusing considerably broadens the discharge areas (see the bottom line in Table 1). The boundaries of these areas in the saturated mode are determined below. However, even a simple consideration shows that the charge of the electron bunches produced here must increase with increase in the secondary-emission coefficient $\sigma$ and must decrease with increase in the area number $k$ very rapidly since the field $E_b$ of the electron bunch cannot exceed $E_1 (\varepsilon_{\max} - \varepsilon_{\min})$ (Table 1). This makes