SOME ASPECTS OF NON-RESONANT MULTIPACTOR DISCHARGES IN RF CAVITIES

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Abstract

The influence of the initial velocity spread of electrons and of the distribution of electric fields on the dynamics of multipactoring has been investigated. Electric charge on the surface of a dielectric material in the cavity has been taken into account. The results and some conclusions will be given.

1. Introduction

In the PETRA II 52 MHz cavities, which are described elsewhere [1] in more detail, the vacuum in the beam tube is separated from the normal air pressure in the cavities by a ceramic cylinder in the gap. After several years of successful operation a ceramic cylinder had to be exchanged because of a vacuum leak. Unlike the original cylinder its replacement showed strong signs of multipactor which made operation practically impossible.

We prepared [2] another ceramic cylinder for installation in the cavity during the shut down by coating its inner surface with a layer of TiN of 100-200 Angström thickness. After a few hours of conditioning with pulsed RF multipactoring disappeared completely, and we could increase the RF voltage up to the maximum value of 100 kV without any further signs of resonant or non-resonant multipactor.

Also, in order to improve our understanding we have performed an analysis in terms of numerical simulation of the multipactoring process in this cavity [3]. The most important process we observed - a non-resonant one-electrode discharge on the inner surface of the ceramic cylinder- was well reproduced by these simulations.

In this study we develop an analytical description of the phenomenon which is based on a few simple assumptions.

2. Formulation of the Problem

The main properties of the non-resonant one-electrode multipactor discharge in the presence of the positive surface charge of highly emitting ceramic when the RF electric field is parallel to the surface of the ceramic are discussed in [3, 4, 5].

Let us consider a flat dielectric plate with a uniform positive surface charge so that there is an electrostatic field E_e perpendicular to the surface of the plate and let there be an RF field E_{RF} parallel to the surface.

Under the influence of these fields electrons emitted from the ceramic move along arc-like or loop-like trajectories. The time of flight of an electron, i.e. the time between its emission from the plate (caused for example by the impact of another electron) and its return to the plate, is determined by the initial velocity component $v_{0\perp}$ perpendicular to the plate and by the field of the positive charge:

$$\theta = \omega \cdot t = \frac{2m}{e} \cdot \frac{v_{0\perp}}{E_e} \cdot \omega, \qquad (1)$$

where e and m are the electron's charge and mass and ω is the frequency of the RF field E_{RF} times by 2π.

During its flight an electron is accelerated by the RF field and receives a velocity component parallel to the surface of the dielectric. Direction and magnitude of this acceleration depend on the initial phase φ of the RF field at the moment of emission.

Since θ does not depend on the value of the RF field, the electron can return to the dielectric surface at any phase. Therefore the secondary electrons can move in both directions without moving the center of gravity of the discharge.

The electron's velocity component v_{II} parallel to the ceramic is of course changed by the RF field and the final energy of the electron at the moment of its collision with the ceramic can be written:

$$\varepsilon[eV] = F^2\left[\cos\varphi - \cos(\varphi+\theta)\right]^2, \qquad (2)$$

where $F^2 = \frac{eE_{RF}^2}{2m\omega^2}$.

Here we assume that $v_{0\perp}$ and $v_{0II} << v_{final}$.

An incident electron causes secondary emission with a probability coefficient $\sigma(\varepsilon)$. But all electrons have different initial velocities and consequently different times of flight at a given level of E_e. In addition, the initial phases φ are randomly distributed. As a result, all incident electrons have different energies of collision. Therefore an integral coefficient of re-emission, integrated over all possible collision energies of the incident electrons, must be used to calculate the probability of the re-emission process.

So, our task is to determine the integral coefficient $<\sigma>$ as a function of the emission properties of the electrode material and the values of the electrostatic and RF fields.

3. An Integral Re-emission Coefficient

Suppose that the emitted electrons are uniformly distributed in the region of $0 \div (v_{0\perp})\max$ and therefore they are uniformly distributed in the region of $0 \div \theta_{\max}$. Also let them be uniformly distributed over the initial phases. These simplifications will not change the qualitative picture and are reasonable enough to make quantitative estimations at low levels of the fields. Under these assumptions we may determine the integral re-emission coefficient as

$$\langle\sigma\rangle = \frac{1}{\pi\theta_{\max}} \int_0^{\theta_{\max}} \int_0^{\pi} \sigma(\varepsilon)\, d\varphi\, d\theta. \qquad (3)$$

For most of the experimental data the re-emission coefficient may be approximated in the vicinity of its maximum value by the second order polinomial:

$$\sigma(\varepsilon) = a\varepsilon^2 + b\varepsilon. \qquad (4)$$

Here $a = -\sigma_m / \varepsilon_m^2, b = 2\sigma_m / \varepsilon_m, \sigma_m$ - maximal value of $\sigma(\varepsilon)$ and ε_m - a collision energy at which $\sigma(\varepsilon_m) = \sigma_m$.

The experimental data used in [3] and their approximation by (4) are shown in Fig.1..

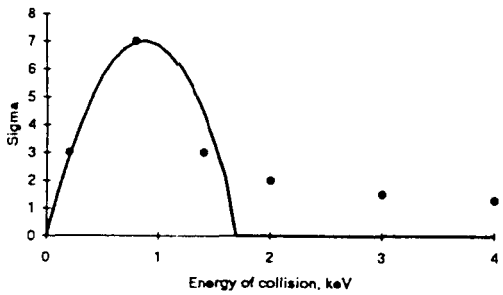

Fig. 1 Re-emission coefficient σ as a function of collision energy ε. Circles - experimental data for the ceramic used in [3]. Solid line - approximation by second order polinomial up to $\varepsilon_1 =$ 1.7 keV and $\sigma = 0$ for $\varepsilon >$ 1.7 keV.

After substitution of (4) into (3) and solving (3) we get the desired function:

$$\langle\sigma\rangle = 2.25aF^4 + bF^2 - (3aF^4 + bF^2)\cdot\frac{\sin\theta_{max}}{\theta_{max}} + 0.375aF^4\frac{\sin(2\theta_{max})}{\theta_{max}}. \qquad (5)$$

Only the last two terms of (5) depend on θ_{max}. Fig. 2 shows $<\sigma>$ as a function of θ_{max} calculated by (5). Here the material properties of the ceramic cylinder used in [3] were taken into account by properly choosing the constants a and b.

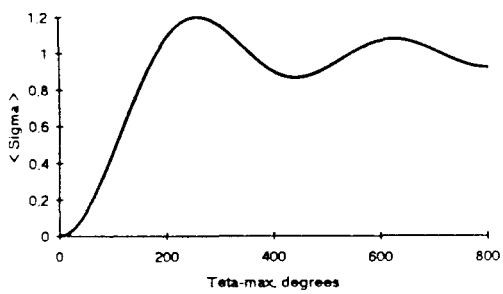

Fig. 2 Integral re-emission coefficient <σ> as a function of θ_{max}. Calculated for the critical value of the parameter of RF field F = 0.26 keV for the given ceramic material.

The representation of $<\sigma>$ as a function of E_e is equally instructive and is shown in Fig. 3. In this example for the initial energy of the electrons the fixed value of 3 eV has been used.

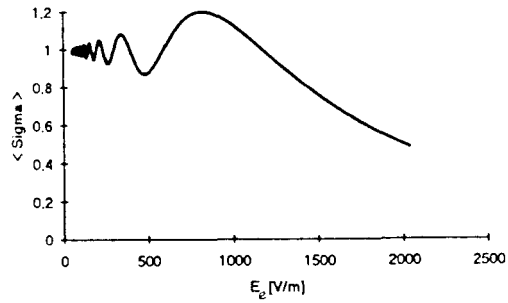

Fig. 3 Representation of <σ> as a function of E_e for the same example as in Fig. 2.

At low values of E_e $<\sigma>$ is almost constant and close to 1 whereas it changes for larger values of E_e. In the following we will discuss both cases.

4. Multipactoring at Low E_e

At low values of E_e the time of flight $\theta >> 1$ and we may neglect the last two terms of (5). Let $<\sigma> = 1$ in this case and therefore we can rewrite equation (5) in the following way:

$$2.25\frac{\sigma_m}{\varepsilon_m^2}F^4 - 2\frac{\sigma_m}{\varepsilon_m}F^2 + 1 = 0 \qquad (6)$$

The roots of this equation are

$$F_{1,2}^2 = \varepsilon_m(1 \pm \sqrt{1 - 2.25/\sigma_m})/2.25. \qquad (7)$$

F_1^2 is a lower threshold of the RF field above which $<\sigma>>$ 1 and a multipactor discharge can exist. One can also draw the important conclusion that σ_m must be greater than 2.25. Otherwise the discharge cannot exist at any value of the RF field. For high values of σ_m equation (7) is in a good agreement with the estimation from [4, 5] which was derived for the case $-\frac{\sigma_m}{\varepsilon_m^2}\varepsilon^2 \approx 0$ in (4). This can be easily seen if we rewrite the estimation from [5] in our terms:

$$F_1^2 = 0.88\varepsilon_m(1 - \sqrt{1 - 1/\sigma_m}) \qquad (8)$$

The upper threshold F_2^2 must be considered with caution because in our model $\sigma(\varepsilon)$ is not determined for the high collision energies.

5. Multipactoring at High Levels of RF and Electrostatic Fields

For evaluation of the integral coefficient of re-emission at high levels of RF and electrostatic fields we must consider electron losses:

In real accelerating cavities at high RF fields one does not expect secondary electrons of large θ to contribute to the multipactoring process since they would be captured by the RF field and end up far away on the cavity walls.

Multipactoring can only occur at high levels of the electrostatic fields which provide a sufficiently strong returning force for the electrons back to the surface from which they have been emitted.

The necessary charge on the ceramic or even on an isolated metal electrode can result from collisions with background electrons as was shown by the experiments described in [5].

We can take these factors into account by properly choosing the boundaries of the integral and then evaluate (3) at large fields E_{RF} and E_e.

For values E_e < 800 V/m which corresponds to the minimum field below which no multipactoring can occur we define a maximum cut off value θ_{crit} as an upper limit of integration in (3).

This value of E_e was choosen to give agreement between our results and the ones from [3]. For E_e > 800 V/m the previously defined θ_{max} is taken.

Furthermore we take $\sigma(\varepsilon) = 0$ for energies $\varepsilon > \varepsilon_1 = 1.7$ keV.

This approximates the experimental data displayed in Fig. 1 which show that σ decreases indeed for energies $\varepsilon > 1$ keV.

The curves shown in Fig. 4 were calculated by (3) under the conditions mentioned above. For comparison the curve from Fig. 3 which was calculated for lower values of E_e and E_{RF} is also shown.

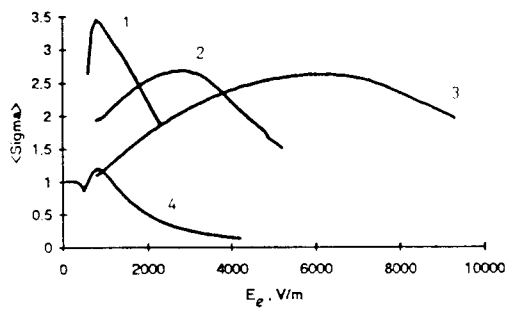

Fig. 4 Integral re-emission coefficient as a function of E_e calculated at high levels of RF and electrostatic fields and taking into account of losses of electrons. Curve 1 - parameter of RF field F = 0.63, curve 2 - F = 1.2, curve 3 - F = 2.5. Curve 4 is the example from Fig. 3 and is given for comparison.

One sees that up to a certain level of RF field (in our case up to F = .63) the value of $< \sigma >$ just increases and the maximum preserves its position because, so far, the energies of the electrons lie in the interval $0 < \varepsilon < \varepsilon_1$.

A sudden increase in E_e would lead to a decrease of the value of $< \sigma >$. This results in an autoregulation process which keeps E_e at the value of maximum $< \sigma >$.

If now E_{RF} is increased such that the maximum electron energy exceeds ε_1, σ and also $< \sigma >$ will start decreasing. Then only the electrons with $\varepsilon < \varepsilon_1$ will contribute to the multipactoring process. But these electrons belong to small θ values or, equivalently, to large values of E_e. Therefore the maximum $< \sigma >$ values are shifted towards higher values of E_e for decreasing electron energy in Fig. 4. For comparison the results of the numerical simulation of the multipactor discharge from [3] are given in Fig. 5.

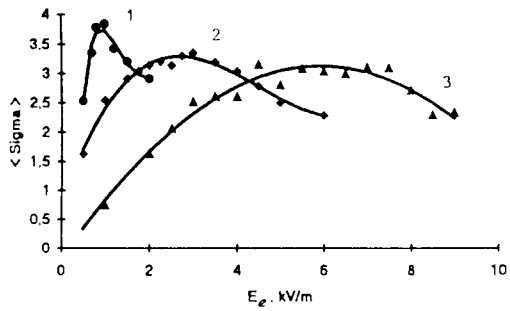

Fig. 5 The results of numerical simulation of the multipactor discharge performed for the PETRA II cavity. Curve 1 corresponds to 5 kV of accelerating voltage, curve 2 - 10 kV, curve 3 - 20 kV.

6. Conclusions

We have derived an analytical expression for the integral coefficient for emission of secondary electrons which may cause non-resonant multipactoring in an accelerating cavity. The influence of electrostatic field amplitude and of RF field value has been taken into account.

The good agreement between the curves shown in Fig. 5 and 4 suggests that the previous results which were obtained by numerical simulation of the multipactor discharge under similar conditions using the code TRAJ2 can be understood in terms of our present model calculations with all their simplifications.

References

[1] L.W. Funk et al., "52 MHz RF System for PETRA II", Proceedings of the European Particle Accelerator Conference, pp. 1102, Rome, June (1989).

[2] Moyses Kuchnir, to be published.

[3] I. Gonin et al., "A Study of Multipactor Phenomena in the 52 MHz PETRA II Cavities at DESY", Proceedings of the IV European Particle Accelerator Conference, London, June (1994).

[4] I.N. Slivkov. "The Processes at High Voltage inVacuum", Energoatomizdat, Moscow (1986) (in Russian).

[5] L.V.Grishin et al., "Investigation of Secondary-Emission RF-Discharge at Big Angles of Electron Flight", Proc. of Lebedev Physical Institute, Vol. 92, pp.82-131, (1977) (in Russian).