MULTICOAX: A SOFTWARE TOOL FOR PREDICTING MULTIPACTOR RF BREAKDOWN THRESHOLD IN COAXIAL AND CIRCULAR WAVEGUIDES

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INTRODUCTION

In the last years many numerical techniques and CAD tools have been developed in order to characterize the electromagnetic response of microwave devices such as filters or resonators. On the other hand, today applications also demand a higher component integration as well as more power hadling capabilities. Both requeriments lead to higher electromagnetic field densities inside the devices which results in a higher risk from the microwave breakdown point of view.

The multipactor breakdown still presents a critical problem in Satellite communications (SatCom) applications. This problem also appears in the accelerator components operating in vacuum. In few words, multipactor is a microwave breakdown discharge occurring in vacuum conditions caused by the formation of an electron avalanche. The avalanche originates due to the release of secondary electrons when high energy electron collide with the metallic walls of the device. This finally results in the appearance of an electron plasma which reduces the output power of the component increasing its return loss, heating up the walls. If the multipactor conditions are maintained within the device for a long time, outgassing of the walls increases the pressure inside the component and finally a corona discharge can develop resulting in the total destruction of te component. In superconducting accelerator structures a large rise of temperature can eventually lead to a thermal breakdown.

To predict the breakdown threshold inside arbitrary microwave devices two problems need to be solved: First of all, the spatial electromagnetic field distribution has to be computed. Once the field is known at any point of the structure, the resonant trajectories of the electrons have to be determined. In a more general way, electrons are followed within the component. An exponential increase of the electron population with time indicates that the resonant conditions are fulfilled and consequently that a multipactor avalanche is taking place.

Most of the publications in the recent years studying the multipactor problem in microwave devices deal with special cases or simplified geometries to obtain the electromagnetic field distribution. Complex geometries or complete waveguide devices, e. g. filters, are not considered or, in such cases, e. g. coaxial, a parallel plate configuration is assumed Woode & Petit model [1],[2]. The specifications imposed by space agencies are very restrictive [3], and flight modes have to be tested in multipactor. For designing, it is very important to have a tool to predict the breakdown threshold. Multipactor is a complex phenomenon that depends on many conditions: geometry, materials and the electromagnetic field in the device. This tool must predict with enough accuracy the breakdown threshold. At the moment, the software used to predict this effect is called “Multipactor Calculator” [1]. This code is based on the simple model of parallel plates [2] which does not take into account the exact geometry of the coaxial waveguide and produces results more conservative.

In this work a tool called MULTICOAX is presented. This software allows to predict the multipactor RF breakdown threshold in coaxial waveguides under excitation of the fundamental mode TEM. The model employed is based on the calculation of the electron trajectories that travel in the coaxial with electric and magnetic fields of a superposition of two TEM modes. This computation allows to calculate at each impact the number of electrons released. When these electrons growth exponentially, the discharge takes place.

THEORY

Electron dynamics

It is assumed that the electron dynamics is given by the non-relativistic Lorentz equation and that the effect of the field of the electron itself on the external field is negligible. Thus, the electron dynamics in an electromagnetic field is given by

$$\begin{cases} \dfrac{d\vec{v}}{dt} = \dfrac{q}{m_0}\left(\vec{E} + \vec{v} \times \vec{B}\right) \\ \dfrac{d\vec{x}}{dt} = \vec{v} \end{cases} \tag{1}$$

where $q = -e$ is the charge of electron, m_0 is a electron mass, $\vec{x}(\vec{r},t)$ position vector, $\vec{v}(\vec{r},t)$ velocity vector, t is time and $\vec{E}(\vec{r},t)$ and $\vec{B}(\vec{r},t)$ are the electric and magnetic field of flux density that interact with such an electron, $\vec{x}$ the electron position, $\vec{v}$ the electron velocity, an t is time.

The electromagnetic field

In this work, the electromagnetic field is described as a superposition of two TEM wave-modes with opposite directions, each one with different amplitude and phase. Then the fields in the coaxial waveguide are given by

$$\vec{E}(\vec{r},t) = \frac{|V_1|}{r\ln(b/a)}\cos(\omega t - \beta z + \theta_1)\hat{r} + \frac{|V_2|}{r\ln(b/a)}\cos(\omega t + \beta z + \theta_2)\hat{r} + \frac{V_{DC}}{r\ln(b/a)}\hat{r} \tag{2}$$

$$\vec{H}(\vec{r},t) = \sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{|V_1|}{r\ln(b/a)}\cos(\omega t - \beta z + \theta_1)\hat{\varphi} - \sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{|V_2|}{r\ln(b/a)}\cos(\omega t + \beta z + \theta_2)\hat{\varphi} \tag{3}$$

where V_1, V_2 are the voltage amplitude of the two TEM modes that travel in direction $z > 0$ and $z < 0$ respectively, θ_1, θ_2 are their phases, the V_{DC} is the bias voltage, $\omega = 2\pi f$ is the angular frequency, $\beta = \omega\sqrt{\mu_0 \varepsilon_0}$ is the propagation constant, b and a are external and internal radius respectively, and t is the time measured in the laboratory reference system. The equations of motion of the electron (1) have been solved by means of a fourth-order Runge-Kutta algorithm, in order to calculate numerically the trajectories inside the coaxial waveguide. The initial conditions are the position and the velocity in a particular time t_0.

The model of secondary emission electron

It is well known that the multipactor effect characteristics strongly depend on the surface properties. They are quantitatively considered by means of the secondary electron yield (SEY). The typical curve aspect of this coefficient as a function of the impacting electron energy is shown in Fig. 1 for the low energy range with three different impact angles. In our simulation, the model for the SEY formulated by Vaughan [4], and modified in [5] has been used:

$$\delta(W,\xi)=\begin{cases}1 & , \quad \gamma<1\\ \delta_{\max}(\xi)\,(\gamma e^{1-\gamma})^{0.25}, & 1<\gamma\leq 3.6\\ \delta_{\max}(\xi)\dfrac{1.125}{\gamma^{0.35}}, & 3.6<\gamma\end{cases} \tag{4}$$

where

$$\delta_{\max}(\zeta)=\delta_{\max}\,(1+\frac{k_W\,\zeta^2}{2\pi}),$$

$$W_{\max}(\zeta)=W_{\max}\,(1+\frac{k_\zeta\,\zeta^2}{2\pi}),$$

where W is the kinetic energy of impact, ξ is the impact angle, $\gamma\equiv(W-W_0)/(W_{\max}(\xi)-W_0)$, W_0 is the threshold energy of the material and $W_{max}(\xi)$ is the maximum energy for impact angle, k_W and k_ξ are parameters dependent on the roughness of the surface (normally taken equal to 1), W_{max} is the impact energy at which the SEY is maximum and δ_{max} the maximum SEY at this energy.

Algorithm

The simulation code essentially consists of two core parts, one for computing the electron trajectories and the other for searching and analysing the multipactor effect. For a given geometry, an electron is launched at a known field level from a known surface location with respect to the chosen phase of the RF field. The kinetic energy and direction of the electron at emission are also specified in an initial time. The trajectory of the electron is tracked by solving its equations of motion, which are a coupled ordinary differential equations system. Numerical integration is made by method of fourth-order Runge-Kutta. RF fields in the structure are obtained analytically (2), (3). At each integraton step, judgment is made to check if the electron strikes a surface. If the answer is no, the integration goes on to the next step. If the answer is yes, the impact location, the velocity of the electron and the phase angle of the RF field upon impact are registered. Then, the electron is re-emitted with a Gaussian distribution of mean 5 eV and standard deviation 3 eV typically and the angles are calculated using the cosine law distribution from the impact site. Its tracking is continued until next impact to a surface, and so on. After a certain number (usually 30-40) of impacts, the tracking is stopped and the multiplicity function given by

$$e_N=\prod_{i=1}^{N}\delta_i$$

is calculated where N is the total number of impacts, i is the index for each impact, and δ_i is the SEY computed for each impact according to the corresponding kinetic energy and direction of the electron upon impact. e_N is the so-called counter function, introduced in [6].

In order to check the developed algorithm, two criteria have been employed, conservation of energy principle and angular moment conservation principle.

$$\int_1^2 \vec{F}_L\,d\vec{r}=-e\int_1^2\vec{E}\,d\vec{r}=W_2-W_1 \tag{5}$$

$$L_z(t_1)=L_z(t_2),\qquad L_z=m_0\,r(t)\,v_\varphi(t) \tag{6}$$

RESULTS

In this work we have used the electromagnetic fields (3),(4). Then, it has been possible to study two configurations the travelling wave (TW) $V_2 = 0$ and the standing wave $V_1 = V_2$. We present the results for both cases.

Configuration Travelling Wave (TW)

The code has been successfully checked with experimental measurements for prediction of the multipactor RF breakdown threshold. A coaxial sample designed and measured at ESA/ESTEC laboratories [7] is presented in Fig. 2 and the transversal section of the coaxial sample is presented in Fig. 3. Its frequency response is shown in Fig. 4. We have simulated the central section as a coaxial waveguide with b=5.65 mm, a=4.65 mm and f =1.35 GHz. The parameters for secondary emission model for copper are in [8]. In this case, the prediction is in good agreement, see Table 1. These measurements establish the prediction of multipactor for lower a power level than the model of Woode & Petit [1],[2].

Table 1. Prediction of the multipactor RF breakdown threshold

Predicted threshold "Multipactor Calculator"	311.23 (Watts)
Predicted threhold MULTICOAX	209.94 (Watts)
Experimental measurement	204.60 (Watts)

Once the multipactor effect takes place, the trajectory of one electron and the evolution of multiplicity function with time have been plotted, see Fig. 5 (a)-(d). This multipactor process is called first order two point process, (see Fig. 5(a)). The order process is explained in the next subsection. In the other graphics, the angular and the axial variation as a function of the time are shown. In Fig. 5-(d) the multiplicity function is displayed.

Finally, the code has been checked with other theoretical model [8] and several coaxial samples designed and measured at NASA Laboratories [9]. A good agreement has been obtained as well (see Fig. 6)

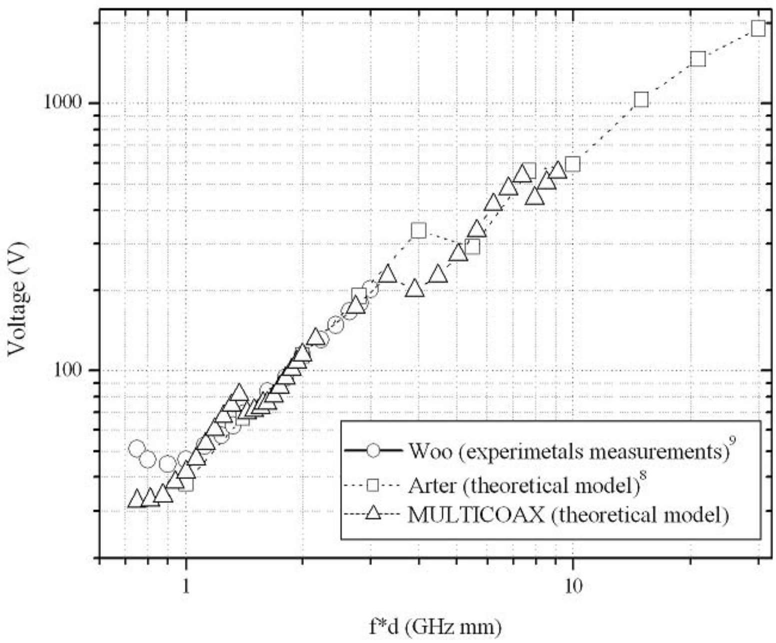

Fig. 6 Comparison between experimental measurements [9] and an theoretical model [8]. b/a=2.3, Z= 50 Ω

Configuration Standing Wave (SW)

We have examined the question whether the multipacting phenomena described above obey some simple scaling laws. More specifically, we have performed the multipacting analysis with coaxial lines with different dimensions as well as with different RF frequencies, and identify in each case the multipacting processes of different type and order.

We have calculated the trajectories of electrons for each value of the maximum of the electric field at the outer conductor and we have identified the multipacting order, see Table 2

Table 2. The maxima of the electric field at the outer conductor versus multipacting order (n).
The frequency is f = 1.3 GHz, b =51.5 mm, Z =50 Ω

Order multipacting (n)	E (V/m) 10^5
6	2.64
5	3.15
4	3.75
3	5.2
2	6.8
1	10

This suggests that multipacting field values are proportional to 1/(n+1). These values are checked with other results [6]. We have checked the effect of varying the frequency f of the field and the effect of geometric dimensions of the coaxial line [6].

These results agree with the scalar law suggested for one-point multipactor [6] and with the experimental ones found by [9]

$$P_{one-point} \approx \frac{d^4 f^4}{(n+1)^2} Z \tag{7}$$

CONCLUSIONS

In this paper, a model is presented for the prediction of the multipactor RF breakdown threshold in coaxial waveguide structures. This code has been successfully checked by comparison with another theoretical model and several coaxial samples designed and measured at ESA/ESTEC and NASA laboratories.

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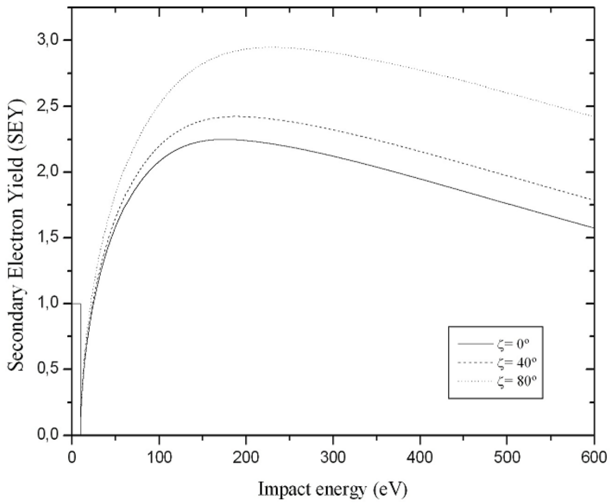
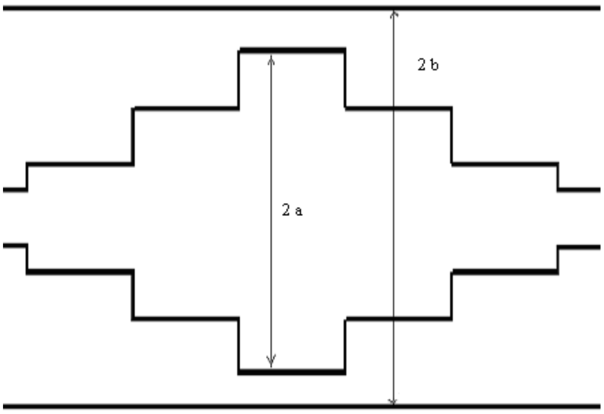


Fig. 1 Secondary Electron Yield for copper with three different impact angles

Fig. 2 Coaxial samples designed and measured at ESA/ESTEC laboratories



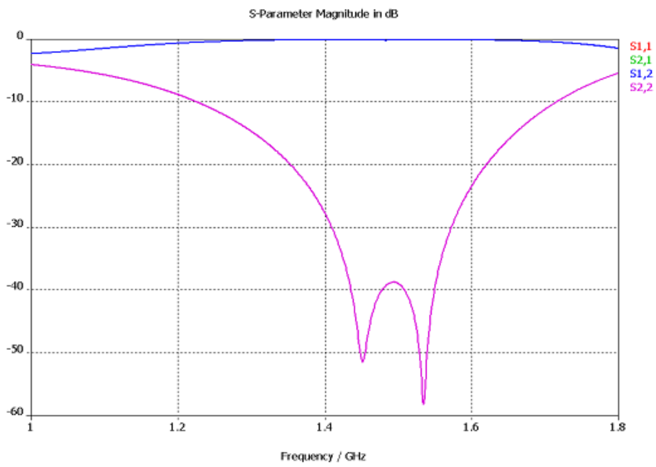
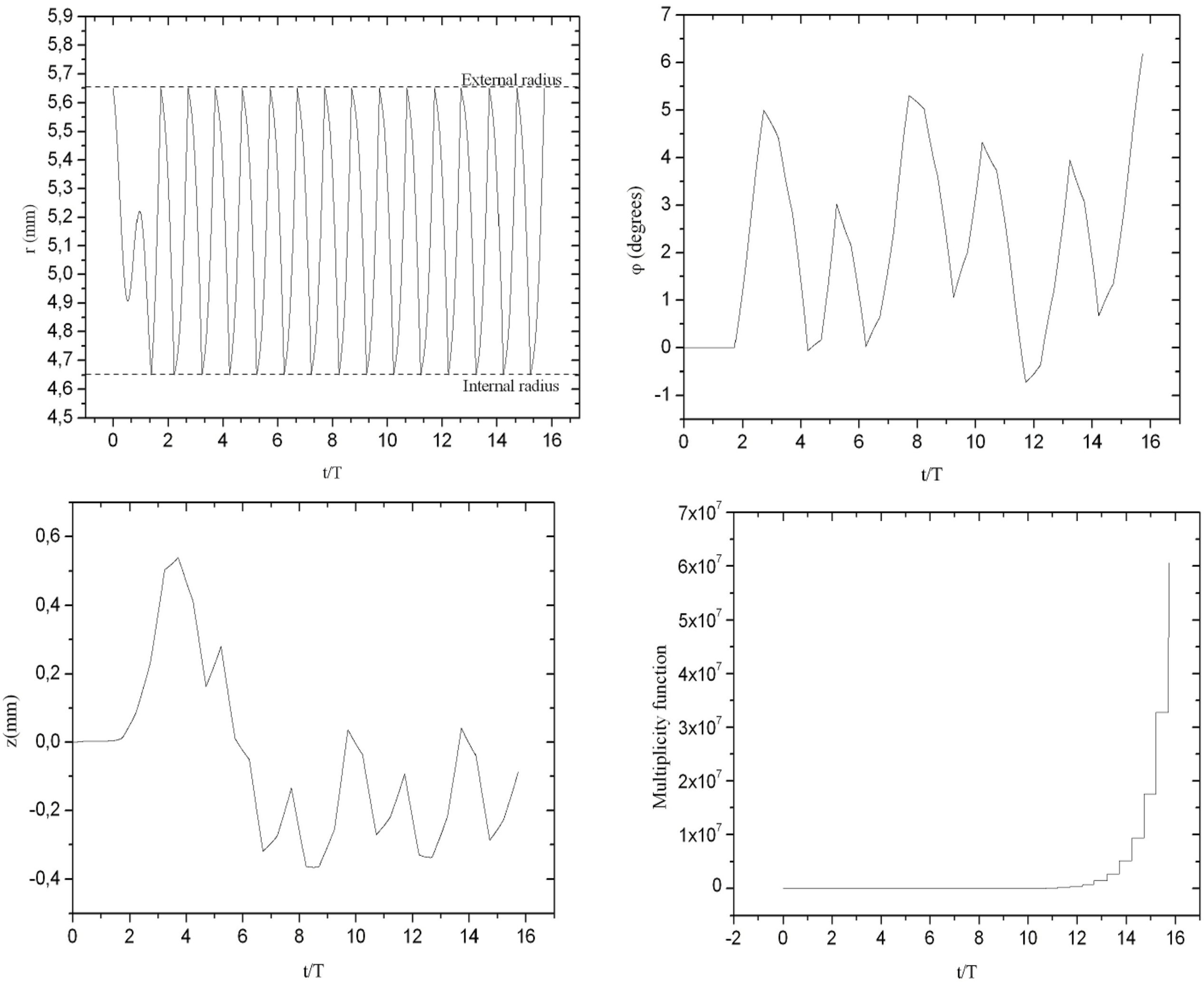


Fig. 3. Transversal section of coaxial sample

Fig. 4. Frequency response of coaxial



In Fig. 5 (a)-(c)it is displayed the trajectory of one electron as a function of time when the multipacting effect is between two surfaces as called the first order two-point process. The time is normalized with the period of RF signal ($T = 1/f$). We assume that there is one TEM wave mode which it is propagated in positive direction $z > 0$ thus $V_1 = 100$ V, $V_2 = 0$ V, $V_{DC} = 0$, $f = 1.35$ GHz, $b = 5.65$ mm, $a = 4.65$ mm. In Fig. 5 (d) is shown the multiplicity function as a function of time.