An Open Platform Tool for 2D Multipactor Simulations in Metallic Microwave Components

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***Abstract*— The paper presents a computer simulation software aimed at assessing the multipactor threshold power in a rectangular waveguide working with single tone excitation. Initial tests demonstrate a strong agreement between the simulation results obtained and those from commercial software. Contrary to the existing commercial software, our tool will be provided as Open Platform, for free use and popularisation of knowledge about physical phenomena resulting from interactions of microwaves with materials.**

***Keywords*— multipactor, secondary electron emission, computer simulation, Open Platform**

I. INTRODUCTION

Multipactor is a discharge based on secondary electron emission (SEE), which is observed in microwave components, particularly in the high-power microwave regime under vacuum or low-pressure conditions [1].

The phenomenon initiates when a free electron, accelerated by electromagnetic field propagating within the microwave component, impinges on a surface causing the emission of two or more secondary electrons, depending on the electron energy, incident angle, and surface roughness [2]. These secondary electrons can be accelerated and impinge on another or the same surface emitting more secondary electrons. Under certain resonance conditions this process can be sustained leading to an avalanche phenomenon, which results in a cloud of free electrons resonating inside the device. As a result, it may detune a microwave signal and heat the surface, thus increasing noise level and causing damage. Under some circumstances multipactor may induce vacuum breakdown. Telecommunication satellite components [3] and particle accelerators [4], among other applications, are commonly affected.

Multipactor is typically an undesirable effect, and mitigating the risk of its occurrence and evaluation of the multipactor threshold power is crucial during the component design stage. It can be obtained by multipactor experimental tests, which are expensive, or multipactor computer simulations, which therefore appear as a promising alternative. However, the commercial multipactor simulation tools available on the market, such as [5,6] are also very costly. Application of commercial software might be problematic for the user, as the theories and specific equations implemented in each tool are not always adequately documented or disclosed. This lack of transparency can undermine engineers' trust in simulation results.

The above considerations have stimulated our work on in-house developments of an open-platform multipactor simulation software. The goal is to have a tool based on well-defined and documented physical assumptions, with simulation parameters consciously controlled by the user. The work was started within the Polish Space Fellowship Internship Program and is currently being adapted for including surface roughness parameters in a EUREKA-Eurostars project. Up to now, a 2D version of the software, Multipactor 2D, has been developed that performs two dimensional simulations of electrons dynamics and SEE of a rectangular waveguide in its height and width plane.

In this paper, we briefly describe the basis of the Multipactor 2D tool and undertake its validation against commercial software [5]. Specifically, we compare power threshold of multipactor breakdown and dynamics of electrons number over time. Multipactor 2D will soon be made available as an Open Platform tool for teaching and dissemination purposes, as previously done in European projects [7], [8].

II. MODEL DESIGN

The simulation model consists of a rectangular waveguide with given width A and height B, operating in a TE10 mode. The Multipactor 2D simulation technique employs a particle-in-cell (PIC) approach, tracking each particle's interaction with the electromagnetic field through the Lorentz force. Instead of individual electrons, macroparticles (MP) are utilized, thereby reducing the level of complexity in the simulation. [9]. When the simulation starts, the initial positions, velocities and energies of primary macroparticles are randomly assigned within the waveguide cross-section, with kinetic energy ranging from 0 eV to 4 eV.

As an input the model takes A and B values, initial number of electrons N, number of MP, frequency of the electromagnetic signal f, power of the signal P_{10} and number of time-steps to be executed in the simulation process (time-step is predefined in the present version of the tool and equals $10^{-12}\ s$).

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A. *Electromagnetic field*

Only E_y and H_z field components are considered, and their values are defined by power P_{10} in watts [10],

$$H_z = A_{10}\cos\frac{\pi x}{A}\cdot\cos(2\pi f n\Delta t) \quad (1)$$

$$E_y = -2f\mu A\cdot A_{10}\sin\frac{\pi x}{A}\cdot\cos\,(2\pi f n\Delta t) \quad (2)$$

$$P_{10} = \frac{2f\mu A^3|A_{10}|^2 B}{4\pi}Re(\beta) \quad (3)$$

where n stands for $\mathrm{n^{th}}$ iteration of the simulation with Δt time step; A_{10} – E-field amplitude; β – phase constant.

B. *Evolution mechanism of electrons*

The differential of the Lorentz equations in time domain are,

$$\frac{v^{n+1}-v^n}{\Delta \mathrm{t}} = \frac{q}{m}\left(E^n + \frac{v^{n+1}+v^n}{2}\times B^n\right) \quad (4)$$

$$\frac{r^{n+1}-r^n}{\Delta t} = v^{n+1} \quad (5)$$

where v, r, q, m stands for velocity, displacement, charge, and mass of the particle respectively; superscripts denote time instants. Due to two-dimensional simulation, (4) and (5) can be written as,

$$v_x^{n+1} = v_x^n + \frac{q\cdot\Delta t}{m}\left(E_x + \frac{v_y^{n+1}-v_y^n}{2}B_z\right) \quad (6.1)$$

$$v_y^{n+1} = v_y^n + \frac{q\cdot\Delta t}{m}\left(E_y + \frac{v_x^{n+1}-v_x^n}{2}B_z\right) \quad (6.2)$$

$$r_x^{n+1} = v_x^{n+1}\cdot\Delta t + r^n \quad (7.1)$$

$$r_x^{n+1} = v_x^{n+1}\cdot\Delta t + r^n \quad (7.2)$$

C. *Secondary emission model*

To describe Secondary Emission Yield (SEY) the empirical formulas, introduced by Vaughan [2] and modified according to [11], are being used, namely

$$\delta(E,\theta) = \delta_{max}(\theta)(V\cdot\exp(1-V))^k \; for\; V \le 3.6 \quad (8.1)$$

$$\delta(E,\theta) = \delta_{max}(\theta)\cdot 1.125/v^{0.35}\; for\; V > 3.6, \quad (8.2)$$

where

$$V = \frac{E-E_0}{E_{max}(\theta)-E_0},$$

$$k = 0.56\; for\; V < 1,$$

$$k = 0.25\; for\; 1 < V \le 3.6,$$

$$\delta_{\max}(\theta) = \delta_{\max}(1 + k_E\theta^2/2\pi),$$

$$E_{max}(\theta) = E_{max}(1 + k_\theta\theta^2/2\pi),$$

$\delta(E,\theta)$ is the SEY value for an impacting electron energy E and incident angle θ respect to the surface normal, E_0 dependent on a surface material, k_E and k_θ parameters dependent on the roughness of the surface, E_{max} is the impact energy at which the SEY value is maximum and δ_{max} the maximum SEY value at this energy. At energies below E_0 SEY values are equal to 1 and electrons are considered as reflected.

The stochastic components of SEE [12] have been simplified as follows: true secondary electrons are emitted at 0 degree angle respect to the surface normal and with energy equal to 5 eV.

D. *Multipactor threshold*

Executing hundreds of timesteps, the temporal evolution of the number of electrons is recorded. When multipactor occurs, the number of electrons will exponentially increase. Threshold power is then determined through manual analysis of dynamics of number of electrons over time.

III. SIMULATION RESULTS AND DISCUSSION

In Multipactor 2D model the threshold power of rectangular waveguide with $A = 22.86mm$ and $B = 3mm$ was simulated and the results were compared with Ansys HFSS multipactor module. Additionally, simulations have been conducted with varying numbers of macroparticles (MP) while keeping N fixed.

For the SEY model the following values are being used (the same as in Ansys software): $\delta_{max} = 2.98$, $E_{max} = 150\; eV$, $E_0 = 12.5\; eV$, k_E and k_θ are equal to 1.

A. *Multipactor 2D simulations and results*

The above defined waveguide was simulated with initial parameters: $N = 1000$, $MP = 20$ and 100 which give us 50 and 10 electrons respectively in one MP, $f = 10\; GHz$, 50000 time-steps which equals to $50\; ns$ of simulated time. The simulation was repeated several times, with each iteration adjusting theP_{10} value to determine the multipactor breakdown threshold.

After performing a few simulations with the Multipactor 2D model, threshold power was found between 7.5 and 8.5 kW. Number of MP was not a factor influencing the threshold, as will be discussed later.

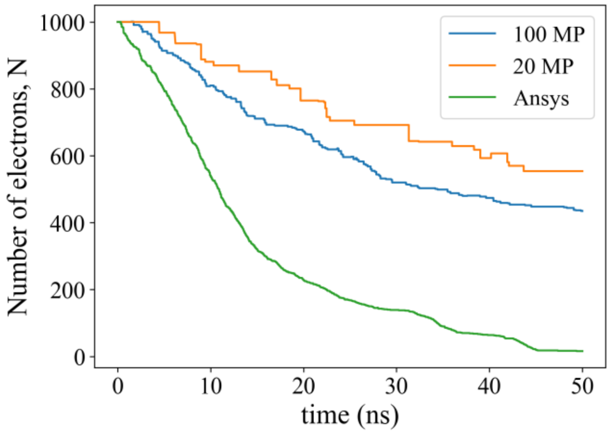

Fig. 1. Simulation results for the field power 2 kW.

B. Ansys software simulations and results

Simulations of the 3D waveguide section were first conducted in Ansys with the same initial parameters. To approximate the simulated problem to that of our 2D solver, a feature of the Ansys software was utilized, allowing simulation of a restricted section within the 3D domain. The effect to changing the length of simulated section of the waveguide on simulated results was examined. The results are shown in Table I. Simulations of the models of different length may differ due to two factors: differences in the model (internally set by the applied commercial software) and the stochastic nature of the SEE phenomenon. Even so, the differences in the threshold power estimated by software remain within ±3%, with the average value of 8.28 *kW*, which we shall further use as a reference for our 2D model and simulations. In further tests, we shall limit the waveguide length to 0.1 *mm*.

TABLE I. SIMULATION RESULTS VARYING THE LENGTH OF WAVEGUIDE SECTION AS SIMULATED IN ANSYS SOFTWARE

Length of the section (mm)	***Threshold Power (kW)***
0.1	8.48
0.5	8.33
1	8.48
3	8.02
5	8.33
10	8.02

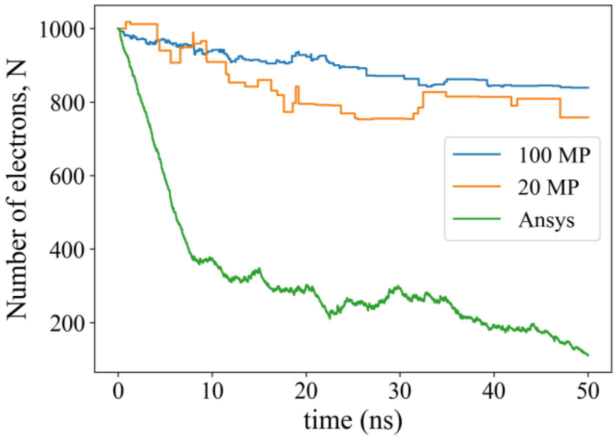

Fig. 2. Simulation results for the field power close to the threshold 8.5 *kW*.

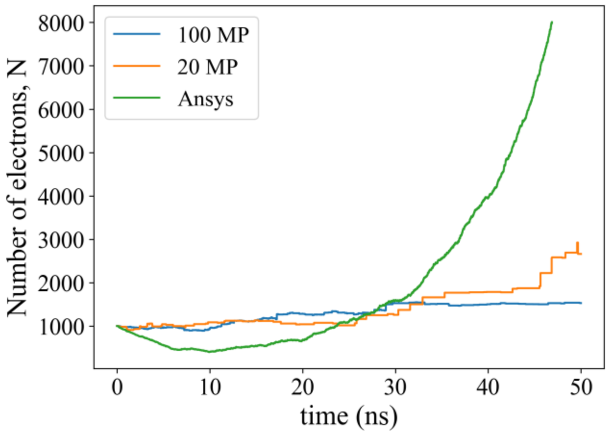

Fig. 3. Simulation results for the field power 12 *kW*.

C. Results comparison and discussion

Figures 1, 2, 3 show comparison of changes in the number of electrons over time, derived from Multipactor 2D model with 20 and 100 *MP* and from Ansys software, for three values of field power: well below threshold power (Fig. 1), near the threshold (Fig 2.) and well above the threshold (Fig. 2).

We observe that for all simulations with power values well below the threshold, the number of electrons substantially decreases over time (Fig.1), even if a minor increase maybe sporadically observed. Close to the threshold, cyclical increases in the number of electrons can be seen, which indicate a high probability of the multipactor effect (Fig 2). For values well above the threshold, the number of electrons tends to increase exponentially (Fig. 3).

Our Multipactor 2D simulations qualitatively agree with the commercial software and allow estimating the power threshold values for the multipactor phenomenon. In terms of the number of electrons over time, there are differences, which (at this stage of the research) we attribute to the different boundary condition implicitly assumed in the longitudinal direction. Our investigation and development continue and further discussion will be presented at the conference.

ACKNOWLEDGMENT

This work was partially performed within the EUREKA-Eurostars 5G_Foil project, which receives funding from the Polish National Centre for Research and Development under contracts DWM/InnovativeSMEs/176/2023 and InnovativeSMEs/4/90/5G_Foil/2023. Tomasz Nalecz thanks the Industrial Development Agency JSC (ARP S. A.) for supporting the first stage of his work under the Polish Space Fellowship Internship Program 2023.

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