

Multipacting analysis in micro-pulse electron gun^{*}

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Abstract: Modeling multipacting to steady state saturation is of interest in determining the performance of the micro-pulse electron gun. In this paper, a novel method is proposed to calculate the multipacting resonance parameters for the gun. This method works well, and the 2-D simulation results suggest that steady state saturation can be achieved in the gun. After saturation the transition from two-surface multipacting to single-surface multipacting occurred, and an extensive range of electron emission time is a suggested way to avoid this kind of transition.

Key words: multipacting, micro-pulse electron gun, MultiPac, VORPAL

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1 Introduction

In recent decades, the phenomenon of multipacting has been deeply investigated in many areas in order to suppress its adverse effects [1]. The Micro-Pulse Electron Gun (MPG), as a positive application of the multipacting effect, can be triggered with a single electron and resonantly amplified to saturation inside a vacuum RF cavity [2]. MPG can give rise to electron beams with high currents and short pulses, which are useful for industrial applications as well as high energy accelerators [3].

Owing to the complexity of the multipacting effect and its great impact on the performance of MPG, study should be focused on detail. The main purpose of this paper is the description of one novel method for determining the resonance condition in MPG design. The design model consists of a reentrant cavity and a grid-anode (as shown in Fig. 1), across which a time varying RF voltage is applied. Under the condition of resonance, steady state saturation is achieved in 2-D simulations. In addition, the transition from two-surface multipacting to single-surface multipacting, which is found to prevent MPG from output micro-pulses, occurred after saturation in 3-D simulations, and we obtained a solution to suppress this kind of transition.

The article is organized as follows: In Section 2, we first present the MPG concept, and a novel solution which is used to calculate resonance parameters easily

for MPG design is provided based on the basic equations. In Section 3, 2-D VORPAL simulations have been taken in order to confirm this kind of method. In Section 4, 3-D simulation results are provided for the design, and finally we give a brief conclusion.

2 A novel method to calculate resonance parameters

2.1 MPG concept and electron resonance equation

MPG is one kind of microwave gun that employs secondary electrons which resonantly amplified in an RF cavity to produce micro-pulses [1]. A number of initial electrons, which emit off one side (as shown in Fig. 1), transit the cavity under the work of RF field, and finally they strike the other side in odd multiples of half period and generate secondary electrons.

In the gun, the multiple of secondary electrons in one period can be written as $\delta_1 \delta_2 (1-T)$ [2]. In order to have a gain in the cavity, the following condition should be met:

$$\delta_1 \delta_2 (1-T) > 1, \quad (1)$$

where δ_1 , δ_2 are the secondary emission yield of cathode and grid-anode, respectively. T is the transmission factor of the grid-anode.

The effect of multipacting in MPG is similar to that in the parallel-plate, and the equation of motion of a

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single electron is:

$$d^2y/dt^2 = (eV_{rf0}/mD)\sin(\varphi + \omega t), \quad (2)$$

where e/m is the charge -mass ratio, V_{rf0} is the amplitude of RF voltage and $\omega = 2\pi f$ (f is the frequency of cavity).

Assuming that electrons have an initial velocity v_0 at position $y=0$ with an initial phase $\varphi = \theta_0$, then velocity dy/dt and position $y(t)$ of the particle are readily solved from Eq. (2) to be

$$dy/dt = (eV_{rf0}/mD\omega)[\cos\theta_0 - \cos(\varphi + \omega t)] + v_0, \quad (3)$$

$$y = (eV_{rf0}/mD\omega^2)[\sin\theta_0 - \sin(\varphi + \omega t) + \omega t \cos\theta_0] + v_0 t. \quad (4)$$

When the electrons reach the opposite side at $y=D$, the transit-time $\omega t = N\pi$ (N is an odd number), and $\varphi = \theta_0$. So the impact velocity v_y and resonance equation can be written as follows:

$$v_y = (2eV_{rf0}/mD\omega)\cos\theta_0 + v_0, \quad (5)$$

$$V_{rf0} = [mD\omega(D\omega - N\pi v_0)]/[e(N\pi\cos\theta_0 + 2\sin\theta_0)]. (N=1, 3, 5 \dots). \quad (6)$$

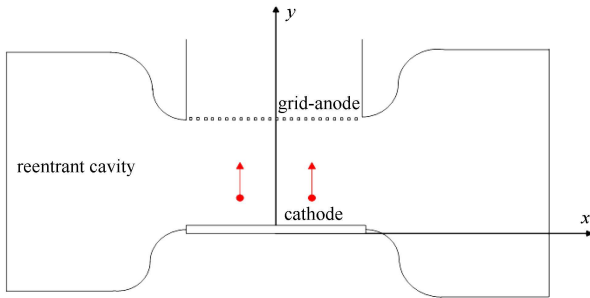


Fig. 1. (color online) The reentrant cavity of micro-pulse electron gun.

2.2 A novel method for MPG design

It is convenient to find a resonance condition by using Eqs. (5) and (6). The steps to figure out the basic parameters have been shown in Fig. 2. Here, we set the initial θ_0 to 0 for the sake of simplicity.

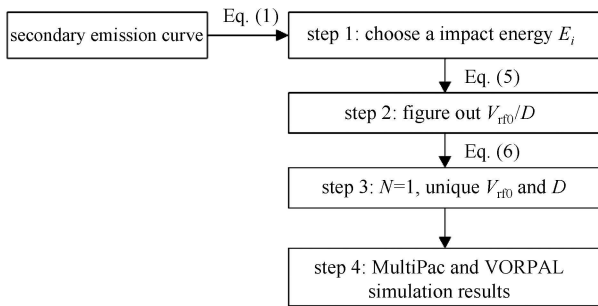


Fig. 2. A flow chart used to calculate the resonance parameters in the cavity.

In step 3, we set N to 1 for two reasons: Firstly the first-order multipacting has a wider resonance voltage range than that for higher orders [4]. The second reason is that the first-order multipacting can give rise to better pulse quality. Depending on the electron emission phase, hybrid-orders mode commonly exists in multipacting as shown in Fig. 3. Setting N to 1 is a suggested solution to avoid the possibility of hybrid-orders. Based on this setting, the resonance parameters are calculated as shown in Table 1.

Table 1. Basic simulation condition.

parameters	values
cathode/anode materials	MgO
frequency/GHz	2.856
target impact energy/keV	5
gap distance D /mm	4
$(V_{rf0}/D)/(MV/m)$	2.08
transmission of grid-anode(%)	50

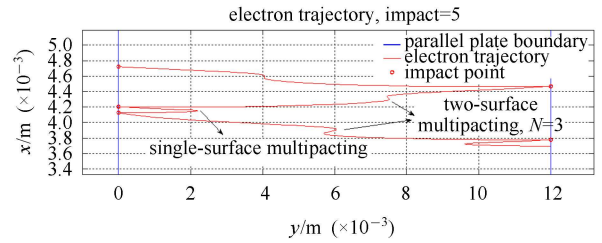


Fig. 3. (color online) Hybrid-orders mode in multipacting, for gap distance $D=1.2$ cm.

MultiPac, which is widely used by researchers around the world, is a 2D multipacting code with known secondary emission properties [5]. As gap distance D and RF electric field V_{rf0} have been calculated, scanning an extensive electric field zone in MultiPac is proposed here in order to find a proper resonant condition, and Fig. 4 shows the simulation results.

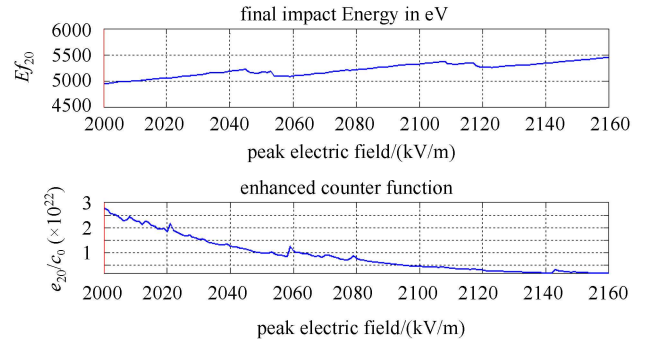


Fig. 4. (color online) MultiPac simulation results. (above) Average impact energy in eV after 20 impacts; (below) Enhanced function after 20 impacts, note that multipacting occurs only when the enhanced function is greater than one. MultiPac ignores the space charge effect.

In summary, this method provides a convenient way to determine the resonance condition in the gun. Combining with the MultiPac results, the proper running parameters for the gun are obtained, and these parameters work as the input in our further simulations.

3 2-D VORPAL simulation

VORPAL is the PIC simulation code for complex geometries and allowing the study of effects of multipacting in vacuum devices [6, 7]. It is easy for VORPAL to simulate the effect of multipacting with up to hundreds billion of physical electrons than other codes, such as CST. Table 1 shows the basic parameters for both 2-D and 3-D simulations. At the beginning, a y -direction sinusoidal RF voltage was motivated in the cavity and a group of electrons were loaded ten periods later in order to synchronize with the field. The electrons were emitted from the cathode and hit the grid-anode a half of a period later. The process of grid-hitting can't be directly observed before saturation in Fig. 5, but it exactly shows as a sub-peak of the curve after saturation.

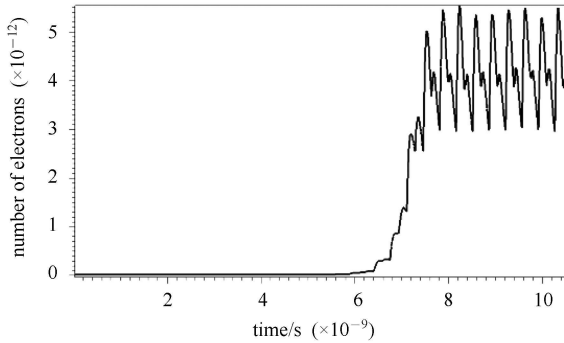


Fig. 5. Number of physical electrons as a function of time in 2-D simulation, steady state saturation had occurred after 8 ns.

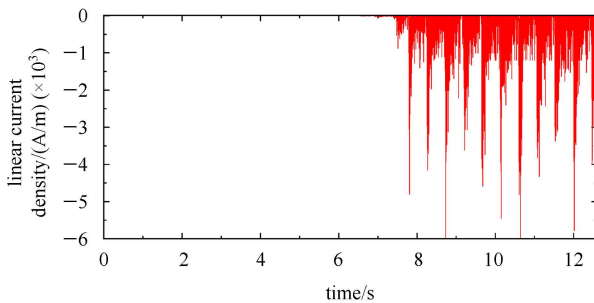


Fig. 6. The time history of linear current density monitored by a sheet behind the grid-anode.

Steady state saturation, which is needed for the running of MPG, had occurred after 8 ns. Fig. 6 shows the linear current density as a function of time, and the linear current density that monitored outside of the cavity saturates at about 5500 A/m. Hence the saturation current equals 22 A.

4 A transition phenomenon from two-surface multipacting to single-surface multipacting in MPG

The final steady state characteristics of multipacting discharge are important for MPG. Steady state saturation is achieved in our 2-D VORPAL simulation, and it is necessary to construct a 3-D model to study multipacting effects because of its complexity. Here TM010 has been motivated in the 3-D reentrant cavity, and steady state of E_z occurred ten periods later (as shown in Fig. 7). Table 2 shows two kinds of codes for running VORPAL simulations; the conditions are the same except for a different emission time.

Table 2. electron emission time for VORPAL code.

code	start_emission	end_emission
1	10*period	10*period+1*period
2	10*period	10*period+5*period

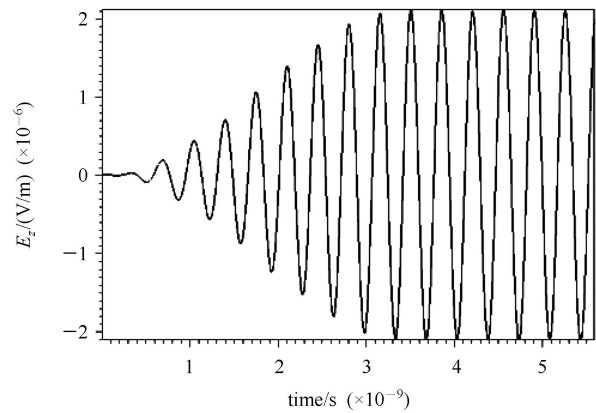


Fig. 7. Z-direction electric field E_z as a function of time.

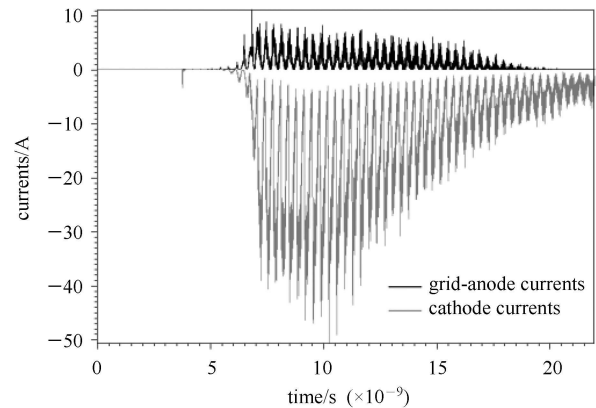


Fig. 8. Time history of cathode and grid-anode currents (namely, monitored in the cathode and grid-anode) for code 1 in Table 2.

The same as with Ref. [8], the transition that was caused by space charge effect from two-surface multipacting to single-surface multipacting in MPG is observed by analysis of simulation results. In Fig. 8, the impact currents of the grid-anode gave rise to a peak due to saturation, then they gradually decreased with the axial electric field and finally to zero, while the cathode currents still kept steady state. Those changes strongly suggest the existence of transition from two-surface multipacting to single-surface multipacting.

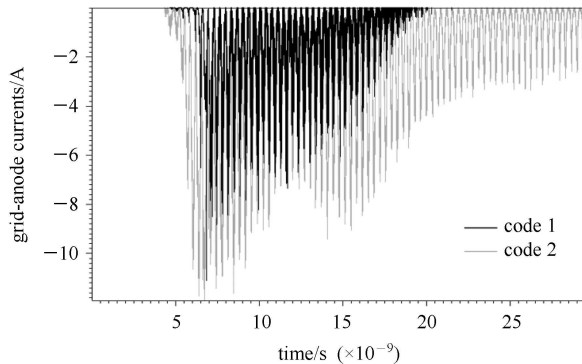


Fig. 9. (color online) Currents monitored in grid-anode. The anode impact currents of code 1 (light dark curve) are compared with impact currents of code 2 (darker shading curve). The darker shading curve decreased to 0 after 18 ns, suggesting no impacts in the grid-anode. The light dark curve indicates steady state saturation, the time distance of the nearby two summits is one period.

The transition from two-surface multipacting to single-surface multipacting would destruct the mechanism of the micro-pulse gun and it is not expected in our gun design. This kind of transition is caused by the mismatch between electron emission time and resonance voltages. Enhancing the range of emission time would help to determine the resonance condition. The light dark curve in Fig. 9 shows the solution to suppress the transition, and the currents after 25 ns indicate a steady state for multipacting.

5 Conclusion

In this paper, a comprehensive analytical study has been made of the effect of multipacting in the micro-pulse electron gun with the combination of 2-D and 3-D simulations. The basic parameters for the cavity of the gun were calculated, which worked as the input parameters for MultiPac and VORPAL. In 2-D VORPAL simulation, steady state saturation has been reached due to the balance of electron loss caused by space charge effect and secondary emission, but a harmful transition from two-surface multipacting to single-surface multipacting found in a few VORPAL 3-D simulations would prevent the micro-pulse gun from outputting micro-pulses. In case of this kind of transition, an extensive electron emission time has been used in order to have a steady performance for the gun.

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