# STEADY STATE MULTIPACTING IN A MICRO-PLUSE ELECTRON GUN

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*Abstract*

Multipacting is a resonant electron discharge phenomenon via secondary electron emission, while micropulse electron gun (MPG) utilizes the multipacting current in a radio-frequency (RF) cavity to produce short pulse electron beams. The concept of MPG has been proposed for many years. However, the unstable operating state of MPG vastly obstructs its practical applications. This paper presents a study on the steady state mulitpacting in a MPG. The requirements for steady state multipacting are proposed through the analysis of the interaction between the RF cavity and the beam load. Accordingly, a MPG cavity with the frequency of 2856 MHz has been designed and constructed. Various kinds of grid-anodes are tested in our primary experiments. Both the unstable and stable multipacting current have been observed. Presently, the stable output beam current has been detected at about 12.2 mA. Further experimental study is under way now.

## INTRODUCTION

Multipacting is a resonant electron discharge phenomenon via secondary electron emission [1], which is frequently observed in microwave systems. When the multipacting effect occurs, it usually causes some undesirable problems, such as deterirorating the vacuum, absorbing incident power, leading to quenching of superconducting cavity, etc. So, most studies on multipacting focus on how to suppress or eliminate it. Until 1993, Fredrick M. Mako and William Peter proposed the concept of MPG [2], which utilized the multipacting current in a RF cavity to produce pulsed electron beams. Due to its self-bunching property, MPG is capable of providing high current and short pulse electron beams. In addition to that, its simple structure and high tolerance to contamination make it a potential electron source for accelerators and microwave systems.

The main problem in the development of MPG is the stability of the output beam current. To get high beam current and low emittance, previous studies on MPG always tried to feed high power into the cavity to get high surface field [3,4]. The stable multipacting current in the MPG was considered to be formed as the equilibrium result of the self-bunching effect and the space charge effect [1]. However, we believe the beam loading effect also plays an important role in the forming process of stable multipacting current.

This paper presents a study on the steady state mulitpacting in a micro-pluse electron gun with theory and experiments. In the second section, a MPG model is setup to show the basic characteristics of the MPG. The requirements for the steady state multipacting is proposed through the analysis of the interaction of the RF cavity and electron beams. In the third section, a MPG cavity with the frequency of 2856 MHz has been designed and constructed. Different kinds of grid-anodes are tested in our experiments. Both the unstable and stable multipacting current have been observed sucessfully. The detected stable output beam current has reached 12.2 mA. Finally, a conclusion of this paper is given.

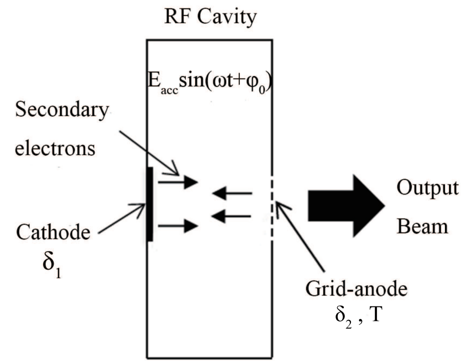


Figure 1: The schematic diagram of the MPG model [3].

## ANALYSIS OF STEADY STATE MP

### *The MPG Model*

The MPG model (Fig. 1) consists of three parts: an RF cavity working in the $TM_{010}$ mode, a secondary emission surface and a grid, which is opaque to the microwave electric field but partially transparent to the electrons in order to extract the electron beams [3]. We suppose the secondary emssion surface to be the cathode with secondary emission yield (SEY) $\delta_1$ and the grid to be the grid-anode with SEY $\delta_2$ and transmission coefficient T. Here, we adopt Vaughan′s empirical formula for $\delta_1$ and $\delta_2$ [5].

$$\delta_1(E_i) = \delta_{\max 1}(v_1 e^{1-v_1})^k \tag{1a}$$
$$\delta_2(E_i) = \delta_{\max 2}(v_2 e^{1-v_2})^k \tag{1b}$$

Where $E_i$ is the electrons impact energy, $\delta_{\max 1}$ and $\delta_{\max 2}$ is the maximum value of $\delta_1$ and $\delta_2$, $v_1 = (E_{i1} - E_0)/(E_{\max 1} - E_0)$, $v_2 = (E_{i2} - E_0)/(E_{\max 2} - E_0)$, in which $E_{max1}$ and $E_{max2}$ are the impact energy corresponding to $\delta_{max1}$ and $\delta_{max2}$, $E_0$ being the initial energy of secondary electrons and $k = 0.62$ for $v < 1$; $k = 0.25$ for $v > 1$. For one RF period, the total effective secondary electron emission yield $\delta$ is:

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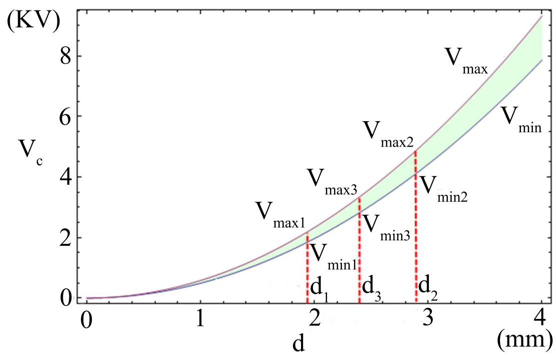


Figure 2: The resonant gap voltage range versus the gap d when the cavity frequency is 2856 MHz.

$$\delta = \delta_1(E_i)\delta_2(E_i)(1-T) \tag{2}$$

Now, we consider a RF cavity operating at the resonant frequency $\omega_0$. The gap distance between the cathode and the grid-anode is d. Under the force of the electric field, electrons in the cavity move back and forth between the cathode and the grid-anode. The transit time from one anode to the other is just one-half RF period [1]. We obtain the resonant condition:

$$V_c = \frac{m}{e}\frac{\omega_0 d(\omega_0 d - \pi v_0)}{2\sin\varphi_0 + \pi\cos\varphi_0} \tag{3}$$

In which, m is the mass of electron, e is the elementary electric charge, $v_0$ is the initial velocity of the emitted electrons and $\varphi_0$ is the initial phase of the RF field.

The MPG also needs to satisfy the requirement of the self-bunching property. The self-bunching property demands the secondary electrons emitted within an appropriate initial phase range. For electrons with emitted energy $E_0 = 0$, the appropriate initial phase range is 0 to arctan $2/\pi$ ($\approx$ 32.5°) [1]. Substituting the phase range into the resonant condition (Eq. 3), we get the corresponding resonant gap voltage range:

$$V_{min} = \frac{m}{e}\frac{\omega_0^2 d^2}{\sqrt{\pi^2+4}} \tag{4a}$$

$$V_{max} = \frac{m}{e}\frac{\omega_0^2 d^2}{\pi} \tag{4b}$$

Figure 2 shows the resonant gap voltage region (light green area) varying with the gap distance d when the cavity frequency is 2856 MHz. If the gap voltage is outside of this resonant range, the electrons cannot gather together in the longitudinal direction so that the electron beam will break up.

### *Requirements for Steady State Multipacting*

Basically, the higher the gap voltage is, the more energy will be gained. According to the secondary emission property of common meterials, we can map the total effective SEY curve versus the gap voltage qualitatively (Fig. 3).

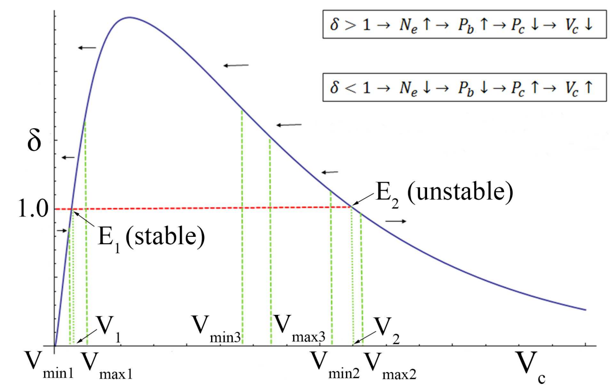


Figure 3: The total effective SEY curve versus the gap voltage $V_c$. ($E_1$ is the first crossover point and $E_2$ is the second one. $V_1$ and $V_2$ are the gap voltages corresponding to $E_1$ and $E_2$. [$V_{min1}$, $V_{max1}$], [$V_{min2}$, $V_{max2}$] and [$V_{min3}$, $V_{max3}$] are the corresponding resonant gap voltage ranges when the gap distance d takes different values. In addition, $V_1 \in [V_{min1}, V_{max1}]$ and $V_2 \in [V_{min2}, V_{max2}]$.)

Supposing that the resonant gap voltage range is [$V_{min1}$, $V_{max1}$], if the gap voltage $V_c$ is greater (less) than $V_1$, more (fewer) secondary electrons will be released, so the number of electrons $N_e$ will increase (decrease). As a result, more (less) microwave power will be drained from the cavity as it accelerates more (fewer) secondary electrons. This leads to a higher (lower) $P_b$ and lower (higher) $P_c$ as well as a lower (higher) gap voltage $V_c$, which makes $V_c$ closer to $V_1$ in subsequent RF periods. Similarly, $V_c$ will move far away from $V_2$ automatically if [$V_{min2}$,$V_{max2}$] is the resonant gap voltage range. Thus $E_1$ is the steady state operating point for the MPG, not $E_2$. This conclusion is consistent with R. Kishek and Y.Y. Lau's theoretical analysis on multipactor discharge in a closed RF cavity [6, 7].

However, if the resonat gap voltage range is set to be [$V_{min3}$, $V_{max3}$] as many previous studies did, $\delta$ will be always greater than 1. When the gap voltage reaches the resonant range, the multipacting current will grow to a very large value in a very short time. A great deal of microwave power will be drained from the cavity to accelerate these multiplied electrons. So the gap voltage will eventually fall outside of the resonant range and the electron beam will break up due to the longitudinal debunching. Therefore, there is no stable working point in [$V_{min3}$, $V_{max3}$]. This explains why previous MPGs could not work stably.

To obtain steady state multipacting, the working point should be set in the vicinity of the first crossover point $E_1$ and [$V_{min1}$, $V_{max1}$] should be set as the resonant gap voltage range. Meanwhile, $V_1$ must be included in this resonant range. Noting that the value of $E_1$ depends on the secondary emission property of the cathode and the grid-anode as well as the transmission factor T (Eq. 2), while the resonant gap voltage range [ $V_{min1}$, $V_{max1}$] is determined by $\omega_0$ and d.



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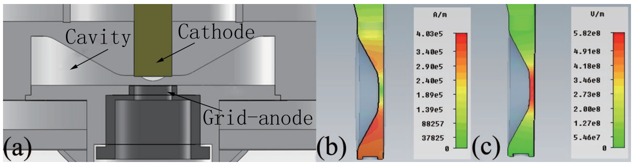


Figure 4: (a) the cross section of the MPG, (b) the magnetic field distribution, (c) the electric field distribution.

Table 1: The Designed RF Parameters of the MPG Cavity

| RF parameters | Designed Value |
|---|---|
| Resonant frequency $f_0$ (MHz) : | 2856 |
| Gap distance d (mm) | 1.75 |
| Unloaded quality factor $Q_0$ | 653 |
| Shunt impedance $r_{shunt}$ $(M\Omega)$ | 0.036 |
| Unloaded coupling coefficient $\beta_0$ | 1.25 |

So, as long as the above requirements are satisfied, it is possible to get steady state multipacting in the MPG.

## PRIMARY EXPERIMENTS

### *The MPG Cavity and the Test Stand*

According to the requirements for steady state MP, a micro-pulse electron gun working in the $TM_{010}$ mode with the frequency of 2856 MHz has been designed and constructed. Table 1 lists the designed RF parameters of the MPG cavity. The micro-pulse electron gun (Fig. 4a) consists of a RF cavity made of stainless steel, a cathode made of Cu-Al-Mg alloy and a grid-anode. The impact energy corresponding to the maximum secondary emission yield $\delta_{max}$ is about 1 KeV for Cu-Al-Mg alloy [8]. The gap distance between the cathode and the grid-anode is adjustable with the precision of 0.01 mm. The cathode and the grid-anode are also dismountable and can be replaced easily. The distribution of the magnetic field and the electric field are shown in Fig. 4b and Fig. 4c. Obviously, the electric field is mainly concentrated in the region between the cathode and the grid-anode.

The test stand is shown in Fig. 5. The microwave power is supplied by a soild-state power amplifier with 1 kW maximum output power. The output electron beams from the grid-anode are collected by a faraday cup parallelly connected to a 50 Ω resistance and the beam current is measured by a HP 54503A oscilloscope with 1 MΩ input resistance.

Table 2: The Measured Output Beam Currents ($I_b$) with Various Grid-anodes

| Grid-anode No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Material | SS | SS | OFC | OFC |
| T | 6% | 18.3% | 18.3% | 25% |
| Measured $I_b$ (mA) | ≈0.2 | 3.8 | 4.2 | 12.2 |

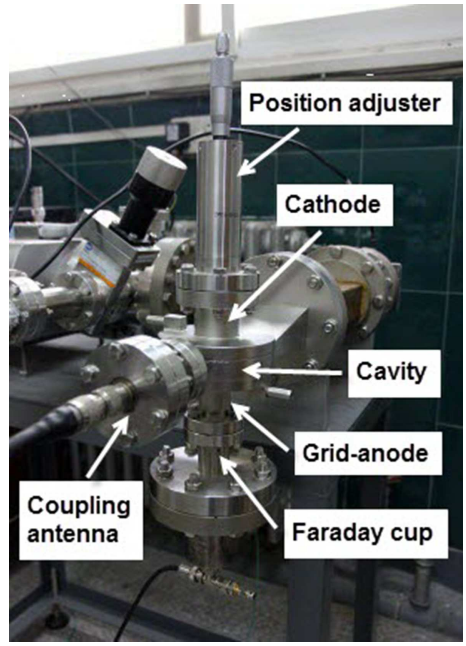


Figure 5: Photogragh of the test stand.

### *Experiment Results and Discussions*

Various grid-anodes are tested in our experiments. Table 2 lists the measured output beam currents corresponding to four kinds of grid-anodes with different meterial and transmission coefficient (T). In Table 2, SS refers to stainless steel and OFC represents oxy free copper. Figure 6 shows our primary experimental results. The macro-pulse width is 15 us and the repetition rate is about 100 Hz. Figure 6a shows the output beam current when No.1 grid-anode is used. The output siganl is very small and unstable on the oscilloscope. The waveform is fluctuating with the "spikes" on the pick-up signal and reflected signal in Fig. 6b. Figure 6c performs a very stable output beam current when the grid-anode is No.2. The signal waveform can remain unchanged for more than half an hour, which reveals that we have already obtained the steady state multipacting in the MPG. The output beam current is about 1.7 mA. Moreover, it can be adjusted up to 3.8 mA, which is shown in Fig. 6d. We also obtained the stable output beam current successfully, when No.3 and No.4 grid-anode are tested (Fig. 6e and Fig.6f). The output beam current measured in the experiments are about 4.2 mA (T=18.3%) and 12.2 mA (T=25%) respectively.

The spikes appearing on the pick-up signal and the reflected signal in Fig. 6b indicate the typical unstable multipacting processes in the cavity. In this situation, the total effective SEY is above 1, but the actual working point is not in the vicinity of $E_1$. So, the electrons in the cavity grows rapidly without restraint. The multiplied electrons absorb plenty of RF power, leading to the cavity voltage falling out of the resonant gap voltage range, so the electron beam collapses. After that, the cavity voltage returns to the initial state. The remaining electrons in the cavity will begin

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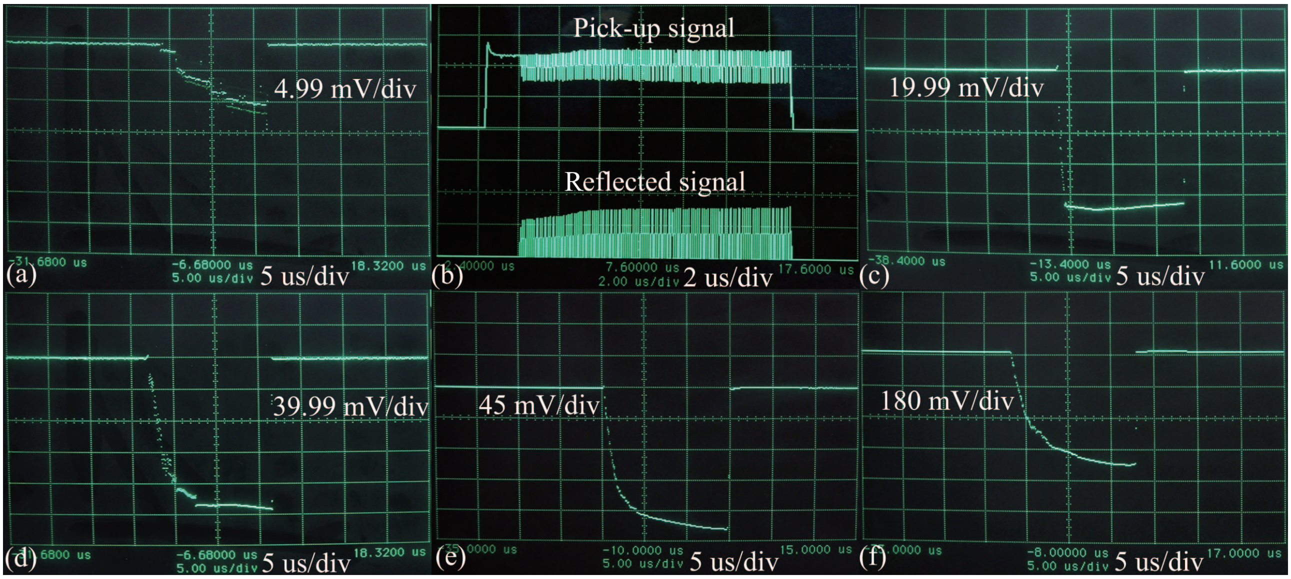


Figure 6: Primary experimental results. (a) is the output beam current (≈0.2 mA) when the grid-anode is No.1; (b) is the pick-up signal and reflected signal corresponding to (a); (c) is the output beam current (≈1.7 mA) when the grid-anode is No.2; (d) is the maximum detected output beam current (≈3.8 mA) when the grid-anode is No.2; (e) is the output beam current (≈4.2 mA) when No.3 grid-anode is tested; (f) is the output beam current (≈12.2 mA) when No.4 grid-anode is tested.

the multiplication again and a new cycle keeps on. So the "spikes" appears on the pick-up signal successively as well as the reflected signal due to the variation of the loaded coupling coefficient.

## CONCLUSION

In summary, this paper presents a study on the steady state multipacting in a micro-pulse electron gun with theory and experiments. In theory, the requirements for steady state multipacting is proposed. The working point should be set in the vicinity of the first crossover point $E_1$ and [$V_{min1}$, $V_{max1}$] should be set as the resonant gap voltage range. Meanwhile, $V_1$ must be included in this range. As for experiments, a MPG cavity with the frequency of 2856 MHz has been designed and constructed. Various kinds of grid-anodes are tested in our experiments. Both the unstable and stable multipacting current have been observed. Presently, the measured stable output beam current has reached 12.2 mA. Further experimental study is under way now.

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