Toward a multipacting-free cavity design for a very-high-frequency continuous-wave electron gun

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Abstract

A very-high-frequency (VHF) photocathode electron gun serves as an electron source capable of generating high-repetition-rate, high-brightness electron bunches. It operates in continuous-wave mode with a 100% microwave duty cycle, a configuration where multipacting emerges as a critical operational challenge requiring meticulous mitigation. The exponential amplification of secondary electrons within the electron gun may cause power dissipation, cavity material degradation, and beam quality deterioration, ultimately compromising both the performance and operational lifetime of the VHF gun. This study investigates the influence of radio-frequency (rf) cavity geometry and copper secondary electron yield on multipacting behavior through CST simulations. We present an equatorial cavity geometry exhibiting extremely low multipacting intensity, offering a promising approach for ensuring stable VHF electron gun operation.

Full Text

Preamble

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bunches. It operates in continuous-wave mode with a 100% microwave duty cycle, a configuration where multipacting emerges as a critical operational challenge requiring meticulous mitigation. The exponential amplification of secondary electrons within the electron gun may cause power dissipation, cavity material degradation, and beam quality deterioration, ultimately compromising both the performance and operational lifetime of the VHF gun. This study investigates the influence of radio-frequency (rf) cavity geometry and copper secondary electron yield on multipacting behavior through CST simulations. We present an equatorial cavity geometry exhibiting extremely low multipacting intensity, offering a promising approach for ensuring stable VHF electron gun operation.

Keywords: multipacting, secondary electron, VHF electron gun, cavity shape

Introduction

Multipacting [1–5] is a nonlinear electron multiplication phenomenon driven by high-frequency electromagnetic fields in radio-frequency (rf) devices, occurring under vacuum conditions. When primary electrons, accelerated by electromagnetic fields, impact metallic or dielectric surfaces, they generate secondary electrons that subsequently strike the surfaces, producing additional electrons and creating an electron avalanche. In particle accelerators, multipacting predominantly occurs in resonant cavities operating in long-pulse [3] or continuous-wave (CW) [1, 6–8] modes. CW resonant cavities are particularly susceptible, as continuous microwave excitation enables rapid secondary electron accumulation. This process induces multiple detrimental effects: vacuum degradation from surface outgassing, metallic surface damage, dielectric window rupture due to breakdown, and beam quality deterioration resulting from impaired electromagnetic field establishment within the cavity. Consequently, suppressing multipacting remains a critical challenge in developing CW resonant cavities for particle accelerators.

The very-high-frequency (VHF) photocathode electron gun [6, 7, 9, 10] is a typical resonant cavity operating in CW mode. It is an electron source capable of producing high-quality electron bunches with MHz-class repetition rates, which can be applied to scientific facilities such as high-repetition-rate free-electron lasers and ultrafast electron diffraction. In recent years, the VHF electron gun developed by Tsinghua University has been successfully applied to the Shanghai high repetition rate x-ray free electron laser and extreme light facility (SHINE) [11, 12] and the Dalian Advanced Light Source Test Facility [13]. The resonant frequency of the electron gun is 216.667 MHz. During high power conditioning, the gun achieved a cathode gradient of 27 MV/m and a voltage of 780 kV under an rf power of 75 kW [6]. This gun currently holds the record for the highest cathode gradient among CW electron guns operating at room temperature.

In the SHINE gun, multipacting occurs at cathode gradients below 16 MV/m but is suppressed above this threshold. While multipacting is absent at the target operational cathode gradient, the required gradual power ramp-up from 0 to 75 kW during system startup transiently traverses field levels conducive to multipacting. To mitigate this, pulsed mode operation is necessary to bypass the intense multipacting regime before transitioning to CW operation. Furthermore, operational stability may be compromised during power reflection anomalies, which could inadvertently shift the system into the multipacting regime. If the gun enters the multipacting regime during high-power operation, the vacuum within the gun deteriorates rapidly, thereby shortening the semiconductor cathode's operational lifetime. Additionally, multipacting-induced breakdown events may occur, increasing the risk of ceramic window damage. Collectively, these factors present potential risks to the long-term reliability of the VHF gun.

In this paper, we propose an equatorial cavity geometry and demonstrate through simulations that this configuration significantly reduces multipacting strength. The paper is structured as follows: Section 2 details the methodology for multipacting simulations, Section 3 presents the results of optimizing the outer circle dimensions of the equatorial cavity, and Section 4 discusses the influence of copper's secondary electron yield (SEY) on simulation results. By incorporating a more realistic SEY model, the optimized cavity geometry exhibits exceptionally low multipacting intensity, rendering it effectively negligible.

II. Simulation Setup

Multipacting simulations were performed in CST Studio Suite [14], utilizing CST Microwave Studio for rf field simulations and CST Particle Studio for particle dynamics simulations. First, the rf cavity geometry was optimized using CST Microwave Studio's built-in optimizer with an eigenmode solver. The cathode gradient, resonant frequency, and cathode–anode gap were fixed at 27 MV/m, 216.667 MHz, and 3.5 cm, respectively. Remaining cavity dimensions were parameterized and optimized within the software. Optimization objectives included minimizing input power, peak surface power density, and peak surface electric field while maximizing gun voltage.

[Figure 1: see original paper] displays the optimized cavity profile alongside the corresponding electric and magnetic field distributions. In particle dynamics simulations, the SEY of copper critically influences multipacting strength. Numerous physical models have been developed to describe secondary electron emission phenomena. The Vaughan model [15], a seminal semi-empirical approach, is widely adopted for rapid SEY estimation due to its simplicity, requiring only 10 parameters [16]. A foundational assumption in Vaughan's formulation is that SEY drops to zero for electron impact energies below a critical threshold. In contrast, the Furman model [17] employs 47 parameters to rigorously characterize material emission properties, making it indispensable for high-precision applications in the particle accelerator community [2]. Furthermore, Furman's framework decomposes secondary electron emission into three components: true secondary, rediffused, and elastically backscattered electrons, with total SEY equaling their sum. As shown in [Figure 2: see original paper], the generation of secondary electrons involves the following physical processes [18]: (a) elastic collisions between incident electrons and the surface, producing elastically backscattered electrons; (b) penetration and scattering of incident electrons via interactions with atomic electrons or lattice structures, yielding rediffused electrons; (c) energy transfer from incident electrons to bound material electrons, followed by their transport to the surface and emission as true secondary electrons.

The scatter plots in [Figure 3: see original paper] present measured SEY of copper as a function of incident electron energy from two independent research groups [19, 20]. Three solid lines in the figure represent theoretical SEY values frequently employed in multipacting simulations: the purple line corresponds to the CST-embedded Furman model, the orange line to an adjusted Furman model [21], and the green line to the ECLOUD model [22–24]. The ECLOUD model, developed at CERN, derives from laboratory measurements of copper surfaces utilized in the Large Hadron Collider. Notably, significant discrepancies exist among the measured SEY values from different groups, attributable to variations in copper impurity composition and surface treatment methodologies. To ensure conservative simulations, the CST-embedded Furman model was selected. The impact of SEY variability on multipacting predictions will be analyzed in Section 4.

A quarter-symmetry copper cavity model was implemented in CST Particle Studio (Figure 4: see original paper), significantly accelerating simulations while preserving multipacting analysis accuracy. The rf field distribution was directly imported from CST Microwave Studio. A total of 2000 seed electrons with 5 eV initial kinetic energy were generated on the copper cavity surface. Electrons were emitted isotropically within the hemisphere, ensuring comprehensive sampling of initial particle trajectories. Figure 4: see original paper illustrates the multipacting localization within the quarter-symmetry cavity under a 3 MV/m cathode gradient. The analysis reveals that multipacting primarily localizes near the outer cavity periphery, where the radius is large. Consequently, spatial distributions of multipacting activity remain consistent across other cathode gradients. Therefore, geometric optimization of the outer periphery—targeted at suppressing multipacting strength—will be implemented in Section III.

[Figure 5: see original paper] shows the temporal evolution of particle populations for four cathode gradients. Beyond 60 ns, the particle count exhibits a linear relationship with time on a logarithmic y-axis, confirming exponential growth. This exponential temporal dependence signifies multipacting onset. For quantitative analysis, the tail region demonstrating unambiguous exponential growth was fitted using the following equation:

$$N_e(t) = N_0(t) \times e^{\alpha t}$$

where $N_e(t)$ is the particle count at time t, N_0 the initial particle population, and α the exponential growth rate constant. The parameter α directly quantifies multipacting strength.

III. Effect of Outer Cavity Geometry on Multipacting

The VHF gun predominantly exhibits two-point multipacting. This phenomenon requires three conditions: (a) alternating electric field polarity between successive electron-wall impacts; (b) electron flight time matching an integer multiple of half the rf period; (c) impact energies yielding SEY $>$ 1. Geometric cavity modifications at multipacting-prone regions alter local electromagnetic field distributions, thereby disrupting these multipacting conditions. This work evaluates multipacting suppression through systematic cavity geometry adjustments. Earlier studies demonstrated that replacing circular outer corners with elliptical profiles reduces multipacting strength [6].

Figure 6: see original paper defines critical geometric parameters influencing multipacting strength: cavity radius r, major axes (a_1, a_2), and minor axes (b_1, b_2) of the elliptical corners. Prior designs retained a linear segment between elliptical corners (Figure 6: see original paper). The proposed equatorial cavity geometry (Figure 6: see original paper) eliminates this linear segment while maximizing elliptical major axes.

The cavity geometry optimization proceeds in three phases:

Phase 1: Major Axis Optimization. The initial parameters are fixed as follows: cavity radius $r = 34.7$ cm, elliptical minor axes $b_1 = b_2 = 5.7$ cm, and cathode-anode gap = 3.5 cm. The elliptical major axes a_1 and a_2 are incrementally increased until full contact between the ellipses is achieved ($a_1 = a_2 = 17.5$ cm). Concurrently, remaining cavity dimensions are optimized in CST Microwave Studio to maximize rf performance. Subsequent beam dynamics simulations in CST Particle Studio quantify multipacting intensity via the growth rate parameter α across cathode gradients. Prior studies confirm that multipacting in the VHF gun occurs between 0–15 MV/m [6]. 7 MV/m is the middle of this interval and can be considered as the cathode gradient where the multipacting intensity is relatively strong. Therefore, as a representative example, we investigate the effect of different cavity shapes on the multipacting strength under a cathode gradient of 7 MV/m. [Figure 7: see original paper] illustrates the relationship between elliptical major axes and α at 7 MV/m, which demonstrates a significant reduction in multipacting strength as elliptical major axes increase.

Phase 2: Equatorial Radius Optimization. With $b_1 = b_2 = 5.7$ cm, $a_1 = a_2 = 17.5$ cm (fully contacting ellipses forming the equatorial cavity), and cathode-anode gap = 3.5 cm, the equatorial radius r is scanned from 34.7 cm to 33.5 cm. For each geometry, rf parameters are reoptimized. [Figure 8: see original paper] reveals a progressive suppression of multipacting strength (α) as r decreases. Continuing to decrease r below 33.5 cm results in larger input power and peak surface power density. Therefore, from comprehensive consideration of rf performance, we fix $r = 33.5$ cm.

Phase 3: Minor Axis Optimization. Fixing $r = 33.5$ cm, $a_1 = a_2 = 17.5$ cm, and cathode-anode gap = 3.5 cm, the minor axes b_1 and b_2 are scanned. The variation of multipacting growth rate α with b_1 and b_2 is shown in [Figure 9: see original paper]. The growth rates α under cathode gradients from 0 to 30 MV/m were calculated. No multipacting occurs for cathode gradients greater than 20 MV/m, therefore it is no longer plotted in the figure. The analysis identifies $b_1 = b_2 = 6$ cm as the optimal configuration for minimizing α.

Following systematic simulation studies, an optimized electron gun cavity with dramatically suppressed multipacting has been developed, featuring critical dimensions $a_1 = a_2 = 17.5$ cm, $b_1 = b_2 = 6$ cm, and $r = 33.5$ cm. [Figure 10: see original paper] compares the growth rate α versus cathode gradient for this optimized geometry against the SHINE gun baseline. It can be seen that the multipacting intensity of the new cavity shape is extremely low and significantly better than that of the SHINE gun. Key rf performance parameters for the optimized cavity are quantified in , while [Figure 1: see original paper] visualizes the corresponding electromagnetic field distribution.

IV. Effect of SEY on Multipacting

[Figure 3: see original paper] illustrates that the default SEY curve in CST's Furman model exhibits elevated values. Experimental data demonstrate significant SEY reduction following surface treatments such as vacuum baking and glow discharge. Similarly, the VHF gun undergoes vacuum baking at 120–200°C (during conditioning) prior to high-power operation. This process, combined with high-power conditioning to eliminate spurious field emission sites, synergistically reduces operational SEY. Current research focuses on modifying the Furman model's SEY parameters to align with ECLOUD-compatible values [21].

In this study, we systematically reduce SEY within the Furman framework to evaluate its impact on multipacting dynamics. [Figure 11: see original paper] (solid lines) displays the default Furman model's SEY components: true secondary, elastic, and rediffused electrons. By lowering the true SEY component from 1.8848 to 1.4 while retaining original elastic and rediffused values (dashed lines, [Figure 11: see original paper]), the total SEY decreases to 1.6. This adjustment better matches experimentally measured copper SEY data, thus producing more physically representative multipacting simulations.

Subsequent numerical simulations employing the adjusted Furman emission model—while retaining the optimized cavity geometry—demonstrate significant multipacting suppression. [Figure 12: see original paper] displays the multipacting growth rate α as a function of cathode gradient (green line) after the SEY adjustment. For comparison, growth rates for both the SHINE gun and the new cavity geometry simulated with CST's default SEY are plotted. The adjusted

SEY model reduces α to near-zero values, rendering multipacting effectively negligible under high-power operational conditions.

V. Conclusion

This study systematically evaluates the influence of rf cavity geometry on multipacting dynamics in VHF photocathode electron guns. The proposed equatorial cavity design—featuring enlarged elliptical major axes—achieves significant multipacting suppression. Further analysis demonstrates that reducing the cavity radius additionally suppresses multipacting intensity. Optimization of the elliptical minor axes completes the geometric refinement process. Through these optimizations, we developed a cavity geometry exhibiting both extremely low multipacting strength and satisfactory rf performance. The investigation extends to copper's SEY effects. By implementing a physically more realistic SEY model, multipacting intensity decreases to negligible levels. This work effectively eliminates multipacting risks during high-power operation, providing critical insights for ensuring long-term operational stability in next-generation VHF electron guns.

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