University of Electronic Science and Technology of China

A Static Magnetic Field Focusing Electron Gun for 915 MHz Inductive Output Tubes

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Contents

1. Introduction

- The concept of the IOT was first proposed by Haeff in 1939. The IOT has attracted significant attention due to its high efficiency and excellent linearity.

- However, the development of IOTs was once limited by two major challenges: the thermal limitation of grid materials and the difficulty of grid fabrication.

- The electron gun of an IOT is a grid-controlled Pierce gun. The cathode operates under the space-charge-limited emission, and the electron emission is affected by both DC and RF voltages.

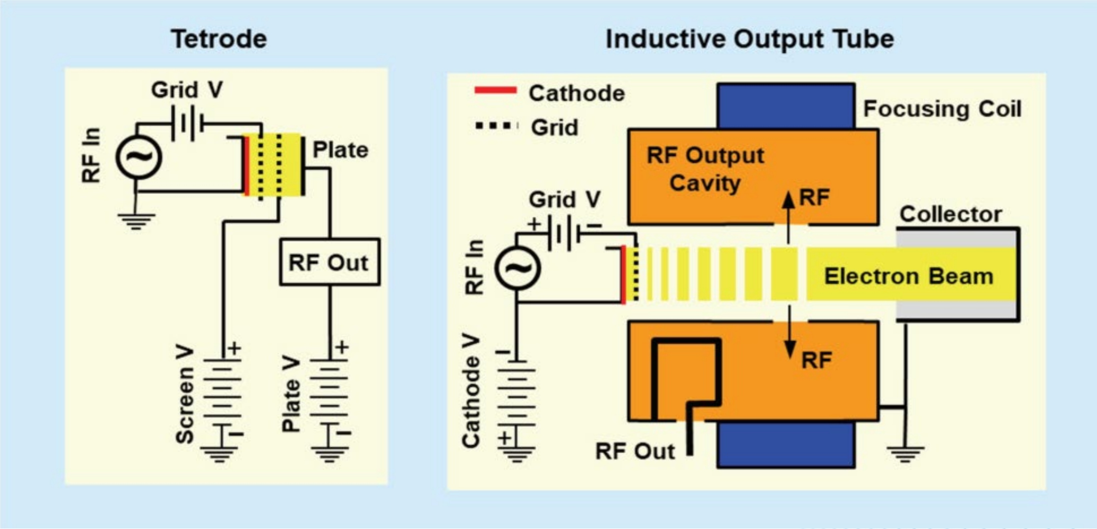

Fig.1.1 Comparison of output parts of a tetrode and an inductive output tube[1].

[1] Gilmour Jr A S. Microwave and millimeter-wave vacuum electron devices: inductive output tubes, klystrons, traveling-wave tubes, magnetrons, crossed-field amplifiers, and gyrotrons[M]. Artech House, 2020.

1. Introduction

- Currently, most IOT applications are focused on long-pulse and high-average-power operations, such as particle accelerators.

- In these applications, electron interception by the grid may cause excessive grid heating and even thermal failure. Moreover, the lifetime of the device is strongly dependent on the grid.

- Therefore, applying the IOT to short-pulse and low-duty-cycle conditions may significantly reduce the thermal load on the grid and improve the operational lifetime.

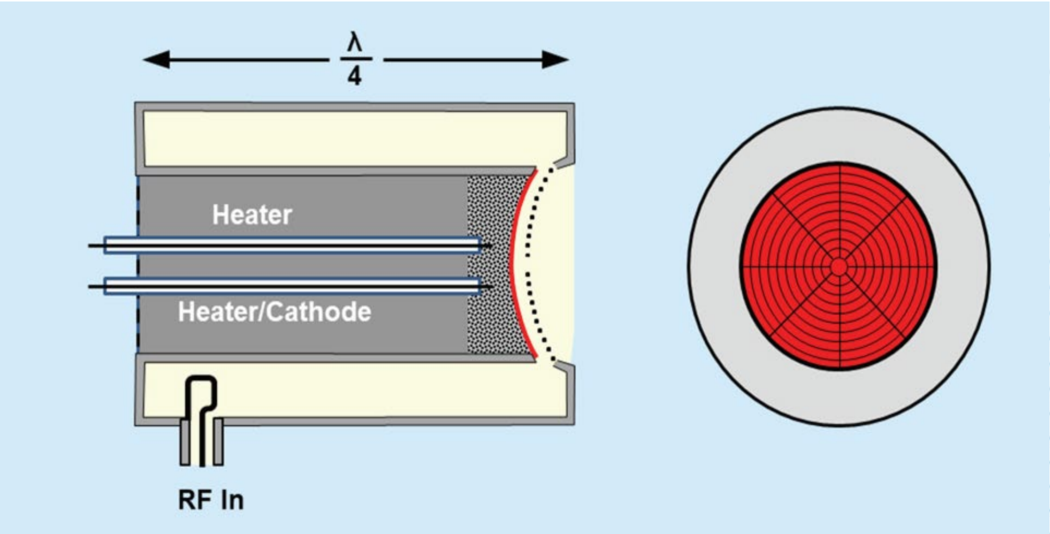

Fig.1.2 Use of $\lambda/4$ resonator to couple grid signal to grid[1].

[1] Gilmour Jr A S. Microwave and millimeter-wave vacuum electron devices: inductive output tubes, klystrons, traveling-wave tubes, magnetrons, crossed-field amplifiers, and gyrotrons[M]. Artech House, 2020.

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2. Simulation methods of electron gun for IOT

- **The simulation work presented in this report was performed using CST Studio Suite. The electron emission process in an IOT is a complex problem because it is influenced by DC and RF voltages.**

- **The iterative calculation process is therefore highly complicated, and simulation software currently does not provide a dedicated simulation module for IOTs.**

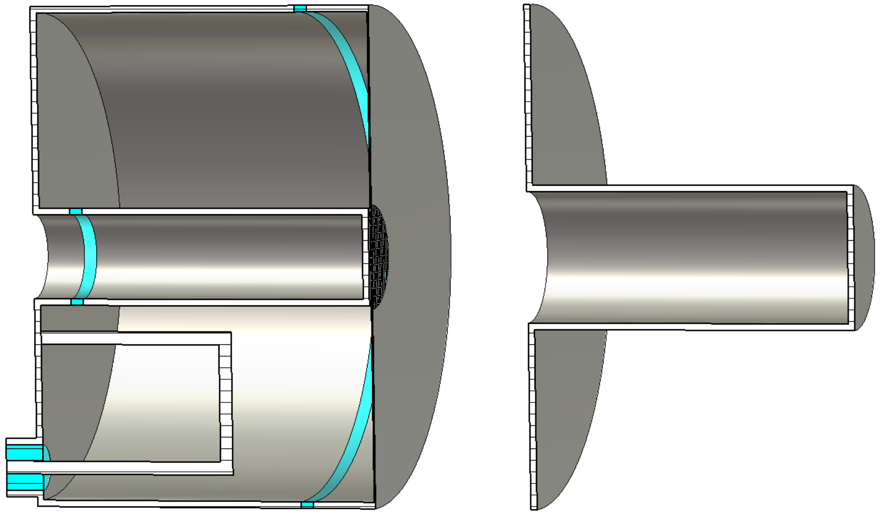

Fig.2.1 Simplified Model of Input Cavity - Grid Controlled Electron Gun.

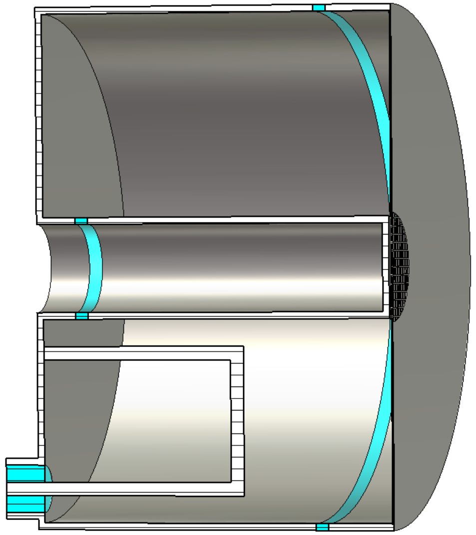

Fig.2.2 Simplified Model of Input Cavity.

2. Simulation methods of electron gun for IOT

- By combining different solvers, we transform the time-dependent electron emission problem into a series of static problems and develop a practical simulation approach.

- The first step of the IOT electron gun simulation is to use the eigenmode solver in CST Studio Suite. The operating mode of the input cavity is designed as the TM010 mode.

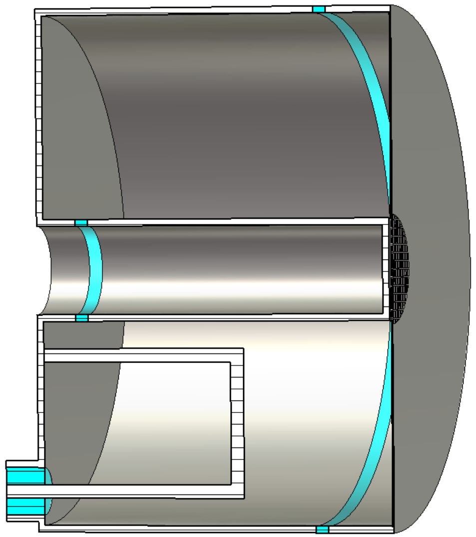

Fig.2.2 Simplified Model of Input Cavity.

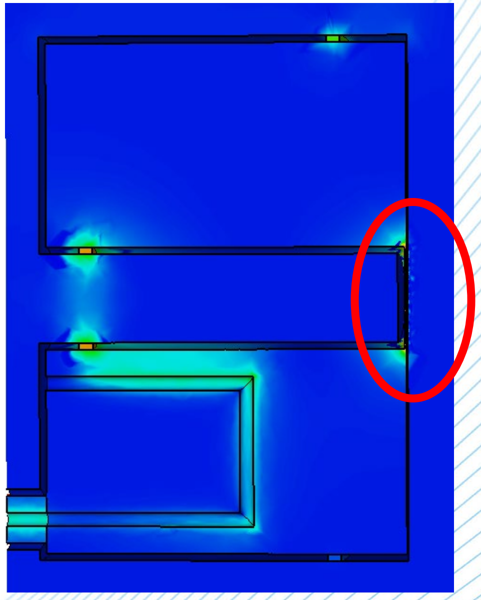

Fig.2.3 RF energy distribution in the input cavity.

2. Simulation methods of electron gun for IOT

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- In the TM010 mode, most of the RF electric field energy is concentrated in the region between the cathode and the grid, while the RF magnetic field in this region is relatively weak.

- Therefore, the emitted electron beam will not experience significant transverse deflection caused by RF magnetic fields.

- A static focusing magnetic field is introduced to compensate for electron beam divergence caused by the initial thermal velocity and space-charge effects.

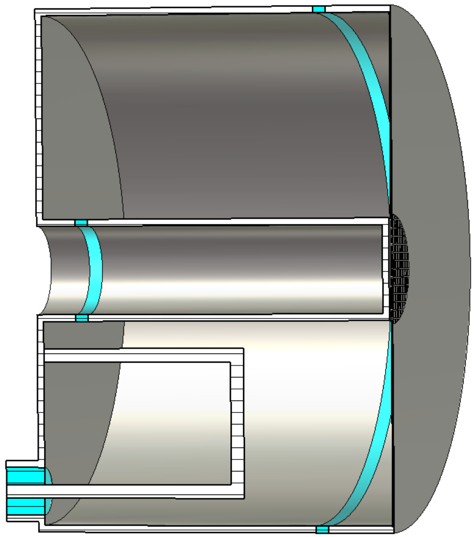

Fig.2.2 Simplified Model of Input Cavity.

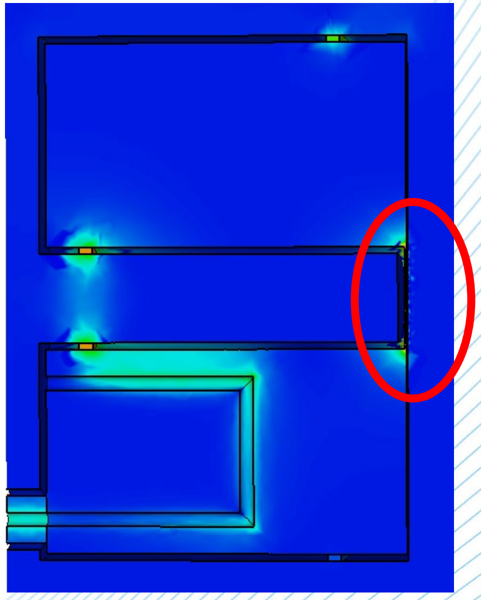

Fig.2.3 RF energy distribution in the input cavity.

2. Simulation methods of electron gun for IOT

- This approach also simplifies the simulation model and allows us to focus on the simulation methodology. For a planar cathode, the electron beam starts to diverge immediately after emission.

- In the eigenmode simulation, the anode is not included because the grid confines the RF field inside the input cavity, and almost no RF electric field exists between the grid and the anode.

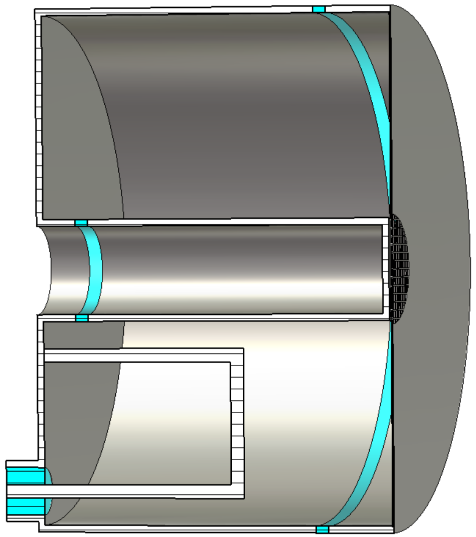

Fig.2.2 Simplified Model of Input Cavity.

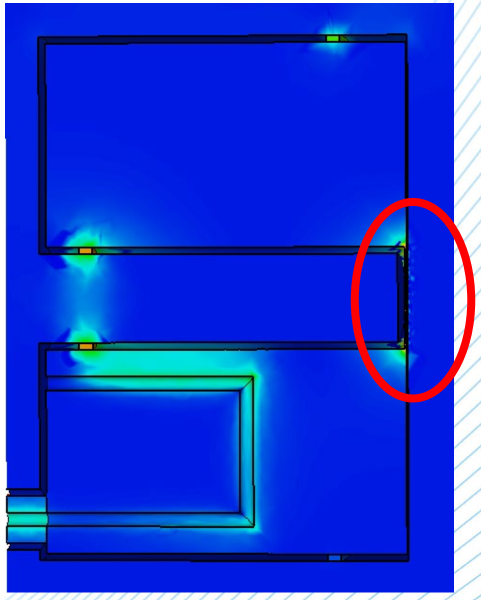

Fig.2.3 RF energy distribution in the input cavity.

2. Simulation methods of electron gun for IOT

- The second step is to use the time-domain solver in CST Studio Suite. A single-frequency microwave signal is applied through the input port, and the operating frequency is set equal to the eigenfrequency of the input cavity.

- The injected microwave establishes a standing-wave electric field between the cathode and the grid.

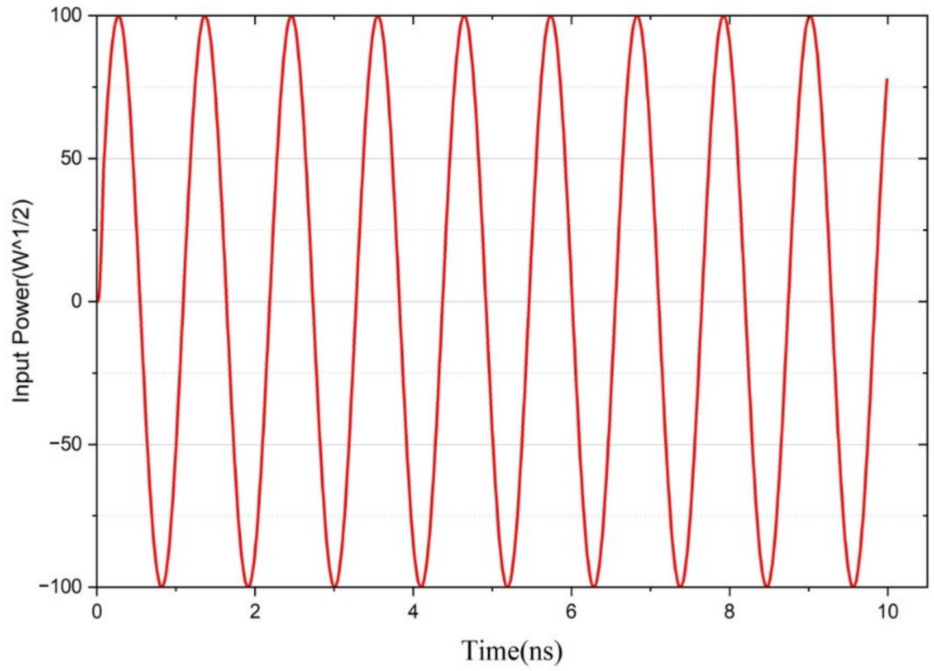

Fig.2.4 Simplified Model of Input Cavity - Grid Controlled Electron Gun.

2. Simulation methods of electron gun for IOT

- Under the RF electric field excitation, the cathode emits electrons during one half of the RF cycle and is cut off during the other half cycle.

- Therefore, the IOT electron gun operates similarly to a Class-B amplifier.

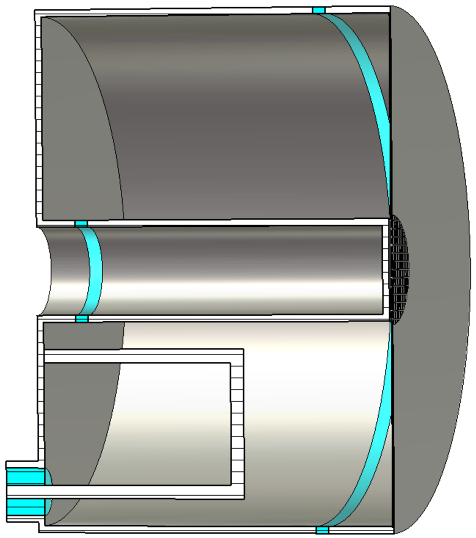

Fig.2.5 Simplified Model of Input Cavity.

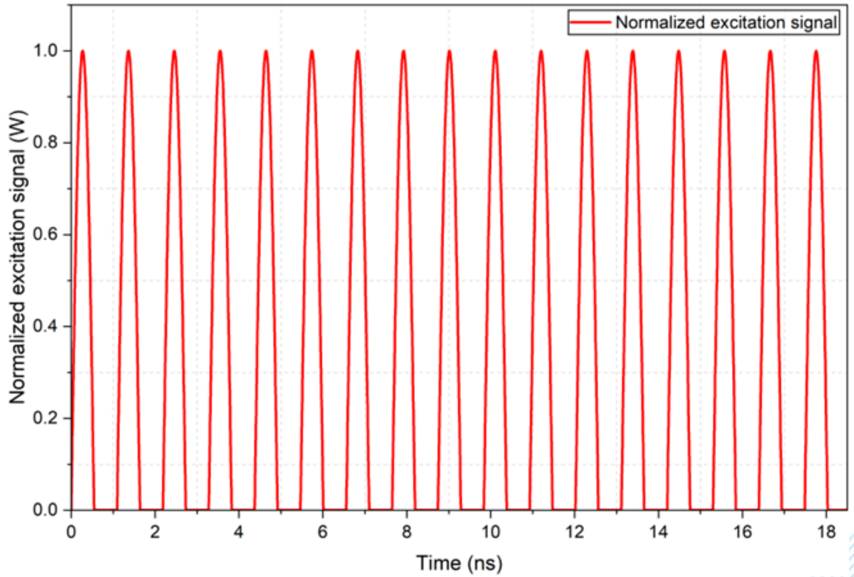

Fig.2.6 Normalized excitation signal.

2. Simulation methods of electron gun for IOT

- The third step is to use the particle tracking solver in CST Studio Suite. Before performing the particle simulation, the RF voltage obtained from the second step is sampled.

- According to the Nyquist–Shannon sampling theorem, if the sampling interval is sufficiently small, the electron emission current at different time points can be reconstructed from the sampled RF voltage.

$$J = \frac{16\pi\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{\left(V_c + V_{gc} + V_{rf}\right)^{\frac{3}{2}}}{(-\alpha)^2}$$

$$-\alpha = \mu + 0.3\mu^2 + 0.075\mu^3 + 0.01432\mu^5 + \cdots$$

$$\mu = ln\frac{R_c}{R_a}$$

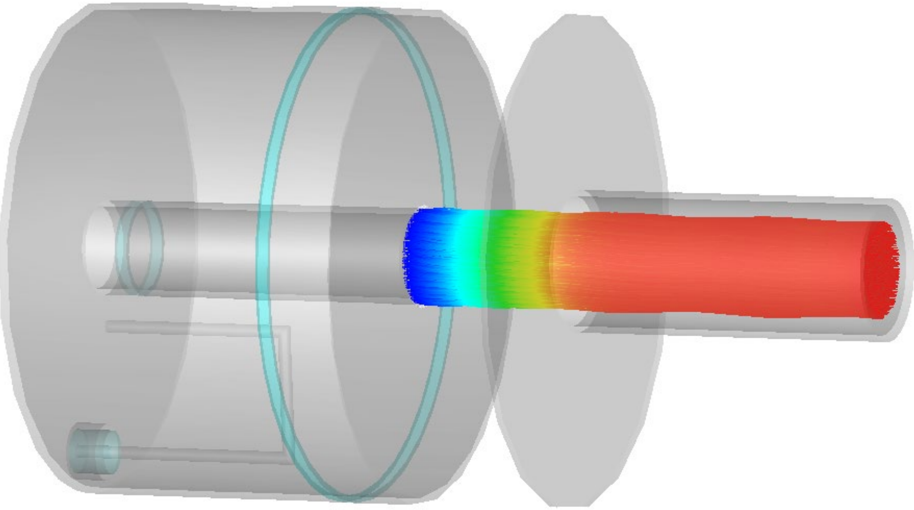

Fig.2.7 Particle Emission Simulation.

2. Simulation methods of electron gun for IOT

- After obtaining the sampled RF voltage, the grid voltage is defined as the superposition of the DC bias voltage and the sampled RF voltage.

- Therefore, the dynamic electron emission process can be converted into a static electron gun simulation problem. Finally, the emission current of the IOT electron gun can be obtained using the particle tracking solver.

$$J = \frac{16\pi\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{\left(V_c + V_{gc} + V_{rf}\right)^{\frac{3}{2}}}{(-\alpha)^2}$$

$$-\alpha = \mu + 0.3\mu^2 + 0.075\mu^3 + 0.01432\mu^5 + \cdots$$

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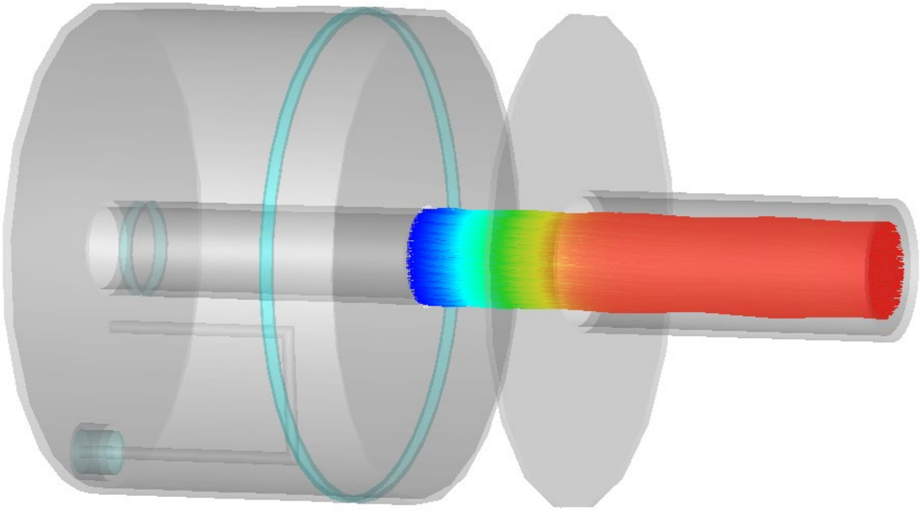

Fig.2.7 Particle Emission Simulation.

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3. Research results of electron gun for IOT

- These two figures show the operating mode of the input cavity obtained from the eigenmode solver. In this mode, the RF electric field energy is mainly concentrated between the cathode and the grid.

- Meanwhile, the RF magnetic field energy in this region is very small. This indicates that the input microwave field can effectively modulate the electron emission from the cathode.

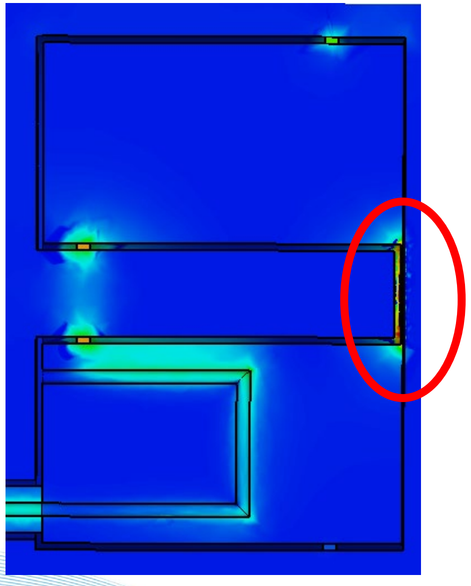

Fig.3.1 Electric field energy distribution of the input cavity operating mode.

Fig.3.2 Magnetic field energy distribution of the input cavity operating mode.

3. Research results of electron gun for IOT

- The following results are obtained using the time-domain solver. With a CW input power of 5 kW, the RF voltage between the cathode and grid reaches its maximum value within approximately 100 ns.

- Meanwhile, no significant high-order harmonics are generated during the excitation process.

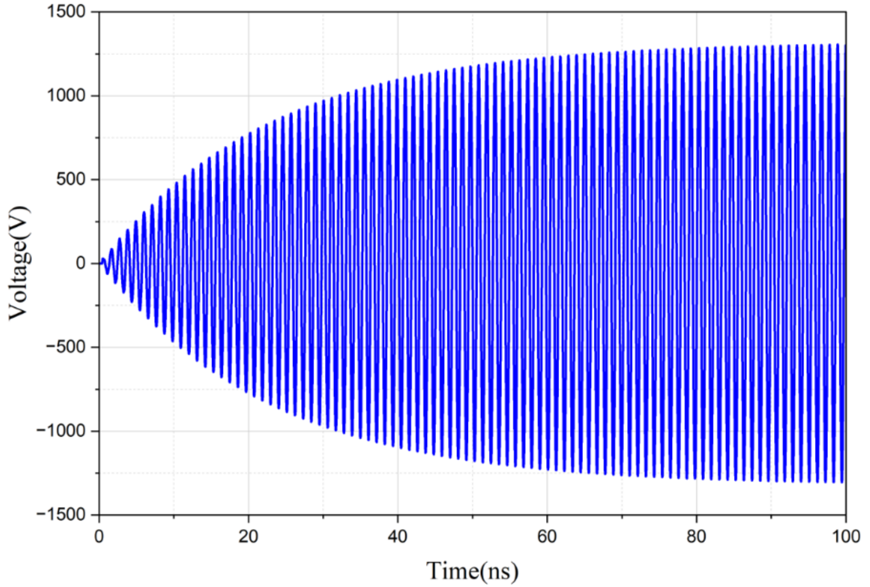

Fig.3.3 Electric field energy distribution of the input cavity operating mode.

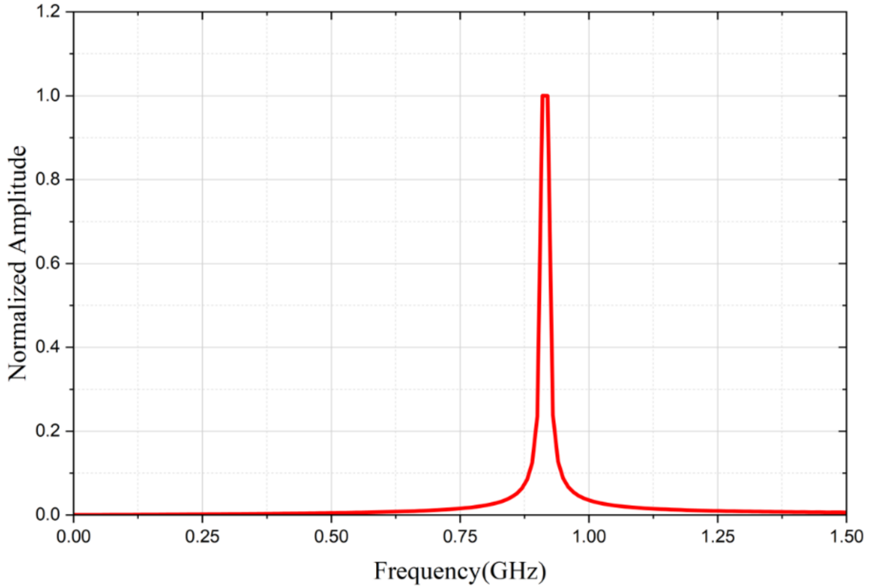

Fig.3.4 Electric field energy distribution of the input cavity operating mode.

3. Research results of electron gun for IOT

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- The RF voltage is sampled with an interval of 0.1 ns. The emission current waveform of the electron gun is obtained by the particle tracking solver.
- The results show that the electron emission occurs during half of the RF cycle, while the electron gun is cut off during the adjacent half cycle.
- The current spectrum indicates that the DC, fundamental, and harmonic components dominate the spectrum. The fundamental component has the largest contribution, accounting for more than 60% of the total.

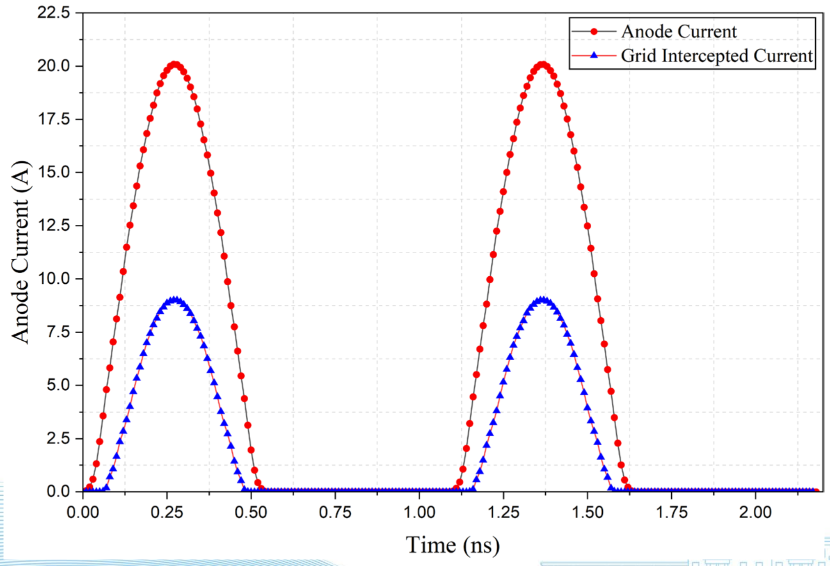

Fig.3.5 Cathode emission current and grid intercept current.

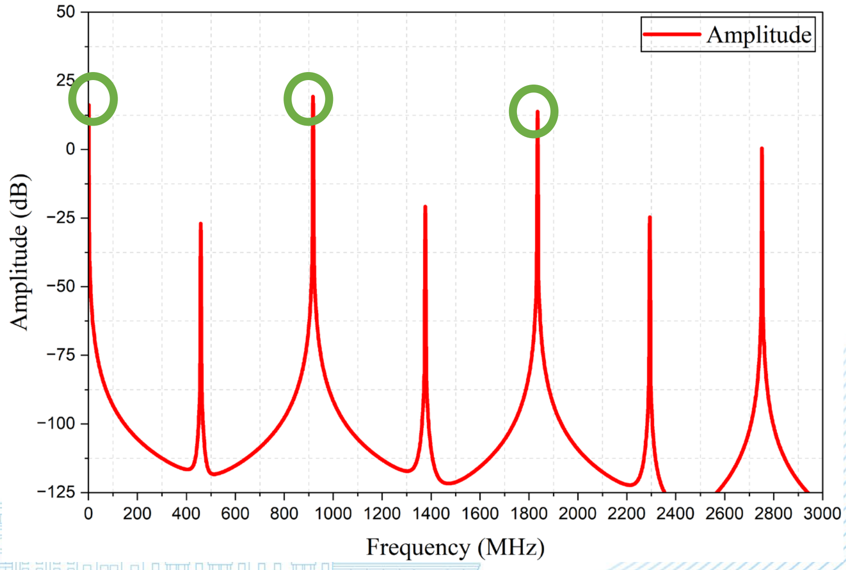

Fig.3.6 Fourier spectrum of the anode current.

3. Research results of electron gun for IOT

- With the applied focusing magnetic field, the electron beam remains well confined during propagation.

- The transverse distribution of macro-particles is uniform, which indicates that the electron beam is suitable for beam-wave interaction and RF energy extraction.

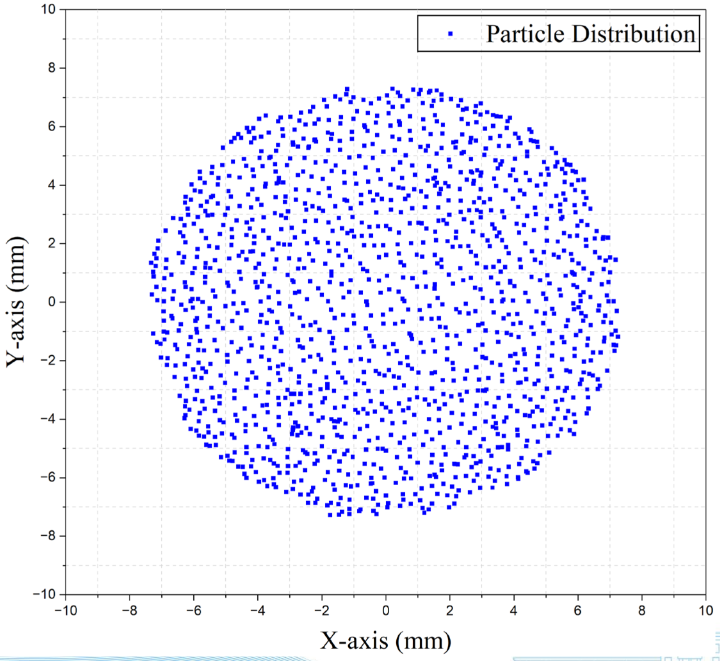

Fig.3.7 Macroparticle distribution of electron beam cross section.

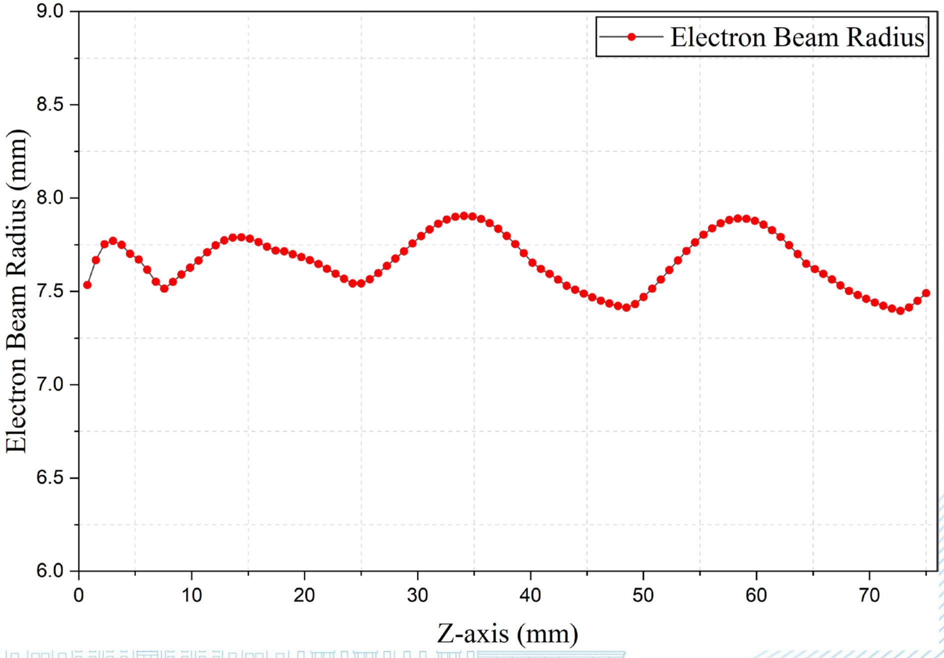

Fig.3.8 Envelope radius of an electron beam under a focused magnetic field.

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Summary

- In this work, a general simulation method for IOT electron guns based on CST Studio Suite is proposed. The eigenmode solver is first used to obtain the operating mode and resonant frequency of the input cavity.

- Then, the time-domain solver is applied to calculate the RF voltage between the cathode and grid. After sampling the RF voltage, the dynamic electron emission problem is transformed into a static electron gun simulation problem.

- Finally, the particle tracking solver is used to obtain the electron emission current. The proposed method provides a practical approach for analyzing and optimizing IOT electron guns using commercial simulation software.

Input cavity operating mode → Eigenmode solver → Electric energy distribution

RF voltage between cathode and grid → Time-domain solver → RF electric field sampling point

RF voltage between cathode and grid → Particle Tracking solver → Current emission

Thank you for your attention!

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