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PHYSICAL DESIGN OF AN S-BAND COLD CATHODE RF GUN*

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Abstract

In recent years, the properties of new field emission materials have been gradually improved with the advancement of materials research fields, which have provided the possibility for the research and realization of cold cathode microwave electron guns. A 0.32+1 cell S-band microwave electron gun was designed based on the emission properties of carbon nanotube films and ultra nano diamond films. This article mainly introduces the selection of electron gun cavity, RF design and corresponding thermal analysis. The physical design results basically meet the design requirements.

INTRODUCTION

With the continuous advancement of accelerator technology, radio frequency guns are also iteratively developed from generation to generation, from the original hot cathode RF gun to the now widely used photocathode RF gun. The hot cathode RF gun has a large beam intensity and serious electronic backlash; Although the photocathode RF gun has good beam quality, the current intensity is not large, and additional costs are required for the laser. At present, with the advancement of material technology, the use of cold cathode is gradually increasing, cold cathode RF gun because of its beam quality is relatively good, the current intensity is large, and does not require additional filament heating power supply and laser, low cost, compact structure, so as to be expected by more and more institutes. Based on the emission characteristics of diamond film cathode [1] and carbon nanotube cathode [2] described in the existing literature, a 0.32+1 cell S-band cold cathode RF gun is designed.

The cold cathode is based on the principle of field-induced emission, and the distribution of field-induced emission current density in the microwave field is similar to the Gaussian distribution on time scales [3].

$$J(t) = J_0 e^{-C\frac{\phi^{3/2}}{\beta E_0}\frac{(\omega t-\pi/2)^2}{2}} \tag{1}$$

Its rms width is:

$$\sigma = \sqrt{\beta E_0/(C\phi^{3/2})} \tag{2}$$

In the microwave field, the maximum value of the field-induced emission current distribution is exactly in the middle of the positive half-period of the microwave field, and since the area occupied by $\pm 2\sigma$ accounts for 95% of the total area of the Gaussian distribution, it can be considered that the width of the field-induced emission is $\pm 2\sigma$.

CAVITY TYPE SELECTION

The general cold cathode RMS width σ is about 15°, and its emission width in the microwave field is about $\pm 2\sigma$, that is, -30°~30°. An emission phase width of 60° will inevitably lead to electron back burst when the field strength of the cathode plane is not large enough. In order to avoid back bombardment, there are two solutions to the design of the first cavity, one is to reduce the length of the first cavity, and the other is to increase the cathode surface field strength. The problem with reducing the length of the first cavity is that the maximum field strength in the first cavity is offset and concentrated on the platter, and the length of the first cavity is too short, which increases the difficulty of processing and commissioning. Increasing the field strength of the cathode surface leads to a sharp increase in the emission phase width for the field-induced emission cathode, making the field-induced emission similar to the hot cathode emission. At present, the opening electric field of nitrogen-doped diamond film cathode is generally about 10 MV/m, and the opening electric field of carbon nanotube cathode is lower, generally 48 MV/m, and its maximum emission electric field is about 20 MV/m, which will inevitably lead to back bombing. Therefore, the only alternative method at present is to reduce the length of the first cavity.

Assuming that the field-induced emission RMS width σ is 15°, the relationship between the minimum field strength required for the last emitted electron at 30° overflows the first cavity and the length of the first cavity, as shown in Fig. 1. As can be seen from the figure, the shorter the first cavity, the smaller the minimum field strength required for the end electrons to overflow the first cavity. Under the cathode

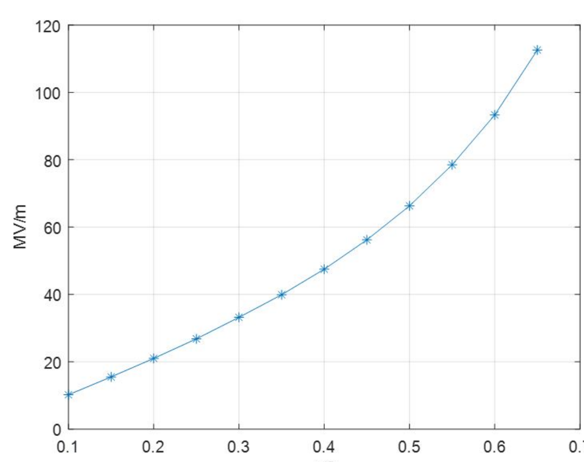

Figure 1: The relationship between the minimum field strength of the cathode plane required for the end electron overflow the first cavity and the length of the first cavity.

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surface field strength of 40 MV/m, the cavity length is less than 0.35 cell, and the design of the first cavity length of 0.32 cell and the secondary cavity of 1.0 cell is adopted.

RF DESIGN

When the length of the first and the secondary cavity were determined, the design of the RF gun entered the RF design part. The RF design process of RF gun is to first determine the basic structure of the cavity, and then enter the eigenmode solution optimization process, and add input waveguide, probe, cathode and other components after the cavity model optimization to complete the design of the whole gun structure. After that, iterative optimization is continued under the driving mode or eigenmode, and a better result of the whole gun is obtained. Here, CST and HFSS are used to optimize the design of the RF gun, and the two results are compared to prevent large error results.

Cavity Structure

The RF gun design requires an operating frequency of 2856 MHz and a π mode of operation, a mode interval greater than 10 MHz, and a field strength ratio of the secondary cavity to the first cavity is greater than 1. The basic structure of the electron gun is shown in Fig. 2.

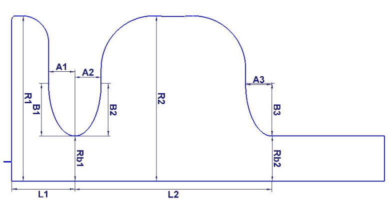

Figure 2: Basic structure of electron gun.

Eigenmode Design and Optimization

After completing the eigenmode optimization of the cavity, on this basis, adding coupling holes, transmission waveguides, vacuum pipes and probes, a complete vacuum model of RF gun is formed, and the RF design of RF gun can be basically completed through iterative optimization of the whole gun model. The results after the optimization are shown in Table 1 below.

Table 1: Optimization Results

Parameter	Value	Unit
f_0	2840.0139	MHz
f_π	2856.0492	MHz
E_2/E_1	1.0624	
β	1.0353	
R/Q	111.6220	MΩ/m
Q_0	11867.32	
Q_e	11462.89	

The mode interval between zero mode and π mode is about 16 MHz, and the probe coupling degree is calculated to be about 53 dB. The axial electric field distribution is shown in Fig. 3. The electromagnetic field distribution and surface current are shown in Fig. 4.

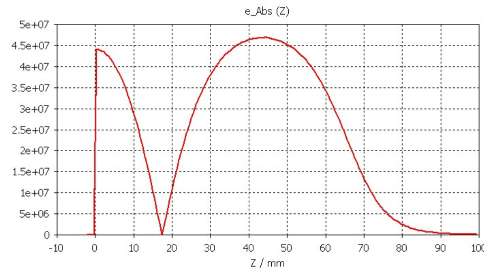

Figure 3: Axial electric field distribution of RF gun.

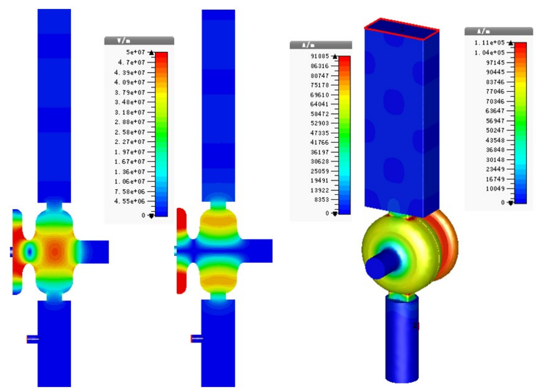

Figure 4: On the left is the electric field distribution, in the middle is the magnetic field distribution, and on the right is the surface current distribution.

Drive Mode Verification

After completing the eigenmode optimization design of the RF gun, the parameters are imported into HFSS and the driving mode calculation is performed on the same model.

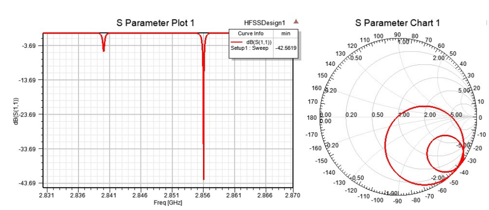

Figure 5: S11 parameter plot and SMITH chart.

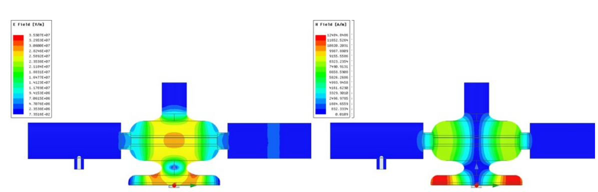

Figure 6: On the left is the electric field distribution, on the right is the magnetic field distribution.

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When the input microwave power is 1 MW, the cathode surface field strength reaches 34 MV/m. Considering the beam load, the microwave coupling must be over coupling state, and the degree of coupling can be seen from the Smith chart. The S11 parameters and the Smith chart are shown in Fig. 5. And the electromagnetic field distribution is shown in Fig. 6.

THERMAL ANALYSIS

Mechanical Design

Using the final optimization results, the mechanical design of the RF gun was completed, and the finished RF gun is shown in Fig. 7.

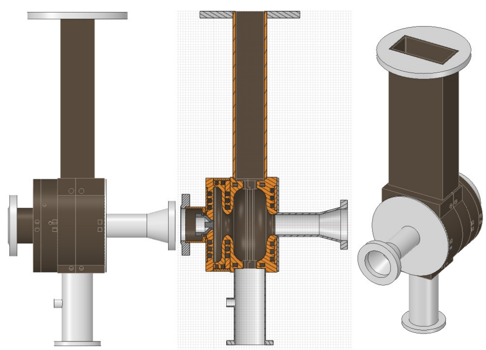

Figure 7: Mechanical design drawing (left is the whole, the middle is the section, the right is the positive triaxial measurement).

Thermal Analysis

After completing the mechanical design of the RF gun, a thermal analysis was performed on the RF gun. The RF gun cavity shape, electric field distribution and surface heat loss distribution are shown in Fig. 8. And it can be seen that the heat loss is mainly concentrated on the side of the coupling hole near the cavity except for the first cavity wall. This indicates that the temperature rise of the coupling hole is relatively high.

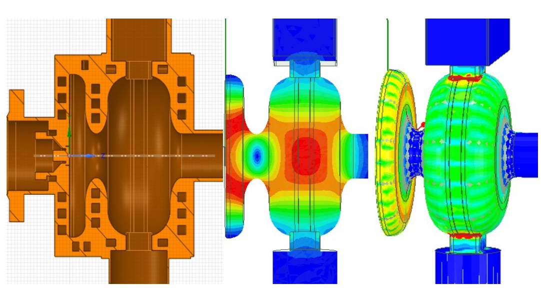

Figure 8: Cavity shape, electric field distribution and surface heat loss.

Using ANSYS' HFSS module, the cathode surface field strength is calculated to be 30 MV/m, and the heat loss of the electron gun cavity wall is 0.73 MW, and the duty cycle of this electron gun is set to be 0.8 %. Since the HFSS simulation is set to a continuous wave condition, the average heat loss in pulse mode can be obtained by using the duty cycle. By adjusting the value of the excitation signal under eigenmode, set the initial setting of the electron gun that can output an average heat loss of 5.82 kW. Enter this setting into the FLUENT module and calculate the temperature distribution of the cavity. By adjusting the flow rate of the cooling water, the heat of the surface heat loss is taken away, so that the electron gun works at the desired temperature state.

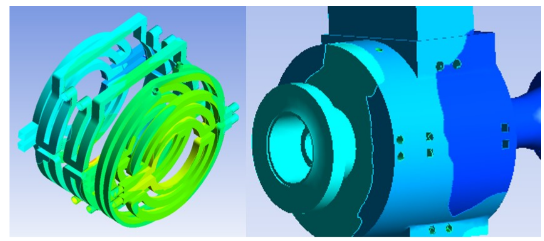

Figure 9: Temperature distribution of cooling water channel and chamber temperature distribution.

The temperature rises more at the cavity wall of the first cavity and at the coupling hole, the first cavity wall is about 25 degrees, and the temperature of the coupling hole below is about 40 degrees. The temperature distribution is shown in Fig. 9. Since the repetition frequency of the cold cathode microwave electron gun is actually very low, below 10 Hz, at this time, the heat loss of the cavity wall is below 0.15 kW, which will be quickly taken away by the cooling water, and the actual temperature rise will be very low. Therefore, the waterway design fully meets the requirements.

CONCLUSION

According to the characteristics of the RF gun and the emission characteristics of the field emission cathode, the appropriate cavity shape of the RF gun was selected, and the optimized design of the electron gun was made by CST and HFSS, and the mechanical design and thermal analysis were carried out according to the optimization design results. Through several iterations of optimization, the design of the S-band cold cathode microwave electron gun was finally completed.

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