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# Structure design for electron beam controlling in microwave tube with carbon nanotube cathode

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**Abstract:** To control the electron beam emitted from the carbon nanotube (CNT) cathode, four different electron chunnels are designed. A common basic structure used in the simulation is an insulating chunnel. When primary electrons hit the surface of the chunnel, secondary electrons are generated, which make the electron distribution at the exit hole of the chunnel more uniform. By analyzing and comparing the state of electrons emitted from the exit of chunnel among the four structures, an optimal structure is obtained. In the optimized structure, the electron distribution at the exit hole of the chunnel is more uniform and the electron beam is rather slim. Furthermore, by adding a magnetic field along the slow wave line, the electron beam can be constrained. In the optimized structure, a very small magnetic field is needed to make most of electrons pass through the slow wave line.

**Key words:** carbon nanotube; electron chunnel; transverse velocity of electrons

Normally, the field emission array (FEA) and the carbon nanotube are studied to be applied in microwave tube[1–2]. For the FEA cathode, there are several important problems that have not been solved, such as sensitivity to ion bombardment, destruction by the large current etc. Carbon nanotube is an ideal field emission material because of its high electrical conductivity, ideal high aspect ratio and remarkable thermal stability[3]. After several years' development, a CNT cathode can generate high emission current[4]. Therefore, the cold cathode has potential to be applied in the microwave amplifier as the electron source[1,5].

However, the initial status of the electrons emitted of a CNT cathode is quite different from that of a thermionic cathode. Because of the large transverse velocity of electrons emitted from the CNT cathode, it is difficult to control the electron beam by using ordinary electron lens. In this paper, we use an inverted funnel-shaped chunnel as a basic structure[6–7]. The chunnel's wall is dielectric, and secondary electrons are generated when electrons hit the chunnel's wall. On the basis of the funnel-shaped chunnel structure, we developed four different structures. The velocity and position distribution of electrons traveling through the chunnel is analyzed. From the simulation results, an optimal and applicable structure is obtained.

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## 1 Four Simulation Models for Electron Beam Controlling

In our simulation models, a basic structure is an insulating chunnel. The inner wall of the chunnel is coated with MgO, being a material with a high secondary emission coefficient. When primary electrons hit the surface of the chunnel, secondary electrons are generated, which makes the electron distribution at the exit hole of the chunnel more uniform.

In this section, four different models are simulated. In each of the four models, first the electrical field is calculated, then electrons emit from the cathode and hit the dielectric wall, secondary electrons generate and travel through the chunnel under the influence of the electrical field.

### 1.1 Model A

Fig. 1 shows the structure of Model A. It consists of a cathode, a grid, an insulating chunnel and an accelerating electrode. In our study, the inner wall of the chunnel is coated with MgO. The voltages added on the cathode, the grid and the accelerating electrode are 0, 200 and 2 000 V, respectively. The primary electrons emit from the cathode with emitting angles which satisfy the cosine distribution.

Fig. 2 shows the electron equi-potential lines and trajectories in an almost steady state for the simulation of Model A. From Fig. 2 (b), we can see that some primary electrons go through the chunnel without hitting the wall of the chunnel. Others hit the chunnel's wall and produce secondary electrons.

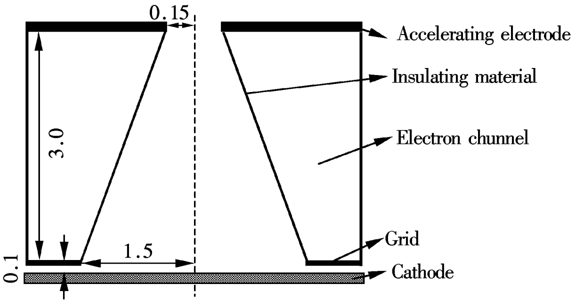


**Fig. 1** Structure of Model A (unit: mm)

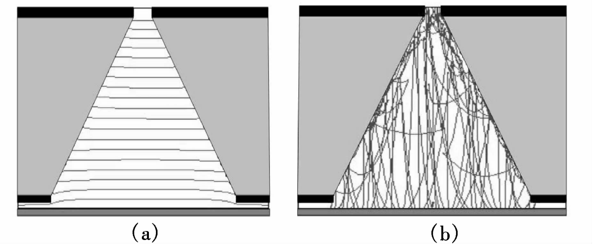

**Fig. 2** Plot of equi-potential lines and electron trajectories in Model A. (a) Equi-potential lines; (b) Electron trajectories

## 1.2 Model B

The structure of Model B is shown in Fig. 3. The difference between Model A and Model B is that in Model B there is a filler-shaped part. The inner wall of this part is coated with metal. The voltages added on the cathode, the grid, the metal part and the accelerating electrode are 0, 200, 1 500 and 2 000 V, respectively.

Fig. 4 shows the electron equi-potential lines and trajectories in an almost steady state for the simulation of Model B. From Fig. 4 (a), we can see that along the filler-shaped part, the equi-potential lines are down bended. When electrons travel to this part, there will be an additional axial force. This force will lower the transverse velocity of the electrons.

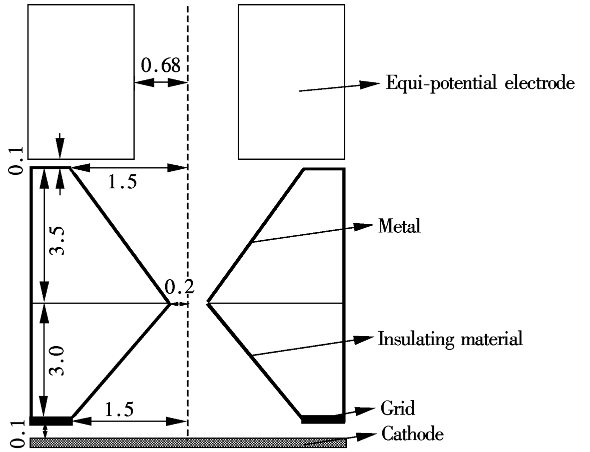


**Fig. 3** Structure of Model B (unit: mm)

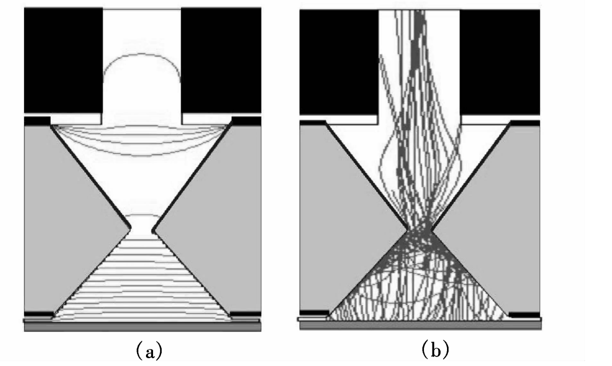

**Fig. 4** Plot of equi-potential lines and electron trajectories in Model B. (a) Equi-potential lines; (b) Electron trajectories

## 1.3 Model C

Based on Model B, we add another focusing metal electrode in Model C as shown in Fig. 5. The voltages added on the cathode, the grid, the lower metal part, the upper metal part and the accelerating electrode are 0, 200, 1 500, 2 000 and 3 000 V, respectively.

Fig. 6 shows the electron equi-potential lines and trajectories in an almost steady state for the simulation

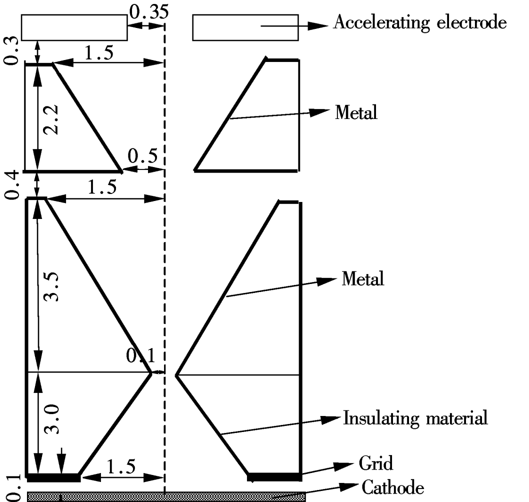


**Fig. 5** Structure of Model C (unit: mm)

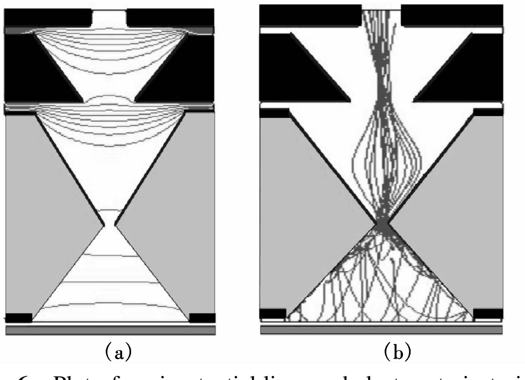

**Fig. 6** Plot of equi-potential lines and electron trajectories in Model C. (a) Equi-potential lines; (b) Electron trajectories

of Model C. From Fig. 6 (b), we can see that the shape of the electron beam is improved. But in this model, there are two more electrodes than in Model A, and it is difficult to realize in technique.

### 1. 4 Model D

By comparing and analyzing the simulation results of Models A, B and C, we propose the structure of Model D (see Fig. 7). In this structure, besides the funnel-shaped chunnel, there is a column-shaped chunnel. The inner wall of the column-shaped chunnel is coated with insulating material (MgO in our study). The voltages added on the cathode, the grid and the accelerating electrode are 0, 200 and 2 000 V, respectively.

In the calculation of Model D, $G = 0.1$ mm, $L_1 = 2.2$ mm, $L_2 = 4.0$ mm, and $R_1 = 1.0$ mm. The value of $R_2$ is inconstant. We calculated four situations with different $R_2$ ($R_2 = 0.05, 0.10, 0.15, 0.20$ mm).

Fig. 8 shows the electron equi-potential lines and trajectories in an almost steady state for the simulation of Model D. From Fig. 8 (b), we can see that the electrons travel along the column-shaped chunnel and the diameter of the electron beam is rather small.

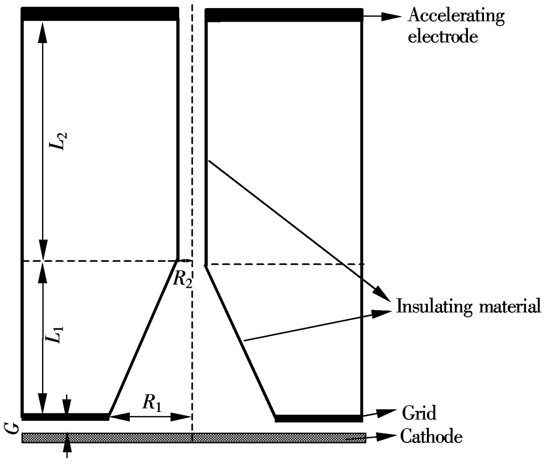


**Fig. 7** Structure of Model D

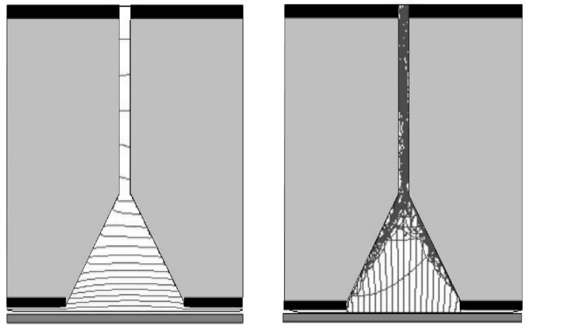


**Fig. 8** Plot of equi-potential lines and electron trajectories in Model D. (a) Equi-potential lines; (b) Electron trajectories

## 2 Comparing the Proportion of Electrons Passing through Slow Wave Line

### 2. 1 Using magnetic field to control electron beam

Electrons traveling through the chunnel have transverse velocity; it is necessary to apply a magnetic field to electrons traveling through the slow wave line as shown in Fig. 9. We suppose that the magnetic field is even, and the direction of the magnetic field is parallel with the slow wave line. The magnetic force of the electron is

$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B} \tag{1}$$

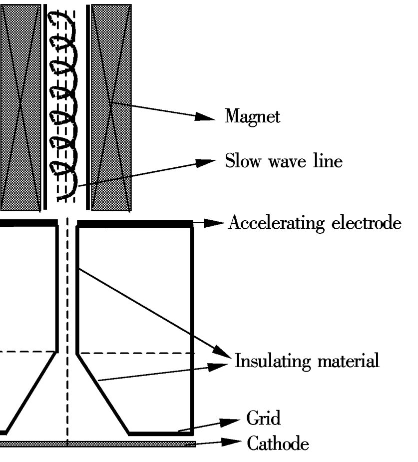


**Fig. 9** Structure of magnet and slow wave tube

The magnetic field only changes the direction that the electrons travel, not the energy of electrons. So electrons travel along a circular track in the plane that is vertical to the axis. The velocity of electrons $\boldsymbol{v}$ can be set to $\boldsymbol{v}_z$ and $\boldsymbol{v}_r$. $\boldsymbol{v}_z$ is the velocity parallel with the axis, and $\boldsymbol{v}_r$ is the velocity vertical to the axis. $B = B_z$. So

$$F = qv_r \times B_z = m\frac{v_r^2}{R} \tag{2}$$

$$R = \frac{mv_r}{qB_z} \tag{3}$$

From Eq. (3), the radius of electrons circumgyration is influenced by $\boldsymbol{v}_r$ and $B_z$.

### 2. 2 Comparison of simulation results

Besides the fact that the radius of electrons circumgyrate will influence the radius of the electron beam that travels along the slow wave line, the distribution of the electrons that leave the exit of the chunnel is also an important factor. Fig. 10 gives the plot of the ratio of average transverse velocity and axial velocity $V_r/V_z$ and the number of electrons in each mesh in Models A, B and C.

In Fig. 10(a), the maximum radius of electron distribution when they leave the exit of the chunnel is

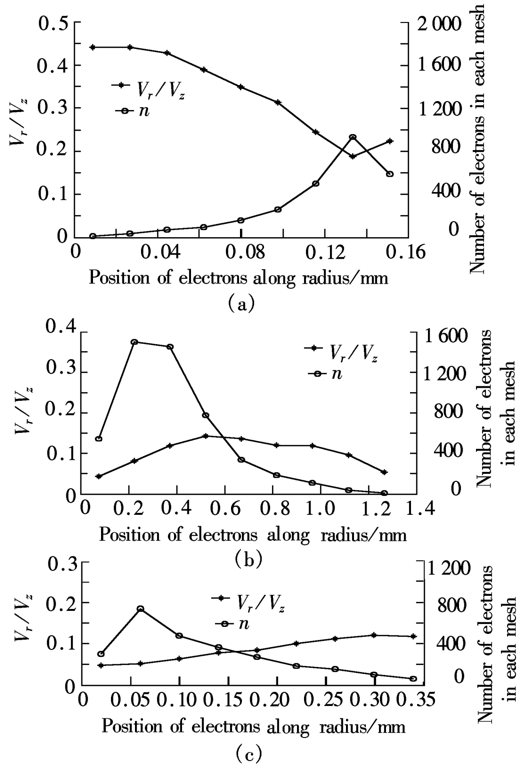


**Fig. 10** Plot of $V_r/V_z$ and the number of electrons in each mesh. (a) Model A; (b) Model B; (c) Model C

about 0. 15 mm, but most electrons are at the edge of the region, and the transverse velocity is large.

In Fig. 10(b), the maximum radius of electron distribution when they leave the exit of the chunnel is about 1. 3 mm, it is greater than that of Model A. Because of the focusing metal part in Model B, the transverse velocity is smaller than that of Model A.

In Fig. 10(c), the maximum radius of electron distribution when they leave the exit of the chunnel is about 0. 35 mm. And the transverse velocity is smaller than that of Model B. But in Model C, there are two more electrodes than in Model A, and it is a more complex structure.

In our calculation, when the electrons travel along the slow wave line, if the the radius of electrons circumgyration is larger than the radius of the slow wave line, we assume that this electron disappears. So we calculate the proportion of electrons that pass through the slow wave line in different magnetic field intensities among Models A, B and C, as shown in Fig. 11. The length of slow wave line in our calculation is 1. 2 m. The magnetic field intensity changes from 0. 08 to 0. 50 T. In Model A, when the magnetic field intensity is large enough, almost all of the electrons can pass through the slow wave line; while in Models B and C, the proportion of electrons that pass through the slow wave line is rather low. From Fig. 11, it implies that between the two parameters: the transverse velocity of electrons and the position distribution of electrons, the latter one is more important to control the trajectory of the electrons.

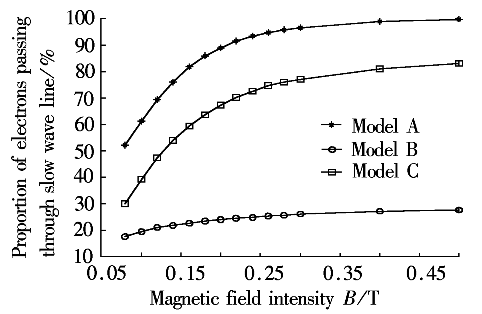


**Fig. 11** Comparison of the proportion of electrons passing through slow wave line in different magnetic field intensities

In Model D, electrons that leave the exit of the chunnel distribute in a small region. If the magnetic field intensity is set to be 0. 08 T, the relationship between the proportion of electrons that pass through the slow wave line and the parameter $R_2$ is shown in Tab. 1. From Tab. 1, the smaller the parameter $R_2$, the higher proportion of electrons that pass throught the slow wave line. When $R_2$ = 0. 05 mm, the proportion is high enough although the magnetic field intensity is not very high.

**Tab. 1** Relationship between the proportion of electrons passing throught slow wave line and $R_2$

| Magnetic field intensity $B$/T | $R_2$/mm | Proportion of electrons passing throught slow wave line/% |
|---|---|---|
| 0. 08 | 0. 20 | 71. 5 |
| 0. 08 | 0. 15 | 87. 6 |
| 0. 08 | 0. 10 | 95. 1 |
| 0. 08 | 0. 05 | 96. 7 |

## 3 Conclusion

As a kind of excellent cold cathode material, carbon nanotubes have the potential to be applied in the microwave tube system. To use CNTs as electron source, corresponding structures must be developed to control the electron beam. In this paper, four different models are simulated. Model A is an inverted funnel-shaped chunnel; in Model B, a focusing electron lens is added; Model C has two focusing electron lenses. We analyze the transverse velocity of electrons and the position distribution of electrons that leave the exit of the chunnel. We also calculate the proportion of electrons that pass through the slow wave line. By analyzing and comparing the simulation results, we find that between the two parameters (the transverse velocity of electrons and the position distribution of electrons), the latter one is more important to the beam performance. So in Model D, one more cylinder-shaped chunnel is introduced to control the trajectory of the electrons within a small region. From the calculation results, Model D is an optimal structure. It requires a very small magnetic field for beam focusing and the proportion of electrons that pass through the slow wave line is very high. Model D is expected to be applied in practice.

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# 碳纳米管阴极微波管的电子束聚束系统设计

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**摘要:**为了控制碳纳米管阴极发射电子束的形状,设计了4种电子通道来控制电子束轨迹.在设计结构中,其基本结构是一倒置的内壁涂有绝缘材料的漏斗状通道.当初始电子碰撞绝缘壁时,会产生二次电子,而二次电子能改善电子在通道出口处的电子能量分布的均匀性.通过分析和比较电子在通道出口处的状态,得到了一种理想的通道结构.在该结构中,电子在通道出口处的分布更加均匀,电子束的束径较小.而且通过在慢波线外部加磁场的方法来控制电子束在慢波线中的扩散,所加的磁场越大,电子在慢波线中的通过率则越大.通过分析4种不同的结构,在所得到的一种理想的通道结构中,需要较小的磁场就能使得电子在慢波线中的通过率较高.

**关键词:**碳纳米管;电子通道;横向电子速度

**中图分类号:**TN124