Optical simulation analysis and study of UTEM electron gun

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Abstract. In this paper, the electric field intensity of the electrode structure of the thermally emitted electron gun of UTEM is simulated, and the relation between the electric field intensity distribution and the electrode plate is analyzed. Using the electronic optics software, the optical system of the electron gun is simulated, the performance parameters of the electron gun are obtained, and the advantages and disadvantages of the whole optical system are analyzed. The research results of this paper can provide a reference for the design and simulation of similar electron gun.

1. Introduction
With the development of science and technology, the appearance of electron microscope makes it possible for people to explore the microscopic field. But the emergence of ultrafast electron microscope makes people from the micro static field of research to the micro dynamic change of research. At present, the research on ultrafast electron microscopy is divided into multiple directions, including analysis, research and design of instrument hardware[1-2], modeling and simulation analysis[3-4], experimental observation of materials and image analysis spectroscopy[5-7]. The research content of this paper is based on the first ultrafast transmission electron microscope (UTEM) built by Institute of Physics, Chinese Academy of Sciences. This electron microscope was built on the basis of Japanese electron (JEOL) 2000EX, with a temporal resolution of about 1 ps. It was modified from transmission electron microscope (TEM), and it was thermal emission, with a spatial resolution of better than 0.35 nm after modification[8].

2. Emission mechanism and simulation of electron gun
2.1. Research on emission mechanism of electron gun
The components of an electron gun are usually cathode, grid and anode. With the development of the instrument, the triode electron gun was gradually replaced by the multi-stage accelerated form. When a negative bias is applied to the grid and the cathode voltage is zero, a rotationally symmetric bell-shaped zero equipotential surface can be formed on the cathode surface. There is emission beam on one side of the positive zero equipotential plane, and there is no emission on the other side. Because the cathode is very small in size and the field distribution near the axis is fairly flat and stable, the electrons emitted near the axis of the cathode are almost parallel to the axis. With only a small number of electrons with radial muzzle velocity, the initial energy of the electron beam is slightly dispersed.

The electron beam is accelerated under the action of the electric field between the electrode plates. According to the electrostatic field theory, the electron is acted on by the electric field force, and its equation is[9]:

\[ \mathbf{F} = q \mathbf{E} \]

where \( \mathbf{F} \) is the electric force, \( q \) is the charge of the electron, \( \mathbf{E} \) is the electric field vector.

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In the non-relativistic case, the motion of electrons satisfies Newton's equation:

$$F = -qE$$  \hspace{1cm} (1)

$$F = ma = m\frac{dv}{dt}$$  \hspace{1cm} (2)

The simultaneous equations can be obtained as follows:

$$m\frac{dv}{dt} = -qE$$  \hspace{1cm} (3)

Integrate both sides of $v$ to get:

$$\frac{1}{2} \frac{d}{dt} (mv)^2 = -qE \cdot v$$  \hspace{1cm} (4)

Further simplification can be obtained as follows:

$$\frac{1}{2} \frac{d}{dt} (mv)^2 = q \frac{d\varphi}{ds} \cdot \frac{ds}{dt}$$  \hspace{1cm} (5)

Finally, we can get:

$$\frac{d}{dt} \left( \frac{1}{2} mv^2 \right) = -q \frac{d\varphi}{dt}$$  \hspace{1cm} (6)

To sum up, the stronger the electric field is, the greater the electric field force is, and the higher the electron velocity is. Under this mechanism, the electron beam is continuously accelerated in the axial direction until it is ejected from the end of the electron gun. There is conservation of energy and we can know:

$$\frac{1}{2} mv^2 - E_i = q\varphi$$  \hspace{1cm} (7)

The $m$ is the mass of the electron, $q$ is the charge of the electron, $v$ is the velocity of the electron, $\varphi$ is the potential difference of the position of the electron, and $E_i$ is the initial kinetic energy of the electron. Usually the cathode potential is zero, the initial velocity of the electron is zero, so $E_i$ is equal to zero, and once we know the potential difference we can calculate the velocity of the electron at different positions.

In fact, when in an axial velocity increases at the same time, the radial force also varies with the change of the field intensity (the interaction between electrons should also be considered under the strong beam), in order to get available within the scope of the electron beam, we need to adjust the grid potential, to a certain degree of radial displacement and speed control, which reaches a certain focus conditions.

2.2. Simulation analysis of electron gun

In order to analyze the electric field distribution of the electron gun in the UTEM, we made a simulation analysis. The electron gun usually has six accelerating plates. When the output voltage values on the plate are respectively 33.33 kV, 66.67 kV, 100 kV, 133.33 kV, 166.67 kV and 200 kV, the electric field intensity distribution of the electron gun can be obtained as shown in the figure below.
Fig 1. The potential distribution of the electron gun section.

Fig 2. The potential distribution on the axis of electron gun.

Fig 3. Electric field intensity distribution of electron gun section.
Fig 4. The distribution of electric field intensity on electron gun axis.

As can be seen from Figure 1 and Figure 2, with the increase of the acceleration voltage, the electric potential around the electrode plate is also increasing. The potential increases uniformly from the first to the fifth accelerating electrode, but decreases first and then increases between the fifth and sixth accelerating electrode. As can be seen from Figure 3 and Figure 4, the electric field intensity on the axis is always positive, and the electron beam is always accelerated under the action of electric field force until it leaves the electric field.

In order to further understand the emission characteristics of the electron gun, we perform optical simulation on the whole structure of the electron gun. The cathode material is a tungsten filament, the loading temperature is 2000 K, the work function is 4.5 eV, and the Richardson emission constant is 120. The beam trajectory shown below is obtained.

Fig 5. Electron gun beam trajectory.

As can be seen from Figure 5, the electron beam enters the accelerator region after gird modulation, and at the same time, the electron beam gradually diverges with the change of axial displacement until the electron gun is emitted. At this time, the electron beam current is blocked due to the small anode aperture, which will affect the current and brightness of the electron beam accordingly. Therefore, the anode aperture can be appropriately expanded here.
Fig 6. Relation between beam half angle and brightness of electron gun.

It can be seen from Figure 6 that the brightness of the electron gun decreases with the increase of the beam half angle. When the beam half angle is 15.858 mrad, the brightness of the electron gun is 0, which means that the maximum emission half angle of the electron beam is 15.858 mrad. At this time, the emission characteristic parameters of the electron gun obtained are shown in the table below:

| Parameters                   | Exit Plane (mm) | Beam size (uA) | Brightness (A/cm²/Sr) | Position of crossover (mm) | Diameter of virtual crossover (um) | Energy spread (eV) |
|------------------------------|-----------------|----------------|-----------------------|----------------------------|-----------------------------------|-------------------|
| Value                        | 158.67          | 0.3309         | 1.1e+03               | 5.771884                   | 3.147757                          | 0.1723            |

As can be seen from Table 1, when the beam size is 0.33 uA and brightness is 1.1 E +03 A/cm²/Sr, the grid voltage is -50 V. In order to adjust the beam and brightness, the grid voltage can be adjusted so as to obtain better beam attributes.

3. Conclusion
In this paper, the emission mechanism of the electron gun of the UTEM is analyzed and studied, and the electric field distribution of the electron gun is simulated and studied through the physical model, and the beam trajectory and corresponding characteristic parameters of the electron beam are obtained through simulation. The research theory and simulation research in this paper can provide theoretical basis and simulation flow for the design of electron gun of similar instruments.

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