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ELECTRON BEAM DYNAMICS SIMULATIONS IN ELECTRON GUN AND FABRICATION OF COLD FIELD EMITTERS BY ELECTROCHEMICAL ETCHING

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Abstract

In this paper, beam dynamics simulations in a compact 200 kV DC electron gun at Tsinghua University are carried out and pm·rad-scale low normalized transverse emittance is obtained in the preliminary results. Small emission areas and low initial electron energies contribute to the generation of beams with low transverse emittance. We used electrochemical etching to fabricate tips for cold field emitters and got several regularly shaped tips with a small radius of curvature of the apex in some attempts. We anticipate that sharp tips in high-gradient electron guns can provide high-quality electron beams for different applications, e.g. high spatial resolution electron microscopy.

INTRODUCTION

Nowadays different types of electron sources have a wide range of applications and their demand is gradually expanding with the development of science and technology. The thermal cathode is a typical kind of electron source. Monocrystalline or polycrystalline LaB_6 is a commonly used material for thermal cathodes, of which the operating temperature is usually up to 1800 K [1], asking the heat-resistant requirements for related components. Photocathodes can produce beams with low emittance, however, this process requires a complete laser system. As for cold field emission cathodes, electrons can be extracted from them due to the quantum tunneling effect in intense electric fields and do not need to rely on external heating or a laser system. The cold field emission cathode also has the advantage of generating electrons with low emittance and high brightness, making it a good prospect for development.

COLD FIELD EMITTERS

In 1928, R.H. Fowler and L.Nordheim gave a quantitative description of the field emission process and derived a formula for current density under a certain external field [2]. The formula is as in Eq. (1), where E_s is the electric field at the metal surface, θ, represents the Nordheim function, A, B, and C are constants related to the electron mass and elementary charge, etc. Obviously, the intensity of the emission current density is mainly influenced by the work function of metal and the strength of the applied electric field. As shown in Fig. 1, the current density grows roughly exponentially with the external field gradient for a given 4.5 eV work function of tungsten.

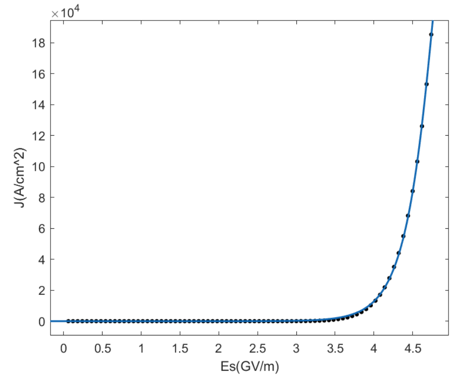

Figure 1: Electric fields at a metal surface (the work function is 4.5 eV) and the corresponding current density.

In order to obtain a certain current under a limited field gradient, we expect the electric field at the cathode surface to be sufficiently field-enhanced. The field enhancement factor β is defined as Eq. (2), where E_{appl} is the applied electric field gradient.

$$J_0 = \frac{AE_s^2}{\phi}\exp[\frac{B\phi^{3/2}}{E_s}\theta(C\frac{\sqrt{E_s}}{\phi})] \tag{1}$$

$$\beta = \frac{E_s}{E_{\text{appl}}} . \tag{2}$$

The field emission tip is an ideal choice because its sharp structure makes the field enhancement significant and the effective emission area is very small, which makes it more likely to produce an electron beam with high brightness and low emittance. A simple model of a hemispherical top with a radius of curvature of 1 μm and a tapered shank is established to represent the tip. Firstly, the space with a width of about 2 mm along the axis of symmetry of the tip is divided by Gmsh [3], then we used a finite element algorithm (FEA) to calculate the surface field gradient.

During the calculation process, the boundary condition of Dirichlet has been used and unequal lattice was solved by the way of interpolation. The results are shown in Fig. 2. The field enhancement factor β at the apex of the tip can reach nearly 300 under an applied field gradient of 10 MV/m, and the corresponding theoretical value of current density is about 16.26 A/cm^2. Considering a room temperature of 300 K, the actual current density should be slightly different from the theoretical value. The electric field changes dramatically near the apex of the tip, then β decreases sharply. In our other attempts to draw the model with different apex

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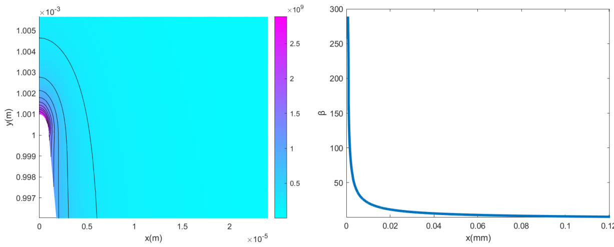


(a) (b)

Figure 2: (a) Electric field distribution of the tip model and (b) corresponding field enhancement factors.

radii and tip lengths, it can be assumed that the sharper the tip the stronger the field enhancement effect.

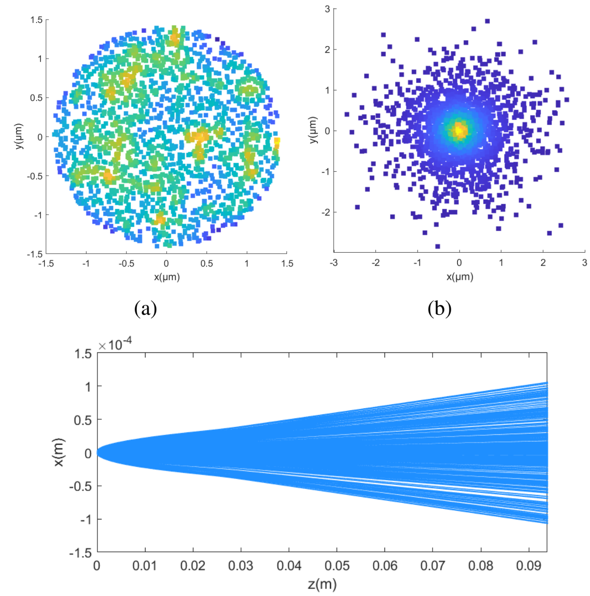
BEAM DYNAMICS SIMULATION

Electron beam dynamics simulations were carried out with the field distribution in the cavity and other parameters of a compact 200 kV DC electron gun at Tsinghua University [4]. After a more detailed calculation of the electric field at the apex of the tip by interpolation, it is assumed that the field emission in a very small region can be approximated as circular planar emission so that a uniform distribution of the initial particles is an acceptable approximation. In addition, a Gaussian distribution is also used, whose most particles are concentrated in the central region coincides with the fact that the escaping electrons are more coming from the apex of the tip where the field strength is the greatest. Both distributions assume that the electrons escape from the cathode with a small energy (0.1 eV) and have an isotropic velocity distribution.

The General Particle Tracer (GPT) [5] was used to simulate the electron beam trajectory. The relevant parameter settings are shown in Table 1. In each set of simulations we sequentially increased the number of macro particles until the calculation results converged, making the results more credible. After adding the effect of space charge in the simulation process, it is found that the change in the results is very slight in the case of a small charge. Therefore, the influence of space charge is temporarily ignored to save calculation time in the subsequent simulations. Considering that the beam length of emission electrons in the DC gun is generally long, the emittance we use in this paper is statistical at a fixed location which better characterizes the beam properties instead of the usual definition of the state of all particles at the same moment.

Table 1: Parameter settings

Parameters	**Values**	**Units**
Init.energy	0.1	eV
Bunch charge	1.0	fC
Duration	16	ns
RMS size (uniform)	1	µm
RMS size (Gaussian)	1	µm



(a) (b) (c)

Figure 3: (a) Uniform distribution and (b) Gaussian distribution of initial particles. (c) Schematic of particles trajectory in DC gun.

The results (shown in Fig. 3) show that the initial distribution of uniform and Gaussian have normalized transverse emittance of 82.20 pm·rad and 222.78 pm·rad, respectively and the normalized longitudinal emittance is 353.54 pm·rad and 340.83 pm·rad at the exit of the electron gun. This means that all particles undergo a similar acceleration process in the cavity therefore the longitudinal emittance has little difference.

The accelerated electrons have small normalized transverse emittance on the scale of pm·rad with an energy of about 712 keV at the exit of the electron gun. Since the DC gun structure is not completely symmetric, the transverse distribution center of the beam in x and y directions shifting from the beam propagation axis not identically is reasonable. The case can be optimized by placing several pairs of deflectors on the beamline. In addition, the solenoids in the present layout can be adjusted to focus and defocus the beam to meet various experimental requirements.

We gradually adjusted the initial energy of the particles from 0.1 eV to 1.5 eV, the result shows that the normalized transverse emittance of electrons with Gaussian initial distribution increased to about 850 pm·rad with rms transverse spot size varied from 75.29 µm to 290.72 µm. As for electrons with uniform initial distribution, the normalized transverse emittance also increased to 290 nm·rad at the exit of the electron gun (see Fig. 4). The transverse normalized emittance for both increased but remained at a very low level. In Summary, the results indicate that the initial energy and the emission area are the significant factors that allow the beam to have a low transverse emittance. For cold field emission, low operating temperatures and small emission areas are both important for producing high-quality beams.

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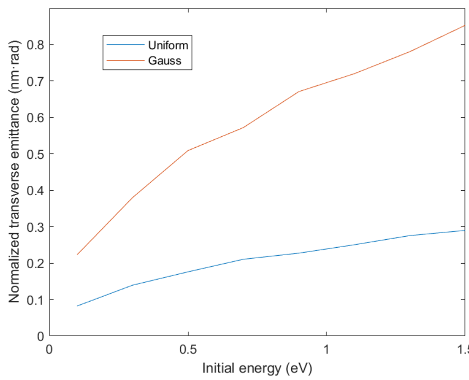

Figure 4: Normalized transverse emittance at the exit of the electron gun for different initial electron energies.

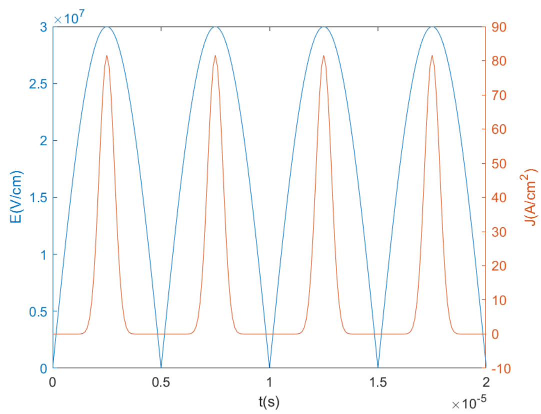

Figure 5: Instantaneous current density during RF cycles.

According to the second part of this article, the electric field of the part between the apex and the shank is smaller than that of the apex, and the corresponding theoretical values of current density are several orders of magnitude smaller. Therefore, it is acceptable to neglect the small emission current from the shank of the tip in the above simulations. In practice, the field emission current from areas other than the apex of the tip will decrease the quality of the main beam. In microwave fields, the instantaneous emission current in each RF cycle is concentrated near the 90° phase, and 90 % of the maximum theoretical value of current density occupies a phase width of about 20°. More experimental data is needed to support this. Compared with the DC mode above, the beam in microwave fields will be shorter, and the high gradient allows the particles to obtain higher energy.

FABRICATION OF TUNGSTEN TIPS

Referring to the work of Matthew Redshaw *et al.*, electrochemical etching was used for the fabrication of the tips [6], which has the advantages of simple experimental set-up, low cost, and short time. The main materials we used in this experiment were high-purity tungsten rods with 0.5 mm diameter and 1.5 mol/L NaOH solution. The etching current was set from 100 mA to 300 mA, corresponding recorded etching time of 425 seconds to 130 seconds, which meant the high current had shortened the etching time effectively.

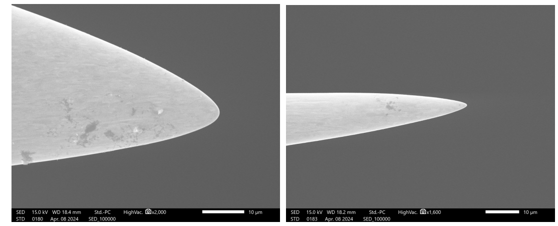
Figure 6: SEM images of selected regular shaped tips.

When the etching process is completed, the tungsten rod will form an upper and a lower part, namely two tips. After dozens of attempts, it is found that the radius of curvature of the smallest tip can be below 300 nm, but the tip is in terrible shape. Moreover, the upper tips are more likely to be irregularly shaped than the lower ones.

We assume that it is related to the fact that the tungsten rods were not perpendicular enough to the platform, and the solution did not drop smoothly down from the rods. The lower tips are more ideally shaped than the upper ones with a radius of curvature on a few micrometers scale, the sharpest of which is about 0.625 µm. The scanning electron microscope (SEM) images of selected regular-shaped tips as Fig. 6. Elemental analysis reveals a small residue of organic matter and oxides on the surface of the tips, which can be removed by ultrasonic cleaning. It is expected that a smaller and sharper tip can be obtained by adjustment of the alkali solution concentration and etching current and optimization of the experimental set-up.

Currently, the vacuum level of the available 200 kV DC gun can reach 10^{-8} Pa to meet the vacuum requirements of the cold field emission cathode. Before the experiment, the replaceable cathode plug needs to be modified and optimized for the tip assembly. Experiments in microwave fields are planned to be carried out on the very-high-frequency (VHF) gun [7], and the new beamline is under construction.

CONCLUSION

Calculations obtained by FEA show that the maximum value of the field enhancement factor β of the tip model can reach nearly 300 under an applied field gradient of 10 MV/m. Two types of the initial distribution of electrons, uniform and Gaussian, are placed in the electric field of a 200 kV DC electron gun for dynamics simulations of field emission. The preliminary results indicate that small emission areas and vary low initial energy of electrons allow low normalized transverse emittance on the order of tens to hundreds of pm · rad. The low normalized transverse emittance in the simulation means a higher spatial resolution for transmission electron microscopes (TEM). The tungsten tips fabricated by electrochemical etching can meet the requirement of a small emission area. We expect to obtain stable, low transverse emittance and high-quality electron beams in subsequent experiments, and we think the combination of a sharp tip as a cold field emitter and the high-gradient electron gun is a promising electron source for various applications.

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