

INITIAL BEAM CHARACTERIZATION FROM A COLD FIELD EMITTER IN A VHF ELECTRON GUN

Y. Qin, Y. Wang, B. Song, R. Zou, L. Zheng, R. Li, Y. Du*
Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

High-quality electron beams are critical for imaging experiments that provide detailed microscopic structural insights into materials. The Very-High-Frequency electron gun, capable of operating in continuous and pulsed modes, is a preferable option. In this paper, we employ a tungsten tip with an apex radius of curvature approximately 100 nm as a cold field emission cathode in the VHF gun and measure the beam charge, transverse emittance, and energy spread to characterize the beam quality. In preliminary experiments, we have achieved a normalized transverse emittance of 54.01 nm-rad. With an electron gun power of 37 kW, we obtained a strong beam current of approximately 6 μ A, which remained stable and continuous for several hours in a single experiment. By using an aperture to block electrons with large divergence angles and adjusting the solenoid's focusing strength, we propose to converge the target-energy electron beam onto the aperture, increasing its transmission rate and optimizing the energy spread. Prior to optimization, the energy spread was approximately 3.57% at 536 keV when using a 20 μ m diameter aperture.

INTRODUCTION

The Very-High-Frequency (VHF) electron gun is capable of operating in both pulsed and continuous wave modes at room temperature, providing a high-quality electron source for large-scale facilities such as ultrafast electron diffraction (UED) platforms and X-ray free electron laser (XFEL). The VHF electron gun at Tsinghua University is integrated with a loadlock and utilizes a replaceable plug, allowing different types of cathodes to be used to meet various experimental requirements. Currently, commonly used cathode types include photocathodes, thermionic cathodes, and field emission cathodes. Among these, photocathodes are limited by quantum efficiency and laser repetition frequency, resulting in relatively low average current density. While semiconductor photocathodes can achieve quantum efficiencies $1 \times 10^{-3} - 2 \times 10^{-1}$ [1], higher than those of metal photocathodes, but they also suffer from disadvantages such as short lifespan, high fabrication costs, and strict operational environment requirements.

Although thermionic cathodes offer the advantage of higher average current density, they have a broad emission phase and carry the risk of electron back-bombardment [2]. The principle of field emission is based on the Fowler-Nordheim equation (Eq. (1)) [3], the characteristic of current density varying approximately exponentially with electric field strength gives it the advantages of a narrow emission

phase and high average current density, without the need for heating or reliance on complex and expensive laser systems. Current research demonstrates that a small single diamond pyramid with a 20 μ m base can emit a current of 10 μ A; experiments have yielded a normalized transverse emittance of 0.689 μ m-rad [4], further demonstrating the potential of field emission cathodes:

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

We employed a modified conventional replaceable plug combined with a sharp tip emitter to create a cold field emission cathode, which was assembled into a VHF gun for beam experiments. We confirmed that the current signal could be generated continuously and stably for several hours in a single experiment. The beam charge, transverse emittance, and energy spread are measured to characterize the beam quality.

PLUG DESIGN AND OPTIMIZATION

We employ a replaceable cathode plug, which is inserted into the electron gun via a loadlock while maintaining a high vacuum (as low as 1×10^{-9} Pa) throughout the process. In previous attempts, we tried drilling small holes directly into the flat surface of the plug to allow the emitter to protrude. However, during experiments, stray dark current frequently appeared on the detection screen, causing it to mix with the desired field emission current signal and making it impossible to separate them. These spurious signals likely originate from intense field enhancement caused by uncontrollable microstructures at the sharp, vertical edges of the holes, even though the plug's surface has undergone precise mirror polishing.

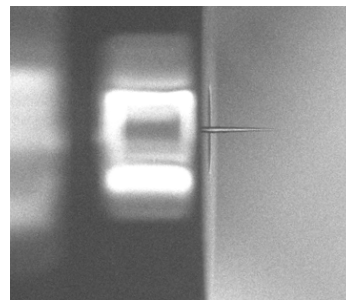


Figure 1: Tungsten tip protruding from the plug center.

In these experiments, the upper surface of the plug was machined with a dimple 1 mm deep and 2 mm in diameter, and the hole was drilled at the center of the dimple. The recessed structure suppresses the electric field, thus decreasing the

* dych@tsinghua.edu.cn

possibility of field emission. The dimple diameter is much larger than that of the small hole, reducing the difficulty of polishing the edge chamfer (to minimize sharp features as much as possible). Even if the dimple edge generates interfering field emission signals, the fact that the emission points are farther from the central emitter facilitates the separation of unwanted signals from the main beam by adjusting the solenoid's focusing strength. We aim to further suppress the possibility of dark current generated by all cathode structures other than the tungsten tip, and the new plug structure is currently undergoing optimization.

SIGNAL IDENTIFICATION AND CHARGE MEASUREMENT

The current beamline layout (Fig. 2) consists mainly of a 216.67 MHz VHF electron gun with a loadlock, solenoids, a Faraday cup, correctors, cameras, and several YAG screens mounted on lifting devices.

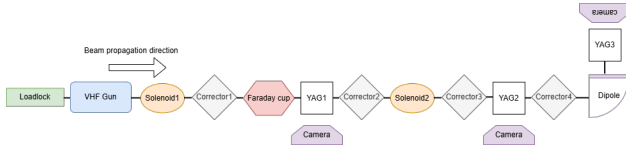


Figure 2: The layout of the experimental beamline.

The emitter used in this round of experiments was a high-purity tungsten tip with an apex curvature radius of approximately 100 nm, protruding 1.7 mm above the plug's upper surface. After inserting the plug into the electron gun using the magnetic rod in the loadlock, a well-focused electron signal appeared; that is, scanning the solenoid current over a wide range revealed that the position of this signal varied little with changes in magnetic field strength. When the plug is removed from the electron gun, a completely different long-tailed dark current signal under the same conditions was observed (Fig. 3).

At this point, slight adjustments to the solenoid current caused these dark current signals to shift significantly and exit the monitoring screen. Since the beamline was collimated using a laser during assembly, it can be assumed that the geometric center of the electron gun and the geometric center of the solenoid are precisely aligned, and that the plug fits closely within the electron gun. Therefore, the well-focused signal at this time was confirmed to originate from the cathode plug. The radius of the small hole through which the tungsten tip protrudes is 0.35 mm.

Simulations indicate that the electron emission point is offset by 0.35 mm from the centre of the cathode (i.e. assuming the signal originates from the edge of the hole); for every 0.05 A change in the solenoid excitation current, the centre of the beam spot on the detection screen shifts by approximately 500 μm . However, experimental data showed that under the same current variation, the signal deviation remained within 200 μm , which aligns well with expectations, confirming that the signal originates from the tungsten tip. As for the upper surface of the plug, the simulation

yielded a maximum field strength of 28 MV/m, which has not yet reached the range where a current would be observable as calculated by the F-N equation, generally considered to reach the order of gigavolt per meter.

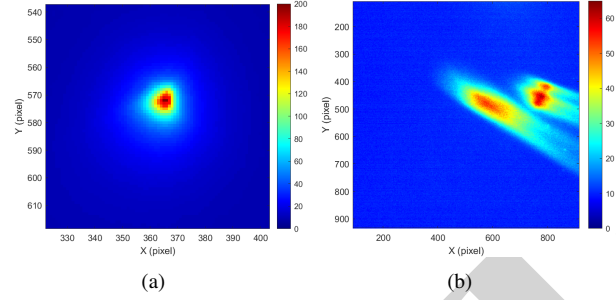


Figure 3: (a) Field emission signal from tungsten tip. (b) Dark current when the cathode plug is removed.

The charge quantity was measured using a Faraday cup. During the experiment, adjust the solenoid and the corrector to focus the field emission signal, continue adjusting until no other stray dark currents appear on the YAG screen, at which point lower the Faraday cup. The position of the Faraday cup was fine-tuned in two dimensions until the connected oscilloscope signal reached its peak; at this point, it can be assumed that all electrons to be measured have been captured by the Faraday cup. With a total power input to the electron gun of 37 kW and a repetition frequency of 10 Hz, the single-shot charge is 1.3 nC. From this, the charge per RF cycle is 28 fC, with an average current of 6 μA , indicating a relatively substantial signal strength.

SOLENOID SCANNING METHOD FOR BEAM EMITTANCE MEASUREMENT

The transverse emittance is defined as Eq. (2), where x is the transverse position of the electron and x' is the divergence angle. Then the normalized emittance is Eq. (3).

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} \quad (2)$$

$$\epsilon_{x,n} = \beta \gamma \epsilon_x \quad (3)$$

Let the solenoid transfer matrix be $M_{sol} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$, and the drift distance be L , then the corresponding matrix is $M_L = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$. The state of the electron after passing through the solenoid can be written as:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = M_L M_{sol} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \quad (4)$$

Therefore, the transverse beam size is

$$\begin{aligned} \sigma_x^2 &= \langle x^2 \rangle \\ &= (m_{11} + L m_{21})^2 \langle x_0^2 \rangle \\ &\quad + 2(m_{11} + L m_{21})(m_{12} + L m_{22}) \langle x_0 x'_0 \rangle \\ &\quad + (m_{12} + L m_{22})^2 \langle x_0'^2 \rangle \end{aligned} \quad (5)$$

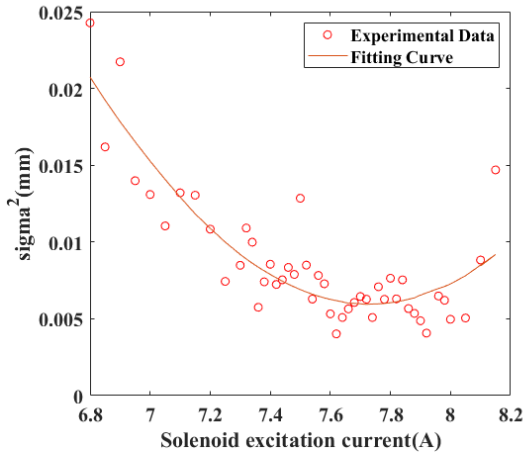


Figure 4: Solenoid excitation current and the transverse beam size on the YAG screen.

By adjusting the solenoid current within a certain range, the electrons exhibit different focusing states on the YAG screen, including the case where they are focused to the minimum spot size. By fitting the experimental data using the least squares method, we obtained that the electron beam size at the entrance of the second solenoid is 122 μm , the transverse emittance is 28.94 nm-rad, and the normalized emittance is 54.01 nm-rad. Due to current experimental constraints, further measurements are not yet available and will be pursued in future work.

DIPOLE DEFLECTION METHOD FOR BEAM ENERGY SPREAD MEASUREMENT

We placed an EMCCD after the dipole to capture the deflected beam image, as illustrated in Fig. 5.

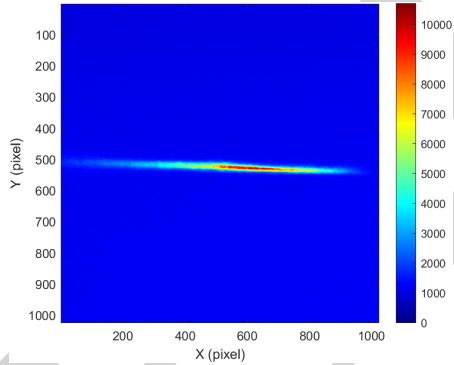


Figure 5: Image of the beam on the EMCCD after deflection by a dipole.

When the electron beam passes through a small aperture, electrons with large divergence angles are directly cut off. For the remaining electrons with small divergence angles, we plan to alter the solenoid's focusing strength by finely

adjusting the solenoid excitation current. This allows the beam spot at the aperture to be minimized for electrons of a specific energy; at this point, the transmission rate for target-energy electrons is highest, thereby effectively compressing the energy spread. Downstream of the beam, we have installed a dipole to deflect the beam, converting the energy distribution of the electrons into a spatial distribution on the detection screen, thereby enabling the calculation of the energy spread. In the experiment, we utilized apertures with diameters of 60 μm , 40 μm , and 20 μm . When the electron energy was 536 keV, the energy spread measured using the 20 μm aperture was 3.57%. Further fine-tuning and optimization are expected to further reduce the energy spread.

CONCLUSION

In this work, we have demonstrated a cold field emission cathode based on a tungsten tip operated in a VHF electron gun. Stable continuous emission was achieved with an average current of 6 μA (28 fC per RF cycle). The measured normalized transverse emittance is 54.01 nm-rad. Using a 20 μm aperture, the energy spread was measured to be 3.57% at 536 keV; further optimization of the solenoid focusing and reduction in the diameter of the aperture are expected to reduce this value. A dimple structure on the cathode plug effectively suppresses spurious dark currents by reducing local field enhancement. Future work will focus on further improvement of the plug design and collection of more comprehensive beam data.

REFERENCES

- [1] D. H. Dowell *et al.*, "Cathode R&D for future light sources", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 622, no. 3, pp. 685–697, 2010. doi:10.1016/j.nima.2010.03.104
- [2] C. B. McKee and J. M. J. Madey, "Computer simulation of cathode heating by back-bombardment in the microwave electron gun", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 296, no. 1, pp. 716–719, 1990. doi:10.1016/0168-9002(90)91294-L
- [3] R. H. Fowler and L. Nordheim, "Electron emission in intense electric fields", *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, vol. 119, no. 781, pp. 173–181, May 1928. doi:10.1098/rspa.1928.0091
- [4] D. Kim *et al.*, "Divergence study and emittance measurements for the electron beam emitted from a diamond pyramid", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 953, p. 163055, 2020. doi:10.1016/j.nima.2019.163055