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Design and development of a sheet-beam electron gun with large current for a THz traveling-wave tube

Xuyuan Chen[1], Lin Xu[1], Xiao Sun[1], Shengkun Jiang[1], Yasong Fan[2], Guang Yang[2], Zhifang Lyu[1], Tao Tang[1], and Zhaoyun Duan[1]

[1]*National Key Laboratory of Science and Technology on Vacuum Electronics in Chengdu, School of Electronic Science and Engineering, University of Electronic Science and Technology of China* (*UESTC*), *611731 Chengdu, China*

[2]*Nanjing Sanle Group Co., Ltd,211800 Nanjing, China*

Dedicated to Prof B N Basu

In this paper, the design, development and experimental investigation on a sheet-beam electron gun with large current for a THz traveling-wave tube (TWT), which can operate typically at 0.22 THz frequency, is reported. The cylindrical cathode is made of scandate, and the pencil electron beam is compressed into a sheet beam by an elliptical focusing electrode. The maximum beam current of 123.4 mA was predicted with the emission current density of 24.56 A/cm^2 in simulation with 22 kV beam voltage. In the sheet-beam electron gun, the distance between the emission surface of the cathode and the beam-waist was found as 11 mm, and the wide edge and narrow edge of the beam waist cross-section are 0.38 mm and 0.1 mm, respectively. The components of the sheet-beam electron gun were fabricated and subsequently assembled. Its assembly errors were detected. The simulation predicts that the beam transportation in the sheet-beam electron gun under the condition of assembly errors exceeds 96%. The study also includes the experimental characterization of the cathode emission of the gun. The preliminary experimental results of the sheet-beam electron gun indicate that the beam current of 80 mA with the beam voltage of 22 kV was obtained from the proposed design. The experiment remained useful towards development of a 0.22 THz futuristic TWT.

Keywords: Sheet beam, Electron gun, Terahertz TWT.

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1 Introduction

With the urgent demand for high-frequency and high-power devices, it becomes pertinent to develop millimetre-wave and terahertz (THz)-wave vacuum electron devices [1], THz-wave refers to electromagnetic waves of frequencies ranging from 0.1 to 10THz [2]. THz radiation sources in demand need to exhibit unique characteristics such as wide bandwidth, coherence, high power, and high efficiency, setting them distinct from traditional sources. Such THz sources have a wide range of applications encompassing many fields [3-6].

The research, applications, and development of THz technology greatly rely on the development of stable THz radiation devices [7,8]. One such THz radiation device, namely, the THz TWT plays a significant role in high-speed communication, high-resolution radar, high-precision imaging, and biomedicines [9,10]. However, with the increase of frequency, the device size and, correspondingly the cross-sectional area of the electron beam in the device decrease. This in turn imposes tough limitations due to the space charge effect

Corresponding author
e mail: zhyduan@uestc.edu.cn (Zhaoyun Duan)

[11,12]. The employment of a sheet electron beam in a THz TWT alleviates this problem since, for a given current density, the sheet beam can be realized with a larger cross-sectional area and larger beam current than the conventional beam of circular cross-section. The larger beam current obtainable from a sheet beam yields larger beam power and hence larger device RF output power as well [13]. Further, the larger cross-section of the sheet beam leads to lower current density, weaker space charge effect, and higher perveance, thereby relaxing the operating cathode emission density of the cathode and hence improving the lifetime of the cathode. Moreover, the larger cross-section of the sheet beam is helpful for the transverse expansion of the beam-wave interaction region. Consequently, the research on sheet-beam TWTs has emerged as a prominent area of focus in the field of vacuum electronics [14-18]. Extensive research has been conducted on the design and implementation of electron gun specifically tailored for THz TWTs [19-24]. The successful development of THz TWTs with the desired gain, efficiency, and operational stability greatly depends on the fabrication of tiny gun parts and their assembly with utmost precision. The sheet-beam electron gun proposed here has a large emission current under a small cathode emission area, and its structure is simple, which greatly facilitates the subsequent processing and assembly process. The design and experimental evaluation of a sheet-beam electron gun are reported in this paper. In Section 2, the design and simulation study on the sheet-beam electron gun of a THz TWT is given. In Section 3, the fabrication of the sheet-beam electron gun and the experimental evaluation of its performance characteristics have been described. In Section 4, this work is summarized.

2 Design of a sheet-beam electron gun with a thermal cathode

The emission theory of thermal cathode under actual working conditions can be approximately described by the Longo equation [25]:

$$J = J_{SC}\, J_{TL} / (J_{SC} + J_{TL}) \tag{1}$$

where J represents the cathode emission current density, J_{SC} is the current density in the space-charge-limited region, given by Child-Langmuir law [26], and J_{TL} is the current density in the temperature-limited region, given by Richardson equation [27]. J_{SC} appearing in Eq (1) is given by:

$$J_{SC} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m_0}}\,\frac{V^{3/2}}{d_{ca}^2} \tag{2}$$

where ε_0 represents the free-space permittivity, q represents the electron charge, m_0 represents the electron rest mass, V is anode voltage, and d_{ca} represents the cathode-to-anode distance. J_{TL} appearing in Eq (1) is given by:

$$J_{TL}(T) = AT^2 \exp(-\phi / k_B T) \tag{3}$$

where A is the Richardson constant, T is the cathode surface temperature, ϕ is the cathode work function, and k_B is the Boltzmann constant. It follows by simple algebra from Eq (1) that, when $J_{SC} >> J_{TL}$, J becomes the temperature-limited current J_{TL}, whereas when $J_{TL} >> J_{SC}$, J becomes the space-charge-limited current J_{SC}.

Based on the Pierce electron gun theory [28,29] and Longo equation (1), we have designed the sheet-beam electron gun consisting of a cylindrical cathode, an elliptical beam focusing electrode and an anode. The initial value of the design is mainly determined by four parameters: the beam voltage V, the beam current I, the cathode emission current density J, and the beam-waist size. According to the requirements of the THz TWT, the following design values are specified for the sheet-beam electron gun: beam voltage of 22 kV, target emission current of ~120 mA with an emission current density of ~24 A/cm^2, and beam-waist transverse dimensions of less than 0.4 mm×0.1 mm.

After optimization of the design, the cathode-to-anode distance d_{ca} is finalized as 3.6 mm (Fig 1), and Δd_{cf} representing the relative position of the cathode with respect to the focusing electrode is taken as 0 mm. Using the particle tracking solver of CST under the space-charge limited condition, and with complete iterative stabilization at –30 dB accuracy, the current of the sheet-beam electron gun is found as 123.4 mA, and the emission current density at the cathode emission surface is 24.56 A/cm^2. Figure 2 illustrates the trajectory of the sheet-beam and the cross-section at the sheet-beam waist of transverse dimensions 0.38 mm × 0.06 mm.

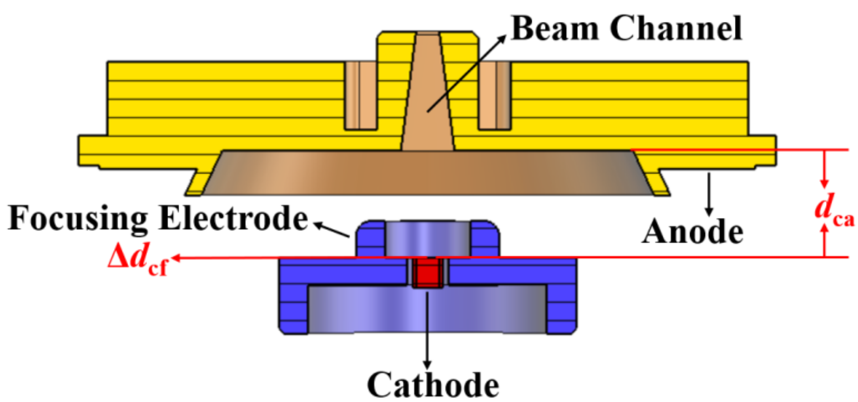

Fig 1. Simulation model of the sheet-beam electron gun, (d_{ca} and Δd_{cf} are defined in the text).

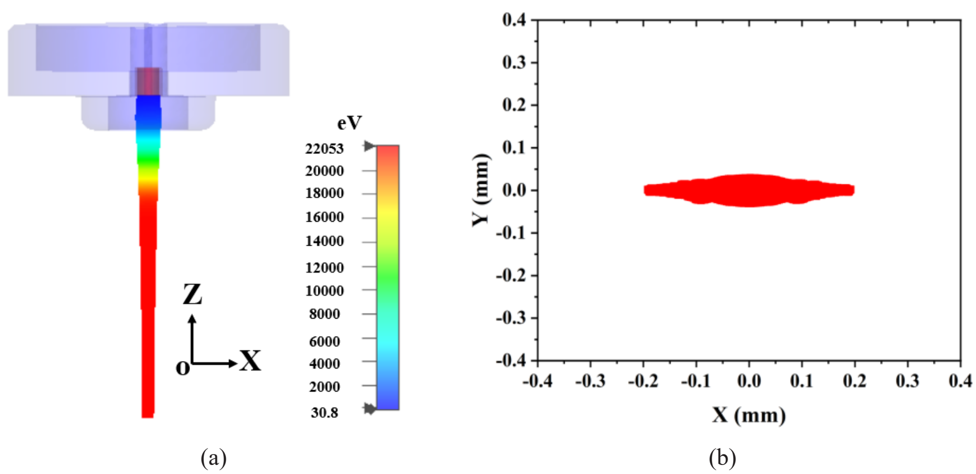

Fig 2. (a) Sheet-beam trajectory and (b) Cross-sectional distribution of the sheet beam at the beam waist.

3 Experiments and results

An electron gun with the scandate cathode of radius 0.4 mm was assembled, and the emission characteristics of the cathode were evaluated. After a series of trials, a scandate cathode with high emission current density was obtained. Figure 3 demonstrates the relationship between the surface temperature of the cathode and the power applied to the heater. Since the cathode exhibits variable emission current densities at different temperatures, the emission current of the cathode can be adjusted by changing the heater power.

After packaging the cathode component in a glass tube, it was tested on the cathode emission platform. Electrical connections were established between the heater, cathode, and anode leads; and the cathode temperature was gradually increased until the work function barrier was overcome; and electrons were emitted from the cathode surface and accelerated by the applied electric field. The working temperature of the cathode was determined by measuring the luminance of the cathode emission surface using an optical thermometer, while keeping the heater power constant. The test results of the cathode emission performance are illustrated in Fig 4. It is encouraging that, for the cathode temperature between 1095 and 1140 °C, we achieved the maximum emission density between 25.88 and 41.80 A/cm^2, respectively, thus satisfying our design requirements for a THz TWT (typically, 0.22 THz).

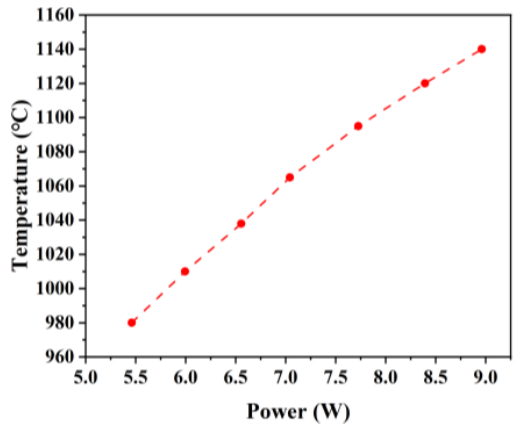

Fig 3. Relationship between the heater power and the cathode temperature.

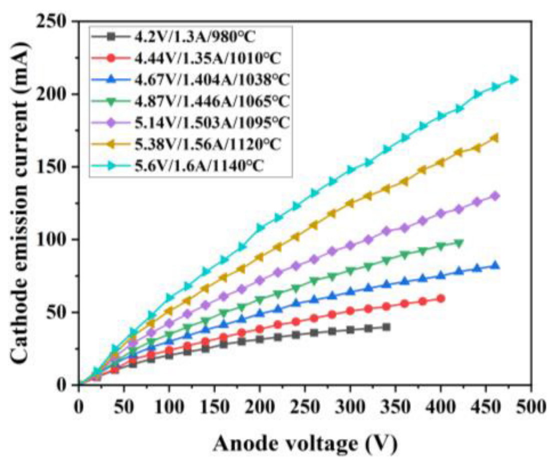

Fig 4. Test results of cathode emission current vs anode voltage.

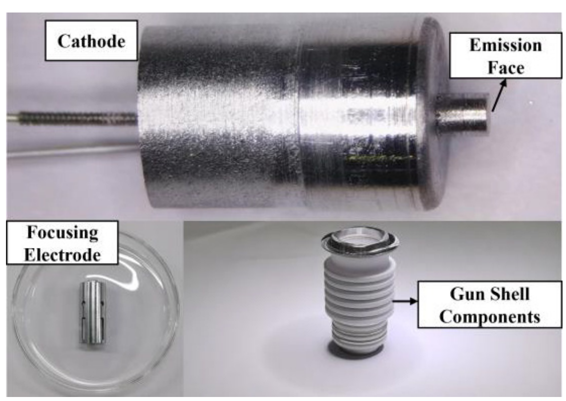

Fig 5. Main components of the sheet-beam electron gun.

Then based on the simulated geometric shapes and dimensions, we developed an assembly of the sheet-beam electron gun, and the main components of the sheet-beam electron gun are shown in Fig 5. The complete assembly process of the electron gun relies on the utilization of molds, which are crucial in ensuring the accurate positioning, levelling, and uniformity of the components under assembly. High power laser welding was employed during the assembly, and any oxidized spot that appeared after welding was carefully removed by scraping and cleaning. The assembled sheet-beam electron gun is shown in Fig 6.

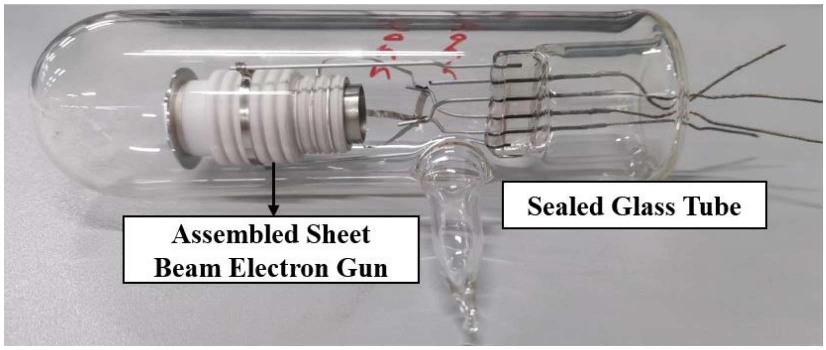

Fig 6. Assembled sheet-beam electron gun with a sealed glass tube.

In order to evaluate the dimensional accuracy of the sheet-beam electron gun, several key measurements were made with due care to evaluate the concentricity error between cathode and focusing electrode ($\Delta\phi_{cf}$), the relative distance error between the cathode and the beam focusing electrode (Δd_{cf}), the concentricity error between the beam focusing electrode and the anode ($\Delta\phi_{fa}$), and the cathode-to-anode distance error (Δd_{ca}). For the reliability of the measurements, four orientations were measured for Δd_{cf} and $\Delta\phi_{fa}$, and the average value was calculated as the error value. The measurement errors of the electron gun are listed in Table 1.

Table 1. Measurement errors

$\Delta\phi_{cf}$ (mm)	Δd_{cf} (mm)	$\Delta\phi_{fa}$ (mm)	Δd_{ca} (mm)
0.032	0	0.01	+0.01

For assessing the impact of assembly errors on the performance of the sheet-beam electron gun, an error simulation model was set up based on the measurement errors given in Table 1. Simulation calculations were then performed to predict the emission current and beam transport of the sheet-beam electron gun.

As the outer edges of the electron gun components are machined into circles, the accurate modelling of the concentricity errors in a sheet-beam electron gun can become complex in simulation. Therefore, the analysis process is simplified by considering four extreme cases based on the measurement errors: case 1: $\Delta\phi_{cf}$ and $\Delta\phi_{fa}$; all occurring in the narrow edge of the sheet beam (+Y direction); case 2: $\Delta\phi_{cf}$ and $\Delta\phi_{fa}$;all occurring in the wide edge of the sheet beam (+X direction); case 3: $\Delta\phi_{cf}$occurring in the +Y direction, while $\Delta\phi_{fa}$ occurring in the -Y direction; and case 4: $\Delta\phi_{cf}$ occurring in the +X direction, while $\Delta\phi_{fa}$ occurring in the –X direction. By evaluating these extreme cases, we can gain insights into the effects of assembly errors on the performance of the sheet-beam electron gun and make adjustments to improve its concentricity precision and reliability.

Figure 7 illustrates the results with respect to the beam current obtained under the four error conditions cases. It is evident that when the cathode-to-anode distance error is +0.01mm, the beam current is less than 123.4 mA in all four error condition cases. In addition, according as the concentricity error occurs in the X or Y direction, the electron beam shifts away from the center in the corresponding wide or narrow side.

Notably, in case 1, when the concentricity errors all occur in the +Y direction, the electron beam is intercepted by the metallic envelope, resulting in a beam transportation of 96.81%, while the other three cases achieve a beam transportation of 100%. This discrepancy may be attributed to the smaller compression ratio of the sheet beam in the Y direction and the larger channel margin in the X direction, which provides less impact in the X direction when compared with the case of Y direction.

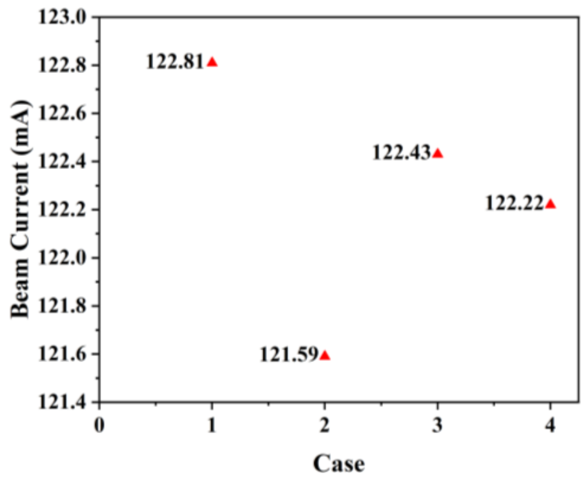

Fig 7. Beam currents under four error conditions.

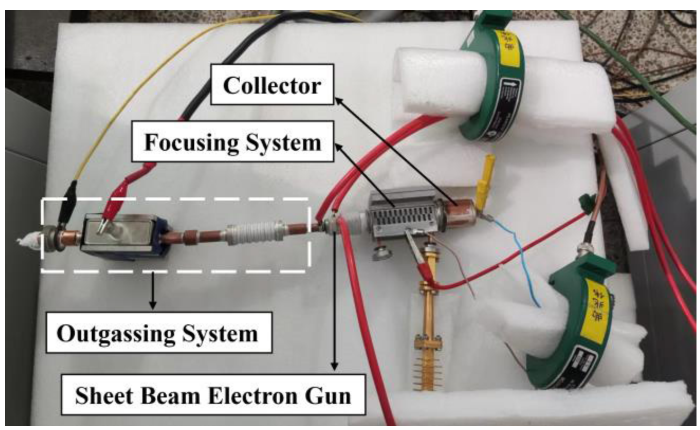

Fig 8. Experimental test platform.

Subsequently, we carried out the preliminary experimental test of the sheet-beam electron gun using the experimental test platform shown in Fig 8. The experimental results indicate that when the cathode voltage was set to –22 kV, the heater voltage was 5.5 V, and the heater current was 2.9 A, the cathode emission current reached 80 mA. However, the emission current measured in the experiment was found to be about 65-67% of that predicted by simulation. The heater power was ~16W, which is significantly higher than the power required for the cathode emission experiment. Several possible reasons accounting for this phenomenon are as follows: (i) The heating efficiency of the heater may be low, possibly due to the presence of the dirt, oxides, or other undesirable substances on the surface of the heater during assembly. Poor thermal contact between the heater and the support structure, as well as high ambient temperature and improper air pressure, can also decrease the heating efficiency of the heater. (ii) Electron gun experiments usually require a high vacuum environment. Insufficient vacuum can lead to scattering and energy loss of the electron beam due to the presence of air molecules, resulting in the reduction of emission current. (iii) The surface of the cathode may have been contaminated during the processing and assembly of the electron gun. (iv) The current emitted by the cathode is intercepted by the metallic envelope or other structures, resulting in a smaller measured current than the actual emitted current.

Based on the results of the preliminary experiment reported here, we have planned our future experimental investigations exploring improved methods. The following actions will be taken in our further endeavour. (i) A dedicated experimental test will be conducted on the sheet-beam electron gun to specifically identify the main reason for the low emission efficiency. By focusing on this specific factor, we can gain a deeper understanding of the underlying issues and develop effective solutions to improve the emission performance; (ii) efforts will be made to enhance the molds and electron gun components to reduce the concentricity error during the assembly process. By addressing this issue, we aim to improve the overall performance and dimensional accuracy of the electron gun, leading to better emission efficiency; and (iii) prior to conducting the next experiment, attempts will be made to control the external factors such as vacuum and environmental conditions. By ensuring optimal conditions, we can minimize the influence of these factors on the experiment and enhance the reliability and repeatability of the results. By implementing these actions (i)-(iii), we hope to gain further insights into the performance of the electron gun, identify components for improvement, and refine the design and assembly processes. This will contribute to enhancing the overall precision and reliability of the electron gun.

4 Conclusion

A sheet-beam electron gun for a THz TWT (typically, 0.22 THz) has been designed, developed and tested. The precise assembly of the electron gun has yielded beam transport greater than 96% under the error conditions. The emission current found by the present preliminary experiment is ~65-67% of that predicted by simulation. It is felt that, in order to find the reasons for this discrepancy, further investigations are required. The present study serves as a foundation for future experiments on the sheet-beam electron gun of a THz TWT (typically, 0.22 THz).

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Xuyuan Chen received her Bachelor’s degree from Xiangtan University in 2021. She is pursuing her Master’s degree in electronic science and technology at the University of Electronic Science and Technology of China. Her current research focuses on THz sheet beam electron gun.
e-mail: xtuchenxuyuan@163.com.

Lin Xu serves as an Engineer at the University of Electronic Science and Technology of China, where his main research interests include cathode fabrication and vacuum electronic device process.
e-mail: 86925670@qq.com.

Xiao Sun received her Master's degree in Material Science and Engineering from Qilu University of Technology in 2020. Since then, she has been pursuing her Ph D degree in the University of Electronic Science and Technology of China. Her research focuses on the experimental study of THz absorbing materials and cathode materials used in THz sheet-beam electron guns.
e-mail: xiaosun@std.uestc.edu.cn.

Shengkun Jiang received the Ph D degree in Electronic Science and Technology in 2023 from University of Electronic Science and Technology of China. He is an Assistant Professor at the Jiangxi University of Science and Technology. His current research interests include the THz sheet beam traveling-wave tubes.
e-mail: jsk7078@163.com.

Yasong Fan received his Master's degree from Sichuan University, and is currently employed at the Nanjing Sanle Group Co., LTD., China. He has a long-standing commitment to the design and preparation of high emission density cathodes.
e-mail: fanyasong2013@163.com.

Guang Yang received his Master's degree from the University of Electronic Science and Technology of China and is currently employed at the Nanjing Sanle Group Co., LTD., China. His focus involves the development of space traveling-wave tubes.
e-mail: 1968568905@qq.com.

Zhifang Lyu received his Bachelor's degree from the University of Electronic Science and Technology of China (UESTC) in 2019. He is currently pursuing the Ph D degree in Electronic Science and Technology at UESTC. His current research interests include THz radiation sources, metamaterials, and metamaterial-based vacuum.
e-mail: lvzhifang2015@163.com.

Tao Tang received his M S degree in Mechanical Engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2003. He is currently a Senior Engineer with the School of Electronic Science and Engineering, UESTC. He is involved in improving the design and fabrication techniques of traveling-wave tubes.
e mail: tang_tao70s@163.com.

Zhaoyun Duan received the Ph D degree from the University of Electronic Science and Technology of China in 2004. He is currently Professor and serving as the Deputy Dean in the School of Electronic Science and Engineering, UESTC. His research interests include metamaterial and its applications in high-power microwave radiation sources, THz vacuum electron devices, and so on. He is the Founding Chair of IEEE NPSS Chengdu Chapter. In addition, he is a Fellow of IET and a Fellow of CIE.
e mail: zhyduan@uestc.edu.cn.