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A New Method to Focus SEBs Using the Periodic Magnetic Field and the Electrostatic Field

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Abstract: In this paper, a novel method, named PM-E, to focus the sheet electron beam (SEB) is proposed. This new method consists of a periodic magnetic field and an electrostatic field, which are used to control the thickness and width of the SEB, respectively. The PM-E system utilizes this electrostatic field to replace the unreliable $B_{y,off}$, which is a tiny transverse magnetic field in the PCM that confines the SEB's width. Moreover, the horizontal focusing force of the PM-E system is more uniform than that of the conventional PCM, and the transition distance of the former is shorter than that of the latter. In addition, the simulation results demonstrate the ability of the PM-E system to resist the influence of the assembly error. Furthermore, in the PM-E system, the electric field can be conveniently changed to correct the deflection of the SEB's trajectory and to improve the quality of the SEB.

Keywords: SEB; focusing system; electron optical system

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1. Introduction

Recently, considerable attention has been focused on vacuum electronic devices (VEDs) as a breakthrough in powerful coherent radiation source development in the terahertz wave regime of 0.1 to 1 THz [1,2], because of their high-energy conversion efficiency and large thermal power capacity. In particular, SEB has many advantages for high power vacuum electron devices, such as increasing the input DC power and reducing the beam current density proportional to the beam width [3–6]. Previous work has indicated that devices driven by SEBs could output more power. So, in many high-power millimeters wave or terahertz wave vacuum electron devices, there is a growing trend to incorporate sheet beam designs instead of solid cylindrical beams.

However, the stability of SEB transport has been recognized as one of the key technologies required for VEDs employing SEBs, resulting from the non-axisymmetric space-charge distribution shown in Figure 1. The simplest method to confine SEBs into a narrow interaction region is the uniform magnetic field. Unfortunately, the uniform magnetic field is an unstable configuration for SEBs, due to the $\vec{E} \times \vec{B}$ drift velocity shear arising from the uniform magnetic field and the transverse space-charge field. The common instabilities stemming from the drift velocity shear are deformation and diocotron instabilities. Both experiments and theories have illustrated that these instabilities may be suppressed by increasing the strength of the uniform magnetic field. However, the strength needed to achieve this stability may be too high to implement [7–11].

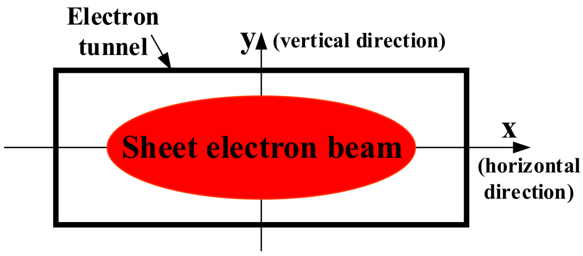

Figure 1. Cross-sectional view of SEB transportation in a tunnel.

An alternative method for focusing the SEB is the periodically cusped magnet (PCM) [12,13], which consists of periodic pole pieces and magnetic blocks. The PCM system is more suitable for focusing the SEB than the uniform magnetic system, because of its miniaturization and modest magnetic flux density. The Los Alamos National Laboratory developed a traveling wave tube (TWT) employing a 120-kV SEB focused by PCM [14]. A Ka-band TWT employing an SEB and a PCM reached a 93% transmission rate, which was designed by UESTC [15]. A Q-band SEB TWT was investigated in [16], which used a PCM system to achieve 92% beam transmission under a 30-kV beam voltage and 100-A/cm^2 current density.

Nevertheless, the sensitivity of PCM is a non-negotiable factor in experiments, resulting from a tiny transverse magnetic field. Because of the non-uniform distribution of remanence in the permanent magnetic material, it is hard to ensure that this transverse field meets the design well. Moreover, a tiny transverse magnetic field is generated by the staggered pole pieces, causing a limitation to the longitudinal magnetic field's strength.

To avoid these problems arising from the tiny transverse magnetic field, a new method, which consists of a periodic magnetic field and an electrostatic field, is presented in this paper. The electrostatic field is used to replace the tiny transverse magnetic field. For convenience, the new method is named PM-E. In addition, the PM-E system has the ability to resist assembly errors. The analysis and simulation results are presented in the following.

2. The Analysis of the PCM

The conventional PCM field with off-set pole pieces is expressed in the following form [12]:

$$\left.\begin{aligned} B_z &= B_0 \cosh(2\pi y/p)\cos(2\pi/p) \\ B_{y,off} &= \frac{B_s}{\pi}[\arctan(\frac{\frac{\omega_s}{2}+x}{\left|y-\frac{b_m}{2}\right|}) - \arctan(\frac{\frac{\omega_s}{2}-x}{\left|y-\frac{b_m}{2}\right|})] \\ B_{y,pcm} &= -B_0\sinh(2\pi y/p)\sin(2\pi z/p) \end{aligned}\right\} \tag{1}$$

where $B_{y,pcm}$ and B_z are the transverse and longitudinal components of PCM fields, respectively. They are used to focus the SEB in the Y-direction. The $B_{y,off}$ represents the y component stemming from the staggered pole pieces, which is used to control the SEB in the X-direction. In fact, the distribution of $B_{y,off}$ is periodic in the Z-direction, owing to the periodicity of the pole pieces. An accurate description of the $B_{y,off}$ is shown in the following:

$$B_{y,off} = (k_a \cos(4\pi z/p) + k_a)x \tag{2}$$

where k_a denotes the coefficient of variation of $B_{y,off}$ along the Z-direction. k_b is the coefficient of variation of $B_{y,off}$ along the X-direction. Usually, because k_a is smaller than k_b, k_b plays a major role in controlling the width of the SEB. In the vicinity of the SEB, the $B_{y,off}$ can be simplified as

$$B_{y,off} = k_b x \tag{3}$$

When an electron with a longitudinal velocity v_z enters the PCM field, the interaction between the longitudinal velocity v_z and $B_{y,off}$ produces an inward force. The force can be used to balance the space-charge force, described as follows:

$$v_z B_{y,off} = E_x \tag{4}$$

Because of the ultra-high velocities of the electrons in the VEDs (the kinetic energies of the electrons are usually higher than 10 keV), $B_{y,off}$ is generally very small, only a dozen Gauss. For example, for a W-band SEB with a 0.2-A current, 19-kV voltage, and cross section of 0.2 mm $\times$ 0.8 mm, the electric field E_x arising from the space charges is 105,000 V/m at the left end of the SEB. The corresponding $B_{y,off}$ is only 13 Gs, which is much smaller than B_z (usually several thousand Gs). Considering the non-uniform distribution of remanence in the permanent magnetic material, the tiny $B_{y,off}$ tends to deviate from the ideal value, causing experimental failure. Therefore, $B_{y,off}$ is the main factor for the sensitivity of PCM.

3. PM-E

To avoid these problems stemming from $B_{y,off}$, the new method, named PM-E, which uses the electrostatic field to replace the unreliable $B_{y,off}$, is proposed. The electrostatic field is produced by the potential difference between the electron tunnel and two charged wires placed into the tunnel. The model of the PM-E system is shown in Figure 2.

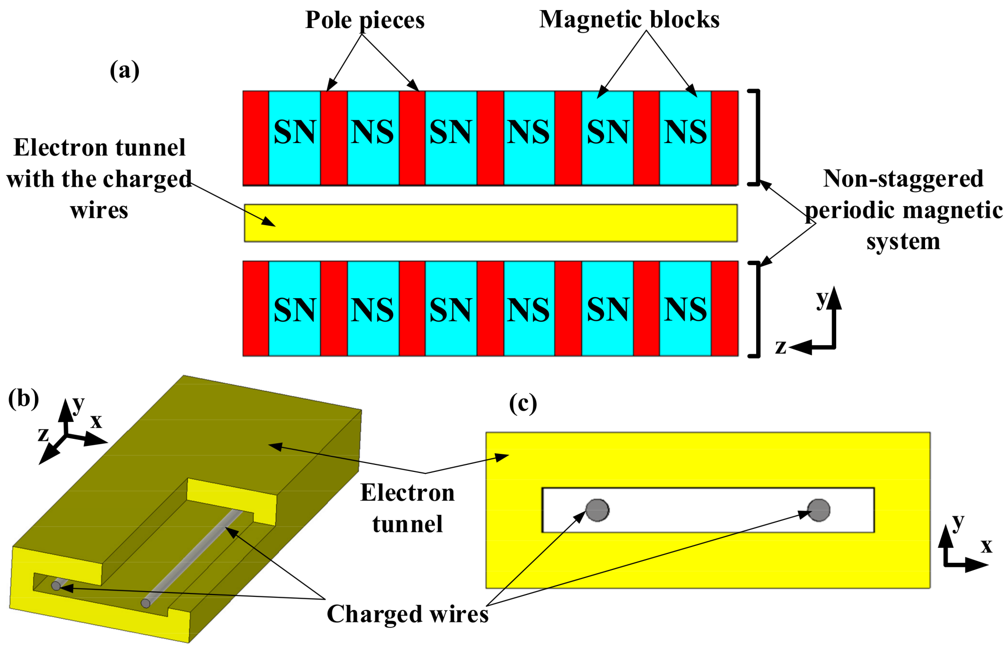

Figure 2. (**a**) The sketch of the PM-E system. (**b**,**c**) The model of the electron tunnel with two charged wires.

To resist the space-charge force in the X-direction, the potential of these two wires was slightly lower than that of the electron tunnel, as shown in Figure 3. Ordinarily, the potential difference between the charged wires and the electron tunnel would be less than 100 V. This potential difference produces an electric field opposite to the space-charge field in the X-direction, contributing to preventing the defocusing of the SEB in the X-direction.

Because $B_{y,off}$ is replaced by the electric field, the sensitivity stemming from $B_{y,off}$ is eliminated. Moreover, the staggering of the pole pieces of the periodic magnetic system is canceled. This means that the limitation of the periodic magnetic system's width is removed, which assists in increasing the peak value of the periodic magnetic field.

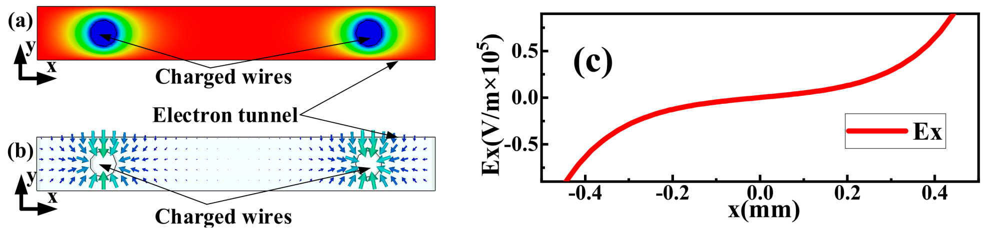

Figure 3. (**a**) The potential distribution of the electron tunnel on the X-Y plane. (**b**) The electric field distribution of the electron tunnel on the X-Y plane. (**c**) The distribution of E_x near the SEB.

According to Equation (2), $B_{y,off}$ is variable in the z-direction, while the transverse electric field provided by the PM-E system is uniform in the z-direction. In addition, the magnetic system is far from the electron channel, so the transition distance of $B_{y,off}$ is long. In contrast, the transition distance of the horizontal electrostatic focusing field is very short, due to the close distance between the two wires. The normalized horizontal focusing force of the two systems at the (−0.4 mm, 0 mm) coordinate is displayed in Figure 4. This figure indicates that the normalized horizontal focusing force of the PM-E system is more uniform and changes rapidly, assisting in providing a high-quality focusing effect.

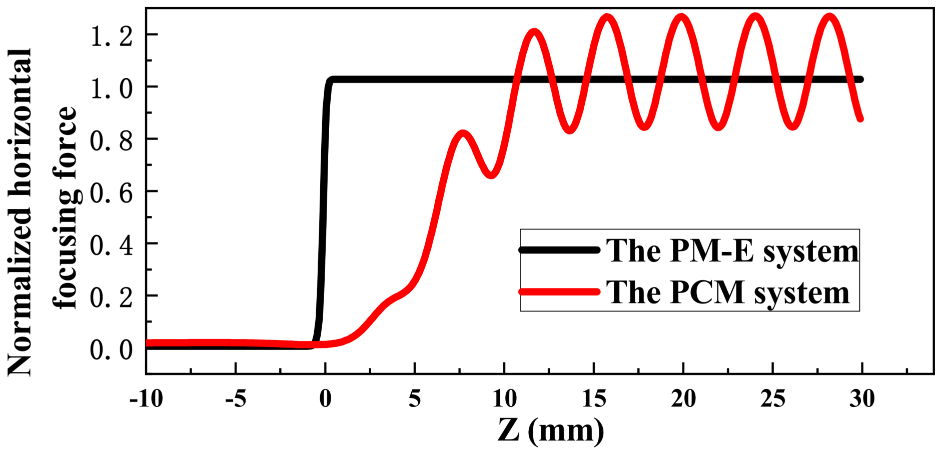

Figure 4. The normalized horizontal focusing forces of PCM and PM-E at the (−0.4 mm, 0 mm) co-ordinate.

4. Simulation

To verify the focusing effect of the PM-E system, a W-band SEB with a 0.2-A current and a 19-kV voltage was selected. The emission surface of the SEB was a 0.8 mm × 0.2 mm ellipse. The length of the tunnel was 50 mm. The dimension of the tunnel's cross section was 2 mm × 0.4 mm. The distance between the two wires with a 0.1-mm radius was 1.5 mm. The voltages of the tunnel and wires were 0 V and −60 V, respectively. The period of the magnetic system was 6 mm, and the peak value of the magnetic field was 0.15 Tesla.

The CST particle tracking solver [17] analyzed the design of the PM-E system. Figure 5 depicts the trajectory of the SEB under the influence of the field created by the PM-E system. The simulation results show that SEB could be stably transported in the PM-E field. Moreover, PM-E achieved focusing SEB in the X-direction, without $B_{y,off}$.

In addition, the PM-E system could eliminate the influence caused by assembly error, by adjusting the voltage of the wires. For example, in the above electron optical system, the left wire shifted to the right by 0.24 mm (30% of the SEB's width), as shown in Figure 6a. According to Figure 6b, under the influence of the assembly error, the trajectory of the SEB blended to the right, and the some electrons collided with the right wire.

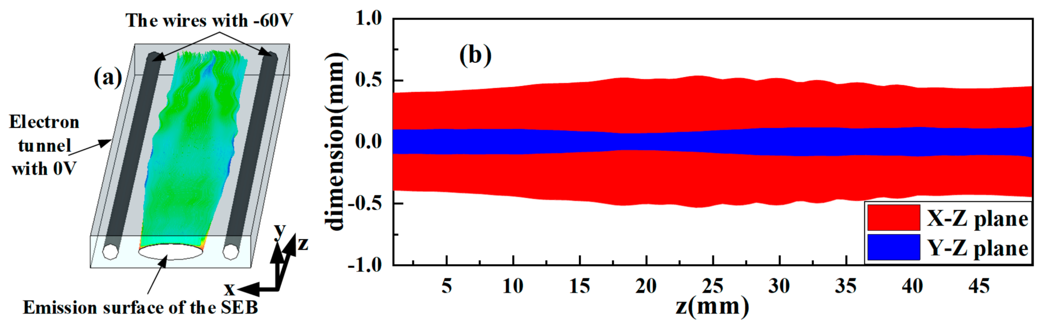

Figure 5. (**a**) 3D trajectory of the SEB analyzed by CST. (**b**) The beam trajectory on the Y−Z plane and the X−Z plane.

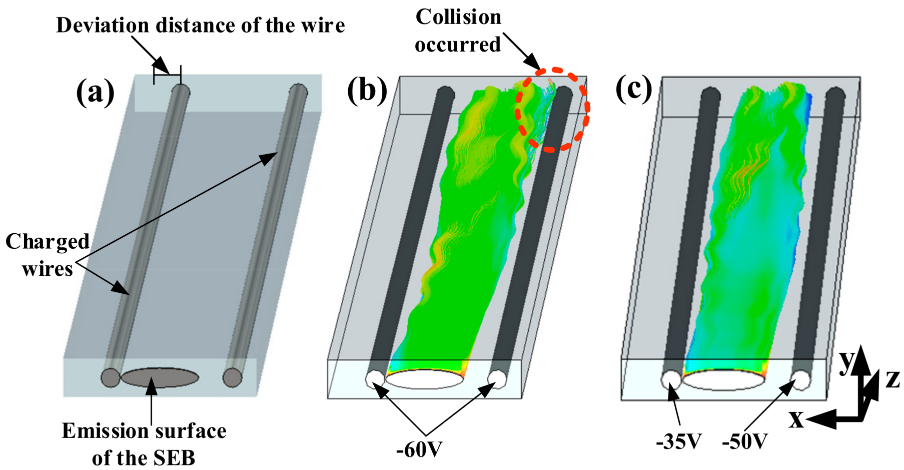

Figure 6. (**a**) The model with the assembly error. (**b**) The beam trajectory without voltage correction. (**c**) The beam trajectory with voltage correction.

In order to avoid collisions, the voltages of the two wires were set to −35 V and −50 V, respectively. As shown in Figure 6c, the direction of SEB motion was gradually corrected under the influence of the modified electric field.

Additionally, the closer the electrons were to the wire, the greater the horizontal focusing force on the electrons. Therefore, the PM-E system had a certain self-adaptive capability. In particular, when the initial position of the SEB shifted in the X-direction, the trajectory of the SEB was still confined between the two wires. For instance, Figure 7 displays that the emission surface of the SEB shifted left by 0.2 mm (25% of the width of the SEB). As can be seen in Figure 6b, the trajectory of the SEB returned to the center of the tunnel under the influence of the electrostatic field. Of course, in order to keep the SEB away from the boundary of the tunnel, the voltages of the two wires were changed slightly, and the simulation result is shown in Figure 7c. Comparing Figure 7b,c, it can be found that the quality of the SEB can be improved effectively by modifying the wire voltage when the initial position of the SEB is moved horizontally.

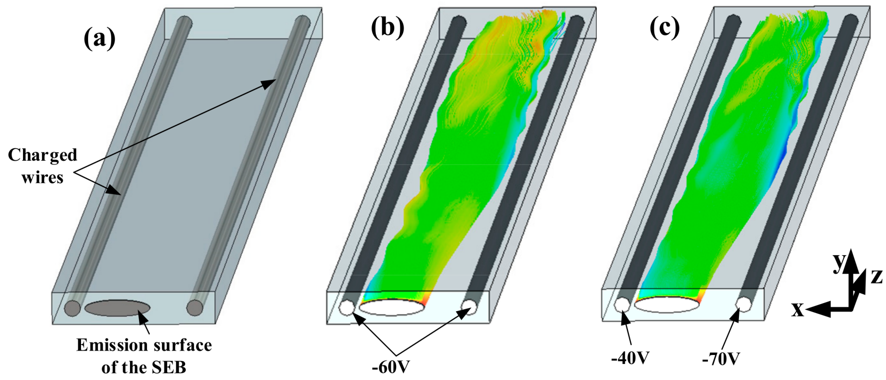

Figure 7. (**a**) A model of the emission surface moving 0.2 mm to the left. (**b**) The simulation result without changing the wire voltage. (**c**) The simulation result with changing wire voltage.

5. The Electron Optical System with the Electron Gun and PM-E System

To further verify the performance of the PM-E system, a complete electron optical system with an electron gun was designed and analyzed. The model is shown in Figure 8.

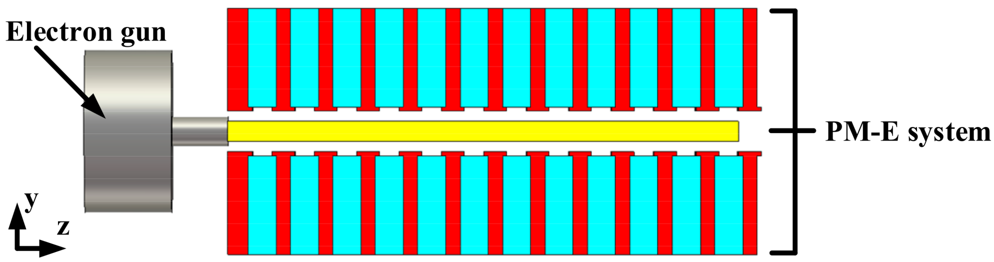

Figure 8. The model of the electron optical system with a PM-E system and electron gun.

The electron gun generated an SEB with a 19-kV voltage and 0.2-A beam current. The beam waist of the SEB was 0.2 mm × 0.8 mm with a current density of 160 A/cm^2. The emission surface of the cathode was a 1.34 mm × 1.92 mm ellipse with 9.8 A/cm^2 cathode current density. The period of the magnetic field was 8.3 mm. As shown in Figure 9, the peak value of the magnetic field was 0.22 Tesla at the axis.

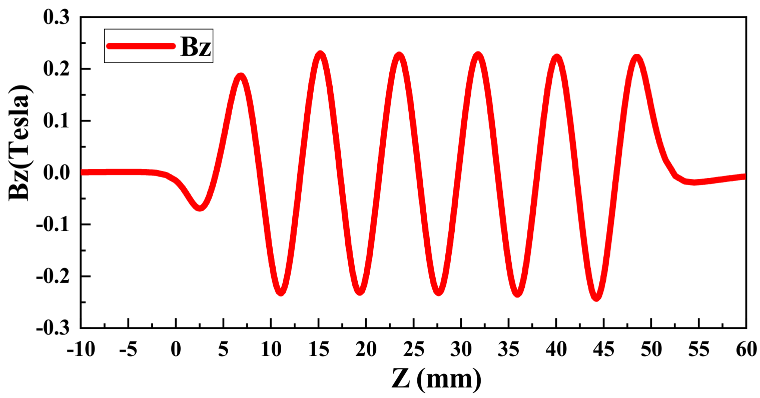

Figure 9. Distributions of the longitudinal magnetic field B_z.

The distance between the two charged wires was 1.5 mm. The voltages of the two wires with a radius of 0.1 mm were set to −60 V. The simulation result can be identified from Figure 10. And the detailed parameters used in the CST Particle Studio are listed in Table 1.

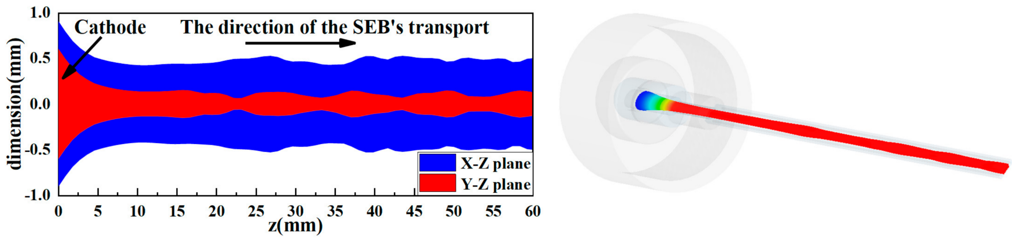

Figure 10. The simulation results of the electron optical system.

Table 1. The parameters used in CST Particle Studio.

Parameters	Values
Accuracy of the tracking solver	−50 dB
Maximum time steps	100,000
Minimum pushes per cell	5
Time step dynamic	1.2
Number of the mesh cells	13,000,000
Number of macroparticles	11,294

As can be seen in Figure 11, the cross-sectional views of SEB show that the PM-E system can maintain the laminar during transport, and the PM-E system achieves stable and efficient transport of SEB.

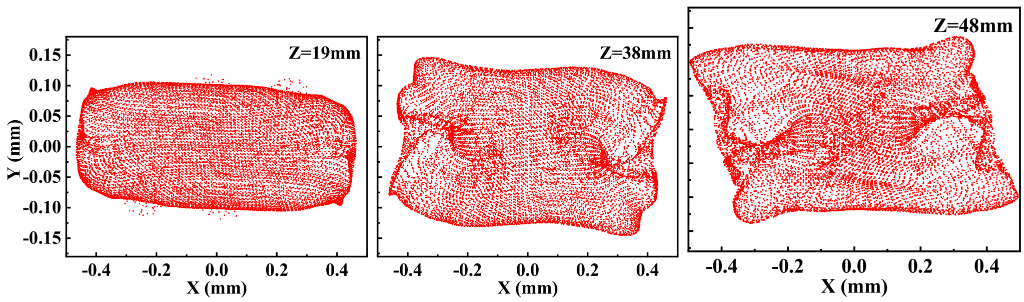

Figure 11. The cross-sectional views of the SEB in different locations.

6. Conclusions

In this paper, a novel focusing method, named PM-E, based on the electrostatic field and the periodic magnetic field, is proposed. The electric field and magnetic field control the width and thickness of SEB, respectively. The electrostatic field is produced by the potential difference between the electron tunnel and two charged wires placed into the tunnel. The periodic magnetic field is generated using a non-staggered period magnetic system. Compared with the conventional PCM system, the PM-E system utilizes an electric field instead of the unreliable $B_{y,off}$ to focus the SEB in the X-direction. The non-staggered pole pieces remove the limitation of the periodic magnetic system's width, assisting in increasing the peak value of the periodic magnetic field. Furthermore, the horizontal focusing force of the PM-E system has a uniform distribution and short transition distance. The system has a certain adaptive capacity to resist the influence of assembly errors. Furthermore, the electric field can be easily changed to correct the deflection of the trajectory and to improve the quality of the SEB. Finally, to further verify the performance of the PM-E system, a complete electron optical system with an electron gun is designed and analyzed. The simulation results demonstrate that the transmission efficiency reaches 100% under the PM-E system. As a focusing system, PM-E may have potential applications, such as traveling wave tubes and EIKs, as well as for use in other devices employing SEBs, in the future.

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