Adding a control grid to a high-current electron gun

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Recently, I was asked to consider whether a control grid consisting of parallel or crossed wires could be added to an existing space-charge-limited electron gun for beam modulation. I identified two main questions:

> Because considerable effort had been invested in the gun design, would it possible to add the grid without significantly changing the macroscopic beam optics?
>
> What was the contribution to the angular divergence of the beam relative to the focal requirements?

With regard to first question, the best approach would be to locate the wire grid at the former position of the cathode surface and to move the cathode a short distance upstream. The grid would be attached to the focus electrode bounding the former cathode surface. Figure 1 is a schematic view of the cathode-grid region. The values of D and V_c should be chosen to generate an electron current density j_e equal to the space-charge limited design value in the main acceleration gap. In this way, the grid surface would act almost like the original cathode, preserving the gun optics.

There are two options to fabricate a grid: 1) parallel wires with spacing W or 2) a crossed grid with square openings with side length W. For a rough estimate, I did not consider the effect of the wire width. The assumption is that electron flow is space-charge limited in both the cathode grid-gap and in the extraction gap. Therefore, the electric field on the downstream side of the grid would be close to zero. Following **CPB5.2**[1], the current density in the cathode-grid gap is

$$j_e = \beta \frac{V_c^{3/2}}{D^2}, \tag{1}$$

where

$$\beta = \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m_e}} = 2.33 \times 10^{-6}. \tag{2}$$

The electric field in a planar gap varies as

$$E_z = \frac{4 V_c z^{1/3}}{3 D^{4/3}}. \tag{3}$$

The value of the electric field near the grid is

$$E_z(D) = \frac{4V_c}{3D}. \tag{4}$$

[1]References are to sections in my books available on the Internet: **Charged Particle Beams** (`http://www.fieldp.com/cpb.html`) and **Principles of Charged Particle Acceleration** (`http://www.fieldp.com/cpa.html`).

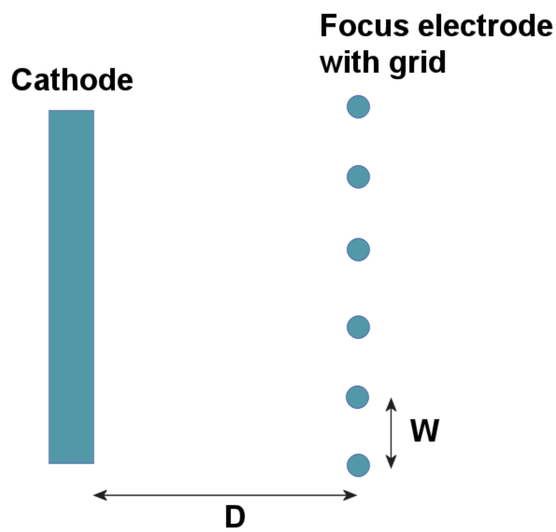

Figure 1: Schematic view of the displaced cathode and a grid at its former location. The grid is at the potential of the focus electrode and the cathode has relative voltage $-V_c$.

To estimate the effect of discrete wires on the beam divergence, I used the derivation of the aperture effect in **CPA6.5**. Consider the effect of a grid consisting of parallel wires that point along y on electrons propagating along z. The discrete wires produce a local field component E_x that is given approximately by

$$E_x \cong = -x \; \frac{\partial E_z}{\partial z}. \tag{5}$$

The equation of motion for non-relativistic electrons passing the grid is

$$\frac{dv_x}{dz} \cong \frac{eE_x}{m_e v_z} = -\left(\frac{e}{m_e v_z}\right) \; x \; \frac{\partial E_z}{\partial z}. \tag{6}$$

We integrate Eq. 6 over the region near the grid and divide the result by v_z to obtain the deflection angle in radians:

$$\Delta\theta = \frac{\Delta v_x}{v_z} = -\left(\frac{e}{m_e v_z^2}\right) \; x \; (E_{z2} - E_{z1}). \tag{7}$$

From above discussion, $E_{z2} \cong 0.0$ and E_{z1} given by Eq. 4. Substituting in Eq. 7, taking $x_{max} = W/2$ and recognizing that

$$m_e v_z^2 \cong 2eV_c, \tag{8}$$

leads to following simple result:

$$\Delta\theta_{max} \cong \frac{W}{3D}. \tag{9}$$

Applying the derivation in **CPA6.5**, the following approximation holds for a square grid pattern:

$$\Delta\theta_{max} \cong \frac{W}{6D}. \tag{10}$$

The divergence is reduced by a factor of two and applies in both the x and y directions.

The next step is to relate the angular divergence at the control grid (Eq. 9) to the beam focal requirements. Suppose the total voltage between the cathode and a grounded anode downstream from the grid in Fig. 1 is V_0. The angular divergence of the full energy beam is

$$\Delta\theta_0 \cong \sqrt{\frac{V_c}{V_0}}\ \theta_{max}. \tag{11}$$

If the beam propagates a distance L to a line focus, then the minimum half-height is about $\Delta x = L\theta_0$.

The final issue is how to pick values of W and D. Practical fabrication and the need for a high transparency set a minimum value for W. I expect that it would be difficult to made a robust grid with W significantly smaller than 1 mm. The relationship between gap spacing D and voltage V_c is constrained for a specified current density through Eq. 1. Combining this equation with Eq. 11, we find the following relationship:

$$\Delta\theta_0 \cong \frac{W(j_e/\beta)^{1/3}}{3V_0^{1/2}D^{1/3}}. \tag{12}$$

There is only a weak dependence on the cathode-grid spacing.

As an example, I consider a planar beam gun designed at the Stanford Linear Accelerator Center[2]. The gun design has $j_e = 1.04 \times 10^5$ A/m^2 and $V_0 = 7.4 \times 10^4$ V. For $W = 1.0 \times 10^{-3}$ m and $D = 4.0 \times 10^{-3}$, Eq. 12 implies that $\Delta\theta_0 = 0.027$ radian. For a drift distance $L = 30.0$ mm, the half height at the focus is $\Delta x \geq 0.83$ mm. The value is larger than the required short-direction focal dimension of 0.25 mm. The implication is that the wires in the grid array must be parallel to the short direction. This orientation is not possible in the present gun design with a concave cathode surface.

I set up a **Trak** simulation to test the model with full space-charge effects. The cathode-grid gap had spacing $D = 4.0$ mm and a voltage difference of 7.89 kV to generate an electron beam with $j_e = 10.0$ A/cm^2. I modeled three

[2] G. Scheitrum, *Design and Construction of a W-band Sheet-beam Klystron*, (Stanford Linear Accelerator Center, **SLAC-11688**, 2005), unpublished.

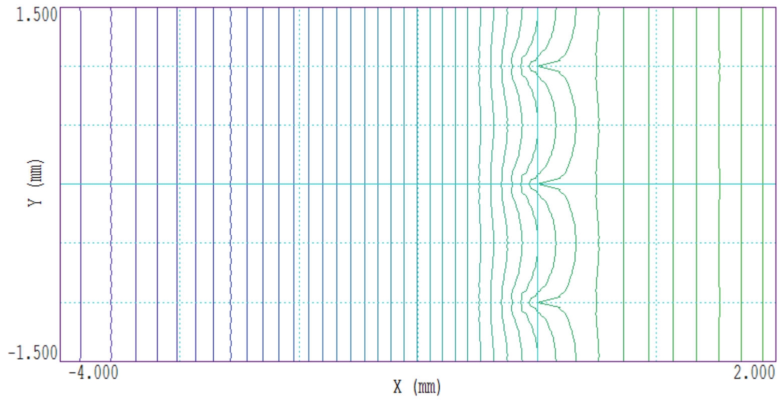

Figure 2: Distortion of equipotential lines by a parallel wire grid with $W =$ 1.0 mm. The electric field includes contributions from the electron beam space charge.

wires of a periodic grid with $W = 1.0$ mm as shown in Fig. 2. The main acceleration gap had width 24.0 mm with accelerating voltage 66.11 kV.

Figure 3 shows the variation of $|E_z|$ from the cathode to the anode. The scan was taken at a vertical position midway between wires. Because electrons left the grid region with non-zero velocity, the electric field on the downstream side did not return to zero. As a result, the beam divergence at the anode was lower than the theoretical prediction. Figure 4 shows the vertical phase-space distribution at the anode. The maximum deflection angle is 0.015 radians. With the reduced divergence, the minimum beam half height after propagating 30 mm was 0.45 mm.

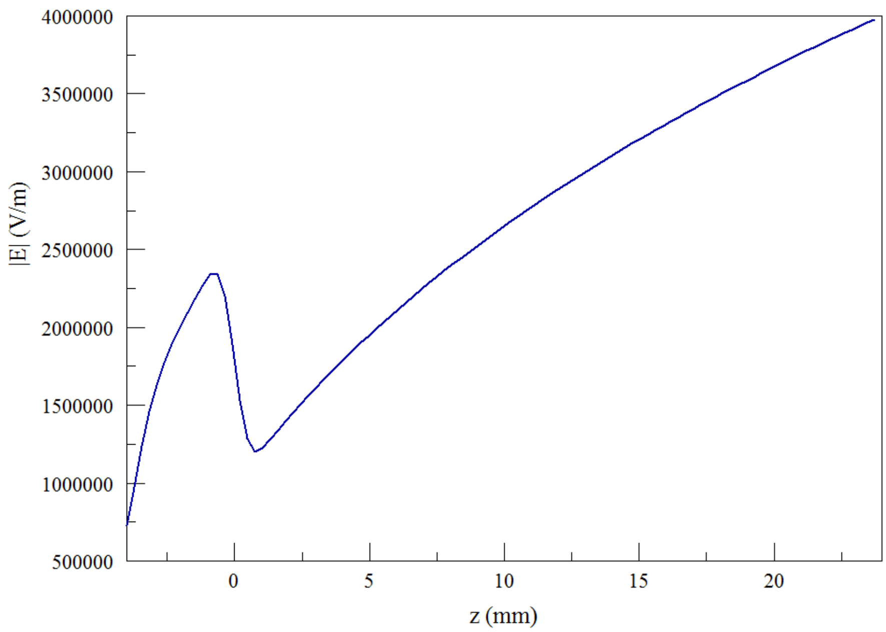

Figure 3: Plot of $|E_z|$ from the cathode to the anode along a line midway between wires. The electric field includes contributions from the electron beam space charge.

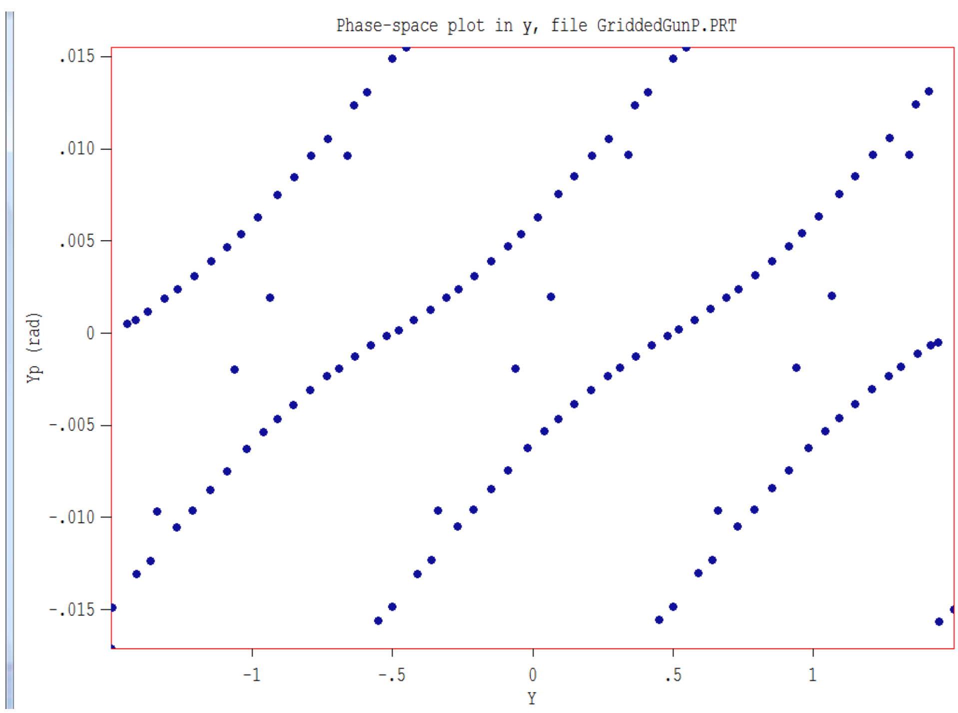

Figure 4: Phase-space distribution in the direction normal to the wires at the anode.