THE DESIGN OF SHEET-BEAM ELECTRON-GUN FOR HIGH–POWER MICROWAVE SOURCES*

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Abstract

A set of software tools based on Pierce theory and the Cutler-Hines approach for thermal velocity effects have been developed for the design of sheet-beam electron guns. The tools yield parameters for rudimentary gun geometry, which are further refined using the 2-D particle-in-cell code EGUN. Candidate designs for guns suitable for applications to high-power, high-frequency microwave sources have been obtained. The results indicate good potential for the use of sheet-beams to generate microwaves applicable to future accelerators.

1 INTRODUCTION

High power microwave sources in the 30 to 100 GHz range are needed to power the next generation of linear accelerators and colliders. Several recent proposals for the generation of high power microwaves make use of sheet electron beams. The inherent advantage of these beams, with a typical width-to-height ratio of 10, is the reduced space charge effect for a given beam current. In comparison with round beams, past design work of sheet beams is quite scanty, particularly in the relativistic, high-current density, cases now being considered. This paper describes efforts to design such beams. A two-pronged approach is taken. Preliminary designs with rudimentary geometry of electrodes are first made using the Pierce method, supplemented by the effects of thermal velocity. Although the basis of these methods are well-known, substantial developmental work has been gone through to carry out the formulation and to produce a computer code for design purposes. Detailed designs are then performed by particle simulation using the 2-D code EGUN.

2 PRELIMINARY DESIGN

2.1 Pierce Method

A preliminary design of sheet-beam electron guns can be made using an approach pioneered by Pierce[1]. The rudimentary gun geometry consists of a cathode in the form of a circular arc of half-angle α, an anode with a slit to let the beam through, and an exit plane at equal potential to the anode. The electron flow and the potential distribution between the cathode and the anode are approximated by those of the space-charge-limited diode with concentric cylindrical electrodes. The anode slit acts as a diverging lens. Beyond the anode, the beam moves under the influence of its own space charge. The paraxial approximation is taken throughout. The treatment is fully relativistic.

For a given geometry, the beam current and the electron paths depend only on the anode potential, which is characterized by the relativistic energy factor $\gamma = 1 + eV / mc^2$ of the beam. The electron paths beyond the anode are self-similar and parabolic. They either cross the mid-plane or achieve a minimum deviation at some location beyond the anode. The only geometry parameter which controls such behaviors is κ, defined as d/a where d is the anode-cathode separation and a is the radius of curvature of the cathode. This factor is always less than unity. When it is too small, the beam diverges from the mid-plane upon emerging from the anode. When it is too large, the beam crosses the mid-plane. It would appear that the optimum design is to choose κ so that the minimum beam thickness is zero, and let the actual beam thickness be determined from considerations of thermal effects. Indeed, such an approach has been undertaken in the past[2]. However, a new calculation of thermal effects reveals that this approach is far from optimal.

2.2 Thermal Velocity Effects

The effects of transverse velocity spread of electrons originating from the cathode can be investigated using the method of Cutler and Hines[3]. This entails computing the perturbed orbits from the cold beam paths. It gives rise to an expression for the deviation from the cold path for a warm path of a given transverse velocity at the cathode. The expression diverges at the location where the cold beam crosses the mid-plane, a result at variance from those of earlier calculations[4] quoted by Reference [3]. The divergence is traceable to the fact that, in the region between the anode and the exit plane, the deviation y from the mid-plane satisfies the linear equation

$$\frac{d^2y}{dz^2} = \frac{K}{s(z)} y \qquad (1)$$

where K is a constant and $s(z)$ is the envelope of the cold beam, which is a quadratic function. As a result, all paths

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except those with zero initial transverse velocity approaches infinity at the location where $s(z)$ vanishes. Therefore, designs for which the cold beam crosses or touches the mid-plane are to be avoided as the thermal spread would be large. The location of the exit plane can still be chosen to be where the thickness of the cold beam is the smallest.

For a given temperature T of the cathode, the current density profile at the exit plane is found to be

$$dI = \frac{I}{4s_m}\left[erf\left(\frac{y+s_m}{\sigma_{th}}\right) - erf\left(\frac{y-s_m}{\sigma_{th}}\right)\right]dy \qquad (2)$$

where S_m is the minimum half-thickness of the cold beam, and σ_{th} equals $f(\kappa,\gamma)d\sqrt{kT/eV}$ for some function f involving integrals that can be computed numerically. The thickness t_{95} containing 95% of the beam current can be found from Eq.(2).

2.3 Design Optimization

A MATLAB based computer program has been created to make optimum designs. The program accepts as inputs the beam energy, the current per unit width, the current density at the cathode, and the temperature of the cathode. It completely determines the rudimentary geometry by minimizing t_{95}. The code has been partially validated against sheet-beam design calculations and experimental measurements performed in the past[2].

As an example, consider a 140kV and 15A sheet-beam with a width of 0.8cm, which is a candidate for applications to future W-band accelerators. Taking the current density at the cathode to be 5A/cm^2, and the temperature to be 1473K, the optimum design has the following parameters:

$$d = 3.3cm \quad a = 5.0cm \quad \alpha = 21.3^\circ \quad \ell = 12.5cm$$
$$t_{95} = 0.18cm$$

Here ℓ is the distance between the cathode and the exit. The areal compression based on t_{95} is 21. The cold beam thickness in this case is 0.09cm. The beam thickness at the anode is 1.28cm. The electric field at the anode is 93 kV/cm, well within the break-down limit.

2.4 Brillouin Field

An external magnetic field in the direction of the beam near the exit is required to prevent the beam from diverging. For round beam, this is the well-known Brillouin field. A similar derivation based on the conservation of canonical angular moment and the cancellation of the space-charge force by the pinching effect of the self magnetic field and the Lorentz force from the imposed field can be performed for sheet-beams. This gives rise to the following expression for the required field:

$$B^2 = \left(\frac{m}{e}\right)^{3/2} \frac{1}{\sqrt{V}} \frac{1}{\sqrt{1+\gamma}} \frac{I}{w\,t} \qquad (3)$$

where I/w is the beam current per unit width and t is the beam thickness. Although the choice of guide field is immaterial in the Pierce approach, it is needed in detailed designs where electron orbits are obtained with realistic electrode geometry. Note that the scaling of B with beam thickness is favorable with the sheet beam in comparison with the round beam (i.e. $B \propto r^{-1}$ for round beam).

3 DETAILED DESIGN

Detailed designs can be made using specialized or general purposed particle motion simulation codes. These codes determine the trajectories of a large number of electrons emitted from the cathode self-consistently with the electric and magnetic fields, thereby obtaining the current of the beam once the electrode arrangement is specified. Besides improving on the accuracy of the Pierce method, the codes also allow detailed designs of electrode geometry so that optimization can be performed in a large parameter space. The 2-D gun design code EGUN has been used for the purpose. Output from the preliminary design code can be used as guidance for preparing input to EGUN.

A detailed design for a gun with similar parameters as the sample design in section 2.3 has been made. The electrode geometry and the paths of electrons are shown in Fig.1. This gun delivers a 140kV beam with 10.7A/cm and a thickness t_{95} equal to 0.36cm. Other parameters are

$$a = 5cm \quad \alpha = 20^\circ \quad d = 4.5cm \quad \ell = 13.9cm \qquad (4)$$

The angle between the focusing electrode and the cathode arc is chosen to be 65.5°. In addition, the maximum electric field is 94.4kV/cm and the cathode current density is 3.1A/cm^2. It is seen that with the exception of the beam thickness, there is reasonable agreement with the preliminary design.

Smaller beam thicknesses can be achieved by rescaling. For example, rescaling the geometry of (4) above, down by a factor of 2, reduces estimated beam thickness to 1.8 mm and increases current density to 21.4 A/cm. In this case, the maximum E field increases to 189 kV/cm which is still within acceptable limits.

In the numerical calculations, the paths of electrons are not self-similar as in Pierce's theory. The paths and the beam envelope depend on the choice of the magnetic field. Some amount of midplane crossing is unavoidable if the field is close to or exceeds the Brilluoin field. The beam envelope also tends to oscillate, with amplitudes and periods that depend on the value of the field chosen. The paths in Fig.1 correspond to the choice B=300G, below the Brilluoin field of 536G. Design for a higher power beam at 400kV and 78A/cm have also been made, with a thickness equal to 0.2cm.

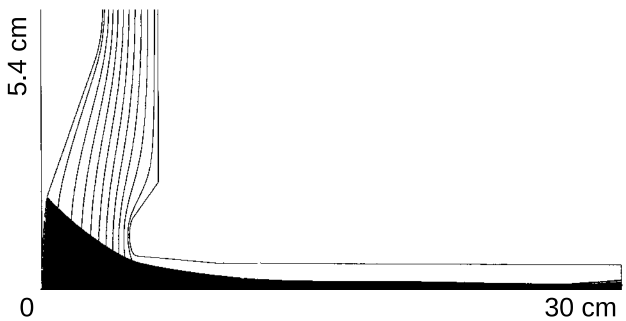

Figure 1: Electrode geometry and electron paths for a 140kV sheet-beam electron gun according to EGUN.

With higher external magnetic fields the beam waist were found to be reduced as shown in Eq. (3). With higher magnetic field, however, the beam tends to cross the midplane as seen in Fig. 2. The crossing occurs more frequently as B increases.

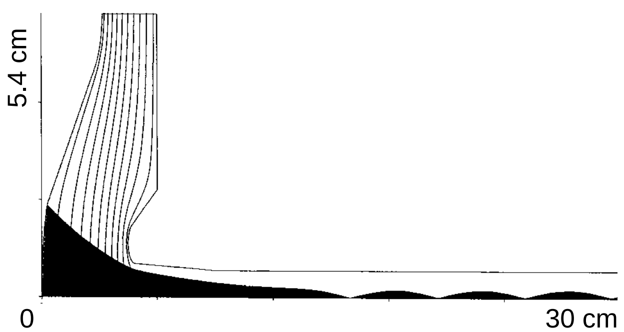

Figure 2: Electrode geometry and electron paths for a 140kV sheet-beam electron gun with 1000G magnetic field according to EGUN.

4 SCALING STUDIES

In an effort to map out the possible parameter range of sheet-beams, scaling studies have been performed using the software which implements the Pierce method with thermal velocity effects. Three parameters are considered: beam voltage (70-280kV), current per unit width (10-40A/cm), and cathode loading (2.5-10A/cm^2). Each is varied while keeping the others fixed at values corresponding to a reference design, which is chosen to be the one discussed in earlier sections. The main results are:

- compression ratio in the range 15 to 40 is achievable
- beam thickness of 0.1 to 0.25 cm can be obtained
- increasing the current per unit width causes the beam to thicken
- Increasing the voltage has the same effect, but to a lesser extent
- increasing the cathode loading is very effective in reducing the beam thickness

5 CONCLUSIONS

Developmental work carried out in the implementation of Pierce theory for the design of sheet-beams and Cutler-Hines approach for the effects of thermal velocity leads to software tools suitable for preliminary design work and scaling studies. New results have also been obtained.

The combination of such software tools and a 2-D particle simulation code proves to be an effective way of designing sheet-beams. Designs have been obtained for beams suitable for the generation of high-power, high-frequency microwaves. Based on point designs and scaling studies, sheet-beams should have good potential for application in future accelerator technology. Future work should include 3-D effects such as edge control, and more detailed characterization of beam qualities.

6 REFERENCES

[1] J.R. Pierce, *Theory and Design of Electron Beams*, D. Van Nostrand Co. (1954)

[2] N.B. Kramer and E.G. Todd, Design of Hollow and Strip Beam Guns, *IEEE Transaction of Electron Devices*, Nov 63 p394 (1963)

[3] C.C. Cutler and M.E. Hines, Thermal Velocity Effects in Electron Guns, *Proc. I.R.E.*, vol. 43, p307 (1955)

[4] L.E. Bakhrakh and V.G. Medoks, Effect of Thermal Velocities on Blurring of Electron Beams, *Radio Engineering and Electron Physics*, vol.1, p107 (1962); C.B. Crumly, Thermal Velocity Effects on Two-dimensional Electron Beams, Stanford Electronics Lab., Rept. No. 457-2 February (1958)