Oct. 20, 1959 R. W. PETER 2,909,704

ELECTRON GUN

Filed Oct. 9, 1953 2 Sheets-Sheet 1

FIG_1

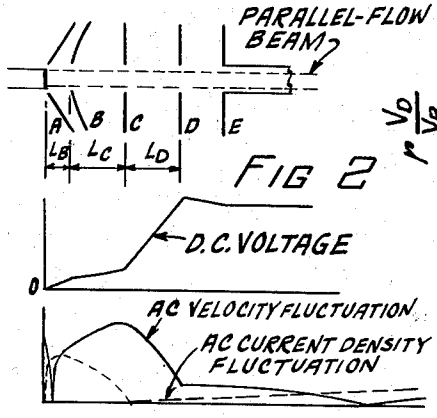


FIG 2

FIG_3

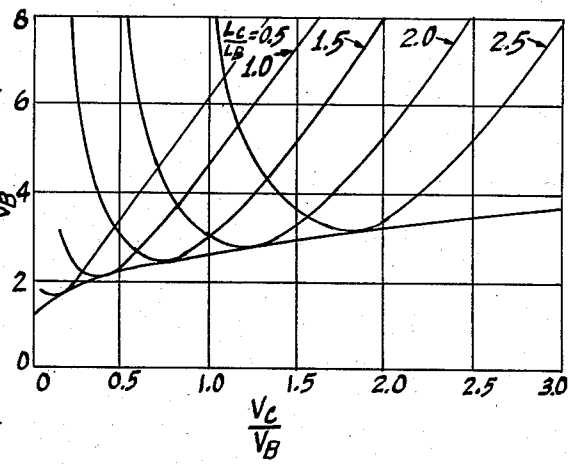


FIG_4

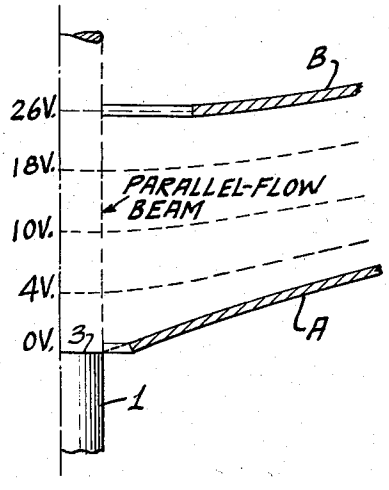


FIG_5

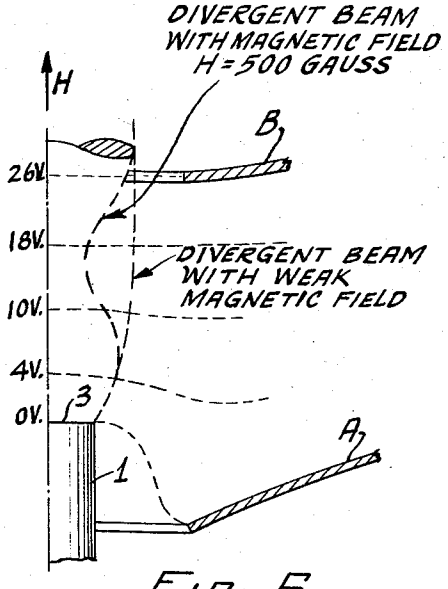


FIG_6

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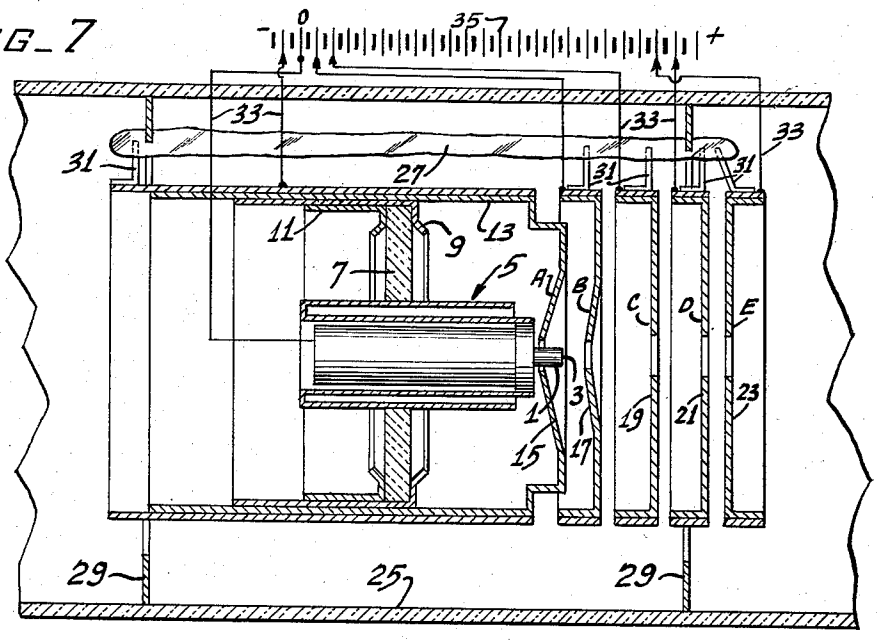
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ELECTRON GUN

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FIG_7



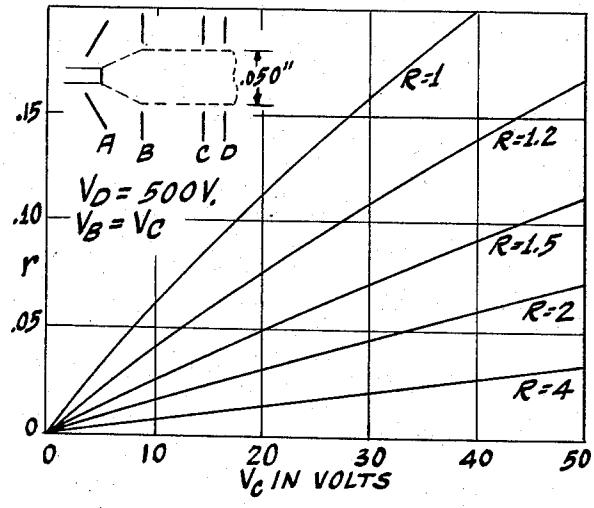


FIG_8

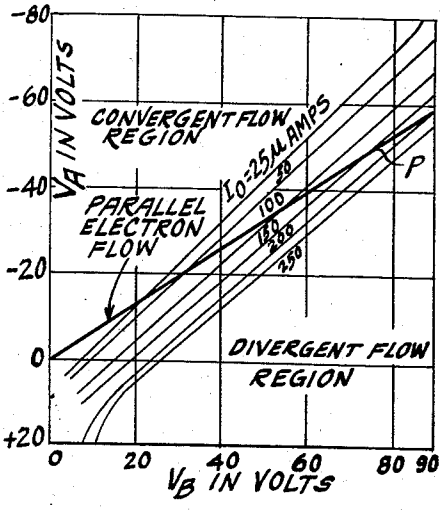


FIG_9

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2,909,704

ELECTRON GUN

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Application October 9, 1953, Serial No. 385,064

18 Claims. (Cl. 315—15)

The present invention relates to electron guns for generating electron beams in beam tubes such as traveling wave tubes and klystrons.

The principal object of the invention is to provide a low-noise electron gun.

Another object of the invention is to provide an improved electron gun capable of producing a divergent electron beam with minimum collection of electrons by the gun electrodes.

The noise theories of Rack, "Effect of Space Charge and Transit Time on the Shot Noise in Diodes," Bell System Technical Journal (17), October 1938, pp. 592–619, show that the noise fluctuations of an electron beam under space-charge-limited conditions leaving the potential minimum consist essentially of velocity fluctuations only. These theories have been verified experimentally for small transit angles. For this case Rack showed that the actual multi-valued velocity electron stream can be replaced by an equivalent single-valued stream which yields the same final noise formula. The equivalent single-valued noise velocity v_a has an R.M.S. value

$$v_a^2=(4-\pi)\eta\frac{kTc}{I_0}\Delta f \qquad (1)$$

where:

I_0=beam current
$\eta=e/m$=electron charge/mass
K=Boltzman constant
T_c=cathode temperature
Δ_f=frequency bandwidth.

Pierce, "Traveling-Wave Tubes," D. Van Nostrand Co., Inc., 1950, applied this concept to noise factor computations of traveling wave tubes.

From the assumption that the beam leaves the virtual cathode free of random density modulation but with random velocity, one has to conclude that, by analogy to the well-known bunching phenomena in klystrons, there exist periodical density and velocity fluctuation maxima and minima along the beam. Such standing noise waves in an electron beam have been observed experimentally by Cutler and Quate, Physical Review, vol. 80, No. 5, pp. 875–878, December 1, 1950, and others, confirming the applicability of these simplified noise concepts to large transit-angle beams.

Computing the noise factor F of a traveling wave tube on the base of the standing noise wave theory yields the following expression:

$$F=1+\tfrac{1}{2}(4-\pi)\frac{T_c}{T_0}\frac{r}{C}f \qquad (2)$$

where:

T_c, T_0=cathode and room temperature, respectively, in ° K.

$$r=\left(\frac{v_m}{v_a}\right)^2=\text{noise-reduction factor of the gun} \qquad (3)$$

v_m=maximum velocity fluctuation amplitude in the drifting beam

v_a=velocity fluctuation amplitude at the virtual cathode, see (1)

$$C=\left(\frac{K}{4V/I_0}\right)^{1/3}=\text{Pierce's gain parameter} \qquad (4)$$

K=circuit impedance seen by the beam
V, I_0=beam D.C. votage and current
f=a function of space charge factor, gain factor, helix attenuation and drift length between last gun anode and helix.

For small space charge and helix loss and for optimum position.

$$f=0.25. \qquad (5)$$

Watkins, "Traveling-Wave Tube Noise Figure," Proc. IRE, vol. 40, No. 1, January 1952, pp. 65–70, has computed function f for different parameter values. His curves show that f increases with circuit loss but is practically unaffected by increased space charge.

The important factors in Equation 2 are r and C. The gain parameter (C) can be increased to a certain extent by using a smaller D.C. beam impedance (V/I_0) and a larger circuit impedance (K). The noise reduction factor (r) can be improved greatly by proper gun design. $1/r$ becomes a factor of merit for a low-noise gun.

Watkins, supra, suggested the incorporation in an electron gun of several elongated drift tubes separated by short accelerating and decelerating gaps suitably correlated in space with the velocity and current maxima and minima of the standing noise wave along the beam path to reduce the amplitude of the noise fluctuations and thereby reduce the noise reduction factor (r).

In accordance with one feature of the present invention, I produced, independently of Watkins and others, substantial reductions in the noise reduction factor (r) by use of a three-region electron gun incorporating three or more spaced apertured accelerating electrodes of short axial length as compared to elongated drift tubes such as those used by Watkins. This three-region gun comprises a cathode surrounded by a focusing electrode near cathode potential, a first apertured accelerating electrode at a low positive potential relative to the cathode, a second apertured accelerating electrode at a somewhat higher positive potential located substantially at a velocity maximum (current density minimum) of the standing noise wave in the beam, and a third apertured accelerating electrode at a high positive potential, which may be the final beam velocity. The adjustable acceleration of the beam between the first and second accelerating electrodes followed by the great acceleration distributed over the relatively long distance between the second and third accelerating electrodes causes a substantial reduction in the amplitude of the noise current and velocity fluctuations in the beam.

The reduction in noise in the three-region gun is enhanced greatly, in accordance with a second feature of the invention, by the use of a beam that is initially divergent near the cathode.

In accordance with this second feature of the invention, I position a focusing ring in a plane behind the emissive surface of the cathode, in which case the beam can be made to diverge initially between the cathode and the first accelerating electrode with a low potential on the focusing ring. All of the accelerating electrodes are shaped and located substantially the same as they would be to produce parallel flow. Experiments have shown that with suitable electrode arrangements divergent flow is produced with the potential of the focusing ring zero or even negative relative to the cathode, which substantially eliminates collection of beam electrons by the focusing electrode. Moreover, this electron gun arrangement has advantages over conventional gun structures, in that parallel flow can be

produced by making the focusing ring more negative, and convergent flow can be produced by making it still more negative.

I discovered experimentally that the initially divergent electron flow which can be produced in the improved gun design described above reduced the noise fluctuations in the beam over the reduction produced with parallel flow. Another advantage of this particular improved gun structure lies in the fact that it has a higher perveance than conventional gun structures having the focusing ring in the usual location at the emissive surface of the cathode.

The present invention was described in my paper entitled "Low-Noise Traveling-Wave Amplifier," RCA Review, vol. XIII, No. 3, pp. 344–68, published October 13, 1952.

In the annexed drawing:

Fig. 1 is a schematic view showing a three-region parallel-flow gun structure embodying my invention;

Figs. 2 and 3 are graphs showing one set of possible D.C. voltage, noise velocity and noise current distributions along the beam path in Fig. 1;

Fig. 4 is a graph showing the variation of the noise reduction factor r as a function of the relative voltage, V_C/V_B, for several relative drift space lengths, L_C/L_B, for the three-region parallel-flow gun of Fig. 1;

Figs. 5 and 6 are schematic views comparing the electric field patterns in a parallel-flow gun and an improved gun operating under divergent-flow conditions, respectively;

Fig. 7 is a longitudinal sectional view of an electron gun structure embodying the present invention;

Fig. 8 is a graph showing the relation between noise reduction factor r and first accelerating electrode potential, V_B, for a three-region gun as shown in Fig. 7 operating under divergent flow conditions, for the special case where V_B and V_C are equal; and

Fig. 9 is a graph showing the relation between focusing electrode potential V_A and first accelerating electrode potential V_B, for several values of beam current, for the improved gun structure of Fig. 7.

Referring to the drawing, Fig. 1 shows a parallel-flow type electron gun comprising a cathode **1**, a focusing ring A surrounding the cathode with its inner edge in the plane of the emitting surface **3**, and four apertured accelerating electrodes B, C, D and E. In operation, the various electrodes are connected by separate leads to a source of direct current voltages (as shown in Fig. 7) to maintain the electrodes at suitable direct-current potentials, as indicated in Fig. 2. The focusing ring A is maintained at zero potential, as shown, relative to the cathode; electrode B is made 10 to 50 volts positive; electrode C is made somewhat more positive than electrode B; and electrode D is maintained at a high positive potential, which may be several hundred volts or more. Thus the potential of electrode D is more than four times the potential of electrode B. Electrode E may be at the same potential as electrode D, or somewhat different, or may be omitted.

Fig. 3 shows the noise standing wave along the beam path due to initial velocity fluctuation originating at the cathode **1**. The solid line represents the velocity fluctuation amplitude of the noise, or the A.C. velocity wave, and the dotted line represents the current density fluctuation or the A.C. current density wave. As shown, the A.C. velocity wave has a maximum at the cathode emitting surface **3** and rapidly drops to zero close to the cathode, while the A.C. current density wave increases to a maximum. Then, the A.C. velocity wave increases up to electrode B. In the region B—C, where the beam drifts in a low accelerating field, the A.C. velocity wave increases somewhat while the A.C. current density wave decreases to zero (beam completely de-bunched). The potential of electrode C is adjusted, for its location along the beam path, so that the A.C. current density minimum and A.C. velocity maximum occur in the plane of this electrode, as shown in Figs. 1 and 3. Under these conditions, when the beam is accelerated between C and D to high velocity the A.C. velocity wave is greatly reduced in the region C—D with little increase in the A.C. current density wave, with the result that the beam leaves the gun and enters the interaction region of the tube, e.g., the helix in a traveling wave tube, with substantially reduced noise fluctuations in the beam.

The three-region electron gun arrangement of Fig. 1 is very flexible in that the potential of each of the electrodes can be independently adjusted, for a given electrode spacing, for optimum noise reduction. Fig. 4 shows the calculated variation of noise reduction factor r, normalized as rV_D/V_B, with the relative voltage V_C/V_B, for several values of relative drift length L_C/L_B. It can be seen that for a particular relative length there is an optimum value of relative voltage to obtain the lowest noise reduction factor r.

As stated above, the noise reduction obtained by a three-region gun can be enhanced considerably by use of a gun structure that will produce a beam that is divergent in the region near the cathode, instead of having parallel flow. Figs. 5 and 6 show a parallel-flow gun and an improved electron gun operated under divergent flow conditions, respectively, for comparison. Fig. 5 shows a conventional Pierce-type parallel-flow gun having a conical annular focusing electrode A starting at the edge of the emissive surface **3** of the cathode **1** and extending outwardly and forward at an angle of 67.5 degrees with the gun axis, and an accelerating electrode B spaced along the beam axis from the cathode **1**. Electrode A is at cathode (zero) potential. Several equipotential surfaces have been shown in dotted lines for the condition where electrode B is at 26 volts. It is impossible to produce stable divergent flow with the electrode arrangement shown in Fig. 5. If any other potential than zero is applied to electrode A the electron flow is greatly disturbed near the edge of the emissive surface of the cathode. If a positive potential is applied to electrode A, to try to produce divergent flow, electron current is collected at A, which produces additional noise. Fig. 6 shows an improved electron gun, in accordance with one feature of the present invention, having a conical annular focusing electrode A starting at a transverse plane spaced substantially behind the emissive surface **3** of the cathode **1**, and a first accelerating electrode B with substantially the same shape and in the same position as electrode B in the parallel flow gun of Fig. 5. In the improved gun the cathode **1** protrudes a substantial distance into the space between the focusing electrode A and the first accelerating electrode B. Several equipotential surfaces S are shown in dotted lines for the same electrode potentials as in Fig. 5. It will be noted that, with the focusing electrode A at cathode potential, the beam diverges sharply in the region near the cathode surface. The electric field pattern in the region between the cathode and electrode B is such that the initially divergent beam is converted into a substantially parallel flow beam of larger cross section than the cathode near electrode B. A focusing magnetic field may be provided axial to the beam to assist the electric field in confining the beam and preventing collection of electrons at the accelerating electrodes. A strong magnetic field (500 gauss) causes the beam electrons to spiral, due to their initial divergence, in a spiral of relatively short pitch, while a weak magnetic field produces a much longer focus, as shown.

Fig. 7 shows in detail a three-region electron gun structure embodying the invention. The gun comprising a cylindrical cathode **1**, having an emissive surface **3**, carried by a cathode support **5**. The support **5** is coaxially mounted, by means of an insulating ring **7** and a pair of flanged rings **9** and **11**, within a metal shell **13**. At the end nearest the cathode **1**, the shell **13** has an inward

flange **15** which serves as the apertured focusing electrode A of the gun. This flange is truncated-cone-like in shape with the aperture surrounding the cathode **1** and spaced substantially behind the emissive surface **3** thereof, with the cone surface extending outwardly and forwardly, as shown. Coaxially mounted in spaced relation on the axis of the cathode are three apertured discs **17, 19** and **21**, which serve as the accelerating electrodes B, C and D of Fig. 1. The diameters of the apertures in electrodes B, C and D are substantially greater than the diameter of the cathode to avoid interception of beam electrons, which would introduce noise. As in Fig. 6, the cathode **1** protrudes a substantial distance into the space between the focusing electrode A and the first accelerating electrode B. Disc **17** is curved in cross section with its convex side facing the cathode **1**, as shown, to conform to the shape of the equipotential surface in that region. Preferably, but not necessarily, the spacing between electrodes B and C is greater than that between the cathode **1** and electrode B, as shown. These spacings, which are designated L_C and L_B in Fig. 1, are not very critical because the potentials of the various electrodes can be separately adjusted for a given geometry to cause a velocity maximum of the noise standing wave to occur near electrode C, to produce optimum noise reduction. Preferably the diameter of the aperture in electrode B is of the order of the distance, L_B, between the cathode and that electrode.

Fig. 7 also includes a fourth apertured disc **23**, which serves as an additional accelerating electrode E. This electrode may be maintained at the potential at which the beam is to be utilized. In a helix traveling wave tube this would be the helix potential. Electrode D may be at the same potential as electrode E, or somewhat different. For example, if electrode D is at a higher potential than electrode E it prevents positive ions from traveling back towards the cathode. For some purposes, electrode E may be omitted and the beam utilized at the potential of electrode D.

The various elements of the gun structure are supported as a unit within the tube envelope **25** by means of three longitudinal glass rods **27**, only one of which is shown in Fig. 7, and two supporting rings **29**. The shell **13** and discs **17, 19, 21** and **23** are mounted on the glass rods **27** by suitable means, such as the tabs **31** shown.

Separate leads **33** for the cathode **1** and electrodes A, B, C, D and E are brought out through the envelope **25** and connected to suitable points on a direct-current supply source **35**, as shown.

Fig. 8 shows the variation of noise-reduction factor r with the potential V_C of the second accelerating electrode C, between the limits 0 and 50 volts, for several values of the ratio R of the beam diameter to the cathode diameter, for the special case where $V_C=V_B$ and $V_D=500$ volts, in a three-region gun of the improved type as in Fig. 7, operated with divergent flow. A comparison of the value of noise reduction factor in Fig. 8 for a given value of $R>1$ with the corresponding value for $R=1$ shows the improvement in noise reduction produced by use of a divergent-flow gun structure.

Fig. 9 shows the relation between focusing electrode potential V_A and first accelerating electrode potential V_B, between the limits +20 and −80 volts for V_A and 0 and 90 volts for V_B, for several values of beam current, I_0. The heavy line P drawn from the point $V_A=V_B=0$ (cathode potential) represents parallel-flow operation. For a given value of V_B, when V_A is below this heavy line, divergent flow is produced, and when V_A is above this line, convergent flow is produced. It can be seen that divergent flow can be produced with the improved gun of the invention over most of the operating region with the focusing electrode A negative with respect to the cathode, which prevents collection of electrons by the focusing electrode.

With the improved arrangement of the focusing electrode and cathode shown in Figs. 6 and 7 operated under divergent-flow conditions, the electrode B can be omitted, provided the potential of electrode C is adjusted to cause a velocity maximum of the noise standing wave to occur near electrode C.

Experimental results on traveling wave tubes utilizing the three-region divergent-flow electron gun of the present invention yielded consistently low noise factors. For example, a tube using the improved gun structure of Fig. 7 and operated at 3000 megacycles and helix voltage of 500 volts, with 400 megacycle bandwidth, yielded a gain of about 20 db at a best noise factor of only 8 db.

What is claimed is:

1. A low-noise electron gun comprising a cathode electrode and three apertured accelerating electrodes spaced along a given axis with the apertures of said accelerating electrodes aligned with said cathode electrode, at least the first two of said accelerating electrodes having an axial length which is short compared to the distances between said three electrodes, the diameter of the apertures in said accelerating electrodes being substantially greater than the diameter of said cathode electrode, the distance between the cathode electrode and the first accelerating electrode being smaller than the distances between adjacent accelerating electrodes, a direct-current voltage source connected to said electrodes for applying low positive potentials to the first two accelerating electrodes and a high positive potential to the third accelerating electrode, relative to said cathode electrode, the potential of the second accelerating electrode being of the same order as the potential of the first accelerating electrode, the potential of the third accelerating electrode being more than four times the potential of the first accelerating electrode.

2. A low-noise electron gun as in claim 1, further comprising a fourth apertured electrode spaced along said axis beyond said third accelerating electrode, and means connected to said fourth electrode for applying thereto a high positive potential somewhat below that of said third accelerating electrode.

3. A low-noise electron gun comprising a cathode electrode and three apertured accelerating electrodes spaced along a given axis with the apertures of said accelerating electrodes aligned with said cathode electrode, at least the first two of said accelerating electrodes having an axial length which is short compared to the distances between said three electrodes, the diameter of the apertures in said accelerating electrodes being substantially greater than the diameter of said cathode electrode, the distance between the cathode electrode and the first accelerating electrode being smaller than the distances between adjacent accelerating electrodes, separate leads connected to said electrodes, and a direct-current supply source connected to said leads for maintaining the first accelerating electrode at a low positive potential of 10 to 50 volts, the second accelerating electrode at somewhat higher potential than the first accelerating electrode, and the third accelerating electrode at a high positive potential of at least several hundred volts, relative to the cathode electrode.

4. A low-noise electron gun as in claim 1, further including an apertured focusing electrode surrounding said cathode electrode and maintained by said direct current supply source at a potential near that of said cathode electrode.

5. A low-noise electron gun comprising means including a cathode for producing along a given axis an electron beam having a noise standing wave with noise velocity and current density maxima and minima spaced along said axis, first and second apertured accelerating electrodes of relatively short axial length as compared to the distance therebetween spaced along said axis from said cathode, the distance between the cathode and the first accelerating electrode being smaller than the distance between adjacent accelerating electrodes, means sepa-

rately connected to said cathode and said accelerating electrodes for maintaining said electrodes at low positive potentials of the same order relative to said cathode, said second accelerating electrode being located substantially at a noise velocity maximum of said noise standing wave, a third apertured accelerating electrode spaced a substantial distance along said axis beyond said second electrode, and means connected to said cathode and said third accelerating electrode to maintain the latter at a high positive potential relative to said cathode, the diameter of the apertures in said accelerating electrodes being substantially greater than the diameter of said cathode.

6. An electron gun as in claim 5, further comprising an apertured focusing electrode surrounding said cathode.

7. An electron gun as in claim 6, further comprising means connected between said focusing electrode and said cathode for maintaining said focusing electrode at a potential near that of said cathode.

8. An electron gun as in claim 5, further including an apertured focusing electrode surrounding said cathode, said cathode protruding a substantial distance into the space between said focusing electrode and said first accelerating electrode to prevent collection of beam electrons by said focusing electrode when the latter is operated at potentials equal to or higher than said cathode.

9. An electron gun as in claim 8, further including means for maintaining said focusing electrode at a potential near that of said cathode, to cause said beam to diverge initially in the region between said cathode and said first accelerating electrode.

10. An electron gun as in claim 9, further including means for establishing a focusing magnetic field along said beam axis.

11. An electron gun for projecting a variable-flow electron beam along a predetermined axis comprising a cathode having an emissive surface coaxial and transverse to said axis, at least one apertured accelerating electrode coaxially mounted on said axis in spaced relation to said cathode, and an apertured focusing electrode coaxially surrounding said cathode and having a truncated-cone-like surface extending outwardly and forwardly from its aperture in the direction of electron travel from said cathode, said cathode protruding a substantial distance into the space between said focusing electrode and said first accelerating electrode whereby said beam can be caused either to be convergent, to have parallel flow, or to be divergent, as desired, in the region between said cathode and said accelerating electrode, merely by the application to said focusing electrode of suitable potentials relative to said cathode.

12. An electron gun as in claim 11, further including means for establishing a focusing magnetic field along said beam axis.

13. An electron gun as in claim 11, wherein said accelerating electrode is curved in cross section with its convex side facing said cathode.

14. An electron gun as in claim 11, wherein the diameter of the aperture in said accelerating electrode is of the order of the distance between said cathode and said accelerating electrode.

15. An electron gun as in claim 11, including at least three apertured accelerating electrodes coaxially mounted on said axis in spaced relation to each other and said cathode, and separate leads connected to said cathode and said focusing and accelerating electrodes for applying suitable potentials thereto.

16. An electron gun for projecting a low-noise electron beam along a given axis comprising a cathode having an emissive surface coaxial and transverse to said axis, an apertured focusing electrode coaxially surrounding said cathode and having a truncated-cone-like surface extending outwardly and forwardly from its aperture in the direction of electron travel from said cathode, first and second apertured accelerating electrodes of relatively short axial length as compared to the distance therebetween coaxially mounted on said axis in spaced relation to each other and said cathode, said cathode protruding a substantial distance into the space between said focusing electrode and said first accelerating electrode, and a direct current supply source connected to said cathode and said electrodes to maintain said focusing electrode at a potential near that of said cathode, said first accelerating electrode at a low positive potential and said second accelerating electrode at a high positive potential, relative to said cathode.

17. An electron gun as in claim 16, further including another apertured accelerating electrode coaxially mounted on said axis between said cathode and said first accelerating electrode and maintained by said source at a low positive potential relative to said cathode.

18. A low-noise electron gun as in claim 1, wherein the ratio of the potentials of the first and second accelerating electrodes for optimum noise reduction factor for various electrode spacings is determined approximately by the minima of the curves shown in Figure 4 of the drawings.

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