Oct. 22, 1957 A. H. W. BECK 2,810,853

ELECTRON DISCHARGE APPARATUS

Filed Nov. 29, 1951 2 Sheets-Sheet 1

FIG. 1.

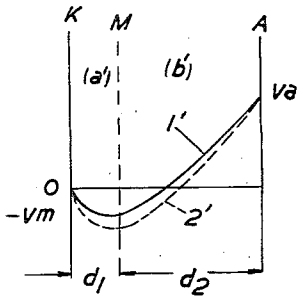


FIG. 2.

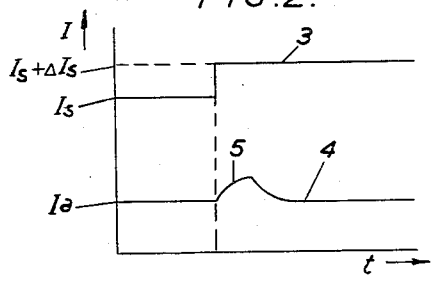
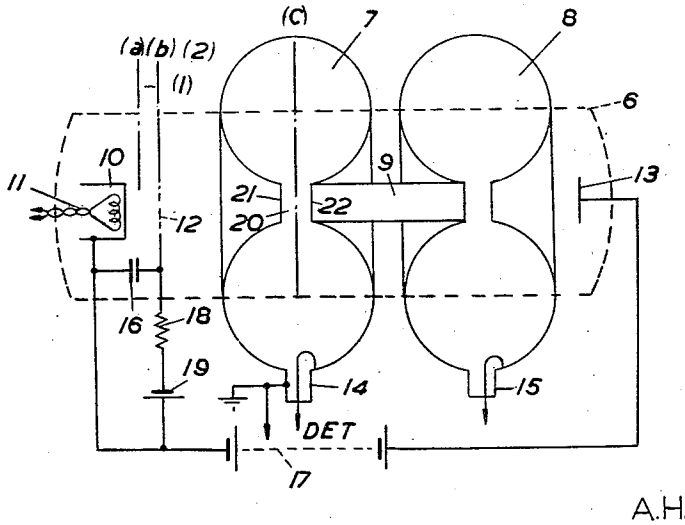


FIG. 3.



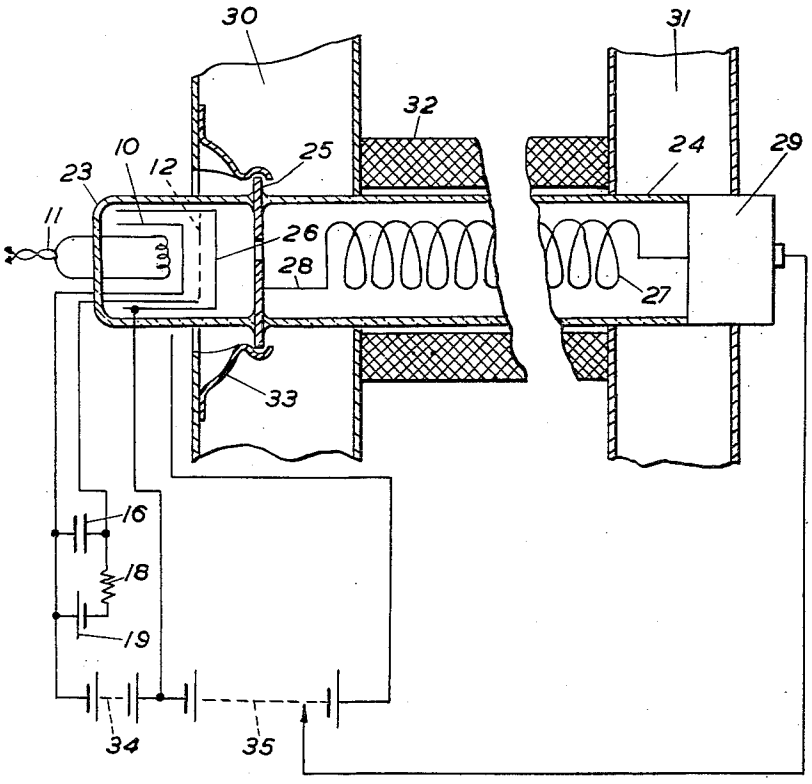
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ELECTRON DISCHARGE APPARATUS

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FIG. 4.



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ELECTRON DISCHARGE APPARATUS

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Application November 29, 1951, Serial No. 258,819

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5 Claims. (Cl. 315—3.5)

The present invention relates to noise suppression in electron discharge apparatus. The invention is concerned with means whereby shot noise fluctuations in the current emitted by a thermionic cathode may be prevented from causing appreciable noise voltages in the circuits associated with the electron beam.

In present day receivers for use at centimetric wavelengths with low level input signals it is usual to feed the signals direct to a crystal detector or frequency-changer stage. This is due to the fact that existing thermionic amplifiers are noisier than silicon crystals. To be useful in front of a frequency changer or detector, the amplifier must have sufficient gain so that the noise power contributed by the amplifier output circuit and detector input may be neglected in comparison with the amplified signal; for this purpose a gain of 10 db may be considered sufficient, the total noise of the receiving system may then be considered as that due to the amplifier input circuit alone. It follows therefore, that the use of a thermionic amplifier in front of the detector stage of a receiver becomes advantageous provided the gain of the amplifier stage can be made greater than about 10 db and provided the input noise is not worse than that of the silicon crystal heretofore used. With present day electron velocity modulation tubes, such as the travelling wave tube, it is a comparatively simple matter to arrange for sufficient gain, but the input noise of these tubes is normally very high. The main cause of the noise generated by the discharge device is the random rate of emission of and the Maxwellian distribution of velocities among the electrons emitted from a thermionic cathode. We refer to the noise from these effects as shot-noise. The remainder of the noise is due to thermal noise fluctuations in the input circuit. We are not concerned with these in this specification.

In triodes and the like having inter-electrode spacings small compared to the electron transit angle, shot noise is considerably reduced by space charge effects. We define the electron transit angle as 2π times the ratio of the electron transit time at any frequency of operation to a period of oscillation at that frequency. For the purposes of the present specification we define a space charge limited electron beam as one in which only a small fraction of the electrons emitted by the thermionic cathode is drawn off, the remainder returning to the cathode thus forming a potential minimum in front of the cathode. It may be taken that a ratio of total cathode emission current density to initial beam current density of 3:1 is sufficient to produce complete space charge current limitation, i. e. any further increase in saturated emission will produce only a negligible change in beam current and we shall assume in the present specification, unless otherwise stated, that we are concerned with a cathode total emission current density of the order of 10 amps./cm.^{2} at temperatures of the order of 1,100° K. These figures are representative of good modern oxide cathodes.

As stated above, it is well known that, at least at low frequencies, shot noise is reduced by the effect of space charge; in fact, if in a diode the cathode emission be increased, the accelerating anode voltage remaining constant, the anode current remains practically unaltered. A transient increase in cathode emission causes a transient increase of anode current which, it can be shown, is due, to a major extent, to electron velocity modulation in the region between the space charge induced potential minimum and the anode. Shot noise, for all practical purposes, can be considered as due entirely to velocity modulation effects in this region between the potential minimum and anode. We shall also show that at the potential minimum (to be strictly correct, just beyond this, so that electrons are moving only in one direction), fluctuations in the conduction current are negligible, there being present merely a velocity fluctuation; a bunching effect converts the electron velocity fluctuations into conduction current variations as the beam progresses beyond the minimum. Space charge effects can reduce the conduction current at one given plane in a manner familiar from the theory of electron velocity modulation devices.

As is common with analyses of this type we replace the real electron beam with variable velocities by a single beam with an A. C. velocity equivalent to the mean square value of the variable velocities.

The space charge induced potential minimum is so close to the cathode that, in most cases, it would be practically an impossibility to place a grid at the potential minimum. Our analysis of the effect of transit time and shot noise in space charge limited beams shows, however, that a very considerable improvement in noise can be obtained if we place a grid within an electron transit-angle of one radian from the potential minimum.

According to one aspect of the present invention, therefore, there is provided an electron velocity modulation apparatus comprising arrangements for projecting an electron beam from an electron gun through a space in which the electrons of the beam may be velocity modulated by interaction with the electro-magnetic field therein, the said gun having a cathode and a grid at the same H. F. potential closely spaced thereto defining between them a region in which electron beam current is fully space charge limited, the cathode-grid spacing and the beam accelerating potential being such that the electron transit angle between the space charge induced potential minimum and the grid is not greater than one radian at the highest frequency of the said electro-magnetic field.

Although with any given electron velocity modulation tube, the external circuit may be adjusted to provide for a wide range of variation in electron transit times in different regions of the electron beam path, it will be realised that the present invention necessitates the provision of a tube having an electron gun with special characteristics. Accordingly, the invention provides an electron velocity modulation tube adapted for the amplification of electromagnetic waves comprising an electron gun having a grid closely adjacent to the cathode defining therewith a region shielded from external electromagnetic fields of the frequency of the wave to be amplified, the spacing between cathode and grid being such that when the tube current and potentials are adjusted for the said amplification and so that the electron current in the said region is fully space charge limited, the electron transit angle between the space charge potential minimum and the said grid is not greater than one radian at the highest frequency of the said electromagnetic waves.

The invention will now be more fully described with reference to the accompanying drawings, in which:

Fig. 1 illustrates the variation of potential in a space charge limited planar diode.

Fig. 2 illustrates the effect of increase in cathode emission current on the anode current of such a diode,

Fig. 3 illustrates diagrammatically an embodiment of the present invention arranged to elucidate our analysis, and

Fig. 4 shows diagrammatically an embodiment in which the invention is applied to a travelling wave amplifier.

In Fig. 1 we represent by the vertical lines K and A the respective planes of the cathode and anode of a diode; we take the potential of the cathode as zero and that of the anode as Va, the potential varying with distance between K and A in the manner indicated by the curve 1', a potential minimum being formed at the plane M distant d, from the cathode and d_2 from the anode, the potential at this minimum being indicated as $-Vm$. At the cathode, electrons are emitted at random instants of time and with a Maxwellian distribution of velocities. In the region (a') between K and M electrons which are emitted with insufficient velocity to pass beyond the potential minimum are returned to the cathode, so that in this region electrons are moving in both directions. In the region (b'), between potential minimum and anode, electrons are moving in one direction towards the anode and are accelerated. The position of the space charge minimum and the mean value of $-Vm$ depends upon the cathode temperature and the ratio of total cathode emission Is to anode current Ia. The values of Va and d_2 for any given anode current are interdependent, so that if one be given the other can have but one value in order to maintain the said anode current. Thus, if Va be maintained constant by means of an external battery, and the cathode emission be increased e. g. by a sudden change in work function, the anode current tends to remain constant. An additional number of electrons, however, are emitted by the cathode, which causes the potential minimum to be depressed to a lower value. At the same time the position of the potential minimum is shifted towards the anode, but to such a small extent that its change in position can be neglected for our purposes, the potential distribution being altered as indicated by the dotted curve 2 in Fig. 1.

In Fig. 2 we show curves relating current I and time t for the cathode emission current and the anode current when, due to any cause, the cathode emission is suddenly changed from Is to $Is+\Delta Is$ as shown by the curve 3. We can consider the effect of this qualitatively as follows. First the potential of the minimum is made more negative; it follows that there is an increase in the number of electrons which have insufficient initial velocity to reach the anode. Had the potential minimum not been made more negative, the increase in emission would have led to a proportionate increase in the number of electrons reaching the anode. Instead of this, however, under the conditions where $Is \gg Ia$, the depression of the potential minimum is such that a greater fraction of the total number of electrons emitted from the cathode is reflected by the potential minimum; hence the increased emission causes a net decrease in the total number of electrons reaching the anode. These electrons, however, since the potential difference between M and A is increased, are subject to a greater acceleration than before, so that the anode current remains substantially unchanged but for a transient pulse. It may be shown that the proportionate change of anode currents ΔIa, is related to the proportionate change of emission currents ΔIs by the equation

$$\left(\frac{\Delta Ia}{Ia}\right)_{t\to\infty}=\frac{3kT}{2e(Va+Vm)}\cdot\frac{\Delta Is}{Is} \qquad (1)$$

where k is Boltzmann's constant, 1.38×10^{-23} joules/° K., T is the cathode temperature in degrees Kelvin, and e is the electronic charge, 1.59×10^{-19} coulomb.

In Fig. 2 the variation of anode current Ia is indicated by the curve 4. The anode current pulse 5 shown in Fig. 2 is to be expected from general principles, but the immediate factors involved warrant further discussion. During the time while the potential minimum is changing its value, at any instant in the region (b) there will be more electrons than appropriate to the value of the potential minimum, for they will have passed the minimum while the retarding potential was less than it now is. During this time interval, therefore, there will always be more electrons in the region (b') than will be present during any time interval after the slowest electron emitted immediately before the step function has reached the anode. These electrons are subject to a greater acceleration than they had before, and hence the anode current, being the product of the number of electrons reaching the anode per second and their final velocity, will increase beyond the value which it will finally attain. Thus, a positive pulse of current will occur at the anode. To some extent this will be off-set by a negative-going pulse at the cathode due to the greater number and velocity of the reflected electrons, a similar argument obtaining for these electrons in the region (a') as for those we have just discussed in the region (b'). However, in practice, the distance d_1 is usually much smaller than d_2, while the screening effect of the space charge at the potential minimum is considerable, so that this negative pulse is not appreciably evident at the anode. The net result of this transit effect therefore is a positive pulse such as 5 shown in Fig. 2. From the above discussion it will be appreciated that the major cause of the transient fluctuation of anode current due to the sudden increase in cathode emission is a velocity modulation effect in the region (b').

As shown above, general considerations lead us to expect fluctuation noise in a diode to be considerably reduced by the presence of space charge, and this is, in fact, well known in short electron beams. In a short electron beam in the absence of space charge, the mean value $\overline{i^2}$ of the fluctuation component i superimposed upon the mean current Io amps emitted by a thermionic cathode within the frequency band Δf cycles/sec. is given (in the absence of space charge) by

$$\overline{i^2}=2eIo\Delta f \qquad (2)$$

If the emission be space charge limited, however, it is known that the mean square fluctuation current is reduced to

$$\overline{i^2}=2eIo\Gamma^2\Delta f \qquad (3)$$

where Γ^2 is a smoothing factor, lying between 0 and 1 depending upon the space charge, but having a value of about 0.1 for most triodes at frequencies up to about 100 mc./s. In what follows we shall introduce a factor $\Gamma\theta$, a function of transit angle θ, applicable for longer electron beams.

From a qualitative consideration of the step function increase in cathode emission represented in Fig. 2 we have concluded that the anode current pulse 5 is due to a velocity variation effect rather than a number variation effect. We have analysed the case represented in Fig. 2 and find that we can represent the anode current fluctuation by means of an equation similar to Equation 3 but in which Γ^2 is given by the expression

$$\Gamma_1^2=\frac{9(1-\pi/4)kT}{e(Va+Vm)} \qquad (4)$$

Comparison with Equation 1 shows that, since the factors 3/2 and $9(1-\pi/4)$ differ by only a small amount, the mean square conduction current just beyond the space charge induced potential minimum has been smoothed by a factor of the order of Γ^4. We conclude, therefore, that the effect of the space charge minimum is to eliminate virtually all conduction current variations at the minimum, leaving only electron velocity modulation which produces by drift action the conduction current variation eventually observed at the anode plane.

In order to analyse the transit time effects of shot noise in electron beams applicable to electron velocity modulation apparatus, we have used Llewellyn's electronic equations, which are applicable to the analysis of conditions between infinite planar electrodes for any degree of space

charge limitation and in which A. C. variations of potential, conduction current and electron velocity are assumed to be superimposed upon average or D. C. values of these quantities. We take the initial plane of emission as that of the plane M of Fig. 1 and consider the case where there is zero H. F. potential difference between the two planes, the initial conduction current variation being negligible and the initial electron velocity variation being given by a known expression previously used in diode noise analysis.

In Fig. 3 we show very diagrammatically a two resonator klystron arrangement embodying the present invention. An evacuated envelope, indicated by the dotted line **6**, to which is sealed a pair of resonators **7** and **8** joined by a drift tube **9**, encloses an electron gun comprising a cathode **10**, heating arrangements for the cathode being indicated at **11**, and a closely spaced grid **12** parallel to the emitting surface of the cathode. In practice other electron gun electrodes following the grid may be desirable but are omitted from the drawing to avoid confusion. The electron beam, after traversing the resonators **7** and **8**, is collected by the collector electrode **13**. Resonators **7** and **8** are provided with the usual input and output wave feed arrangements indicated by the coupling loop and coaxial line attachments **14** and **15** respectively. The grid **12** is shown connected to the cathode **10** by means of a capacitance **16**, which will normally be intrinsic to the mounting of the grid, and which is such that grid **12** is maintained at cathode potential at all frequencies within the band-width of resonator **7**. Grid **12** should be so constructed that it imposes upon the electron beam a unipotential surface orthogonal to the electron trajectories and forms with the emitting surface of cathode **10**, so far as is possible, a region bounded by a pair of planes which in the analysis may be considered to be of infinite extent. It is here pointed out that although our analysis applies strictly only to the infinite planar electrode case, the separation between cathode and grid is so small at microwave frequencies that in the present invention these electrodes, provided they be parallel to one another, may be curved without detriment to the performance of the system. Cathode **10** is connected to the negative pole of potential source **17**, the positive pole of which is connected to the collector electrode **13**. Grid **12** is shown also connected to the negative pole of source **17** through decoupling resistance **18** and biasing potential source **19**, while the wall of resonator **7** is shown connected to a tapping point on the potential source **17**. For the purposes of the following analysis in Fig. 3 we have indicated at (*a*) the plane of the potential minimum in front of the cathode **10**. This plane, together with plane (*b*) coinciding with the grid **12**, defines a region (1) in which the current is completely space charge limited. A region (2) is defined between the boundary planes (*b*) and (*c*), the latter plane being located at the centre of the inter-action gap **20** of resonator **7**. It is assumed, for present purposes, that the inter-action gap **20** is bounded by grids **21** and **22** which ensure that the field within resonator **7** in the absence of an input signal at **14** may be influenced only by the conduction current of the electron beam.

It may be as well to point out at this stage that in previous analyses of shot noise in high frequency diodes, the cathode and collector electrodes have both been within the boundary of the resonator. In the present case all the electrodes affecting the beam before it enters the inter-action gap **20** are maintained at the same high frequency potential, while, at the space charge minimum the total current is equal to the conduction current. It follows, therefore, that we are concerned only with conduction current variations and electron velocity fluctuations. We have found that the latter are proportional to the distance between the planes (*a*) and (*b*) if the transit time involved is short and that, as has been shown above, at the plane (*a*) the conduction current variations are negligible. Hence, if plane (*b*) be very close to plane (*a*), the full effects of the space charge smoothing of the shot noise are manifested at plane (*b*). Ideally, therefore, we should like to place the inter-action gap **20** very close to the space charge minimum, in which case we should expect to obtain a shot-noise smoothing factor of the same order as is obtained at low frequencies. In general, this is physically impossible, but it is possible to place a grid **12** very close to the space charge minimum. Immediately to the right of the grid **12**, i. e. to the right of the plane (*b*), therefore, we obtain the effect of space charge smoothing, and in the region (2) between planes (*b*) and (*c*) we need not maintain the voltages such as to conform to complete space charge limitation of the beam circuit, and, in fact, we find that, in general, the noise at plane (*c*) notwithstanding an electrically long region (2), is very much less than it would be in the absence of the grid **12** whether or not there were complete space charge limitation between the planes (*a*) and (*c*); without the grid **12**, if the region between planes (*a*) and (*c*) were not space charge limited, we could not expect much space charge smoothing; with grid **12** placed according to the invention there is imposed, at a plane intermediate the cathode and the utilisation plane, a region of zero A. C. potential which causes the effect of the large transit angle in the region (2) to become small and we tend to obtain at the plane (*c*) a noise condition not very much worse than that at plane (*b*) adjacent the space charge minimum.

Llewellyn's first order electronic equations upon which our analysis is based are given below in slightly modified form:

$$\left.\begin{aligned} I &= (V_b - V_a)a_{11} + q_a a_{12} + v_a a_{13} \\ q_b &= (V_b - V_a)a_{21} + q_a a_{22} + v_a a_{23} \\ v_b &= (V_b - V_a)a_{31} + q_a a_{32} + v_a a_{33} \end{aligned}\right\} \quad (5)$$

where I is the total alternating current, q is the A. C. component of the conduction current, v is the A. C. component of the electron velocity and V is the alternating voltage at the plane (*a*) or (*b*) as indicated by the suffix. The suffixes to q and v denote similarly the planes to which these quantities apply; the a's are coefficients involving the D. C. conditions, degree of space charge and transit time; the coefficients will have different values, therefore, according to whether we are considering the region (1) or the region (2) and when it is necessary to distinguish these we shall add an appropriate index to the coefficient a. The values of the coefficients in terms of transit angle θ and the velocity u at the appropriate planes are simply related to the coefficients tabulated in Tables I and II of the paper "Vacuum Tube Networks" by F. B. Llewellyn and L. C. Peterson in "Proceedings of the Institute of Radio Engineers," for March 1944, at pages 148 and 149, by transforming Llewellyn's Equation 5 into the form of our Equation 5 above. In both the regions (1) and (2) indicated in Fig 3 the V's vanish, and for region (1) we put the conduction current variation at the potential-minimum equal to zero, i. e. $q_a=0$ for region (1), so obtaining:

$$\left.\begin{aligned} I &= a_{13}{}^1 v_a \\ q_b &= a_{23}{}^1 v_a \\ v_b &= a_{33}{}^1 v_a \end{aligned}\right\} \quad (6)$$

For the region (2), in which we are interested only in the conduction current at plane (*c*), if a fraction α_1, of the conduction currene q_v entering plane (*b*) is captured by the grid wires and a similar fraction α_2 of the conduction current in the region (2) is captured by the grid **20** we have, for the conduction current q_c crossing plane (*c*),

$$q_c = (1-\alpha_2)[(1-\alpha_1)q_b a_{22}{}^2 + a_{23}{}^2 v_b] \quad (7)$$

Substituting for q_3 and v_3 from (6),

$$q_c = v_a(1-\alpha_2)[(1-\alpha_1)a_{23}{}^1 a_{22}{}^2 + a_{33}{}^1 a_{23}{}^2] \quad (8)$$

According to the present invention grid **12** is placed close to the plane of the potential minimum, so that θ_1, the

transit angle of region (1), is small. If the D. C. current density be denoted by I_0, evaluation of the coefficients a for small θ gives us:

$$\left.\begin{aligned} a_{23}{}^1&=\frac{I_0}{u_1}(3+j\theta_1)\exp(-j\theta_1)\\ a_{33}{}^1&=\frac{2}{15}j\theta_1\exp(-j\theta_1)\end{aligned}\right\} \quad (9)$$

where $u_1{}^2=2e/mV_1$, V_1 being the D. C. potential at plane (b), and $j^2=-1$.

We notice, first of all, that as $\theta_1\to 0$ $a_{33}{}^1\to 0$ so that, from Equation 6, the velocity variation to the right of plane (b) is suppressed. On the other hand, the alternating component of the conduction current, which was zero at plane (a), has now become finite. At first sight this result might appear unreasonable until we remember that we still stipulate that the region between the planes is to remain space charge limited, which condition, for any given value of the direct current and transit angle between the planes (a) and (b) fixes the relationship between the other components at the two boundary planes. Thus, the effect is merely one of space charge de-bunching and rebunching.

In the region (2) the direct current is $(1-\alpha_1)$ times the direct current I_0 in the region (1), except to the right of grid **20** where it is reduced by the further factor $(1-\alpha_2)$, and if we assume that the degree of space charge is small,

$$\left.\begin{aligned} a_{22}{}^2&=\exp(-j\theta_2)\\ \text{and}\qquad a_{23}{}^2&=\frac{(1-\alpha_1)I_0}{u_c}j\theta_2\exp(-j\theta_2)\end{aligned}\right\} \quad (10)$$

where $u_c=2e/mV_2$, V_2 being the D. C. potential at plane (c).

It is to be noted that, except for special conditions of space charge which need not concern us here, the same values for the above coefficients a^2 would have been obtained had we assumed the degree of space charge arbitrary but made θ_2 large.

In Equation 8 we substitute the above values for the coefficients a together with the substitution for v_a of the root mean square noise velocity variation at plane (a) as given by the following known expression:

$$u_n{}^2=\frac{4KT}{I_0}\cdot\frac{e}{m}\left(1-\frac{\pi}{4}\right)\Delta f \quad (11)$$

(See, for example, A. J. Rack. "Shot Noise in Diodes," Bell System Technical Journal 17 (1938), page 592.)

We thus obtain for the mean square noise conduction current at plane (c):

$$q_c{}^2=(1-\alpha_2)^2(1-\alpha_1)^2\frac{4kTI_0}{u^2}\cdot\frac{e}{m}\cdot 9\left(\frac{-\pi}{4}\right)\left[\left(1-\frac{1}{u_c}\cdot\frac{\theta_1\theta_2}{4\ 5}\right)^2+\left(\frac{\theta_1}{3}\right)^2\right]\Delta f \quad (12)$$

For present purposes we may put

$$u_1{}^2=2\frac{e}{m}(V_p+V_m)$$

where V_a is the equivalent potential of the grid **12** and V_M has the same meaning as in Fig. 1. Thus, comparing Equation 12 with Equation 4 we obtain

$$q_c{}^2=(1-\alpha_2)^2(1-\alpha_1)^2\cdot 2eI_0\Gamma_0{}^2\left[\left(1-\frac{u1}{uc}\cdot\frac{\theta_1\theta_2}{4\ 5}\right)^2+\left(\frac{\theta_1}{3}\right)^2\right]\Delta f \quad (13)$$

On comparing this with Equation 3 it is seen that we may define a frequency dependent smoothing factor $\Gamma\theta^2$ which, if α_1 and $\alpha_2\to 0$ is given by

$$\Gamma_\theta{}^2=\Gamma_0{}^2\left[\left(1-\frac{u_1}{u_c}\cdot\frac{\theta_1\theta_2}{4\ 5}\right)^2+\left(\frac{\theta_1}{3}\right)^2\right] \quad (14)$$

In order to compare this result with the noise factor obtainable with usual present day velocity modulation

tube designs we must evaluate the coefficients $\alpha_{23}{}^1$ and $\alpha_{33}{}^1$ for region (1) for the case where θ_1 is large.

For θ_1 large we have

$$\left.\begin{aligned} a_{23}{}^1&=j\frac{I_0}{u_1}\theta_1\exp(-j\theta_1)\\ \text{and}\qquad a_{33}{}^1&=-\exp(-j\theta_1)\end{aligned}\right\} \quad (15)$$

giving

$$\Gamma\theta^2(\theta_1\text{ large})=\frac{1}{9}\Gamma_0{}^2\left(\theta_1-\frac{u_1}{u_c}\theta_2\right)^2 \quad (16)$$

which is identical with the result of other workers obtained by different methods in the investigation of noise in a long electron beam.

As a measure of the improvement to be gained by the present invention, let us consider the values of $\Gamma\theta$ for an electrode arrangement as in Fig. 3 of the accompanying drawings for the two cases where the separation between cathode **10** and grid **12** is small, in accordance with the invention, and where it is large, as obtaining in prior electron gun arrangements incorporating a control grid. For convenience we shall assume that the grid **20** is at the same potential as grid **12** and also that the interception factors are zero. Typical results are

Case 1

$\theta_1=0.2$, $\theta_2=6.0$ radians
$\Gamma\theta^2=0.9$, $\Gamma_0{}^2=0.09$

Case 2

$\theta_1=3.0$; $\theta_2=12.0$ radians
$\Gamma\theta^2=9$, $\Gamma_0{}^2=0.90$

In order to evaluate the spacings and voltages required in a practical embodiment of the invention, it is important that we should not neglect the separation between cathode and potential minimum as is done in many transit time approximations; this would lead to results giving us smaller clearances than are, in fact, required. We should also take into account the initial velocity of the electrons at the space charge minimum. For any given transit angle having a corresponding transit time t between space charge minimum and grid **12** the distance d_2 between space charge minimum and grid is given by

$$d_2=\frac{e/m}{6\epsilon_0}I_0t+u_at \quad (17)$$

when ϵ_0 is the permittivity of free space

$$=\frac{1}{36\pi}\times 10^{-9}$$

farad/metre and where u_a is the mean velocity of the electrons leaving the plane of the potential minimum. If V be the required equivalent voltage of the grid **12**,

$$V+V_m=\frac{1}{4\epsilon_0}I_0t^2\left(\frac{e/m}{2\epsilon_0}I_0t^2+2u_a\right) \quad (18)$$

It should be mentioned that, in order to obtain agreement between the values of V and d_2 given by Equations 17 and 18 with the corresponding values given by Langmuir's (ξ, η) tables, we find that u_a cannot be given the often quoted value of

$$\sqrt{\frac{\pi kT}{2m}}$$

but must be taken as a function of $V+V_m$, having a mean value for voltages between 0.1 and 1 volt of

$$\sqrt{\frac{kT}{m}}$$

In order to evaluate u_a more exactly and to obtain V_m and V_1 we use Langmuir's (ξ, η) tables and let

$$u_a{}^2=\lambda\frac{2kT}{m}$$

where λ is given, for low anode voltages, to a sufficient approximation by the relation

$$10\lambda=4.8+\log_{10}\eta \qquad (19)$$

For a given construction we may obtain the average transit angle between space charge minimum and grid for any given current density I_0 and cathode temperature T by determining Langmuir's ξ, in terms of η, from the tables, and hence ξ, and η, using the above expression for λ and substituting in the expression;

$$t=3d_2(2kT/m)^{-1/2}[(\eta+\lambda)^{1/2}+2\lambda^{1/2}]^{-1} \qquad (20)$$

which, for $T=1160°$ K. becomes,

$$t=1.6\times10^{-5}d_2[(\eta+\lambda)^{1/2}+2\lambda^{1/2}]^{-1} \qquad (21)$$

It should be noted that the transit time is a function of I_0 and care should be exercised in choosing I_0 so as not to obtain a minimum value of anode-cathode spacing with respect to I_0.

By way of example we may quote the following figures for cathode-grid separation in the present invention for the case where, at a maximum frequency of 4,000 m./cs., a maximum transit angle of 1 radian is required, the cathode emission current being assumed to be 10 amps./cm.^{2}.

I_0	1.5×10^3	5×10^3	10^4 amps./metre^2.
d_1	1.325×10^{-5}	6.83×10^{-6}	4.48×10^{-6} metre.
Vm	0.42	0.30	0.23 volt.
V	−0.21	1.05	4.50 volts.
d_2	2.02×10^{-5}	3.52×10^{-5}	5.57×10^{-5} metre.
d_1+d_2	3.34×10^{-5}	4.20×10^{-5}	6.05×10^{-5} metre.

Assuming the same value of cathode emission current and a fixed spacing of 1.6×10^{-5} metre, the frequency f_0 at which this separation gives a transit angle of 1 radian between space charge minimum and grid varies for different values of beam current I_0 as follows:

I_0	1.5×10^3	3×10^3	5×10^3	7×10^3	10^4 amps./metre^2.
f_0	6,670	3,420	3,065	3,025	3,105 megacycles/sec.

An embodiment of the invention as applicable to a helix type of travelling wave tube is shown in Fig. 4. In this embodiment the envelope is divided into two portions, **23** and **24**, sealed to either side of a centrally apertured disc electrode **25** which forms the final anode of the electron gun. A screen grid type of electron gun is indicated diagrammatically, the cathode heating arrangements **11** and the grid **12** being connected as described with reference to Fig. 3, the capacitance **16** between grid **12** and cathode **10** being shown for convenience externally of the tube. Cathode and grid assembly are housed within the screening electrode **26**. The helix **27** of the travelling wave tube is connected by a straight section of rod **28** to the disc electrode **25** at one end and to a collector electrode **29** at the other. The ends of the helix project into wave guides **30** and **31** respectively, as in known travelling wave amplifiers and a magnetic focussing solenoid **32** is provided around the helix. The disc **25** clips into an annular member **33** within the wave guide **30** so that disc **25** and member **33** together constitute a "door-knob" probe pick up for the helix. This arrangement is adopted, apart from its other advantages, so as to bring the electron gun as close as possible to the interaction space and so reduce the transit angle between grid **12** and anode **25**. Grid **12** is polarised with respect to cathode **10**, as in Fig. 3, by connection through the decoupling resistance **18** to the bias source **19**, the screen grid **26** is polarised by source **34** which is in series with source **35**, and the collector electrode **29** is shown connected to a tapping point on the source **35**. The screen and final anode potentials of the electron gun, together with the potential of grid **12**, must be chosen so that the region between the cathode **10** and grid **12** is fully space charge limited, but after passing the grid **12**, the beam may be accelerated or decelerated as required.

In the present invention shot noise reduction in an electron beam is obtained by using a grid adjacent to the cathode to maintain the region bounded by these electrodes fully space charge limited, the transit angle between space charge induced potential minimum and grid being small. As has been shown by the examples quoted, at microwave frequencies this criterion leads to very close inter-electrode spacings. From Equations 14 and 16, as an alternative to the present invention it may be suggested that the transit angles in the regions **1** and **2** of Fig. 3, or in the equivalent regions in Fig. 4, should be made such that cancellation occurs. This can be done by adjusting the magnitudes of θ_1 and θ_2 so that $\Gamma\theta^2$ is minimised. It must be remembered however, that when cancellation is obtained by adjustment of the electron trajectories in two separate regions it is not sufficient for the average electron trajectory to obey the cancellation condition. Each individual electron must travel along a path obeying the condition. It is found in practice that such systems of cancellation only produce minor improvement in noise factor because the above mentioned considerations involve a degree of electron optical homogeneity which is not obtainable. For instance, in any real non-infinite plane parallel beam radial space charge forces exist and cause axial electrons to travel more slowly than peripheral electrons, so that it is impossible to satisfy the required condition over the whole beam.

In the invention described use is merely made of space charge debunching effects in a single region which can be made to approximate the ideal plane parallel system rather closely. Beyond the space-charge forming grid it is not material if a variation in transit angle exists.

While the principles of the invention have been described above in connection with specific embodiments, and particular modifications thereof, it is to be clearly understood that this description is made only by way of example and not as a limitation on the scope of the invention.

What I claim is:

1. An electron velocity modulation apparatus comprising means defining a space having an electromagnetic field therein, electron gun means for projecting an electron beam through said space to produce interaction of the beam with the electromagnetic field and velocity modulation of said beam, said gun having cathode and grid positioned outside said space, means for maintaining said cathode and grid at the same high frequency potential, means for producing fully space charge limited electron beam current throughout a region defined by the space between the cathode and grid, said grid being mounted at a distance from the potential minimum of the space charge produced in said region in greater than one radian of the electron transit angle at the highest operating frequency of said field.

2. An electron velocity modulation tube for the amplification of electromagnetic waves comprising means defining an interaction space for said electro-magnetic waves and an electron beam, an electron gun having a cathode and a grid closely adjacent said cathode defining therewith a region shielded from external electromagnetic fields of the frequency of the wave to be amplified, said cathode and grid being positioned outside said space means for producing throughout said region fully space charge limited electron current, said grid being mounted at a distance from the potential minimum of the space charge produced in said region in greater than one radian of the electron transit angle at the highest operating frequency of said field.

3. Apparatus according to claim 2 including means for guiding the electromagnetic waves to be amplified along the path of the beam to interact continuously therewith.

4. Apparatus according to claim 3 in which said means for guiding the waves is a helix surrounding the path of the beam, a wave guide probe terminating said helix at its input end, said electron gun including a final anode from which said probe extends.

5. An electron velocity modulation apparatus comprising means providing a space having an alternating electro-magnetic field therein, an electron gun for projecting an electron beam through said space for interaction with said field, said gun having a cathode and a grid mounted outside said space, and means providing a beam accelerating potential whereby a space charge induced potential minimum is produced between said cathode and said accelerating-potential producing means, said cathode and grid being closely spaced with respect one another to provide a region in which the electron beam current is substantially fully space charge limited, said grid being

mounted at a distance from said potential minimum no greater than one radian of the electron transit angle at the highest operating frequency of said field and means for intercoupling said cathode and grid to maintain them at substantially the same high frequency potential.

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