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ELECTRON BEAM DEVICES

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FIG. 1

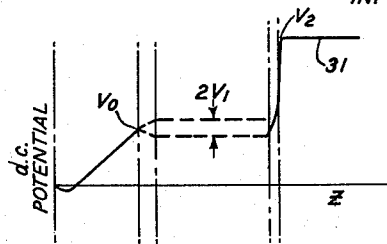
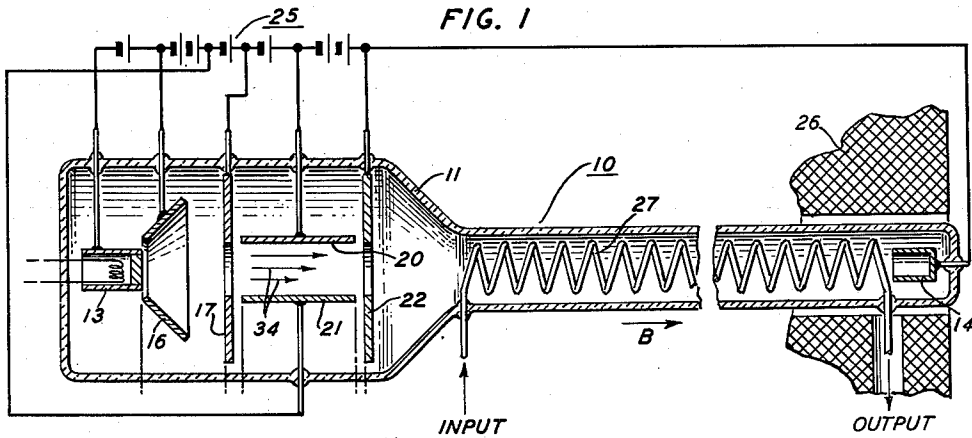


FIG. 1a

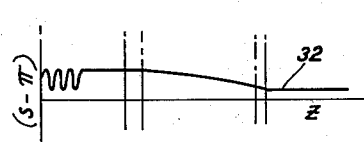
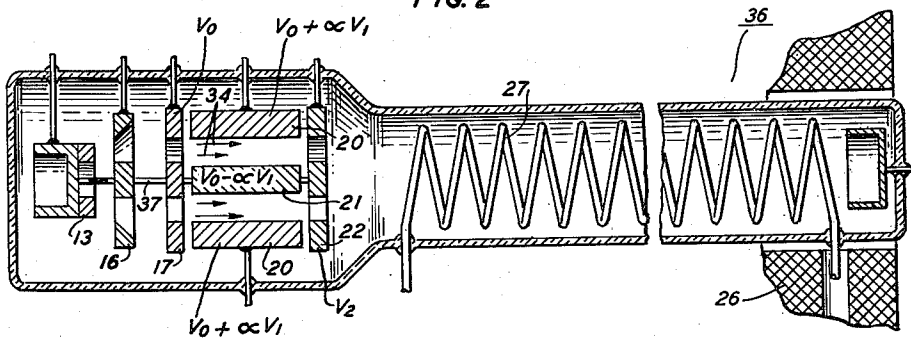


FIG. 1b

FIG. 2



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ELECTRON BEAM DEVICES

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This invention relates to electron beam devices and more particularly to the reduction of noise in the beam of such devices.

Electron beam devices such as traveling wave tubes have proven capable of microwave amplification with reasonably high gain and stability over an exceedingly wide band of frequencies. Detracting from the significant advantages realized by such devices, however, is the noise resulting from the utilization of an electron beam. Considerable research on the nature of electron beams has taken place in an effort to reduce this undesirable noise as much as possible. In a paper entitled "The Minimum Noise Figure of Microwave Beam Amplifiers," by H. A. Haus and F. N. H. Robinson, Proceedings of The Institute of Radio Engineers, volume 43, p. 981-991, August 1955, equations are developed that lead to a theoretical minimum noise figure of a conventional traveling wave tube of approximately six decibels.

Subsequent to the work of Haus and Robinson, workers in the art discovered that certain particular electron guns in conventional traveling wave tubes sometimes yielded noise figures of less than six decibels. Investigation has indicated that these apparent contradictions of theory result from the fact that the Haus-Robinson calculations are based on the assumption that velocity variations in any given transverse plane of the electron beam are negligible by comparison to the D.-C. beam velocity. This assumption is apparently valid in regions of high D.-C. beam velocity, but is not valid in the region adjacent the cathode where the beam has not been accelerated. In the cathode region, where electron velocity variations are large by comparison to the D.-C. beam velocity, certain beam noise parameters, which were priorly considered invariant, have been found to fluctuate. After the beam has been accelerated so that these velocity variations are negligible, the noise parameters no longer fluctuate. It has therefore been theorized that certain electron guns yield unexpectedly low noise figures because the electron beam is suddenly accelerated at a point at which certain of the fluctuating beam noise parameters are at a null.

Because of the complex nature of an electron beam in the cathode region, a comprehensive understanding of the effects of velocity variations therein has not been attained. It is known, however, that the resulting noise parameter fluctuations are very rapid and therefore the distance between any given maximum and null of this fluctuation is extremely small. Practical application of this phenomenon has therefore been hindered for two primary reasons: the exact location of a noise parameter null is not readily predictable; the physical dimensions of apparatus for accelerating the beam at some noise parameter null must be accurate to prohibitively exacting tolerances.

It is an object of this invention to achieve low noise operation of an electron beam device.

It is another object of this invention to take full advantage of the phenomenon of fluctuating noise parameters in a multivelocity electron beam to produce low noise amplification.

These and other objects of this invention are attained in an illustrative embodiment thereof comprising an electron beam device having a cathode for forming and projecting an electron beam and an interaction region

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wherein the beam is allowed to interact with an electromagnetic wave. Between the cathode and the interaction region are a series of electrodes which serve to minimize beam noise as will be explained hereinafter.

In the multivelocity cathode region of the electron beam, the nature of the beam is so complex that reliable, sophisticated apparatus has not, to my knowledge, been devised to take full advantage of the fluctuating noise parameters. According to an aspect of my invention, I therefore include in a traveling wave tube means for introducing controlled transverse velocity variations in the electron beam. These controlled velocity variations are introduced in a relatively high beam velocity region so that the inherent beam velocity variations are negligible. Because the velocity variations are artificially introduced, and because the mean, or D.-C., beam velocity is appropriately high, the various beam parameters are determinable, and it is possible to predict the point at which the beam noise parameter is at a null. Further, the beam noise parameter fluctuations are then relatively slow so that beam acceleration can be effected with fairly simple apparatus.

It is a feature of this invention that there be included between the cathode and interaction region of a beam device a pair of electrodes for introducing transverse velocity variations on the beam. These two electrodes have slightly different voltages thereon so that electrons adjacent the more positively charged electrode will be given a slightly higher velocity than those which are nearer the other electrode.

As will be explained hereinafter, I have found that the noise figure of a multivelocity beam fluctuates at a rate proportional to the beam's plasma frequency. More specifically, the beam noise figure reaches nulls at distances approximately equal to $n/4$ times the plasma wavelength, where n is some odd number. Accordingly, it is another feature of my invention that the pair of electrodes used for introducing transverse velocity variations be of a length equal to $n/4$ times the plasma wavelength of the beam, where n is some odd integral number.

The minimum noise figure represented by the aforementioned null will be maintained throughout the interaction region of the tube only if the beam is suddenly accelerated to a high D.-C. velocity. Accordingly, it is another feature of this invention that a velocity jump transducer be included immediately adjacent the downstream end of the aforementioned pair of conductive electrodes.

A more complete understanding of these and other features of the present invention can be gained from a consideration of the following detailed description, taken in conjunction with the attached drawing, in which:

FIG. 1 is a schematic view of a traveling wave tube embodying the concepts of my invention;

FIG. 1a is a graph of the potential of the electron beam of the device of FIG. 1 versus distance;

FIG. 1b is a graph of the magnitude of the noise parameter of the electron beam of the device of FIG. 1 versus distance; and

FIG. 2 is a schematic view of an electron gun illustrating another embodiment of my invention.

Referring now to FIG. 1, there is shown a traveling wave tube 10 including an evacuated envelope 11 which encompasses a cathode 13 and a collector 14. Cathode 13 produces an electron beam which is focused by beam forming electrode 16 and projected toward the collector by accelerating electrode 17.

In accordance with my invention there is also included a pair of parallel plate electrodes 20 and 21 bordered by an accelerating electrode 22, the purpose of which will be fully explained hereinafter. A D.-C. source such as a battery 25 is connected as shown to maintain the various electrodes at suitable potentials with respect to each other,

A focusing means, such as an electromagnet 26, is used to constrain the beam through the production of a magnetic field B which is parallel with the direction of beam flow, as is well known in the art.

Also included within envelope 11 is a conductive helix 27. High frequency electromagnetic wave energy is applied to the helix as shown by the input arrow. Thereafter, it is amplified in a known manner by interaction of the resulting field, traveling on the helix, with the beam. After amplification, the electromagnetic wave energy is extracted from the helix as shown by the output arrow. It is to be understood that the helix is merely exemplary of many various types of slow wave structures which can be used.

In an electron beam device such as traveling wave tube 10, one of the major obstacles in attaining optimum operation is the noise, or spurious current and velocity fluctuations, present on the beam. Noise is usually of a random nature and has two principal sources. One is thermal agitation in the input circuit and the other is irregularities in the emission of electrons from the cathode, the latter effect being known as shot noise. The noise figure of an electron beam device is the ratio, usually expressed in decibels, of the total noise output power to the noise output power attributable to thermal noise at the input.

The investigations by Haus and Robinson, as disclosed in the aforementioned paper, led to the following relationship:

$$F_{\min} = 1 + \frac{2\pi}{kT_0}(S - II) \quad (1)$$

Where $F_{\min}$ is the theoretical minimum noise figure in a beam device, k is Boltzmann's constant, T_0 is a reference temperature, taken as 293 degrees K., and S and II are noise parameters which are defined in the paper. This relationship is well known to workers in the art. Equally well known is the fact that in the high velocity regions of a conventional beam device the noise parameter ($S-II$) is invariant and the theoretical minimum noise figure is approximately six decibels.

Subsequent to the Haus-Robinson paper, it was determined that in the low velocity region of beam, that is, the region adjacent the cathode, the noise parameter ($S-II$) is not invariant but actually fluctuates with distance to an appreciable degree. Calculations of noise fluctuations along a multivelocity beam were made by the density-function method of analysis and presented in the paper entitled "Density-Function Calculations of Noise Propagation on an Accelerated Multivelocity Electron Beam," by A. E. Siegman, D. A. Watkins, and Hsung-Cheng Hsieh, "Journal of Applied Physics," volume 28, No. 10, pp. 1138-1148, October 1957. These calculations were made with the aid of a computer and it was found that the noise figure at certain distances along the beam was as low as three and one-half decibels. It was also shown mathematically that if the beam is abruptly accelerated at a point at which the noise parameter ($S-II$) is at a null, the resulting low noise figure will be maintained.

Although the analysis of Siegman et al. provides a better understanding of the nature of an electron beam, it does not prescribe a practical method for taking advantage of the multivelocity beam characteristics in the cathode region. The main difficulty in making use of these findings is the extremely rapid fluctuations of the noise parameter ($S-II$). In physical terms, one might say that the drift distance in which the current fluctuations change to velocity fluctuations is extremely short. No beam accelerating apparatus has been devised which can reliably accelerate the beam at the precise point along the multivelocity region adjacent the cathode where the noise parameter is at a predicted null. Further, since the noise parameter fluctuation is so rapid, the physical dimensions involved would have to be accurate to the most exacting

tolerances and the necessary velocity jump would have to be exceedingly abrupt.

In my study of multivelocity beams, I have used a different analysis than that hereinbefore described. Rather than the distribution function approach, I have studied the beam from the standpoint of wave propagation. My analysis is rather complex and lengthy and so, for the sake of brevity, will not be herein included. Suffice it to say that my calculations show that the noise parameter ($S-II$) fluctuates quasiperiodically with distance as a function of the plasma wavelength in a constant velocity region of the beam.

The beam parameter referred to as plasma wavelength is related to a phenomenon known as plasma oscillation. When a beam is modulated by a small quantity of power, individual electrons which are displaced from their equilibrium position tend to return to that position. Since the electron has inertia, it will be carried to a point on the other side of equilibrium where the momentum is overcome by opposing restoring forces. The resulting oscillation is similar to that of a weight supported between two opposed compression springs. The product of the charge on an oscillating electron and the charge density of the surrounding space can be considered as being analogous to the stiffness or elasticity of the spring. Since the charge-to-mass ratio is the same for all electrons, the plasma frequency is dependent on the charge density of the beam. The distance along the beam an electron will travel during one cycle of plasma oscillation is the plasma wavelength. The plasma wavelength is therefore determined by the plasma frequency and the D.-C. velocity of the beam.

Because the parameter ($S-II$) varies as a function of the plasma wavelength, it is possible to adjust the frequency of variation by adjusting the plasma wavelength. This can be done by adjusting the D.-C. beam velocity. However, when the beam is accelerated to a velocity at which the plasma wavelength is long enough to permit the use of velocity jump apparatus of a practicable size, the beam is essentially of a single velocity and the parameter ($S-II$) is substantially invariant. It is therefore necessary to introduce artificial velocity variations so that the beam will have the multivelocity characteristics previously discussed.

Referring to FIG. 1a, curve 31 indicates the variations of beam potential with distance along the tube 10. As shown by curve 31, the beam potential falls slightly below the cathode potential at a small distance therefrom due to space charge concentrations. It then rises to the potential V_0 of accelerating electrode 17. The beam velocity can be considered as being also represented by curve 31 since beam velocity is proportional to the square root of beam potential. Curve 32 of FIG. 1b indicates the variation of the noise parameter ($S-II$) with distances corresponding to those of curve 31. The variation of ($S-II$) near the cathode results from the multivelocity characteristics of the beam at that region. As the beam is accelerated, the inherent velocity variations become negligible with respect to the D.-C. velocity and the parameter ($S-II$) becomes invariant.

After being accelerated by electrode 17 the beam flows between parallel plate electrodes 20 and 21. As shown by the connections to battery 25, plate 20 is at a slightly higher potential than the potential V_0 on electrode 17, while plate 21 is at a slightly lower potential. Considering the deviation from the mean potential V_0 produced by each electrode to be V_1 , electrodes 20 and 21 produce a potential distribution $2V_1$ across the beam as shown by the dashed portion of curve 31. The resulting transverse velocity variations are illustrated by arrows 34, the relative lengths of which are intended to illustrate relative magnitudes of electron velocity. After passing between plates 20 and 21, the beam is abruptly accelerated by electrode 22 having a potential V_2 as shown by curve 31.

From curve 32 one can see that the parameter (S-II) varies much more slowly in the multivelocity region between electrodes 17 and 22 than in the multivelocity region immediately adjacent the cathode. The reason for this is the high beam velocity and hence the longer plasma wavelength between electrodes 17 and 22. As previously mentioned, the (S-II) fluctuates quasi-periodically as a function of the plasma wavelength. More specifically, I have found that minima in the (S-II) parameter reoccur at distances approximately equal to one-fourth of the plasma wavelength. The curve 32 is intended to illustrate a minimum at the position of accelerating electrode 22. The plates 20 and 21 of the embodiment of FIG. 1 are therefore approximately one-fourth of a plasma wavelength long. If plates 20 and 21 were extended, my calculations show that other minima would occur at distances approximately equal to $n/4$ times the plasma wavelength, where n is any odd number. Since the noise parameter fluctuations are not exactly periodic, however, a longer electrical length of plates 20 and 21 than that shown would probably result in a greater margin of error. However, because of the long plasma wavelength associated with the high potential region of plates 20, 21, a length of one-fourth plasma wavelength is easily physically realizable.

In the course of my calculations, certain assumptions were made, among them the assumption that the potential deviation V_1 be small with respect to the mean beam potential V_0 . On the other hand, I have found that the noise figure is reduced as the potential deviation V_1 is increased. Further investigation has indicated that a convenient ratio of potential deviation to mean potential

$$\frac{(V_1)}{V_0}$$

is approximately 1/20. In determining the proper potentials for plates 20 and 21 for a desired potential deviation, account should be taken for plate separation and beam thickness. For a desired beam velocity deviation V_1 it can be shown that voltages on plates 20 and 21 should be:

$$\begin{aligned} V_{20} &= V_0 + \alpha V_1 \\ V_{21} &= V_0 - \alpha V_1 \end{aligned} \quad (2)$$

where α is the ratio of plate separation to beam thickness. Using the ratio

$$\frac{V_1}{V_0} = 1/20: V_{20} = V_0 + \frac{\alpha V_0}{20}$$

$$V_{21} = V_0 - \frac{\alpha V_0}{20} \quad (3)$$

As previously pointed out, the velocity jump which the beam experiences after drifting between plates 20 and 21 must be abrupt. It can be shown that the transition from the beam potential of $V_0 \pm V_1$ to the accelerated potential of V_2 (see curve 31) must take place in a distance which is short compared to the plasma wavelength divided by 2π . Since plates 20 and 21 are only one-quarter of a plasma wavelength long, it is seen that this condition is easily realizable.

In FIG. 2 is shown a traveling wave tube 36 which illustrates another embodiment of my invention utilizing a hollow beam. The various elements of this embodiment function in the same way as the device of FIG. 1 and so have been numbered accordingly. Cathode 13 comprises an annular ring coated with emissive material for producing a hollow electron beam as is well known in the art. Electrodes 16, 17 and 22 are the same as the corresponding electrodes of FIG. 1 except that they

are constructed with annular apertures for the passage of an annular electron beam. Electrode 20 is in the form of a hollow cylinder rather than a plate as shown in FIG. 1. Electrode 21 is a solid cylinder which is coaxial with electrode 20. The voltages of the electrodes 17, 20, 21 and 22 are labelled according to the terms defined with reference to FIG. 1. A rod of insulating material 37 extends along the tube axis to support the central portions of the various electrodes.

The advantages of using a hollow beam in certain instances are well known. The method by which my invention is adapted to such a device is self-explanatory by the illustration of FIG. 2. As shown by the arrows 34, the desired transverse velocity spread is produced around the entire circumference of a portion of the hollow cylindrical beam. The graphs of FIGS. 1a and 1b apply also to the device of FIG. 2.

It is to be understood that the above-described embodiments are only illustrative of the application of the principles of my invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron beam device comprising a cathode for forming an electron beam, a collector for collecting said beam, means for constraining said beam to follow a single predetermined path of flow, a first accelerating electrode, a second accelerating electrode, two elongated electrodes parallel with said beam and between said first and second accelerating electrodes, means comprising a D.-C. voltage source for producing a potential difference between said parallel electrodes, and means for causing electromagnetic wave energy to interact with said electron beam.

2. An electron discharge device comprising means for forming and projecting an electron beam along a path, said means comprising a cathode and a first accelerating electrode, said beam being characterized by a plasma wavelength which is a function of the mean velocity of said beam, means for causing an electromagnetic wave to interact with said electron beam, a second accelerating electrode positioned between said first accelerating electrode and said means for causing interaction, a pair of parallel electrodes positioned between said first and second electrodes and parallel with said electron beam, each of said parallel electrodes having a length approximately equal to one-fourth of said plasma wavelength in the region between said first and second accelerating electrodes and means comprising a D.-C. voltage source for producing a potential difference between said parallel electrodes.

3. A device of the type which effects interaction of electromagnetic wave energy with an electron beam comprising means for forming and projecting a beam of electrons along a path, said beam being characterized by a noise parameter which is determinative of the theoretical minimum noise figure of said device, said noise parameter being invariant when the mean velocity of said beam is large with respect to beam velocity variations, first means for accelerating said beam thereby making any inherent beam velocity variations small with respect to the mean beam velocity, means downstream from said first accelerating means for producing artificial beam velocity variations across a transverse portion of said beam thereby producing fluctuations of said noise parameter, said last-mentioned means comprising a D.-C. voltage source second means for accelerating said beam positioned downstream from said velocity variation producing means at a position along said beam path at which said noise parameter is at a minimum, and means for collecting said beam.

4. An amplifier comprising a substantially tubular evacuated envelope enclosing a cathode for forming an electron beam and a collector for said electron beam, said cathode and collector being at opposite ends of said

envelope, means for producing a magnetic field parallel with the axis of said envelope, a first electrode within said envelope being maintained at a higher positive D.-C. potential than said cathode, a second electrode between said first electrode and said collector being at a higher positive D.-C. potential than said first electrode, a pair of elongated electrodes each parallel with said axis and extending along the same portion thereof, one of said elongated electrodes being at a higher D.-C. potential than said first electrode and at a lower D.-C. potential than said second electrode, the other one of said elongated electrodes being at a lower D.-C. potential than said first electrode and at a higher potential than said cathode, and means included between said second electrode and said collector for causing electromagnetic wave energy to interact with said electron beam.

5. The amplifier of claim 4 wherein the difference of potential between one of said elongated electrodes and said first electrode is the same as the difference of potential between the other of said elongated electrodes and said first electrode.

6. An electron beam device comprising a cathode for forming an electron beam, a collector for collecting said beam, means for constraining said beam to follow a single predetermined path of flow, a first accelerating electrode, a second accelerating electrode, a pair of conductive plates parallel with said beam and on opposite sides thereof, said pair of conductive plates being between said first and second accelerating electrodes and at equal distances from said cathode, means for producing a D.-C. potential difference between said conductive plates, and means for causing electromagnetic wave energy to interact with said electron beam.

7. The electron beam device of claim 6 wherein said electron beam is characterized by a plasma wavelength which is a function of the mean velocity of said beam, and wherein each of said conductive plates has a length substantially equal to one-fourth of the plasma wavelength of the beam in the region between said first and second electrodes.

8. An electron discharge device comprising means for forming a hollow electron beam, a collector for collecting said beam, means for constraining said beam to follow a single predetermined path of flow, a first accelerating electrode, a second accelerating electrode, a pair of cylindrical coaxial electrodes separated by an annular space for allowing passage therethrough of said hollow electron beam, said coaxial electrodes being positioned between said first and second accelerating electrodes, means for producing a potential difference between said pair of coaxial electrodes, and means for causing electromagnetic wave energy to interact with said electron beam.

9. An electron beam device comprising the following elements positioned along an axis in the order recited: a cathode, a focusing electrode, a first accelerating electrode, a pair of elongated electrodes producing therebetween an electric field which is transverse to said axis, a second accelerating electrode, a conductive helix, and a collector; and further comprising an envelope encompassing all of the aforesaid elements, means for maintaining said first accelerating electrode at a higher D.-C. potential than said cathode, means for maintaining said second accelerating electrode at a higher potential than said first accelerating electrode, and means for producing a focusing field along said axis.

10. An electron discharge device having a central axis and comprising means for forming and projecting a beam of electrons along said axis, said forming means comprising a cathode, said beam being characterized by a plasma wavelength which is a function of the mean velocity of said beam, a collector, a first accelerating electrode, a second accelerating electrode positioned between said first accelerating electrode and said collector, and third and fourth electrodes positioned between said first and second elec-

trodes, said third and fourth electrodes producing therebetween an electric field which is transverse to said electron beam.

11. The electron discharge device of claim 10 wherein said third and fourth electrodes are each one-fourth of the plasma wavelength of the beam in the region between said first and second electrodes.

12. The electron discharge device of claim 11 wherein said third and fourth electrodes are parallel and equidistant from said second electrode, the distance between said third and fourth electrodes and said second electrode being small with respect to the plasma wavelength of said beam in the region between said first and second electrodes divided by 2π .

13. The electron discharge device of claim 12 wherein said first electrode is at a higher D.-C. potential than said cathode, said second electrode is at a higher D.-C. potential than said first electrode, said third electrode is at a higher D.-C. potential than said first electrode and at a lower D.-C. potential than said second electrode, and said fourth electrode is at a lower D.-C. potential than said first electrode and at a higher D.-C. potential than said cathode.

14. The electron discharge device of claim 13 wherein said third and fourth electrodes comprise a pair of parallel conductive plates.

15. The electron discharge device of claim 13 wherein said third and fourth electrodes comprise a pair of coaxial conductive cylinders.

16. An electron gun for producing a low noise electron beam comprising a cathode, a first accelerating electrode for accelerating the electron beam from said cathode to a mean beam velocity at which any inherent beam velocity variations are small with respect to said mean beam velocity, means downstream from said first accelerating electrode for producing artificial beam velocity variations across a transverse portion of said beam, and a second accelerating electrode closely adjacent said last-mentioned means and downstream therefrom for providing an abrupt increase in the mean velocity of the beam.

17. The electron gun of claim 16 wherein said beam is characterized by a plasma wavelength which is a function of its mean velocity, said beam velocity variation producing means extending along said beam a distance substantially equal to $n/4$ times the plasma wavelength of the beam at the mean beam velocity produced by said first accelerating means, where n is some odd integral number.

18. An electron discharge device comprising means for projecting an electron beam, said projecting means including a cathode and a first accelerating electrode, means for collecting said beam, and means for reducing the noise in said beam, said last-mentioned means including electrode means positioned on opposite sides of said beam adjacent said first accelerating electrode and downstream therefrom, means for applying potentials to said electrode means to produce artificial beam velocity variations across a transverse portion of said beam, and velocity jump means including a second accelerating electrode directly adjacent said electrode means and downstream therefrom for providing an abrupt increase in the mean velocity of said beam.

19. An electron gun for producing a low noise electron beam comprising means for forming a beam of electrons which inherently includes a quantity of noise energy which fluctuates quasiperiodically with distance when substantial beam velocity variations exist over a transverse portion of the beam, means for accelerating said electron beam from said beam forming means to a velocity at which any inherent beam velocity variations are negligible with respect to the mean beam velocity, means downstream from said accelerating means for producing artificial beam velocity variations over a transverse portion of said beam thereby inducing said quantity of inherent

beam noise to fluctuate quasisperiodically with distance, and means downstream from said velocity variation producing means for abruptly accelerating said beam to a velocity at which said artificial velocity variations are negligible with respect to the mean beam velocity, said last-mentioned accelerating means being at a position along said beam at which said fluctuating quantity of beam noise is at a minimum. 5

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