

July 15, 1958

P. K. TIEN

2,843,776

TRAVELING WAVE TUBE ELECTRON GUN

Filed June 26, 1953

4 Sheets-Sheet 1

FIG. 1A

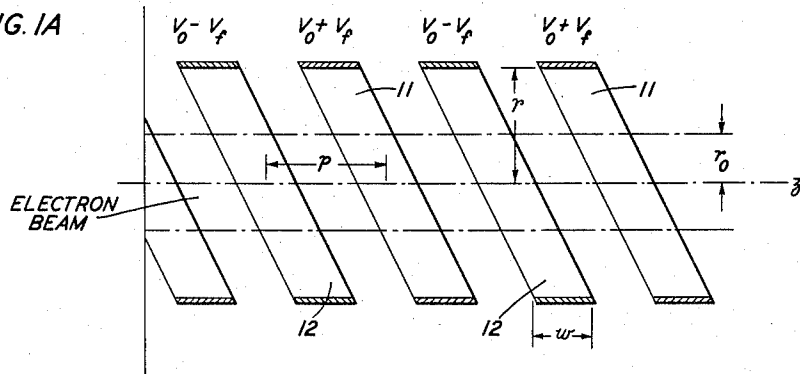


FIG. 1B

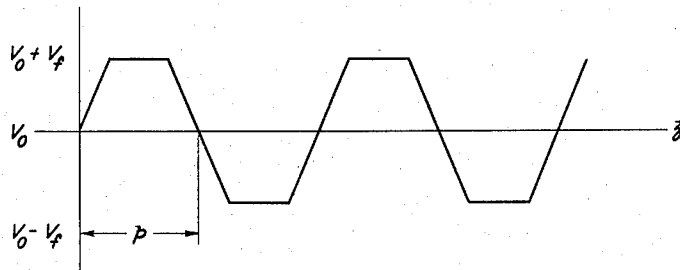
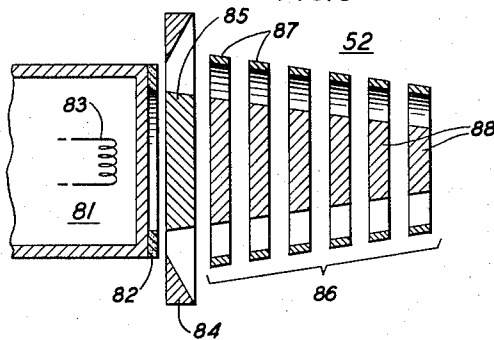


FIG. 6



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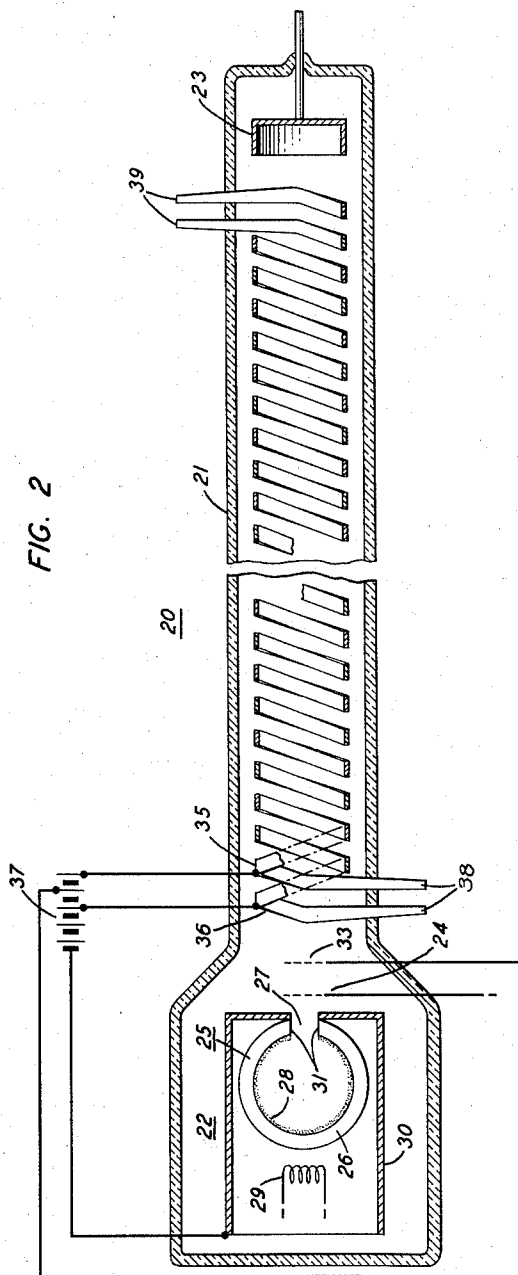
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4 Sheets-Sheet 2



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FIG. 3

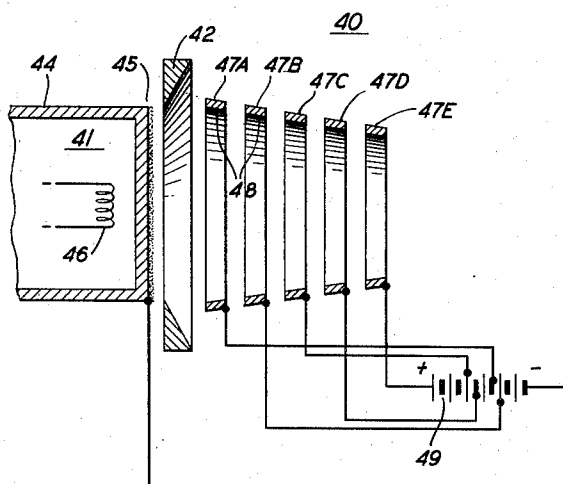
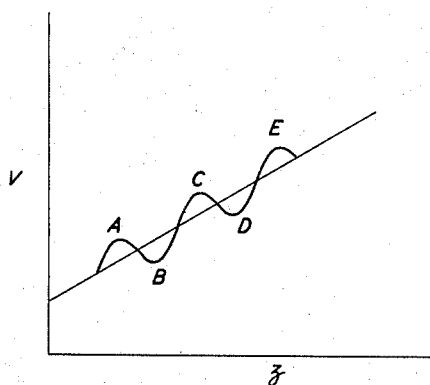


FIG. 4



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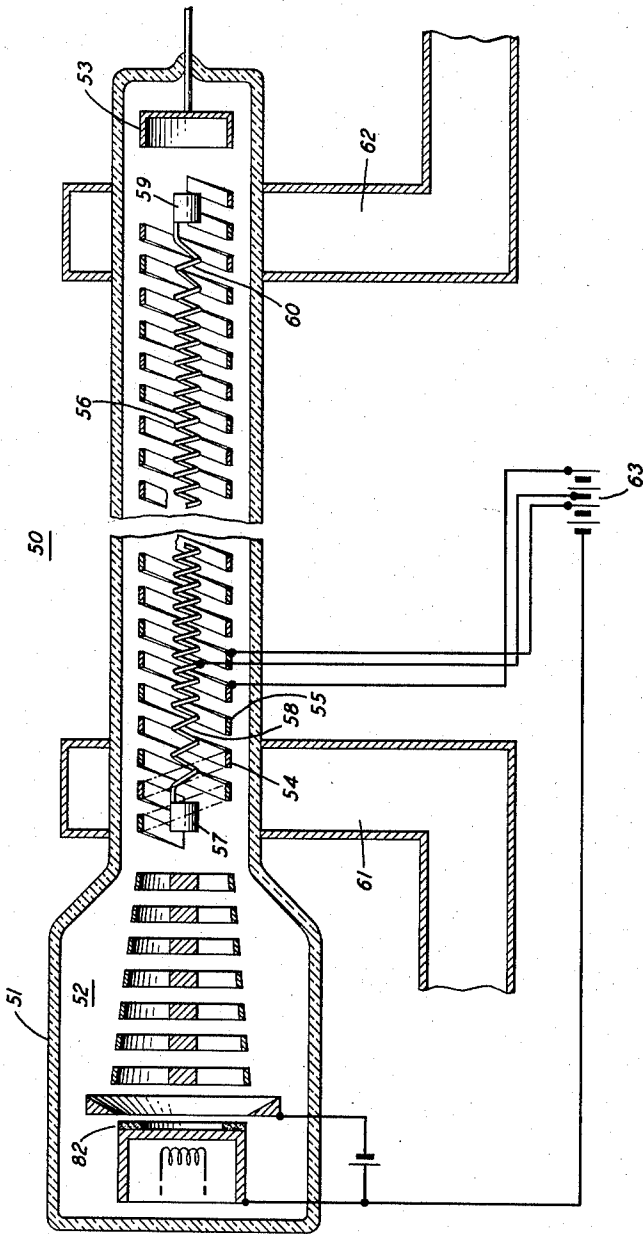
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TRAVELING WAVE TUBE ELECTRON GUN

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FIG. 5



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TRAVELING WAVE TUBE ELECTRON GUN

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Application June 26, 1953, Serial No. 364,242

3 Claims. (Cl. 313—85)

This invention relates to traveling wave tubes which utilize the interaction between an electromagnetic wave propagating along an interaction wave circuit and an electron stream which flows past the interaction wave circuit in coupling relation with the propagating electromagnetic wave over a plurality of operating wavelengths.

One of the difficult problems associated with traveling wave tubes is the focusing of the electron stream over its relatively long path for maintaining its flow close past the interaction wave circuit without striking it. The most common expedient hitherto has been the provision of an axial magnetic field for minimizing transverse components of flow. However, the auxiliary equipment necessary for such an axial magnetic field is bulky and generally adds undesirably to the overall weight.

It has been suggested hitherto that a solid electron beam can be focused by a succession of axially symmetric longitudinal electrostatic field regions provided by projecting the beam axially through a succession of spaced annular cylinders which are maintained alternately at positive and negative D. C. potentials with respect to their mean potential. In such arrangements, it has been the practice to employ solid electron beams produced by electron guns which provide in each case a beam which either is of substantially uniform current density in cross section or has a current density which decreases with distance from the beam axis.

However, in accordance with one aspect of the present invention, it has been discovered that the focusing which can be achieved by axially symmetric periodic electrostatic fields can be enhanced and the requirements on the magnitude of the focusing potentials relaxed by utilizing an electron beam in which the current density increases with increasing distance from the beam axis.

To this end, one feature of the invention is the combination of a periodic electrostatic focusing structure with an electron gun which provides a beam in which the current density increases with increasing distance from the beam axis. An electron gun of the kind which provides an electron beam substantially of the kind desired is described in D. MacNair Patent 2,810,088, issued October 15, 1957. Such an electron gun will be designated a hollow-cathode-type gun, and is more fully described hereinafter.

Additionally, as another feature of the present invention, there is provided a novel electron gun which also provides an electron beam of the kind desired. This electron gun utilizes a succession of annular electrodes for providing a spatially alternating axially symmetric electrostatic field both to converge the emitted electrons into smooth conical flow and to effect a gradual acceleration of the electrons to an axial velocity appropriate for wave interaction. Such gradual acceleration becomes desirable if the desired current distribution is to be maintained.

In a copending application Serial No. 245,503, filed March 30, 1953, by J. R. Pierce, now Pat. No.

2,705,385, it is disclosed that an electron beam can be focused electrostatically by making it hollow and projecting it through the interspace between a bifilar helix and an electrode which forms an equipotential surface where the potential on the electrode is intermediate the different potentials on the two conductors of the bifilar helix. Moreover, for traveling wave tube operation, the bifilar helix additionally is employed as the wave interaction circuit.

However, an analysis of an electrostatic focusing arrangement of this kind indicates that for optimum focusing certain requirements are imposed on the geometry of the bifilar helix. As a result, it can be expected there will be instances when the geometry of the bifilar helix most suited from the standpoint of good electrostatic focusing will not be the optimum geometry from the standpoint of the wave propagating characteristics desired for the bifilar helix.

It is in accordance with another aspect of the present invention to modify electrostatic arrangements of the kind described in the afore-mentioned Pierce application to divorce the wave propagating role of the bifilar helix from its focusing role and instead to utilize the electrode forming the equipotential surface as the wave interaction circuit. To this end, this electrode is advantageously a single wire helix to which is supplied the electromagnetic wave for interaction with the electron stream.

Moreover, even with arrangements of this kind utilizing hollow beams, it becomes advantageous both that the focusing potentials have a particular value and that the electron stream have the right current distribution in cross section when it is injected initially into the region where periodic electrostatic focusing takes over.

To this latter end, another feature of the invention is an electron gun which provides a hollow beam of the desired current distribution across the beam. This electron gun utilizes an electrode system for establishing longitudinal spatially alternating electrostatic fields and radial electrostatic fields whereby the electrons emitted from an annular cathode are converged into a hollow beam of desired characteristics and gradually accelerated towards the axial velocity desired for wave interaction.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Fig. 1A shows a bifilar helix focusing structure for use in the practice of the invention;

Fig. 1B shows the potential distribution along the path of electron flow provided by the focusing structure shown in Fig. 1A;

Fig. 2 shows schematically, as an illustrative embodiment of one aspect of the invention, a traveling wave tube which utilizes a hollow-cathode type electron gun and a bifilar helix both for beam focusing and wave propagation;

Fig. 3 shows schematically a novel electron gun in accordance with another aspect of the invention for use in the traveling wave tube shown in Fig. 2 in place of the hollow-cathode type electron gun shown therein;

Fig. 4 shows the potential distribution along the path of flow in the electron gun shown in Fig. 3;

Fig. 5 shows schematically as an illustrative embodiment of another aspect of the invention, a traveling wave tube which incorporates a novel electron gun and utilizes an outer bifilar helix for focusing the electron flow and an inner single wire helix as the interaction circuit; and

Fig. 6 shows a modification of the novel electron gun incorporated in the tube shown in Fig. 5.

It is to be noted that in the drawings various details such as supports, spacers, lead-in connections, etc., whose

need will be obvious to a worker in the tube art, have been omitted for the sake of simplicity.

Before discussing specific embodiments of the invention, it will be advantageous to analyze the principles applicable to the focusing of an electron beam by axially symmetric periodic electrostatic fields. It will be convenient to discuss first the focusing of a solid beam by a focusing system of the kind shown in Fig. 1A comprising a bifilar helix in which the bifilar helix surrounds the electron beam and the two ribbon conductors 11 and 12 forming the bifilar helix are maintained at D.-C. potentials equal to $V_0 + V_f$ and $V_0 - V_f$, respectively, where V_0 is the average D.-C. potential of the space in which the electrons flow with respect to the cathode from which the electrons originate and which potential is chosen to provide the average value of axial velocity of the electron stream suited for wave interaction and V_f is the focusing potential which acts effectively as an alternating potential superimposed on this average potential.

First, assume at the outer boundary of the electron beam a potential distribution of the form of

$$V(r, z) = V_0 + V_r \cos \frac{\pi}{p} z \quad (1)$$

is produced by the focusing structure where p is the spacing of adjacent turns of the bifilar helix. This represents an assumption that the potential distribution varies sinusoidally with a period of $2p$. There is no θ dependence because we are now considering the simple case in which electron motion is assumed to be prohibited in the θ direction. This, for example, corresponds to the case in which the focusing system comprises a succession of annular cylinders or rings.

Suppose that the electron beam has an average radius r_0 and that the motion of a boundary electron can be described as

$$r(z) = r_0 + r_1(z) \quad (2)$$

For a well focused beam, r_1 (it will be convenient generally to drop the variable in designating a function) should be a periodic function in z , and its magnitude should be always substantially less than r_0 .

It can be shown that such a potential distribution results in a radial component of electric field at the vicinity of $r=r_0$ which can be approximated as

$$E_r(r, z) = (-V' - V''r_1) \cos \frac{\pi}{p} z \quad (3)$$

where V' and V'' are abbreviations for the first and second derivatives, respectively, of the electric potential V with respect to the radial coordinate at $r=r_0$.

In addition to the radial component of electric field produced by the focusing structure, the electron stream exerts a space charge force of

$$\frac{eI}{v_0 2\pi r_0 \epsilon} \quad (4)$$

on the boundary electrons where e is the electron charge, ϵ the dielectric constant of the space, I the total beam current, and v_0 the average axial velocity of the stream which is given by

$$v_0 = \sqrt{2\eta V_0} \quad (5)$$

where η is the ratio of the electron charge to the electron mass. The space charge force in Equation 4 has been evaluated at $r=r_0$ and is assumed constant irrespective of the motion of the electrons.

Now if it be assumed further that the axial velocity of each boundary electron is constant (the effect of the variation in the axial velocity of the electron will be compensated for later), then the equation describing the motion of a boundary electron is found to be

$$\frac{d^2 r_1}{dz^2} = \eta (V' + V''r_1) \cos \frac{\pi}{p} z + \frac{I}{v_0 2\pi r_0 \epsilon} \quad (6)$$

From this, it can be shown that a condition for focusing under the conditions assumed is that

$$V'V'' = \left(\frac{\pi}{p}\right)^2 \sqrt{\frac{2V_0}{\eta}} \frac{I}{r_0 \pi \epsilon} \quad (7)$$

It will be found that the term on the left hand side of Equation 7 is proportional to the square of the focusing potential V_f while the term at the right hand side of the equation contains only the physical quantities of the stream.

Now it is possible to take into account the variation of the axial velocity of a boundary electron. By considering the axial velocity of a boundary electron to be

$$v_z(z) = \sqrt{2\eta(V_0 + V)} \quad (8)$$

by an analysis similar to that set forth briefly above, it can be shown that the condition for focusing is that

$$V' \left(V + V'' \left(\frac{p}{\pi} \right)^2 \right) = \sqrt{\frac{2V_0}{\eta}} \frac{I}{\pi r_0 \epsilon} \quad (9)$$

Equation 9 represents the condition for focusing of an electron beam by periodic electrostatic fields where there is no θ component of electric field and hence no θ component of electron motion. As mentioned above, periodic electrostatic fields of this kind can be achieved by a succession of ring electrodes surrounding the path of flow, alternately at D.-C. potentials of $V_0 + V_f$ and $V_0 - V_f$. However, when the electron stream is focused by a multiwire helix, such as the bifilar helix, there is a θ component both of electric field and electron motion. When we replace the expression in Equation 1 by its complete form,

$$V(r, z, \theta) = V_0 + V(r) \cos \left(\frac{\pi}{p} z - \theta \right) \quad (10)$$

it can be shown that the condition for focusing is substantially that

$$\begin{aligned} \left(\frac{p^2}{\pi} \right) V'V'' + VV' + \left(\frac{p}{\pi r_0} \right)^2 VV' - \frac{1}{r_0} \left(\frac{p}{\pi r_0} \right)^2 V^2 \\ = \sqrt{\frac{2V_0}{\eta}} \frac{I}{\pi r_0 \epsilon} \end{aligned} \quad (11)$$

The terms on the left hand side of Equation 11 represent the focusing action resulting from respectively, the radial, axial, and θ components of the electron motion and the centrifugal force. The term on the right reduces to

$$1.212 \times 10^{-5} \frac{I \sqrt{V_0}}{r_0}$$

In order to evaluate V , V' , and V'' at the stream boundary, the potential distribution inside the bifilar helix must be known. Let us consider a bifilar helix of the kind shown in Fig. 1A of which each conductor 11, 12 is a tape of width w and wound in a helix of radius a pitch distance $2p$ and pitch angle ψ . If the gaps between successive turns are narrow as will generally be the case, the electric field across the gaps may be assumed constant and the potential distribution at $r=a$ may be approximated by the distribution plotted in Fig. 1B. Inside the bifilar helix, the potential field must satisfy Laplace's equation and, accordingly,

$$\begin{aligned} V(r, z, \theta) = \sum_m \frac{2V_f}{\pi m} \left(\frac{\sin \frac{p-w}{2p} m\pi + \sin \frac{p+w}{2p} m\pi}{m\pi \frac{p-w}{2p}} \right) \\ \sin \left(\frac{m\pi}{p} z - m\theta \right) \frac{I_m \left(\frac{m\pi r}{p} \right)}{I_m \left(\frac{m\pi a}{p} \right)} \quad m=1, 3, 5, \dots \end{aligned} \quad (12)$$

It is assumed that the helix is wound so that θ increases in following the wire. I_m is the modified Bessel function of the m th order of the first kind as defined in a book entitled "Fields and Waves in Modern Radio" by Romo

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and Whinnery, published by John Wiley and Sons, New York (1946). So far as the field usable for the electron stream is concerned, the terms in Equation 12 except that for $m=1$ can generally be neglected. This is because fields with larger values of m vary with modified Bessel functions of higher order and of larger arguments. We thus have approximately

$$V(r, z, \theta) \approx \frac{2V_f}{\pi} \left(\frac{\sin \frac{p-w}{2p}\pi + \sin \frac{p+w}{2p}\pi}{\frac{p-w}{2p}\pi} \right) \sin \left(\frac{\pi z}{p} - \theta \right) \frac{I_1 \left(\frac{\pi r}{p} \right)}{I_1 \left(\frac{\pi a}{p} \right)} \quad (13)$$

where the factor

$$\frac{2}{\pi}$$

will be denoted as F for convenience. F depends only upon the ratio of w/p .

Knowing the potential distribution inside the helix, V , V' and V'' can be evaluated. Equation 11 is then reduced to the following form for a bifilar helix,

$$\frac{(FV_f)^2}{I_1^2(\cot \psi)} \left(I_1'(x) I_1(x) + I_1'(x) I_1''(x) + \frac{1}{x^2} I_1'(x) I_1(x) - \frac{1}{x^3} I_1^2(x) \right) x = 1.212 \times 10^6 I V_0^{1/2} \quad (15)$$

where

$$x = \frac{r_0}{a} \cot \psi$$

F is defined as above, and I_1 and I_1' are the modified Bessel function of the first order of the first kind and its derivative, respectively.

Equation 15 can be used for determining the focusing potential necessary in a focusing structure utilizing a series of annular rings surrounding the electron beam by eliminating the terms due to the θ component of electron motion, and by replacing I_1 , I_1' , and I_1'' , respectively, by I_0 , I_0' , I_0'' where I_0 , I_0' and I_0'' are, respectively, the modified Bessel function of the zero order of the first kind and its first and second derivatives, and replacing $\cot \psi$ by

$$\frac{\pi}{p}$$

where $2p$ is the period of the periodic focusing field. A focusing structure of this kind is described in a copending application Serial No. 364,441, filed June 26, 1953, by A. Ashkin.

Accordingly, Equation 15 determines the focusing potential V_f to be used for focusing the solid beam by the bifilar helix. However, to achieve good focusing in this way it can be shown, that it is advantageous that the current density across the beam have as nearly as possible a particular current distribution which is given by

$$\rho(r) = 4.12 \times 10^{-6} \frac{(FV_f)^2 \left(\frac{r_0}{a} \cot \psi \right)^2}{I_1^2(\cot \psi) V_0^{1/2} \pi r_0^2} \left(\frac{1}{y} \left(I_1'(y) + y I_1''(y) \right) \left(I_1''(y) + I_1(y) + \frac{1}{y^2} I_1(y) \right) + I_1'(y) \left(I_1'''(y) + I_1(y) + \frac{1}{y^2} I_1'(y) - \frac{2}{y^3} I_1(y) \right) - \frac{2}{y^3} I_1(y) I_2(y) \right) \quad (16)$$

where

$$y = \frac{r}{a} \cot \psi$$

and I_2 is a modified Bessel function of the second order of the first kind.

An analysis of Expression 16 indicates that the desired current distribution is such that the current density increases with increasing distance from the axis of the beam. Such a current distribution is one that is not

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characteristic of the usual electron beam which is formed by converging the flow from a relatively large emitting surface into a dense stream by a conventional electrode system. However, as indicated above, such flow can be achieved over a considerable region by a hollow cathode type electron gun of the kind described in the aforementioned D. MacNair patent in which a thermionic cathode is constructed to provide an emissive region which is completely enclosed except for a restricted aperture for the egress of electrons. Such a cathode can be designed to emit a cylindrical beam of electrons in which the current density increases sharply from the beam axis towards the edges. Alternatively, a beam of the desired current distribution can be achieved by converging the emission from a conventional cathode in a manner to be described hereinafter.

Fig. 2 shows a traveling wave tube 20 which utilizes an electron gun of the hollow-cathode type described in the MacNair patent and a focusing structure which comprises a bifilar helix. Within an evacuated envelope 21, at one end an electron gun 22 provides an electron beam which is directed along the tube axis towards a target electrode 23 at the opposite end which collects the spent electrons. The electron gun is designed to provide a cylindrical electron beam in which the current density increases from the beam axis towards the edges. The electron gun comprises essentially an anode or intensity control electrode 24 and a cathode assembly 25. The cathode assembly 25 includes a hollow sphere 26, for example of nickel, which is enclosed except for a circular orifice or aperture 27. The internal surface of the sphere 26 is coated with a layer 28 of electron emissive material. Electron emission from the layer 28 exits via the orifice 27 which communicates between the hollow interior of the sphere 26 and the exterior. A heater 29 is mounted in heat transfer relation with the sphere 26. The heater 29 and the cathode assembly are enclosed within a heat shield 30 to insure efficient heating. The anode 24 is positioned adjacent the sphere 26 opposite the orifice 27. The anode, for example, is a mesh grid which is supported by mounting means not shown here in detail. The intensity of the flow is controlled by the potential of this anode.

The sphere 26 has in the region of the orifice 27 an appreciable wall thickness whereby the orifice 27 has an appreciable length parallel to the direction of desired electron flow. The orientation of the wall surface 31 of this orifice is important in determining the direction of flow of the emitted electron beam. For parallel flow, the wall surface 31 is everywhere parallel to the direction of desired flow. The relationship between the diameter D of the orifice 27 and the length L of this wall surface determines to a considerable extent the current distribution across the beam. The larger the ratio D/L the sharper the current density increases with increasing distance from the center of the beam over a considerable region. Additionally aligned with the inten-

sity control anode 24 and the orifice 27, there is supported an accelerating electrode 33 which preferably is maintained at the potential V_0 which is to be the mean potential acting on the electron beam in its flow past the interaction circuit.

The focusing structure comprises a bifilar helix including conductors 35, 36. The bifilar helix is wound to a pitch and of a diameter which adapts it for focusing in accordance with the principles set forth above. The conductors 35 and 36 are maintained, respectively, at

potentials V_0+V_f and V_0-V_f in accordance with these principles by connections to appropriate taps on a voltage supply 37. Additionally, the bifilar helix serves as the interaction circuit for propagating a radio frequency wave in coupling relation with the electron beam. To this end, the conductors 35 and 36 are formed as continuations of a balanced pair transmission line in the manner described in the aforementioned Pierce application. Such a traveling wave tube is adapted for operation in either a forward or backward mode of wave interaction as described therein. For the backward mode of operation illustrated here, input waves are applied to the collector end of the bifilar helix by coupling to the input balanced pair transmission line 39 and output waves are abstracted at the electron source end of the bifilar helix by coupling to the output balanced pair line 38. In such operation, adjacent turns of the two conductors 35 and 36 are operated at radio frequency potentials approximately π radians apart whereby the bifilar helix acts as a helically wound balanced pair line. As described in the above-identified Pierce application, such a bifilar helix is well adapted to serve as a circuit for propagating a radio frequency wave for interaction with the electron beam in the manner characteristic of traveling wave tubes. It is, of course, possible to couple to the bifilar helix interaction circuit in a variety of other ways. For example, the coupling may be provided by means of a second bifilar helix wound external to the tube envelope in a direction opposite to that of the first helix but coaxial therewith and to have a similar phase velocity. Additionally, the two conductors although operated at different D. C. potentials for focusing, may be operated at substantially similar radio frequency potentials and phases whereby the two conductors serve essentially as a parallel arrangement of two helix interaction circuits. Such an arrangement is best adapted for operation in a forward wave mode, of amplification.

Alternatively, the traveling wave tube shown in Fig. 2 can be modified to incorporate therein an electron gun 40 of the kind shown in Fig. 3 and which forms a specific feature of the present invention. This gun would replace the gun 22 and accelerating anode 33 shown in tube 20.

With reference now to Fig. 3, the electron gun 40 includes a cathode assembly 41, a beam forming electrode 42, and an electrode system 43 for converging the electrons emitted into a beam having the desired current distribution and gradually accelerating the flow preliminary to its injection into the region where the bifilar helix serves as the focusing structure.

The cathode assembly 41 comprises a hollow cylindrical member 44 closed at one end. The external surface of this closed end is coated with electron emissive material to form a circular cathode 45. Enclosed within the cylindrical member 44 is the heater 46.

The cathode assembly 41 and the beam forming electrode 42 are of the kind found in the usual Pierce-type electron gun. The electrode system 43, however, is not of the kind characteristic of electron guns which seek to achieve a beam of uniform density in cross section, but rather comprises a series, for example five, of annular electrode members or rings 47A through 47E spaced apart substantially uniformly in the direction of desired flow for surrounding symmetrically the path of flow. The successive rings have their inner diameters graduated in size, decreasing with distance in the direction of flow whereby the electron flow may be converged. Advantageously, the inner surfaces 48 of the rings are sloped to be approximately parallel to the desired envelope of the converging electron beam. Smooth convergent action is achieved both by proper dimensioning of the successive rings and by maintaining successive rings at D.-C. potentials which provide spatially alternating electrostatic field regions. To this end, successive rings are maintained alternately positive and negative with respect to the mean potential of adjacent pairs of rings.

Additionally, in order to achieve a gradual acceleration of the beam, the mean potential of adjacent pairs of rings is gradually increased. The potentials desired are achieved by connections to suitable taps of the voltage supply 49. Fig. 4 is a plot of the potential V acting on the beam as a function of the distance z from the cathode along the path of flow. The successive peaks and modes A, B, C, D, E, correspond respectively, to the potentials of successive rings 47A through 47E. It is characteristic of an electrode system of this kind, that it results in an electric field distribution transverse to the electron beam in which the electric field is strongest at the beam edges rather than being uniform across the beam. Accordingly in converging the flow emitted from the cathode the increase in average current density is achieved primarily by increasing the current density at the beam edges. Accordingly, there is provided an electron beam which is well suited for being focused by a periodic electrostatic field, and also well suited for use in a traveling wave tube of the kind shown in Fig. 2.

An analysis of the current distribution desired across a beam which is to be focused electrostatically, as defined by Equation 16, indicates that the current density at the center of the stream is preferably rather small, generally only a few percent of the average current density. This suggests that this type of focusing has special applicability to hollow beams. An important advantage to the use of a hollow beam is that an electrode, such as a single wire helix, can be interposed inside the beam to propagate the electromagnetic wave for interaction with the beam while a bifilar helix or a succession of rings can be disposed around the beam for focusing.

Fig. 5 shows as an illustrative embodiment of this aspect of the invention a traveling wave tube 50 which utilizes a hollow beam and an inner single wire helix as a slow wave circuit and an outer bifilar helix for focusing the outer boundary of the electron beam in accordance with the principles developed above. An evacuated glass envelope 51 houses the various tube elements. At one end, an electron gun 52 serves as the source of a hollow electron beam. A modification of this gun will be described in greater detail hereinafter. At the opposite end, a target electrode 53 collects the spent electrons after their traversal through the tube. A bifilar helix including conductors 54 and 55 surrounds the desired path of flow for focusing the outer boundary of the stream. A single wire helix comprising the conductor 56 is enclosed by the desired path of flow and serves to propagate the slow wave for interaction with the electron flow. For coupling to external wave guiding elements, the helix 56 is joined at opposite ends to an input coupling strip 57 by an impedance matching section 58 and to an output coupling strip 59 by an impedance matching section 60. These matching sections 58 and 60 are simply extensions of the conductor 56 in which the pitch of the helix is gradually increased. An input wave is applied to the upstream end of the helix 56 by way of input wave guide coupling connection 61 and the output wave is abstracted at the downstream end of the helix 56 by way of output wave guide coupling connection 62 in the manner well known to workers in the art.

In order to utilize the bifilar helix as a focusing structure, the two conductors 54 and 55 are maintained at potentials V_0+V_f and V_0-V_f , respectively, by suitable lead-in connections from taps on a D.-C. voltage supply 63 where the values of V_0 and V_f are chosen as discussed hereinabove. By this arrangement, the focusing of the outer boundary of the electron stream can be achieved.

Additionally, in the case of a hollow beam it becomes necessary to stabilize the inner boundary of the stream. To this end, the inner helix 56 is maintained at a potential V_c which is less than the average potential V_0 of

the outer helix and the potential difference ΔV therebetween produces a radial component of electric field which sets up a radially outward force which is used to balance the inner boundary of the stream.

Let us now analyze the problem of maintaining the stability of the inner boundary of a hollow electron beam, which has an inner radius r_b and an outer radius r_d . Consider a solid beam of the desired current distribution for electrostatic focusing of radius r_d . Since the beam is solid there is some current flow inside the portion corresponding to a cylinder of radius r_b . Now suppose we remove the current inside the cylinder of radius r_b to form a hollow beam having an inner radius r_b and replace the space charge force which existed at the inner boundary in the presence of this cylinder of current by an equivalent force provided by a radial component of electric field. Then electrons at the inner boundary of the hollow beam are subjected to the same forces they experienced when part of the stable solid beam, and accordingly they will remain well stabilized.

The potential of the inner helix 56 is adjusted in accordance with the principles just set forth in order that the potential difference between it and the mean potential of the bifilar helix provides a radially outward force which simulates the space charge radially outward force that would have existed had the beam been solid.

By analysis it can be shown that the potential difference ΔV desired is given by

$$V = \frac{I_b}{v_0 \epsilon 2\pi} \ln \frac{c}{d}$$

where I_b is the current to be found in a cylinder of radius b (where b is the inner radius of the hollow beam) in a solid beam suited for periodic electrostatic focusing of radius d ; c is the radius of the bifilar helix; and d is the outer radius of the hollow beam. The value of I_b can be found by integration processes when the electron beam has substantially current distribution defined by Equation 16 which set forth the desired current distribution.

The inner helix 56 is maintained at the desired potential V_c by lead-in connections from a suitable tap on D.-C. voltage supply 63.

As has been indicated above, it is advantageous for optimum operation of the focusing arrangement described that the current distribution in the hollow beam to be focused increase with increasing distance from the beam axis.

However, in the case of a thin hollow beam, this factor is not particularly important and conventional electron gun arrangements can be utilized for providing a suitable electron beam. However, for a hollow beam of appreciable wall thickness, as in the case of a solid beam, provision should be made for approximating the desired current distribution for optimum operation.

One way of achieving a suitable hollow beam is by use of a hollow-cathode type of electron gun of the kind incorporated in the tube shown in Fig. 2. By increasing the ratio of the orifice diameter D to the orifice length L sufficiently, there can be achieved an electron beam which is substantially hollow and in which the current density increases towards the outer edge over a considerable region. However, in accordance with another feature of the invention, to this same end there is provided a novel electron gun which represents a modification of the electron gun shown in Fig. 3. One form of this gun 52 is shown in Fig. 5 and another form of this gun 52 is shown in more detail in Fig. 6.

With reference now to Fig. 6, the electron gun 52 comprises a conventional cathode assembly 81 which includes an annular emissive cathode 82 and a heater 83, and a conventional beam forming electrode which includes the outer annular member 84 and the inner member 85, and an electrode system 86 which converges the electrons emitted into an annular beam in which the

current density increases with increasing distance from the beam axis as is advantageous for periodic electrostatic focusing and which accelerates the flow gradually in a manner to preserve this current distribution. The electrode system 86 comprises a succession of annular electrodes or rings 87 of the kind which characterizes the electron gun shown in Fig. 3 and additionally includes a corresponding succession of inner electrode members 88 which are inclosed by the annular beam.

The outer rings 87 are aligned along the path of flow and have their inner diameters gradually decreased with distance away from the cathode. Additionally, the slope of the inner surfaces of these rings is adjusted to be parallel to the envelope of the converging beam. The potential distribution of the succession of rings is substantially as shown in Fig. 4 for the case of the solid beam.

The inner electrode members 88 are spaced apart along the path of flow to have positions opposite the outer rings 87. A potential difference is maintained between each inner electrode member and its corresponding ring in order to preserve the inner boundary of the flow as the beam is converged. The potential distribution along the succession of rings is substantially of the same kind as is shown in Fig. 4, the potential of each inner electrode member 88 being in each instance slightly less than the potential of the corresponding ring 87 whereby the potential difference sets up a radially outward force to maintain the inner boundary of the stream. Here too, the slope of the surface of the inner electrode members adjacent the electron beam is adjusted to be parallel to the envelope of the converging beam.

It is to be understood that the various embodiments described are illustrative of the principles of the various features of the invention. Various other arrangements can be devised by one skilled in the art without departing from the scope of the present invention. For example, various other forms of interaction circuits can be utilized in conjunction with focusing systems for providing the desired axially symmetric periodic electric fields. Moreover, these focusing principles can be applied to various forms of traveling wave tubes.

What is claimed is:

1. An electron gun for providing an electron beam in which the current increases with distance from the beam axis over substantially the entire beam cross section comprising an electron emissive cathode, a beam forming electrode spaced adjacent to the cathode along the path of desired flow for shaping the electrons emitted into a beam, a succession of cylindrical annular electrodes spaced apart along and surrounding the path of desired flow, successive annular electrodes having their inner diameters decreasing with increasing separation from the cathode for converging the electron beam, the inner surface of each of said annular electrodes being substantially parallel to the envelope of the converging beam, and means for maintaining successive electrodes at potentials alternately positive and negative with respect to the electrodes proximate thereto, the mean potential of adjacent pairs of electrodes increasing with increasing distance from the cathode.

2. An electron gun for providing a hollow electron beam having a cross-sectional current density which increases with increasing distance from the beam axis over substantially the entire beam cross section comprising an annular electron emissive cathode, beam forming electrode means spaced apart from said cathode along the direction of desired flow, a succession of annular electrodes spaced apart along and surrounding the path of flow, the inner diameter of successive annular electrodes decreasing with increasing separation from the cathode, a succession of inner electrodes spaced apart along and surrounded by the path of flow, and means for establishing a radial electric field between the succession of annular electrodes and the succession of inner

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electrodes and a spatially alternating electric field between the succession of annular electrodes.

3. An electron gun in accordance with claim 2 wherein said beam forming electrode means includes means for forming said electron beam into an annular beam.

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