May 12, 1959 | P. K. TIEN | 2,886,738

ELECTRON BEAM SYSTEM

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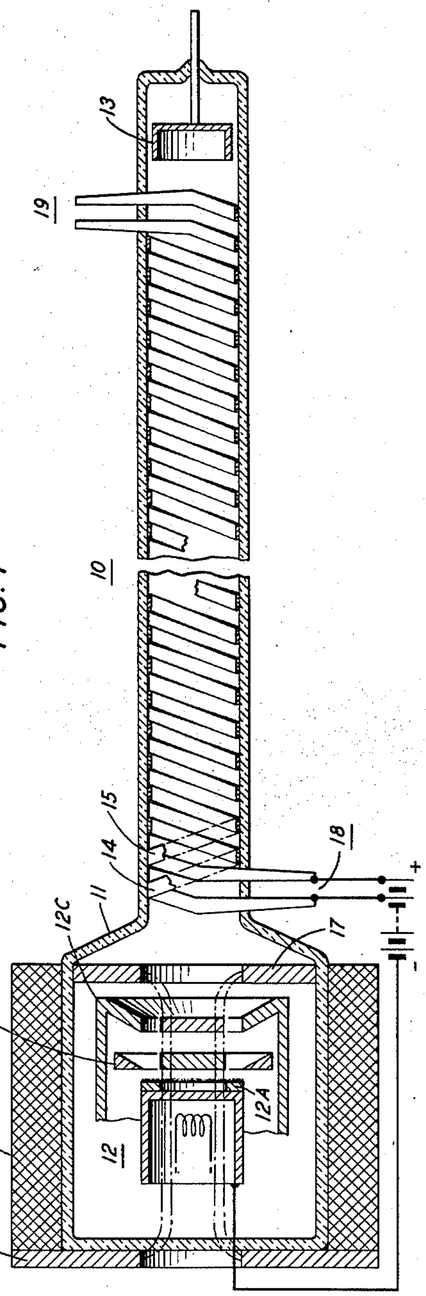

FIG. 1

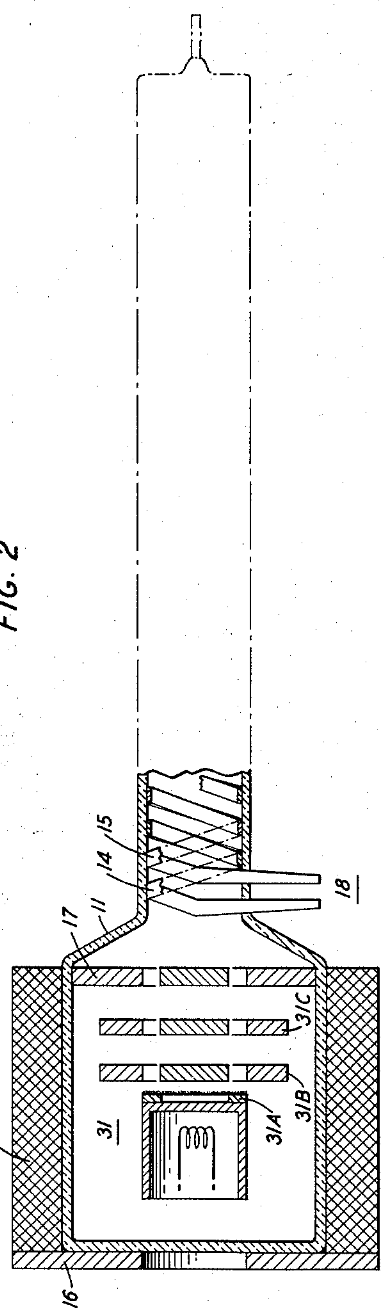

FIG. 2

INVENTOR
P. K. TIEN
BY
Arthur J. Torsiglieri
ATTORNEY

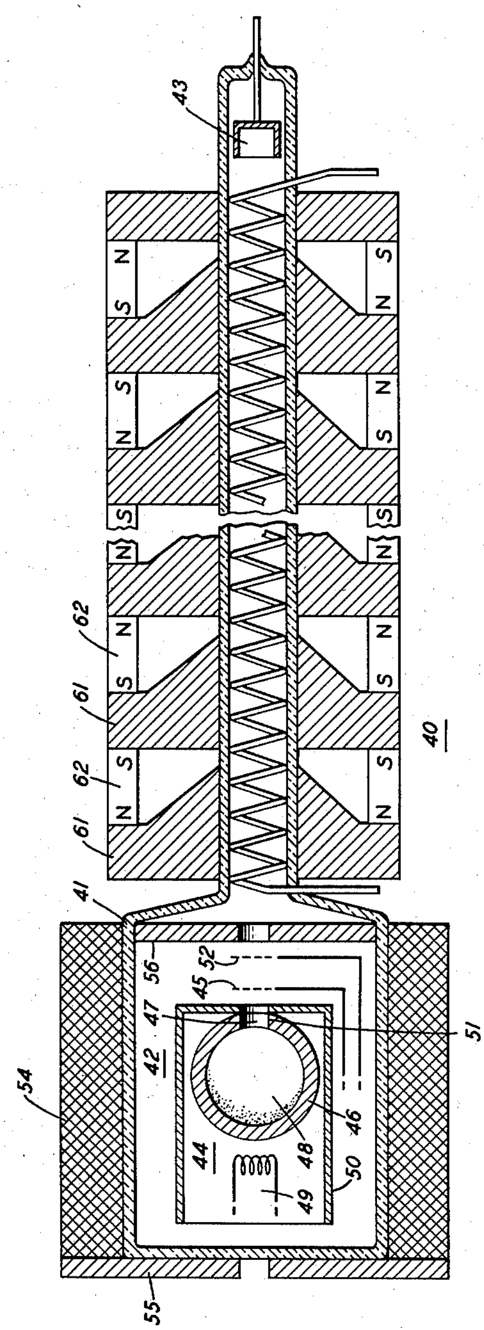

FIG. 3

INVENTOR
P. K. TIEN
BY Arthur J. Torsiglieri
ATTORNEY

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ELECTRON BEAM SYSTEM

Ping K. Tien, Chatham Township, Morris County, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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This invention relates to electron beam systems, and more particularly to systems for focusing an annular electron beam over a relatively long path.

One object of the present invention is to facilitate the focusing of annular electron beams.

Typically, the invention finds application in electronic devices such as traveling wave tubes in which an electron beam is made to flow past a wave interaction circuit for a distance a plurality of operating wavelengths long whereby the beam and a wave propagating along the circuit interact, the beam being velocity and density modulated and the wave being amplified. In such devices, it is desirable to keep the beam flowing close to the circuit where the electric field components of the wave are high and yet to avoid having the beam impinge on the circuit, since such impingement results in a loss of efficiency and noisy operation, and may even damage the circuit. Such flow is most conveniently achieved if the electron beam is kept cylindrical. However, in an electron beam, space charge forces are present which tend to make it diverge. Accordingly, it is generally advantageous to exert on the beam focusing action of some kind to overcome the space charge forces if the beam is to be kept cylindrical.

Various expedients have been utilized hitherto to provide this focusing action. Early arrangements employed a uniform longitudinal magnetic field along the path of flow for focusing the beam. However, except at the shorter wavelengths where a short electron path is sufficient, the auxiliary equipment needed to create such a field has generally been of such weight and size as to make this unattractive. Accordingly, efforts have continuously been directed at alternative arrangements. Among those appearing most attractive at first sight are arrangements described in a paper entitled "Axially Symmetric Electron Beam and Magnetic Field Systems," by L. A. Harris, published in the Proceedings of the IRE, June 1952, pp. 700–708. Therein it is proposed that an electron beam can be focused by making it annular, giving it a rotational component, and then projecting it through an annular passage formed between two coaxial cylindrical electrodes which are maintained at different D.-C. potentials for establishing a radially inward electric field across the passage. The motion of the electrons is sought to be stabilized by maintaining a balance between the radially outward centrifugal forces arising from the rotational component of the annular beam, the radially outward space charge forces in the annular beam, and the radially inward forces set up by the radial electrostatic field between the two cylindrical electrodes defining the beam's annular path.

However, it develops that this technique, although possessing certain desirable characteristics, has several shortcomings.

First, it is found that establishing a potential difference between the two cylindrical electrodes complicates the potential distribution inside the gun structure, which structure is necessarily positioned in a region adjacent the cylindrical electrodes, and as a result a distortion of the

electron trajectories in this preliminary region of the beam path is difficult to avoid.

Additionally, another problem arises in maintaining the electron dynamics in a stable condition across the entire cross section of the beam. For an understanding of this problem, consider the following analysis of the forces on the beam. The radially inward force acting on each electron as a result of the radial electrostatic field decreases gradually with increasing radial distance because of the increasing separation from the more positively charged inner electrode. The radially outward centrifugal force acting on each electron because of its orbital motion decreases gradually with increasing radial distance since the rotational component is imparted by a radial magnetic field density which decreases with increasing radial distance whereby the outer electrons are given a slower angular velocity than the inner electrons. The radially outward space charge force in a beam of uniform current density increases sharply with increasing radial distance. As a result, in such a beam it would be difficult to maintain a balance over its entire cross section. To avoid this problem, in such prior art arrangements, the annular beam is made to have a current density which decreases sharply with increasing radial distance whereby the space charge forces increase only gradually with increasing radial distance. The requirement of such a current density distribution limits the available electron gun structures which can be profitably employed and makes the design of the gun structure difficult.

Moreover, another shortcoming of such prior arrangements is that at the shorter wavelengths where the physical dimensions of the various tube elements are necessarily quite small it becomes a difficult practical matter to provide an electrode within the annular path of flow to establish radial electrostatic fields.

The present invention relates to basic modifications of the above-described arrangement which largely obviate the difficulties discussed.

In accordance with one feature of the invention, along the initial portion of the path of flow there is positioned a magnetic flux producing means adapted to provide a region of longitudinal magnetic field followed by a region of radial or transverse magnetic fields. The electron source is positioned in the region of longitudinal magnetic field whereby the electron beam is magnetically confined for the initial portion of its path of travel. Thereafter, the electron beam before entering into a region of spatially alternating field passes through the region of radial magnetic field where it is given a rotational component. Such an arrangement serves to minimize radial components in the annular beam preliminary to its injection into a region of spatially alternating fields and to provide rotational components to the electrons in the beam. Additionally, in contradistinction to the prior art arrangements described the radial magnetic field density is adjusted to increase with increasing radial distance whereby the outer electrons in the beam are given a larger rotational component. As a result, the radially outward centrifugal forces present in the beam increase gradually with increasing radial distance.

Another feature of the invention is the combination of a spinning annular beam with a time-constant spatially alternating longitudinal field, either electric or magnetic. Such a spatially alternating field can be made to apply radially inward forces on an electron beam which are appreciably larger on the outer electrons of the beam than on the inner electrons. By utilizing such a spatially alternating field, the radially inward electrostatic forces resulting therefrom, the radially outward centrifugal forces and the radially outward space charge forces may be balanced over all of the cross section of the beam, even in cases where the electron beam is of substantially uniform current density over the cross section of the beam and so where the space charge forces increase sharply with radial distance. This simplifies the design of a suitable electron gun.

A further advantage in such novel combinations which utilize a spatially alternating longitudinal field in combination with an annular beam having a rotational component is the elimination of the need for an axially displaced electrode within the annular beam since such a field may be achieved without any inner electrode. In such a combination the inner boundary of the annular beam is maintained as a result of the balance between the outwardly directed centrifugal force of the spinning electrons and the inwardly directed force occasioned by the spatially alternating focusing field. The outwardly directed space charge force at the inner boundary of the annular beam is ordinarily small enough to be neglected. This elimination of the necessity for an axially disposed electrode results in a simplification of the fabrication problems.

As indicated above, the spatially alternating field can be either magnetic or electrostatic. An electrostatic field of the kind desired can, for example, be obtained by utilizing a bifilar helix whose two conductors are maintained at different D.C. potentials. Such a bifilar helix can advantageously be employed simultaneously as the wave circuit for propagating the electromagnetic wave for interaction with the beam. Alternatively, a spatially alternating magnetic field of the kind desired can be achieved, for example, by spacing along the path of flow a series of annular magnetic members for serving as pole pieces and poling successive members oppositely.

Various electron gun structures can be utilized for providing the annular electron beam for projection along the region of spatially alternating fields. In specific embodiments to be described, annular electron beams are provided by a hollow-cathode type gun, an electron gun comprising a planar cathode and two apertured planar electrodes, and a so-called Pierce-type gun. Each of these guns is modified from their usual form to provide annular electron beams.

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

Figs. 1 and 2 each show, in longitudinal cross-sectiontional view as illustrative embodiments of the invention, bifilar helix-type traveling wave tubes in which spinning annular beams are focused by spatially alternating electrostatic fields; the two tubes differing in that the first employs a modified Pierce-type electron gun to provide the annular beam and the second utilizes a planar cathode and two apertured planar electrodes; and

Fig. 3 shows, in longitudinal cross-sectional view as another illustrative embodiment of the invention, a helix-type traveling wave tube in which a spinning annular beam supplied by a hollow-cathode type gun is focused by a spatially alternating magnetic field.

Referring now more particularly to the drawings, in the traveling wave tube 10 shown in Fig. 1, an evacuated glass envelope 11 houses the various tube elements. At one end of the envelope, an electron gun 12 of the type generally designated as the Pierce-type serves as the electron source for providing an annular beam of substantially uniform density over its cross section. The design considerations of such a gun are described in detail in United States Patents 2,268,196 and 2,268,197 which issued on December 30, 1941, to J. R. Pierce. The gun comprises the annular cathode 12A, the annular beam-forming electrode 12B, and the annular accelerating anode 12C. Magnetic materials are avoided in the gun. Consistent with the principles set forth in the above-identified patents, the surfaces of electrode 12B and anode 12C are of such configuration that therealong in the presence of complete space charge the electric field perpendicular to a line extending normal to the emissive surface of cathode 12A is zero. The electrode 12B and the anode 12C each include a central or inner portion and an outer portion defining annular passages therethrough for the annular beam. Each of these inner portions is advantageously planar normal to the path of flow. By the inclusion of such portions, the usual form of Pierce gun may be advantageously modified for providing an annular beam of uniform current density. In operation, the cathode 12A is maintained at reference potential, the electrode 12B at the potential slightly negative thereto, and the anode 12C at a positive potential thereto. In the interest of simplicity lead-in connections to such elements have not been shown.

At the opposite or downstream end of the envelope in target relationship with the gun is the collector 13 which collects the spent electrons. Throughout the specification the term "downstream" is used to denote a point or location closer to the collector than the point or location with which it is being compared. Conversely, the term "upstream" denotes a point or location closer to the electron gun than the point with which it is being compared. Intermediate the gun and the collector along the path of flow is positioned a bifilar helix comprising helical ribbon conductors 14 and 15. The helical conductors are supported by the walls of the tube envelope and aligned to be coaxial with the annular electron beam whose path of flow is surrounded by the conductors. In order to achieve a spatially alternating electrostatic field in accordance with one characteristic of the invention, the two helices are maintained at different D.C. potentials positive with respect to the cathode 12A by suitable lead-in connections (not shown for the sake of simplicity).

Additionally, a magnetic flux producing means, such as the solenoid 20, is positioned adjacent the source or upstream end of the path of flow. Such means serves a dual purpose. First, it provides a longitudinal magnetic field in which the electron gun is immersed to confine the beam from the time when it is first emitted from the cathode and until it is to be confined by the periodic fields. Also, it provides a transverse component of magnetic field just before the beam enters the region of periodic electrostatic field in order to impart a rotational component to the beam. In this arrangement, since the density of the radial magnetic field increases with radial distance from the axis, the outer electrons will get a faster angular rotation and so have a larger centrifugal force acting on them. To shape the magnetic flux to the desired configuration, two annular disks 16 and 17, of highly permeable material such as kovar, are positioned transverse to the path of flow, extending as pole pieces from the solenoid. In the arrangement shown, the disk 16 is external and disk 17 internal the tube envelope. By properly positioning these pole pieces the magnetic flux linking the two through the air gap is shaped to be longitudinal when it passes through the cathode and the annular openings in the beam shaping electrode and accelerating anode, and to be transverse at the region where the electron beam passes the disk 17 and enters into the region of alternating field. In Fig. 1, a typical magnetic flux pattern is shown by the broken lines.

The magnetic disk 17 along the path of flow is preferably maintained, by a lead-in connection not shown, at the potential of one of the two helical conductors, for example the conductor 15, and so cooperates therewith for forming the first half period of the alternating field. The average potential of the two helical conductors with respect to the cathode determines the longitudinal velocity of the beam past the conductors 14 and 15. The two conductors preferably are also of non-magnetic material.

In operation, electrons emitted from the cathode 12A are formed into an annular beam by the action of the beam forming electrode 12B and accelerated towards the accelerating anode 12C. The electrons are confined to longitudinal paths with a minimum of transverse components in following the longitudinal magnetic lines through this gun region. As they approach the pole piece **17**, where the magnetic flux acquires a transverse direction, they are given a rotational component which sets them spinning with an angular velocity which is determined by the strength of the magnetic field. Once beyond the region of transverse magnetic field, the spinning electron beam is focused by the spatially alternating electrostatic field existing therebeyond. A spatially alternating field of this kind can be shown to provide a net convergence force on the beam. A quantitative analysis of the effect of such a field is set forth in my U. S. Patent 2,843,776, issued July 15, 1958. Moreover, it is found that this force increases sharply with increasing radial distance from the axis of the bifilar helix up to a radius equal to the radius of the bifilar helix.

The bifilar helix formed by conductors **14** and **15** is well adapted for serving as a wave circuit for propagating waves for interaction with the electron flow. Such a circuit may be operated either in a forward wave mode, as is characteristic of the usual traveling wave amplifier, or in a backward wave mode as is characteristic of a backward wave oscillator and backward wave amplifier. The general principles of both such types of operation are set forth in my above-mentioned patent.

For purposes of illustration, the tube shown is designed for operation as a forward wave amplifier. To this end, the input wave to be amplified is applied to the electron source end of the bifilar helix and the output wave is abstracted at the collector end. Input and output wave coupling connections **18** and **19**, respectively, are shown schematically for purposes of simplicity. A suitable arrangement for coupling rectangular wave guide connections to such a bifilar helix traveling wave tube is described in U.S. Patent 2,846,613, issued August 5, 1958, of J. R. Pierce.

Various modifications of this described embodiment are possible. It may, for example, be advantageous for higher density electron beams to utilize an electron gun which provides conical flow initially. In this instance, the pole pieces associated with the flux producing means are shaped and positioned to provide in the region between the cathode and the start of the periodic field a confining magnetic field which has both a longitudinal and transverse component. Additionally, the beam focusing electrode and accelerating anode forming the gun electrode system similarly should have surface configurations suitable for cooperating with the magnetic field in keeping the flow uniformly conical preliminary to its being made cylindrical for flow through the region of periodic fields. Various forms of electron guns can be employed. There is described hereinafter tubes incorporating alternative forms of electron guns. Additionally, the periodic electrostatic field can be achieved by a succession of spaced cylindrical disks maintained at appropriate potentials and surrounding the path of flow. In such an instance, an interaction circuit separate from the focusing structure, such as a single wire helix, may be employed to propagate the traveling wave for interaction with the flow.

In Fig. 2 there is shown a bifilar helix-type traveling wave tube **30** differing from tube **10** shown in Fig. 10 essentially only in the electron gun structure. The same reference numerals are used to designate corresponding elements, and accordingly only the electron gun reference numerals are different. Tube **30** incorporates an electron gun **31** which comprises a planar annular cathode **31A** and two spaced annularly apertured planar electrodes **31B**, **31C**, each having coplanar inner and outer portions. The gun **31** is immersed in a longitudinal magnetic field provided between the pole pieces **16** and **17** associated with solenoid **20**. Each of the two apertured electrodes **31B**, **31C** serves as an electron lens. As is described in greater detail in an article by J. R. Pierce entitled "A Gun for Starting Electrons Straight in a Magnetic Field," in volume 30, page 825 of the Bell System Technical Journal, by properly choosing the spacing between and the potentials of electrodes **31B** and **31C** the electron beam emerging beyond the electrode **31C** can be made to have no radial components. For use with such an electron gun, the pole piece **17** can advantageously be provided with inner and outer portions defining an annular opening for passage of the annular beam. As with tube **10**, the potential of this pole piece can be chosen so that the pole piece can cooperate with the bifilar helix in forming the periodic electrostatic field.

As has been indicated above, the spinning annular electron beam can be focused in accordance with the principles set forth by utilizing a time-constant spatially alternating magnetic field in place of the time-constant spatially-alternating electric field. In Fig. 3 there is shown, as another illustrative embodiment of the invention, a traveling wave tube **40** utilizing a periodic magnetic field along the path of flow for focusing the spinning annular beam. At one end of the evacuated glass envelope **41**, a hollow cathode-type electron gun **42** serves as the source of an annular electron beam which is directed along the tube axis towards a target **43** at the opposite end which collects the spent electrons. The electron gun comprises essentially a cathode assembly **44** and an intensity control element **45**. The cathode assembly **44** includes a hollow sphere **46**, for example of nickel, which is enclosed except for a circular orifice or aperture **47**. The internal surface of the sphere is coated with a layer **48** of electron emissive material. Electron emission from the layer **48** exits via the orifice **47** which communicates between the hollow interior of the sphere and the exterior. A heater **49** is mounted in heat transfer relation with the sphere. The heater **49** and the sphere **46** are enclosed within a heat shield **50** to insure efficient heating. The electrode **45** is positioned adjacent the sphere opposite the orifice **47**. The electrode **45**, for example, is a mesh grid supported by mounting means not here shown. The beam intensity is controlled by the potential of this electrode. The various lead-in connections have been omitted in the interest of simplicity. Hollow-cathode type guns of this kind are described in more detail in U.S. Patent 2,810,088, issued October 15, 1957, of D. MacNair.

The sphere **46** has in the region of the orifice **47** an appreciable wall thickness. The orientation of the wall surface **51** of the orifice is important in controlling the direction of electron emission. For achieving a cylindrical annular beam, the wall surface **51** should be everywhere parallel to the direction of desired flow. The relationship between the diameter D of the orifice **47** and the length L of the wall surface **51** largely determines the current distribution across the beam. For sufficiently large values of D/L the emission is substantially annular. Additionally, aligned with the orifice **47** and the intensity control electrode **45** there is supported an accelerating anode **52**.

In accordance with one characteristic of the invention, to maintain the beam cylindrical and to impart a rotational component thereto, the electron gun **42** is immersed in a magnetic field. To this end, there is positioned, preferably external to the tube envelope **41**, flux producing means, such as a solenoid **54**, with which are associated two annular magnetic disks **55**, **56** for serving as pole pieces as described in conjunction with the tube shown in Fig. 1. The magnetic field configuration is adjusted by properly positioning and dimensioning such pole pieces **55**, **56** so that the field is longitudinal through the cathode assembly **44** and past the intensity control electrode **45** and accelerating electrode **52** and becomes transverse therebeyond for imparting a rotational component to the beam as it passes through the annular pole piece **56**. This pole piece is preferably maintained at the same positive potential to be used on the wave interaction circuit for establishing the longitudinal velocity of the beam therepast.

The spinning electron beam is thereafter focused by a time-constant spatially alternating magnetic field. To this end, a succession of annular elements **61**, of a magnetic material such as soft iron, are spaced apart along the path of flow and surrounding the tube envelope for serving as pole pieces. A succession of annular cylindrical permanent magnets **62**, magnetized in an axial direction, are positioned along the path of flow for bridging successive pairs of pole pieces **61**. Successive magnets are reversed in sense as shown whereby successive pole pieces are poled oppositely. In this way, a spatially alternating magnetic field can be achieved along the path of flow which will provide a net converging force on the annular beam. Various other arrangements for achieving a suitable spatially alternating magnetic field, together with an analysis of the converging forces provided by such fields, are found in U.S. Patent 2,847,607, issued August 12, 1958, of J. R. Pierce.

In a tube of this kind, the wave transmission circuit can be chosen independent of the focusing requirements. In the tube shown, a single wire helix **63** is used as the interaction circuit. Such a helix probably forms the most common type of interaction circuit used in traveling wave tubes and its operation is now well understood by workers in the art. The helix is supported by the glass envelope and is coaxial with the annular beam which flows closely past its interior surface. The helix potential is adjusted by means not shown to provide an accelerating field on the beam which gives it a longitudinal velocity suitable for interaction with the traveling wave. Moreover, the winding pitch of the helix provides a measure of control of the phase velocity of the beam. In choosing the helix pitch and helix potential suitable for optimum interaction, a suitable correction for the angular velocity of the electron beam will probably need to be made. Input and output wave coupling connections to the helix circuit, shown schematically here, can be of conventional form, suitably modified for the presence of the magnetic structure. Arrangements which permit extending the spatially alternating magnetic fields as close to the electron source as desired in the presence of input and output connections are described in the aforementioned Pierce patent. In the tube shown, a permanent magnet can be bridged between the pole piece **56** and the first of the pole pieces **61** to start the periodic longitudinal magnetic field in the beam path region immediately beyond the pole piece **56**.

It is to be understood that the various embodiments which have been shown are merely illustrative of the general principles of the invention. Various modifications will be evident to workers skilled in the art without departing from the spirit and scope of the invention. For example, it should be obvious that the focusing principles of the invention can be utilized in electronic devices, other than traveling wave tubes, which utilize relatively long electron beams whose flow should be kept cylindrical.

What is claimed is:

1. In an electron beam system, an annular electron source and a target electrode defining therebetween a path of flow for an annular electron beam, means adjacent the source end of said path for confining the electron beam and imparting a rotational component thereto, and means downstream along the path with respect to said first mentioned means for forming a field which is constant with time and spatially alternates in direction along the path of flow for focusing the annular electron beam.

2. In an electron beam system, an electron source and a target electrode for defining therebetween a path of flow for an annular electron beam, flux-producing means adjacent the electron source end of the path for forming a longitudinal magnetic field along the initial portion of the path of flow for confining the electron beam and forming at a region downstream from said initial portion a transverse magnetic field across the path of flow for imparting a rotational component to the electrons in the beam as they travel therethrough, and means along the path of flow downstream with respect to said flux-producing means for providing a field which is constant with time but spatially alternates in direction along the path of flow for focusing the annular electron beam.

3. In combination, an electron source and a target electrode for forming a path of flow of an annular electron beam, flux-producing means adjacent the upstream end of the path of flow for confining the electron beam in the initial portion of its path of flow and imparting a rotational component to the beam at a subsequent point in its path of flow, and periodic focusing means for forming a periodic field having a succession of field regions along a portion of path of flow downstream of said subsequent point for focusing the electron beam, the sense of adjacent field regions of the succession being opposite.

4. An electron beam system according to claim 3 in which the periodic focusing means includes a plurality of spaced annular magnetic members surrounding the path of flow and permanent magnet means for poling successive members oppositely.

5. In combination, an electron source and a target for defining therebetween a path of flow of an annular electron beam, flux-producing means positioned upstream along the path of flow for providing a longitudinal magnetic field along the initial portion of the path of flow and downstream therefrom a transverse magnetic field across the path of flow for imparting a rotational component to the electrons in the beam, and means downstream from said flux-producing means for forming a succession of electrostatic field regions along the path of flow, the sense of adjacent field regions of the succession being opposite.

6. An electron beam system in accordance with claim 5 in which the last-mentioned means includes two helical conductors arranged to form a bifilar helix and means for maintaining different D.-C. potentials on the two conductors forming the bifilar helix.

7. In a traveling wave tube, means forming a finite region of unidirectional longitudinal magnetic field and a region of transverse magnetic field, means forming a finite region of spatially alternating longitudinal field contiguous with said region of unidirectional longitudinal magnetic field, an electron gun positioned in the region of unidirectional longitudinal magnetic field and spaced upstream from the region of transverse magnetic field for providing an annular electron beam, and a wave interaction circuit positioned downstream of the region of transverse magnetic field in the region of spatially alternating field for propagating an electromagnetic wave in coupling relation with the electron beam.

8. A traveling wave tube according to claim 7 in which the electron gun comprises an electron emissive cathode, a beam forming electrode and an accelerating anode.

9. A traveling wave tube according to claim 7 in which the electron gun comprises a planar cathode and at least two spaced planar electrodes apertured for passage therethrough of the electron beam.

10. A traveling wave tube according to claim 7 in which the electron gun includes a spherical hollow cathode.

11. In combination, an electron gun and a target for defining therebetween a longitudinal path of flow for an annular electron beam, flux-producing means adjacent the electron source end of the longitudinal path for immersing the electron source and an initial portion of the longitudinal path in a unidirectional longitudinal magnetic field and for providing a transverse magnetic field across an intermediate portion of the longitudinal path of flow, and means for forming a field which is spatially

alternating in direction along the portion of the path of flow downstream of said intermediate portion.

12. A combination according to claim 11 which includes means forming a path for electromagnetic waves along the portion of the longitudinal path of flow downstream of said intermediate portion.

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