Oct. 7, 1958 J. T. MENDEL 2,855,537

ELECTRON BEAM FOCUSING

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FIG. 1

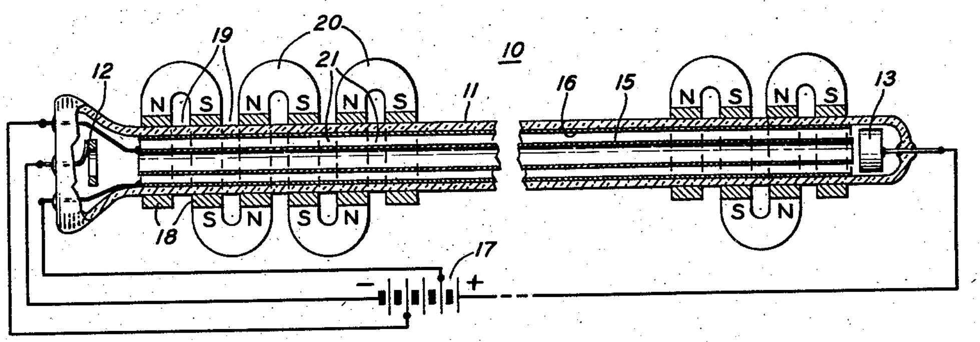

FIG. 2

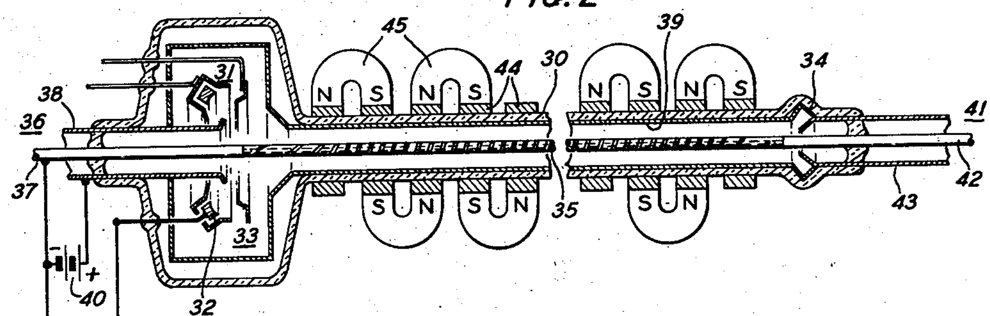

FIG. 3

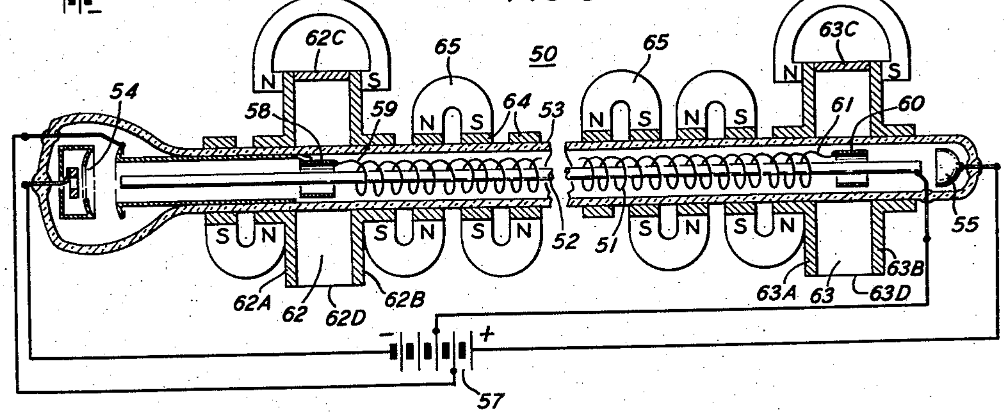

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FIG. 4

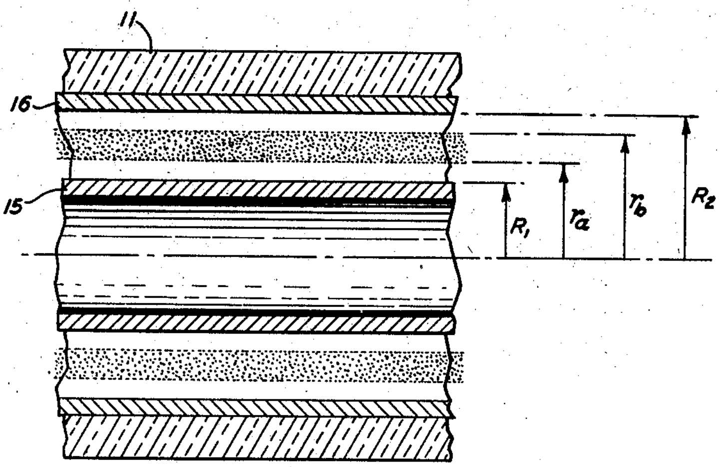
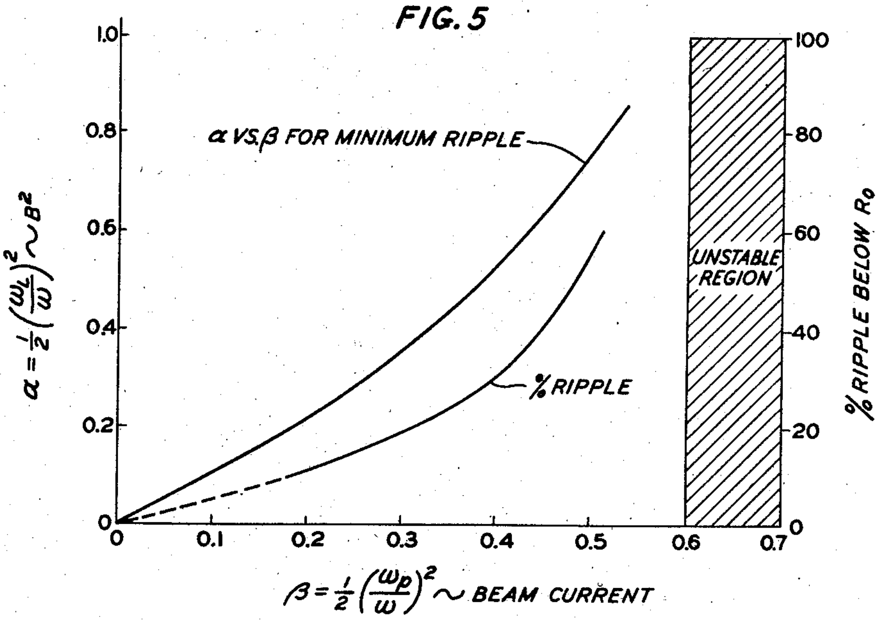


FIG. 5



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ELECTRON BEAM FOCUSING

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This invention relates to systems for focusing hollow beams of charged particles, and more particularly to systems in which a hollow electron beam is collimated by magnetic fields for travel over a relatively long path, such as is the case in some forms of traveling wave tubes.

A broad object of the invention is to provide an improved system for focusing hollow beams of charged particles.

A more specific object is to effect economies in the magnetic field necessary for magnetic focusing of a hollow electron beam, particularly for application in traveling wave tubes.

In a traveling wave tube, an electron stream is made to interact with a traveling wave over a distance a plurality of operating wavelengths long. To this end, an electron stream is projected closely past an interaction circuit along which the wave is propagating. For efficient operation, it is generally important to keep the electron flow cylindrical to avoid having the electrons strike the interaction circuit and to confine the electrons to regions of high signal fields. Therefore, to minimize transverse components of flow resulting from the space charge effects in the beam, it is generally necessary to employ some form of focusing.

Hitherto it has generally been the practice in traveling wave tubes to focus the electron stream by means of a uniform longitudinal magnetic field along the path of flow. However, both because of the relatively long length of the electron path and because of the large space charge forces acting in an electron stream of high density, it has been found that the auxiliary equipment necessary to provide a satisfactorily uniform magnetic field is large and bulky, being many times the size and weight of the traveling wave tube alone. For obvious reasons, it is desirable to minimize the size and weight of this focusing equipment.

In J. R. Pierce Patent 2,847,607, issued August 12, 1958, there are described permanent magnet focusing arrangements, each of which employs a succession of regions of longitudinal axially symmetric magnetic field along the path of flow characterized in that the direction of the field reverses with successive regions. Good focusing has been achieved with a time-constant spatially alternating magnetic field of this kind at a considerable saving in size and weight of the focusing equipment.

The present invention relates primarily to modifications of the arrangements described by Pierce in the above-identified patent for better adapting them to the focusing of hollow electron beams. More particularly, the focusing arrangements of the present invention utilize radial electrostatic fields which provide an outwardly directed force on the electrons to cooperate with the time-constant spatially alternating magnetic field.

Hollow electron beams are becoming more important in traveling wave tubes as a result of the trend toward higher frequencies. For example, in helix-type tubes for use at millimeter wavelengths where the circumference of the helix preferably is approximately half the operating wavelength, it is found advantageous to employ a hollow electron beam which flows past the outside of the helix.

In accordance with the present invention, for focusing a hollow electron beam a time-constant spatially alternating magnetic field is established along the path of electron flow, and additionally the flow is confined to the interspace between two cylindrical electrodes between which is set up a radial electrostatic field for providing a radial outward force, one of the two electrodes preferably serving also as the interaction circuit for propagating the slow electromagnetic wave in coupling relation with the electron beam. By suitable adjustment of the strength of the magnetic and electrostatic fields, the hollow electron beam is focused.

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

Fig. 1 shows schematically an electron beam system in accordance with the invention;

Figs. 2 and 3 show in schematic form traveling wave tubes incorporating hollow electron beam systems in accordance with the invention;

Fig. 4 shows a fragment of the path of electron flow and the associated electrodes of the system shown in Fig. 1 and will be helpful in an exposition of the principles of the invention; and

Fig. 5 is a plot of parameters important in the design of a time-constant spatially alternating magnetic field for use in the practice of the invention.

Referring now particularly to the drawings, Fig. 1 illustrates schematically an electron beam system **10** in accordance with the invention suitable for incorporation in a traveling wave tube. At opposite ends of an evacuated envelope **11**, which, for example, is of glass or a suitable non-magnetic metal such as copper, are positioned a source of a hollow electron beam **12** and a target **13**. The source of electrons generally is an electron gun which includes an electron-emissive ring shaped cathode, a heater unit, an intensity control element, and an electrode system for shaping and accelerating the electron beam. The target **13** serves as the collector of the electrons at the end of their paths, and to this end is maintained at a suitable positive potential with respect to the cathode of the electron source **12** by means of a voltage supply **17**. Two cylindrical non-magnetic electrode members **15**, **16** disposed coaxial with the desired path of flow are positioned inside and outside, respectively, the hollow electron beam, i. e., the electron beam flows through the interspace between inner and outer electrode members **15** and **16**, respectively. In a traveling wave tube, it will generally be convenient to utilize at least one of the two cylindrical members as the slow wave circuit for propagating electromagnetic waves for interaction with the electron beam in the manner characteristic of traveling wave tube operation. The two electrodes **15** and **16** are each maintained by voltage supply **17** at a positive potential with respect to the cathode of the electron gun for providing accelerating electric fields. Additionally in accordance with the invention, the outer electrode **16** is maintained at an appropriate positive potential with respect to the inner electrode **15** for providing an outwardly directed force on the electrons. Moreover, to provide a time-constant spatially alternating longitudinal magnetic field, a regular succession of identical tubular cylinders **18** of magnetic material, such as soft iron or Alnico, are disposed coaxial with the path of electron flow along the elongated portion of the tube envelope. Successive cylinders are spaced apart leaving gaps **19** of uniform length between adjacent cylinders. A series of identical U-shaped permanent magnets **20** are disposed along the path of electron flow. For convenience of illustration adjacent magnets are shown disposed on diametrically opposite sides of the axis of the electron path. Successive magnets are bridged across successive gaps **19**, each having separate pole faces in good magnetic contact with a different one of two adjacent cylinders. Successive magnets are also reversed in sense, so that adjacent cylinders are in contact with oppositely-poled pole faces. Accordingly, the succession of cylinders may be viewed as a succession of oppositely-poled pole pieces of a permanent magnet structure.

As a result of this succession of oppositely-poled pole pieces, there results along the path of electron flow a succession of regions **21**, each corresponding to a gap **19** between cylinders, where there exists a longitudinal magnetic field of substantially axial symmetry, and the direction of this magnetic field reverses along successive regions. By the cooperative effect of this spatially alternating magnetic field and the radial electrostatic field set up between the inner and outer electrodes, the hollow electron beam is focused.

Before describing in detail an illustrative embodiment of the invention, it will be helpful to analyze the principles of focusing a hollow electron stream by a time-constant spatially alternating axially symmetric magnetic field and a radial electrostatic field as is characteristic of the invention.

In the above-identified Pierce patent, there are developed the principles of focusing a solid electron beam by a time-constant spatially alternating axially symmetric magnetic field. It is in accordance with one aspect of the invention to adjust the electric fields existing in the hollow beam by the use of applied radial electric fields to achieve the same spatial variation with radial distance r as is characteristic of a solid beam, so that thereafter the principles developed for focusing a solid beam can be applied to the hollow beam. If it is assumed that the thickness of the hollow beam Δr is much smaller than r, which is the case of principal interest, then it can be shown that this desired condition on the electric fields in the hollow beam is realized when

$$V_2-V_1=-\frac{Q}{2\pi\epsilon}\left[\frac{r_a^2}{r_b^2-r_a^2}ln\frac{r_2}{r_1}+ln\frac{r_2}{r_b}\right] \tag{1}$$

where V_1 and V_2 are the potentials of the inner and outer electrodes **15** and **16**, respectively; r_a and r_b are the inner and outer radii of the hollow electron beam, respectively; r_1 and r_2 are the radii of the inner and outer electrodes, respectively; Q is the charge per unit length of the electron beam; and ϵ is the dielectric constant of the interspace region. In Fig. 4, there is shown a fragment of the electron path and its associated electrodes with the dimension labeled as above.

Equation 1 can be satisfied only approximately since the outside radius of the beam r_b is a periodic function of distance down the tube, and there must be utilized therefor a mean value. However, even with these reservations, the potential difference can be chosen so that the forces acting on the hollow beam are sufficiently identical to those acting in the case of the solid beam analyzed in the Pierce patent that the same analysis is applicable. Consequently, the problem of adjusting the strength and periodicity of the magnetic field can be now solved by reference to the analysis for the periodically focused solid electron beam set forth in the Pierce patent.

Such analysis indicates that if there is defined

$$\omega_p^2=\frac{\rho\eta}{\epsilon} \tag{2}$$

$$\omega_L=\frac{1}{2}\eta B_0 \tag{3}$$

$$\omega=\frac{2\pi u_0}{L} \tag{4}$$

where η is the charge-mass ratio of an electron; ϵ is the dielectric constant of the interspace; L is twice the magnet spacing or the length of one cycle of the magnetic field; B_0 is the peak magnetic field along the path of flow; I_0 is the D.-C. beam current; u_0 is the D.-C. beam velocity; and

$$\rho=\frac{I_0}{\pi u_0(r_b^2-r_a^2)} \tag{5}$$

Then if there is defined further

$$\alpha=\frac{1}{2}\left(\frac{\omega_L}{\omega}\right)^2 \tag{6}$$

$$\beta=\frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2 \tag{7}$$

where α is a magnetic field intensity parameter, and β is a space charge parameter, the relationship between α and β for minimum ripple is plotted in Fig. 5.

Accordingly, for focusing in accordance with the principles set forth a hollow electron beam of given design parameters, there can be derived by means of the curve shown in Fig. 5 the required design parameters of the time-constant spatially alternating magnetic field structure and by means of Equation 1 the required design parameters of the radial electric field structure.

However, due to the aberrations in the initial focusing at the cathode and because of thermal velocities, some electrons will not be confined to theoretical laminar orbits and may drift towards the axis of the hollow beam. To suppress such stray electron flow, it may be advantageous in practice to increase somewhat the potential difference between the inner and outer electrodes beyond that calculated in order to augment the outward force acting on such stray electrons.

It is also to be noted that it is possible that the stable solution analogous to the solid beam case with which the present analysis is concerned may not be the only stable solution. It does, however, represent a mathematically tractable solution.

Fig. 2 illustrates how a typical traveling wave tube can be adapted for use with a hollow electron beam system in accordance with the invention. In the interest of simplicity, the tube is shown in schematic form, many of the specific tube details being omitted. The various tube elements are enclosed in a non-magnetic envelope **30**. Alternatively, it is possible to utilize an envelope of a magnetic material such as Kovar so long as it is made sufficiently thin to become readily saturated without seriously reducing the magnetic field. At one end to serve as a source of electrons there is positioned an electron gun **31** which comprises an annular electron-emissive cathode **32** and an electrode system **33** for shaping and focusing the electrons emitted into a convergent conical annular beam. Suitable lead-in conductors are provided to the various elements of the electron gun from a suitable voltage supply source not shown. At the opposite end of the tube there is positioned a target electrode **34** for collecting the spent electrons.

The tube shown in Fig. 2 is adapted particularly for coaxial input and output connections to the slow wave interaction circuit which comprises a helically coiled conductor **35** coaxially disposed along the path of flow of the hollow beam and enclosed thereby. Input waves are applied by way of the coaxial input termination **36**, of which the inner conductor **37** is an extension of the conductor **35**. To this end, for example, the inner conductor **37** which is initially a solid rod is connected as an extension of a tubular portion which is grooved in a helical pattern, the pitch of the grooving increasing gradually for impedance matching purposes, for forming the helically coiled conductor **35**. Moreover, the outer conductor **38** of the coaxial input termination is extended past the electron gun **31**, having its diameter increased therepast, and an extension thereof serves as the outer cylindrical electrode 39 surrounding the path of electron flow in accordance with the principles set forth in connection with the focusing system shown in Fig. 1. To this end, it is desirable to maintain the outer conductor 38 at a positive D.-C. potential with respect to the inner conductor 37 by means of connections to voltage supply 40 whereby along the path of flow the helical conductor 35 is at a negative potential with respect to the outer electrode 39. However, both are maintained positive with respect to the electron source to provide a longitudinal accelerating field on the electron flow.

At the downstream end, the amplified output wave is abstracted by way of output coupling coaxial connection 41 of which, in a manner analogous to the input coupling coaxial connection 36, the inner conductor 42 and the outer conductor 43 are extensions, respectively, of the helical conductors 35 and the cylindrical electrode 39.

The succession of regions of longitudinal magnetic field of the kind desired for the practice of the invention can be achieved in any of the ways described either in the aforementioned Pierce patent in Patent 2,841,739, issued July 1, 1958, also of J. R. Pierce, or in P. P. Cioffi Patent 2,844,754, issued July 22, 1958. By way of example, there is shown for use with this tube the magnetic structure shown in Fig. 1 which is one of the many possible alternatives. A succession of magnetic annular cylindrical members 44 surround the tube envelope spaced apart longitudinally. By means of permanent magnets 45, the successive cylinders are oppositely poled to serve as a succession of oppositely-poled pole pieces for creating along the path of flow a spatially alternating magnetic field of the kind desired. The various parameters such as spacing and field intensities are adjusted in accordance with the principles set forth above.

Fig. 3 shows a traveling wave tube 50 which incorporates an embodiment of the invention in which the outer of the two coaxial cylindrical electrodes is a helical conductor 51 which serves as the slow wave interaction circuit while the inner is a rod 52 extending along the path of flow. A non-magnetic envelope 53 encloses the various tube elements. At one end, an electron gun 54 serves as a source of a hollow electron beam, and at the opposite end, a target electrode 55 collects the spent electrons. Disposed coaxially along and surrounding the path of electron flow is the helically coiled conductor 51 which propagates the electromagnetic wave to be amplified. Additionally, disposed coaxially along and enclosed by the path of electron flow is the conductive rod 52. In accordance with the focusing principles set forth above, the conductive rod is maintained suitably negative with respect to the helical conductor by lead-in connections to the voltage supply 57.

This tube is adapted particularly for input and output hollow wave guide connections to the wave interaction circuit. To this end, the helix 51 is joined at opposite ends to input coupling strip 58 by an impedance matching section 59 and to an output coupling strip 60 by an impedance matching section 61. These matching sections are extensions of the helix in which the pitch is gradually increased. An input wave is applied to the upstream end of the interaction circuit by way of input wave guide coupling connection 62 and the output wave is abstracted at the downstream end by way of output wave guide coupling connection 63. Each of the wave guide coupling connections 62, 63 is a section of rectangular wave guide which has a pair of opposite side walls 62A, 62B and 63A, 63B apertured for passage therethrough of the tube envelope, and which has a closed end 62C, 63C and an open end 62D, 63D by which it can be connected into a wave guide transmission system. Each of the input and output coupling strips 58, 60 is supported in its corresponding wave guide coupling connection. Input waves are applied to the input wave guide connection 62 to have a mode of propagation having an electric field vector parallel to the coupling strip 58. In this way, an input wave is introduced into the interaction circuit for travel therealong in coupling relation with the electron beam. For accelerating the electron beam longitudinally, the helical conductor 51 and conductive center rod 52 are each maintained at a positive potential with respect to the electron source, by voltage supply 57, the center rod being more negative than the helix.

The desired succession of longitudinal magnetic field regions can again be achieved in any of the ways described in the aforementioned Pierce and Cioffi patents. In this illustrative embodiment, a spaced succession of cylinders 64 of a magnetic material is disposed around the tube envelope to serve as a series of pole pieces. In the region of the input and output wave guide connections special steps are taken to minimize discontinuities in the periodically varying magnetic field desired. To this end, it is desirable that the two apertured side walls 62A, 62B and 63A, 63B of each of the wave guides 62, 63 also be of a magnetic material while the other side walls and the end closures 62C, 63C of each be nonmagnetic. In this way, each of the apertured side walls can be made to serve as a separate pole piece along with the succession of cylinders 64. Between adjacent pairs of pole pieces there are bridged permanent magnets 65 in a way that successive pole pieces are oppositely poled, whereby there is provided along the path of flow a succession of regions of longitudinal magnetic field, the direction of the magnetic field reversing with successive regions.

It should be evident that hollow beam focusing systems which in accordance with the invention are characterized by a magnetic structure for providing a periodically varying longitudinal magnetic field along the path of flow and an electrode system for providing a radial electrostatic field along the path of flow can be utilized in various other forms of traveling wave tubes. Accordingly, it is to be understood that the specific embodiments described are merely illustrative of the principles of the invention. Various other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a traveling wave tube, inner and outer cylindrical electrodes coaxially and concentrically disposed, at least one of said electrodes forming a slow wave circuit for a traveling electromagnetic wave, means for forming and projecting a hollow cylindrical electron beam coaxially with said cylindrical electrodes through the interspace therebetween, means for maintaining the outer electrode at a positive potential with respect to the inner electrode, and permanent magnet means disposed around said outer cylindrical electrode for forming a succession of regions of axial magnetic field along the path of flow, the direction of said field reversing with successive regions.

2. In combination, first and second cylindrical members coaxially disposed, the first surrounding the second and defining an interspace therebetween, the first member being adapted to be at a positive potential with respect to said second member, means for projecting a hollow cylindrical electron beam coaxial with said cylindrical members through said interspace, and permanent magnet means disposed around said cylindrical members for forming along the path of said cylindrical beam a succession of regions of axial magnetic field, the direction of the magnetic field reversing with successive regions.

3. In combination, first and second cylindrical members coaxially and concentrically disposed, the outer of said cylindrical members being adapted to be at a positive potential with respect to the inner of said cylindrical members, means for projecting a hollow cylindrical electron beam coaxial with cylindrical members through

the interspace formed therebetween, and magnetic means disposed around said cylindrical members for producing a time-constant spatially alternating axial magnetic field along the path of flow of the electron beam.

4. In a traveling wave tube, means forming a hollow cylindrical electron beam, a conductor helically coiled disposed coaxial with and surrounding the path of flow of said beam, a conductive member disposed coaxial with and surrounded by the path of flow of said beam, the helical conductor adapted to be positive with respect to said member, and permanent magnet means disposed around said helically coiled conductor for forming along the path of flow a time-constant spatially alternating axial magnetic field.

5. In a traveling wave tube, means forming a hollow cylindrical electron beam, a conductor helically coiled disposed coaxial with and enclosed by the path of flow of said beam, a cylindrical electrode disposed coaxial with and enclosing the path of flow of said beam, the helical conductor adapted to be at a negative potential with respect to said electrode, and permanent magnet means disposed around said cylindrical electrode for forming along the path of flow a time-constant spatially alternating magnetic field.

6. In a traveling wave tube, means forming a hollow cylindrical electron beam, inner and outer cylindrical electrodes coaxially disposed along the path of flow of said beam, one of said electrodes being an interaction wave circuit for propagating an electromagnetic wave, means for maintaining the inner electrode at a negative potential with respect to the outer electrode, a plurality of

cylindrical magnetic elements spaced apart along and surrounding the path of flow, and permanent magnet means in magnetic contact with said elements oppositely poling successive elements.

7. In a traveling wave tube, an annular electron source and a target defining a path of flow for a hollow cylindrical electron beam, inner and outer cylindrical electrodes coaxially disposed along the path of flow and defining therebetween an interspace region for the path of flow, a voltage source having positive and negative terminals, the positive terminal being connected to the outer electrode, the negative terminal being connected to the inner electrode, a succession of magnetic cylinders spaced apart along and surrounding the path of flow, and permanent magnet means oppositely poling successive cylinders.

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