Jan. 13, 1959 G. R. BREWER ET AL 2,869,018

TRAVELING WAVE TUBE

Filed May 2, 1955

2 Sheets-Sheet 1

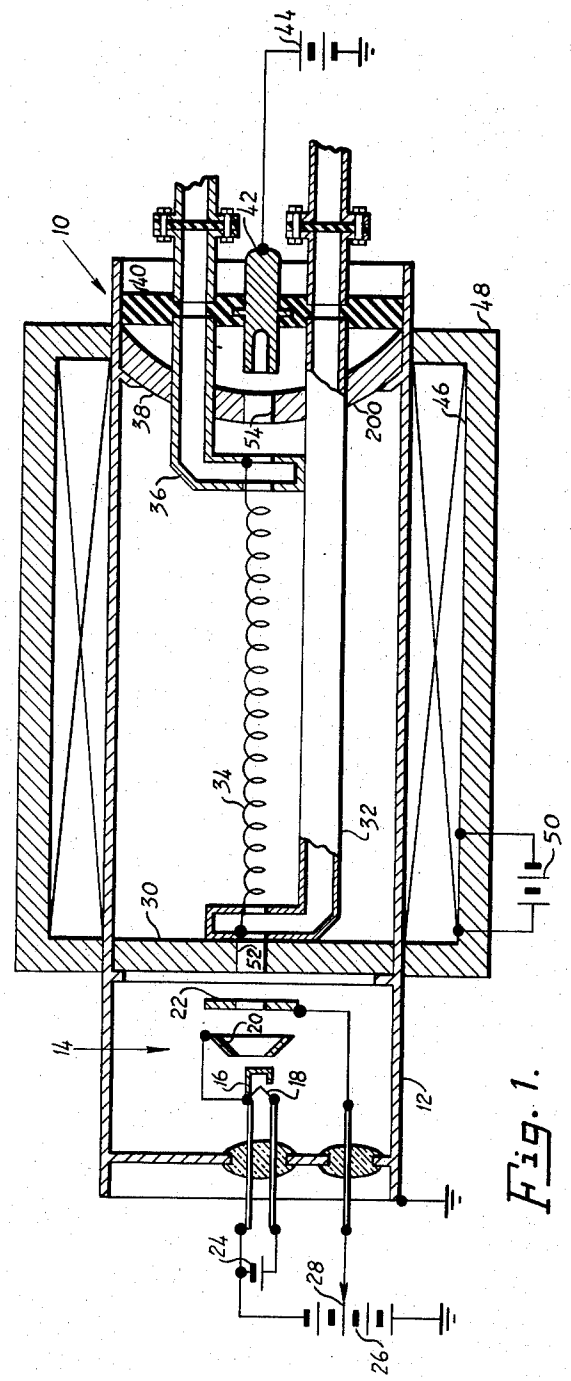
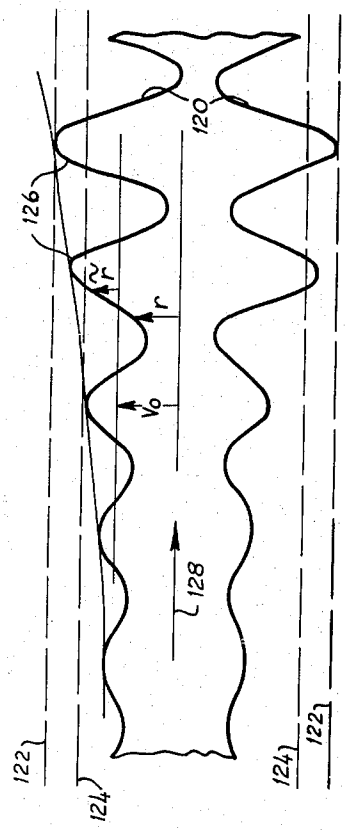


Fig. 1.

Fig. 2.



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2 Sheets-Sheet 2

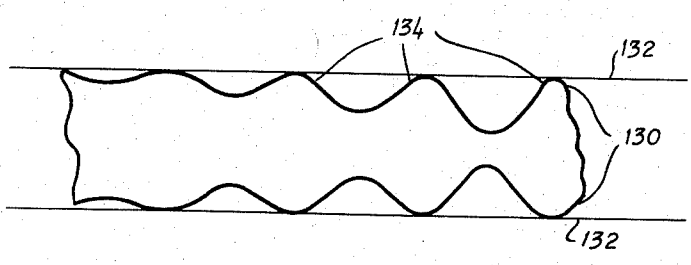


Fig. 3

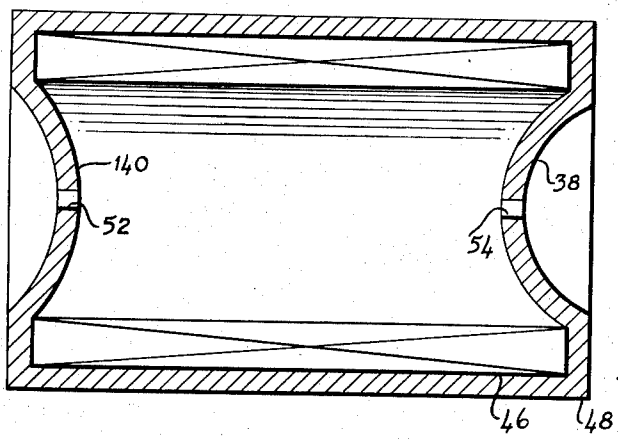


Fig. 4.

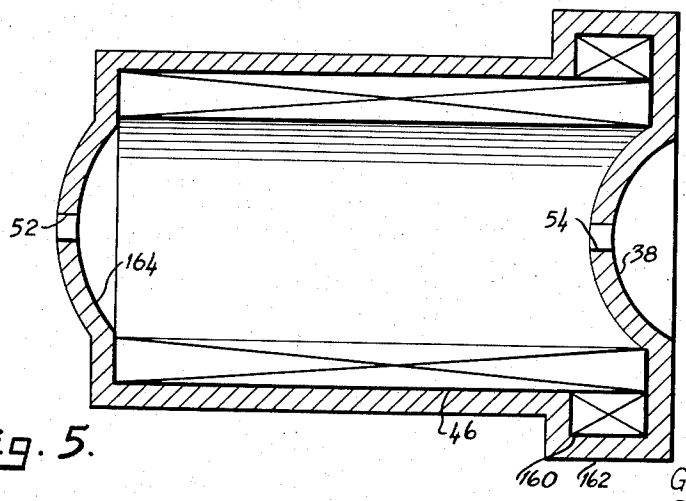


Fig. 5.

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TRAVELING WAVE TUBE

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Application May 2, 1955, Serial No. 505,085

7 Claims. (Cl. 315—3.5)

This invention relates to beam type electron tubes and more particularly to an improved magnetic circuit for focusing an electron stream.

It will be brought out later that the present invention is generally applicable to the control of electron beams. However, since it finds considerable utility in connection with traveling-wave tubes, the invention will be described in detail in connection with traveling-wave tubes.

In a microwave tube known as a traveling-wave tube, an electron stream is projected through a slow-wave structure to interact with an electromagnetic wave propagated therealong, whereby an amplification of the wave may be produced. When the wave is first launched along the slow-wave structure, the electron stream is substantially unmodulated except for thermal noise and has a substantially uniform diameter. However, as the stream becomes modulated by the electromagnetic wave the radial components of the electric fields of the wave cause periodic diameter variations in the stream. These diameter variations move along the stream at the phase velocity of the wave and grow in magnitude along with the fields of the wave as the stream progresses through the slow-wave structure.

For the efficient operation of a traveling-wave tube it is desirable that a uniform diameter slow-wave structure be employed and that the electron stream be projected through it and be projected as close to the slow-wave structure as possible without permitting the slow-wave sructure to intercept a substantial number of the stream electrons.

In the operation of moderately high-powered traveling-wave tubes, it is not uncommon for the electron stream diameter variations due to radio frequency or R. F. modulation to become large in comparison to the average electron stream diameter. Hence, if the stream is initially projected contiguous to the slow-wave structure, since the magnitudes of the diameter variations along the stream increase as the stream progresses along the slow-wave structure, when the maximum beam diameter becomes equal to or larger than that of the latter structure, it intercepts a substantial number of the stream electrons. Stream interception not only prevents maximum interaction with the wave propagated along the slow-wave structure by eliminating some of the electrons from the interaction, but also produces a problem of cooling the slow-wave structure because the electron bombardment by interception results in heat generation. Conversely if the electron stream is initially projected through the slow-wave structure with a diameter small enough to prevent substantial beam interception, the beam is generally positioned too far from the slow-wave structure at the R. F. input end of the tube to permit optimum wave and beam interaction.

A solenoid has necessarily been employed in the past to produce a unidirectional axial magnetic field through the stream to focus it or to confine it. The field is generally uniform throughout the stream cross-section and along its length. To the present time beam interception

due to R. F. modulation thus has not been taken into consideration.

It is, therefore, an object of the invention to provide an improved magnetic circuit for varying a unidirectional axial magnetic field in a predetermined manner.

It is another object of the invention to provide means for improving the overall performance and efficiency of a beam type microwave tube.

It is still another object of the invention to provide means for reducing the electron stream interception current of a traveling-wave tube slow-wave structure.

In accordance with the invention, a magnetic circuit is provided which may have particular utility in connection with its use in beam type electron tubes such as traveling-wave tubes. The magnetic circuit may comprise means for producing a magnetic field increasing in strength with the distance along its axis at a rate to prevent interception of any substantial number of the electrons of an electron stream by a beam-type tube slow-wave structure.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention.

Fig. 1 is is a sectional view of a traveling-wave tube incorporating the magnetic focusing circuit of the present invention;

Fig. 2 is a graphical illustration of the type of electron stream diameter variations which are desirably avoided by practicing the device of the present invention;

Fig. 3 is a graphical illustration of the electron stream diameter variations obtained when the magnetic circuit of the present invention is employed to focus an electron stream; and

Figs. 4 and 5 are sectional views of alternative embodiments of the invention.

Referring to the drawings, there is shown in Fig. 1 a traveling-wave tube 10 comprising an evacuated envelope 12 having an electron gun 14 disposed within its left end. Electron gun 14 comprises a cathode 16 which is provided with a filament 18, focusing electrode 20 and an accelerating anode 22. Filament 18 is provided with the source of potential 24 and focusing electrode 20 is maintained at substantially the same potential as cathode 16 by an appropriate connection thereto. Cathode 16 is maintained a few thousand volts negative with respect to ground by means of an accelerating source of potential 26. Focusing electrode 20 may have a frusto-conical configuration with an internal surface of revolution disposed 67½ degrees from its axis of symmetry. Accelerating anode 22 may be maintained at approximately ground potential by means of a connection to a tap 28 on accelerating source of potential 26.

In the direction of electron flow from the electron gun 14, there is shown disposed within the envelope 12 a first pole piece 30 which may be made of a ferro-magnetic material. Adjacent to the pole piece 30 there is shown a rectangular input waveguide segment 32, to the left side of which a slow-wave structure 34 comprising a conductive helix is connected. A rectangular output waveguide segment 36 then has a right surface connected to the right end of helix 34. A ferro-magnetic pole piece 38 which is convex toward the gun is disposed near the right end of the envelope 12. A dielectric disc 40 is disposed at the right end of envelope 12 for supporting the internal wave-

guide segments 32 and 36 and for supporting a collector electrode 42 which is disposed at its center. Pole piece 30, internal waveguide segments 32 and 36 and pole piece 38 are all provided with apertures through which the electron beam produced by electron gun 14 may pass. Accordingly, the beam is intercepted by collector 42 which is maintained a few hundred volts positive with respect to ground by means of a collector source of potential 44. Collector 42 is maintained positive with respect to its surrounding structures in order to prevent the escape of secondary electrons from the collector 42 to surrounding structures. All of the structures in and around the tube 10 are maintained at ground potential except cathode 16, filament 18, focusing electrode 20, accelerating anode 22 and collector 42.

The magnetic focusing circuit of the present invention comprises the pole pieces 30 and 38 with a solenoid 46 which is disposed outside of the envelope 12 and is encompassed by a ferro-magnetic shielding cylinder 48. Solenoid 46 is supplied with direct current by means of a potential source 50. Pole piece 30 is made of a ferromagnetic material and may have a disc-shaped configuration with an aperture 52 through which the electron stream produced by the electron gun 14 passes. The shape of pole piece 38 at the output end of the tube 10 is of considerable importance and has a somewhat different configuration from that at the input end. Although it may be made of substantially the same material as pole piece 30, it has a generally convex shape as viewed from the gun end of the tube 10 with aperture 54 through which the electron stream produced by the gun 14 may pass to the collector 42.

In order to explain adequately the design of the embodiment of the invention shown in Fig. 1, it is necessary to examine more closely the problem which the embodiment in Fig. 1 is intended to solve in the transmission of the electron stream of the tube 10. In Fig. 2, a graphical illustration represented by curved lines 120 is made of the outer boundary surface of an electron stream which is modulated by an R. F. field traveling along a slow-wave circuit which is situated say, for example, at the position of some outer dashed lines 122 or at some inner dashed lines 124. It is seen that a plurality of maximum diameters 126 appear at the outer boundary surface of the curves 120. These maximum diameters 126 move along the length of the stream with time at the phase velocity of the wave propagated along the slow-wave structure which is situated at the dashed lines 122 or 124. It can be seen that the maximum diameter portions 126 of the boundary curves 120 representing the electron stream also increase in magnitude as the stream flows from the left to right as indicated by an arrow 128. From the curves 120 of Fig. 2, it can be seen that when a slow-wave structure is positioned at the outer dashed lines 122 substantial beam interception will not occur if the right end of the curves 120 represent the end of a traveling-wave tube or a microwave tube. However, it can be readily seen that at the input end of the tube toward the left end of the curves 120 substantial wave and stream interaction will be prevented by the separation in space of the stream represented by the curves 120 and the slow-wave structure which is positioned at the outer dashed lines 122. However, if a slow-wave structure is positioned at the inner dashed lines 124 it can be seen that some separation in space still will exist between the curves 120 and the dashed lines 124 at the left end of the curves 120 and, furthermore, that some stream interception is produced at the right end of the curves 120 at the last two maxima 126. This separation in space between the slow-wave structure and the initial portion of the electron stream and the interception of current tend to reduce tube efficiency when a slow-wave structure is positioned at the dashed lines 124 because optimum wave and stream interaction is prevented.

In Fig. 3, a stream envelope is represented by curves 130. It can be seen that a stream envelope of the type shown by curves 130 is very desirable because a slow-wave structure may be positioned at the lines 132 and be disposed contiguous to the stream without intercepting the latter. The slow-wave structure at the lines 132 may thus propagate the wave which thoroughly interacts with the stream represented by the lines 130.

In accordance with the invention a stream is provided having an outer boundary surface such as that represented by the wavy lines 130 of Fig. 3. By employing the embodiment of the invention in Fig. 1, this may be accomplished. The theory on which the magnetic circuit of Fig. 1 is based requires a closer examination of the exact mechanical movement of an electron in an evacuated envelope which moves within the outer boundary surface of the stream at the maximum diameters 134 which are shown within the curve 130 representing the outer boundary surface of an electron stream.

In order to make the maxima 134 of the stream represented by the lines 130 in Fig. 3 appear substantially along a line parallel to the axis with a minimum axial magnetic field strength, the electrons at these outer orbits in spinning about the axis of the stream are caused to be in equilibrium by the magnetic circuit of the present invention. This equilibrium condition is sometimes described as Brillouin flow. It is characterized by the fact that the sum of the radial forces acting upon the electrons is zero. By using the Brillouin flow force equation in conjunction with the well-known traveling-wave tube equations, it is possible to obtain a mathematical expression for a magnetic field distribution of field strength versus distance along the tube axis necessary for optimum control of the electron beam. By using Laplace's equation, viz.

$$\Delta^2\phi=0 \tag{1}$$

and the definition of Φ: viz.

$$-\frac{\partial\Phi}{\partial z}=B_z=\mu_0 H_z \tag{2}$$

where

Φ is the magnetic scalar potential,
z is the distance along the stream,
B_z is axial magnetic flux density,
H_z is axial magnetic field intensity, and
μ_0 is the permeability of vacuum,

the shape of the pole pieces 30 and 38 may be determined, and in addition, the inner diameter of the solenoid 46 and the strength of the field that must necessarily be produced by the solenoid 46. In order to reduce the power required for the solenoid to a minimum, the ferro-magnetic encompassing cylinder 48 is employed.

The detailed design of the magnetic circuit of Fig. 1 is made as follows:

Let stream radius

$$r=r_0+\tilde{r} \tag{3}$$

as indicated in Fig. 2. From an analysis, the stream perturbations are found to be proportional to the radial field of the traveling-wave

$$\tilde{r}=KE_r \tag{4}$$

where E_r is the radial electric field intensity vector and K is a constant.

If

$$E_r=E_0M(z) \tag{5}$$

then

$$\tilde{r}=KE_0M(z) \tag{6}$$

where E_0 is the radial electric field at some reference position, and $M(z)$ is a function of z, the axial coordinate.

From the usual analysis of a beam in Brillouin flow, one can write the familiar equation

$$\ddot{r}=r\left(\frac{\eta B(z)}{2}\right)^2+\frac{\omega_p^2\tilde{r}_0^2}{2r} \tag{7}$$

where

$\ddot{r}$ is radial acceleration

$$\left(\frac{\partial^2 r}{\partial t^2}\right)$$

r is the distance from the stream axis to any point in the system;

η is the electron charge to mass ratio;

B is axial magnetic flux density;

r_0 is the value of r at $z=0$; and

ω_p is the well-known plasma frequency, $_p$ being defined as follows:

$$\omega_p^2=\frac{\rho\eta}{\epsilon_0}$$

where

ρ is the charge density of the stream and

ϵ_0 is the permittivity of free space.

The electrons move at a substantially constant velocity corresponding essentially to the potential of the slow-wave structure, V_0, disposed about the stream. Thus Equation 7 can be written as follows:

$$B^2(z)=\frac{4}{\eta 2}\left[\frac{2\eta V_0}{r}\frac{d^2r}{dz^2}-\frac{\omega_p^2 r_0^2}{2r^2}\right] \quad (8)$$

Thus, if the rate of change of the electric field of the wave, $M(z)$ is known, or specified, Equation 6 may be substituted into Equation 3 and the resultant equation into Equation 8. $B(z)$ is then determined as a function, say $F(z)$ of distance z. If $G(z)$ is the magnetic scalar potential along the axis of the stream, $G(z)$ may be found from the relationship

$$G=F(z)=B(z) \quad (9)$$

This is the specific expression of a magnetic potential variation which must be satisfied to produce the electron flow indicated by the lines **130** shown in Fig. 3.

The general expression for the magnetic potential distribution within a solenoid between enclosing pole pieces, as indicated in Fig. 1, is obtained from the Laplace equation. It is

$$\Phi=Cz+\sum_{n=1}^{\infty}\left(A_n e^{\frac{-\gamma_n z}{a}}+B_n e^{\frac{+\gamma_n z}{a}}\right)J_0\frac{\gamma_n r}{a} \quad (10)$$

where

J_0 is a Bessel function of order zero and the first kind having the argument

$$\left(\frac{\gamma_n r}{a}\right)$$

a is the inner radius of solenoid **46**;

γ_n is the nth root of the Bessel function such that

$$J_0(\gamma_n)=0$$

C, A_n, and B_n are constants to be determined.

By setting

$$\Phi=G(z) \quad (11)$$

the following structural design of the magnetic circuit of Fig. 1 may be obtained. The length, z_0, of the region over which it is desired to vary the magnetic flux density is substantially fixed by the application of the present invention, such as the length of slow-wave structure **34**. At the inner boundary radius of the source of magnetomotive force either a solenoid or permanent magnet system, the magnetostatic potential, Φ, increases linearly with z for a constant magnetomotive force in this source. It is seen from Equation 10 that Φ will increase linearly with z at a radius equal to a. C is determined by the power requirements of the solenoid, and the number of turns per unit length with which it is provided. By using enough terms in the series of Equation 10 to make the design sufficiently accurate, the coefficients A_n and B_n may easily be determined so as to obtain an adequate

representation of $\Phi(z)$. As a simple example of Equation 10, a flat shape can be chosen arbitrarily for the pole piece **30**. It is then found that $A_n=-B_n$, and Equation 10 is simplified to:

$$\Phi=Cz+\sum_{n=1}^{\infty}An\sinh\frac{\gamma_n z}{a}J_0\frac{\gamma_n r}{a} \quad (12)$$

If the permeability of the material of the pole pieces is sufficiently large in comparison to unity, the entire internal surface **200** of the right pole piece **38** in Fig. 1 can be considered to be at the same magnetic potential, Φ_0, then the shape of pole piece **38** can be found by using Equation 12 to determine the values of r and z which will yield the equality $\Phi=\Phi_0$. Assuming $\Phi=0$ at the pole piece **30** where $z=0$, then Φ_0 may be found by performing the indicated operation:

$$\Phi_0=-\int_0^{Z_0}B_z dz=-\int_0^{Z_0}F(z)dz \quad (13)$$

An alternative embodiment of the invention is shown in Fig. 4 comprising the source of M. M. F., in this case shown as the solenoid **46** which has an encompassing ferro-magnetic cylinder **48** disposed about it, and the pole piece **38** which may be disposed at the output end of any slow-wave structure or specifically at the output end of the slow-wave structure **34**. When a permanent magnet is used as the M. M. F. source, an encompassing ferro-magnetic cylinder is not required. A pole piece **140** is shown at the left end of the solenoid **46** in Fig. 4 which has a somewhat different configuration than that of the pole piece **30** shown in Fig. 1. Pole piece **140** is concave as viewed from the left. The magnetic circuit of Fig. 4 is intended to show that the left pole piece **140** may have any convenient configuration. As explained in the design of the magnetic circuit of Fig. 1, a substantially flat pole piece **30** was employed for purposes of illustration in the analytical design of the magnetic circuit of Fig. 1.

The magnetic circuit shown in Fig. 5 comprises the solenoid **46** having an additional solenoid **160** disposed about a minor portion of its length at its right end and an encompassing ferro-magnetic cylinder **162** is then provided about both of the solenoids **46** and **160**. Convex pole piece **38** is shown at the right end of the magnetic circuit of Fig. 5 and a convex pole piece **164** is shown at the left end of the magnetic circuit of Fig. 5. Fig. 5 thus conveys the idea that any combination of the disclosed structures of Figs. 1 and 4 and additionally solenoids of various configurations may be employed to produce the desired result, namely, the production of a magnetic field system with flux density varying in a predetermined and desired manner.

What is claimed is:

1. A magnetic circuit for producing a substantially cylindrically symmetric magnetic field in which the axial magnetic flux density along the symmetrical axis of said circuit varies according to a predetermined relationship, said circuit comprising a source of magnetomotive force having a substantially cylindrical shape, and a pole piece disposed at each end of said source, said pole pieces having shapes to cause the axial magnetic flux density, B_z, along at least a portion of said symmetrical axis of said source smoothly and continuously to vary according to the relationship.

$$B_z=-C-\sum_{n=1}^{\infty}\frac{\gamma_n}{a}\left(-A_n e^{\frac{-\gamma_n z}{a}}+B_n e^{\frac{+\gamma_n z}{a}}\right)J_0\frac{\gamma_n r}{a}$$

where

J_0 is a Bessel function of order zero and the first kind with the argument

$$\left(\frac{\gamma n r}{a}\right)$$

a is the inner radius of said source, n is any positive integer;

r is the distance from the axis of said source to any point in the system;

z is the distance along the axis of said source;

C, γ_n, A_n, and B_n are constants, and the inner radius a of said source of magnetomotive force has a value such that $J_0(\gamma n)=0$.

2. A traveling-wave tube comprising: an evacuated envelope; an electron gun disposed at one end of said envelope for producing an electron stream; a slow-wave structure; means for directing said electron stream through said slow-wave structure; means disposed at the end of said slow-wave structure adjacent said electron gun for launching an electromagnetic wave therealong, whereby the diameter of said stream is caused to vary with time and with distance along said slow-wave structure, the outer boundary surface of said electron stream having a plurality of moving and growing maximum diameters; and means for producing an axial magnetic field through said stream, said axial magnetic field increasing smoothly and continuously along said stream at a rate to prevent interception of a substantial number of the electrons in said stream by said slow-wave structure while maintaining optimum interaction between said stream and said slow-wave structure, said means for producing said axial magnetic field including a source of magnetomotive force having a substantially cylindrical shape and a pole piece disposed at each end of said source, said pole pieces having shapes to vary in a smooth, continuous manner the axial flux density along the symmetrical axis of said source according to the relationship

$$B_z=-C-\sum_{n=1}^{\infty}\frac{\gamma_n}{a}\left(-A_n e^{\frac{-\gamma_n z}{a}}+B_n e^{\frac{+\gamma_n z}{a}}\right)J_0\frac{\gamma_n r}{a}$$

where

J_0 is a Bessel function of order zero and the first kind with the argument

$$\frac{\gamma n r}{a}$$

a is the inner radius of said source,

n is any positive integer,

r is the distance from the axis of said source to any point in the system,

z is the distance along the axis of said source,

C, γ_n, A_n and B_n are constants,

and the inner radius a of said source of magnetomotive force is such that $J_0(\gamma_n)=0$.

3. A traveling-wave tube comprising: an evacuated envelope; an electron gun disposed at one end of said envelope for producing an electron stream; a slow-wave structure; means for directing said electron stream through said slow-wave structure; means disposed at the end of said slow-wave structure adjacent said electron gun for launching an electromagnetic wave therealong, whereby the diameter of said stream is caused to vary with time and with distance along said slow-wave structure, the outer boundary surface of said electron stream having a plurality of moving and growing maximum diameters; and means for producing an axial magnetic field through said stream, said axial magnetic field increasing smoothly and continuously along said stream at a rate to prevent interception of a substantial number of the electrons in said stream by said slow-wave structure while maintaining optimum interaction between said stream and said slow-wave structure, said means for producing said axial magnetic field including a magnetic circuit having pole pieces disposed at opposite ends of said slow-wave structure, one of said pole pieces at the ends of said slow-wave structure being convex as viewed from the electron gun end of said tube.

4. In a traveling-wave tube having an electron gun for projecting an electron stream through a slow-wave structure, a magnetic focusing circuit for focusing the stream as it is projected through the slow-wave structure, said magnetic circuit comprising a solenoid, a ferro-magnetic enclosing cylinder encompassing said solenoid, and pole pieces disposed at each end of said enclosing cylinder, said pole pieces being disposed at opposite ends of the slow-wave structure, the pole piece at the input end of the slow-wave structure being substantially flat, the pole piece at the output end of the slow-wave structure being substantially convex as viewed from the input end of the slow-wave structure to provide an axial magnetic focusing field which smoothly and continuously increases the magnitude toward said output end of the slow-wave structure.

5. In a traveling-wave tube having an electron gun for projecting an electron stream through a slow-wave structure, a magnetic focusing circuit for focusing the electron stream as it is projected through the slow-wave structure, said magnetic circuit comprising: solenoid means disposed about the slow-wave structure, said solenoid means being wound to provide a predetermined axial magnetic field strength at the output end of the slow-wave structure greater than that at the input end thereof; magnetic shielding means disposed outside of said solenoid means; and a pole piece disposed at each end of said solenoid means at the input and the output ends of the slow-wave structure, said pole pieces being shaped to produce an axial magnetic field through the stream increasing smoothly and continuously along the stream at a rate to prevent the interception of a substantial number of the electrons of the stream by the slow-wave structure while maintaining the diameter of the stream at a value to yield optimum interaction between the stream and the slow-wave structure, said pole piece disposed at the input end of said slow-wave structure being concave as viewed from the electron gun and said pole piece disposed at the output end of said slow-wave structure being convex as viewed from the electron gun end.

6. In a traveling-wave tube having an electron gun for projecting an electron stream through a slow-wave structure, a magnetic focusing circuit for focusing the electron stream as it is projected through the slow-wave structure, said magnetic circuit comprising: solenoid means disposed about the slow-wave structure, said solenoid means being wound to provide a predetermined axial magnetic field strength at the output end of the slow-wave structure greater than that at the input end thereof; magnetic shielding means disposed outside of said solenoid means; and a pole piece disposed at each end of said solenoid means at the input and the output ends of the slow-wave structure, said pole pieces being shaped to produce an axial magnetic field through the stream increasing smoothly and continuously along the stream at a rate to prevent the interception of a substantial number of the electrons of the stream by the slow-wave structure while maintaining the diameter of the stream at a value to yield optimum interaction between the stream and the slow-wave structure, said pole pieces being convex as viewed from said electron gun.

7. In a traveling-wave tube having an electron gun for projecting an electron stream through a slow-wave structure, a magnetic focusing circuit for focusing the electron stream as it is projected through the slow-wave structure, said magnetic circuit comprising: solenoid means disposed about the slow-wave structure, said solenoid means being wound to provide a predetermined axial magnetic field strength at the output end of the slow-wave structure greater than that at the input end thereof; magnetic shielding means disposed outside of said solenoid means; and a pole piece disposed at each end of said solenoid means at the input and the output ends of the slow-wave structure, said pole pieces being shaped to produce an axial magnetic field through the stream increasing smoothly

and continuously along the stream at a rate to prevent the interception of a substantial number of the electrons of the stream by the slow-wave structure while maintaining the diameter of the stream at a value to yield optimum interaction between the stream and the slow-wave structure, at least one of said pole pieces at the ends of said slow-wave structure being convex as viewed from the electron gun end of said tube.

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