

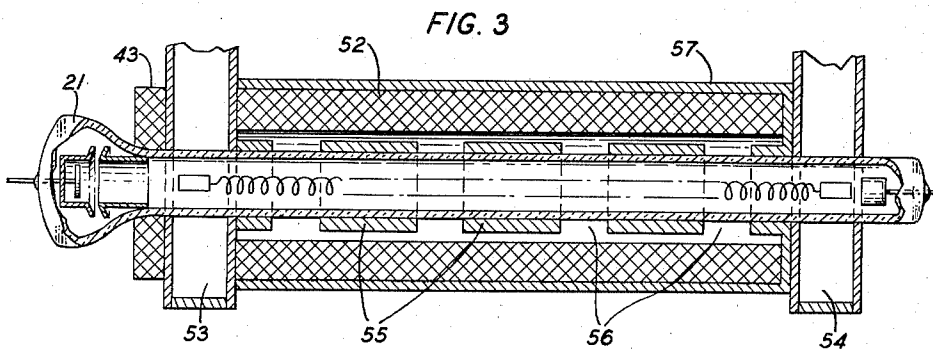
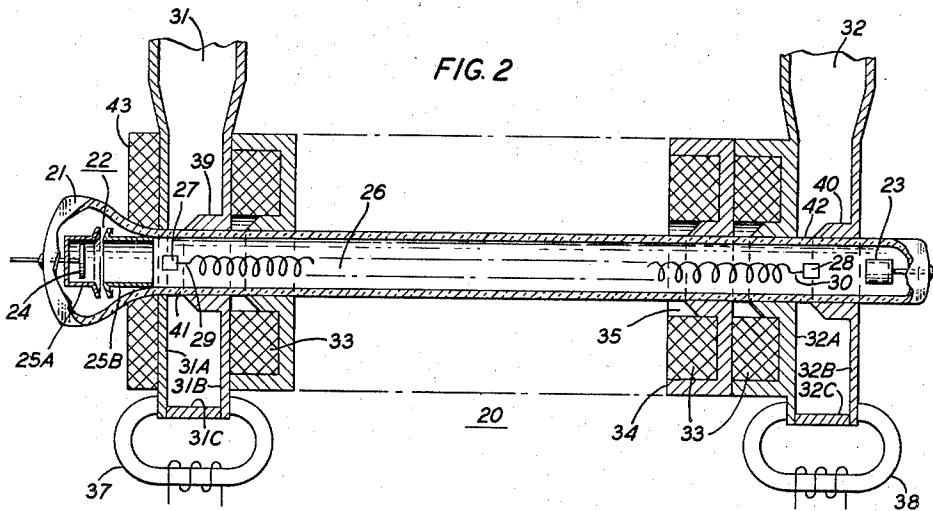
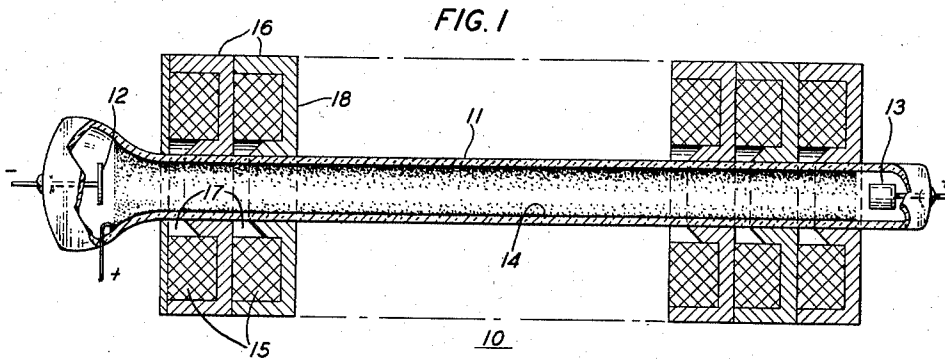
July 1, 1958

J. R. PIERCE
ELECTRON BEAM SYSTEMS

2,841,739

Filed April 29, 1953

4 Sheets-Sheet 1



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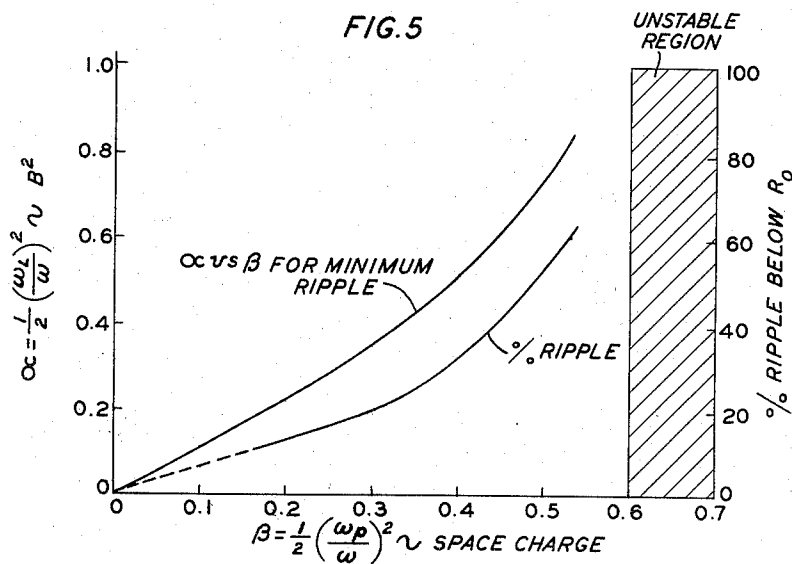
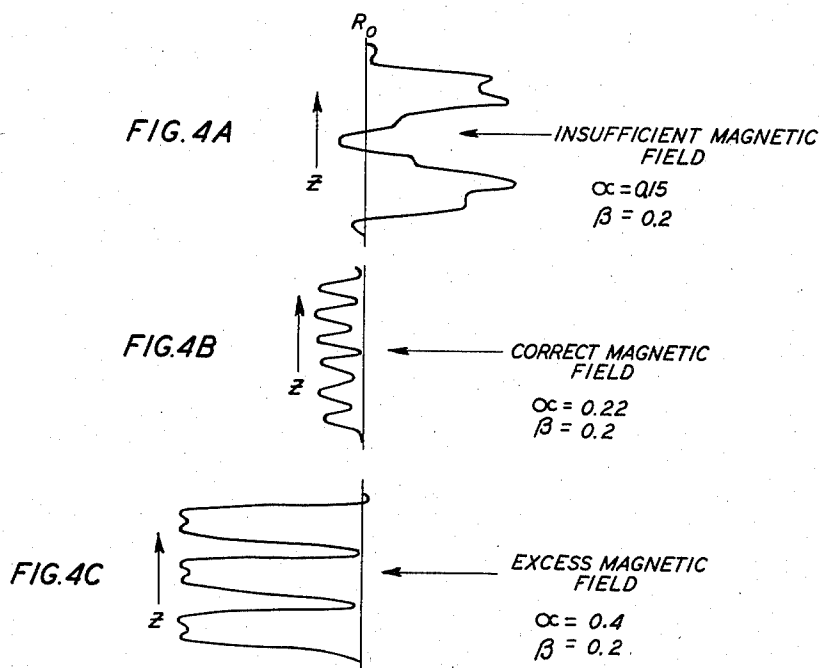
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4 Sheets-Sheet 2



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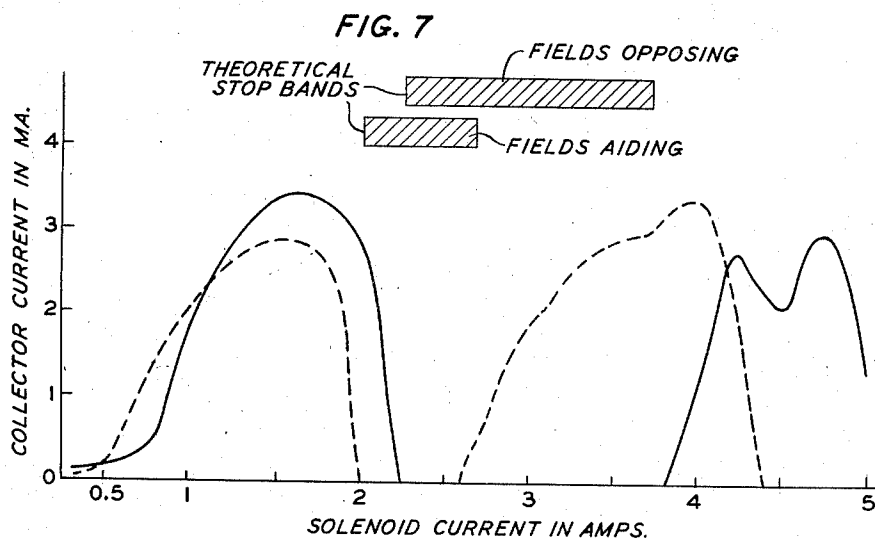
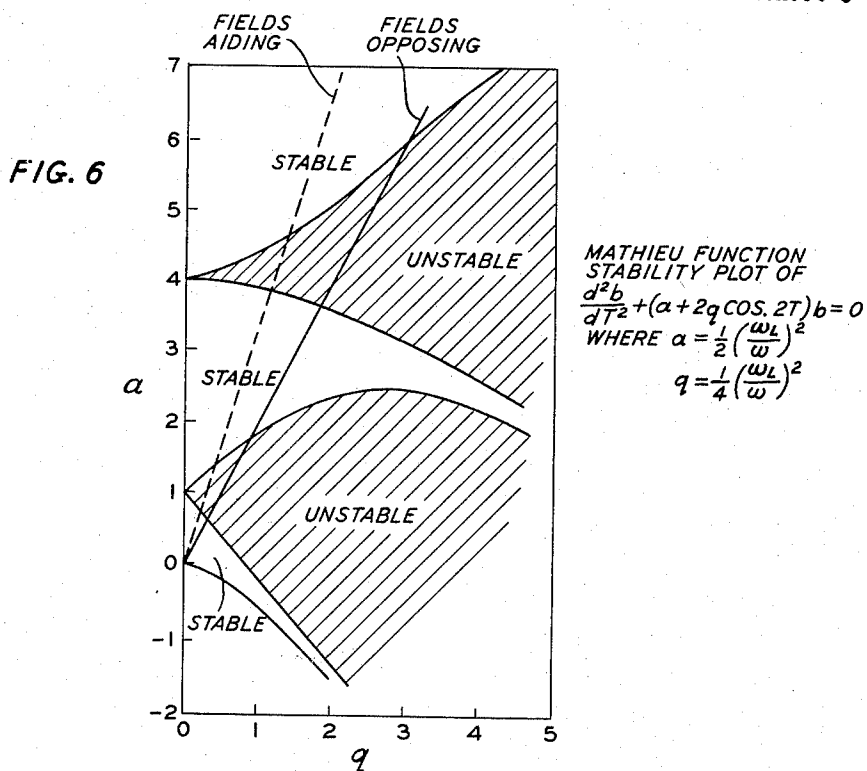
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4 Sheets-Sheet 3



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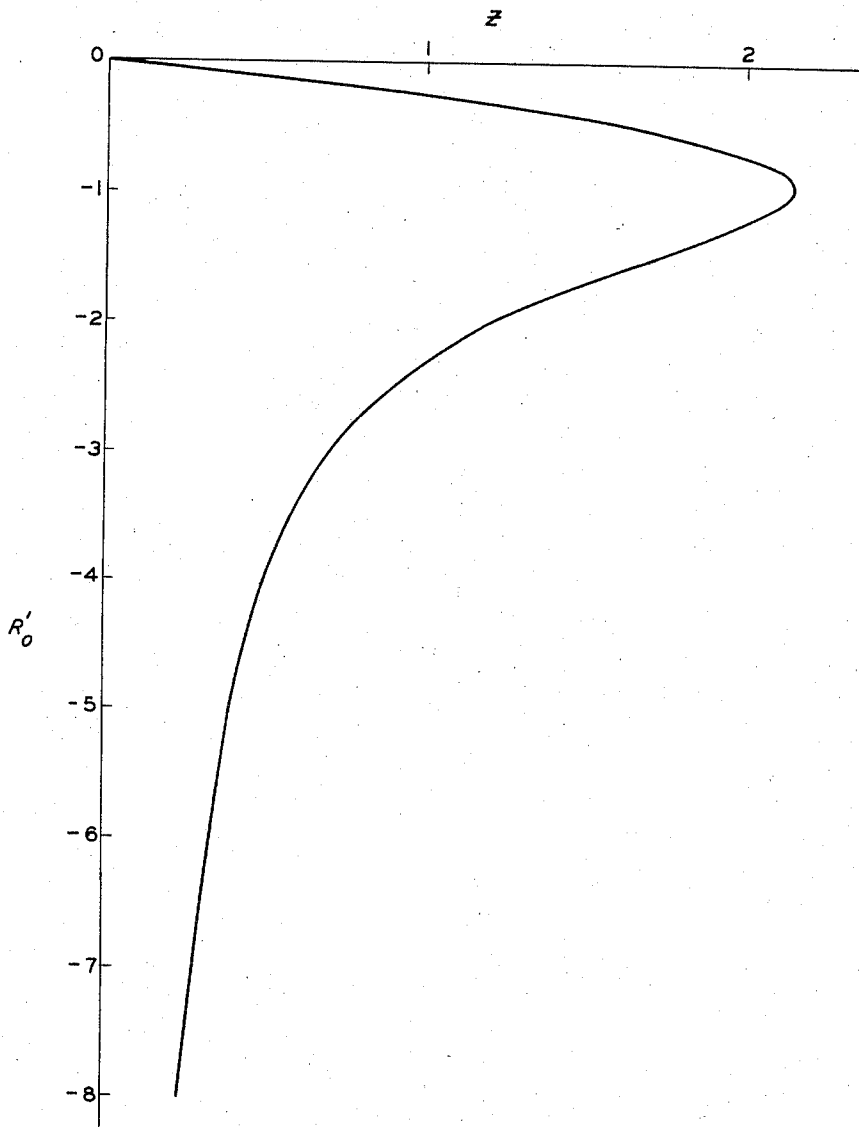
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4 Sheets-Sheet 4

FIG. 8



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2,841,739

ELECTRON BEAM SYSTEMS

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Application April 29, 1953, Serial No. 351,984

7 Claims. (Cl. 315—3.5)

This invention relates to systems for focusing a stream of charged particles, and more particularly systems for keeping electron beams cylindrical over a relatively long path. Such systems have special importance in apparatus, such as traveling wave tubes, in which an electron beam of high density interacts with a traveling electromagnetic wave over a plurality of operating wavelengths.

It is characteristic of an electron beam of high density that space charge effects within the beam exert transverse forces which act to make the flow divergent. In traveling wave tubes where the electron beam flows past an interaction circuit over a relatively long path, it is advantageous to introduce focusing forces to keep the flow cylindrical to minimize the number of electrons lost in striking the circuit and to confine the beam to regions of high radio frequency field.

One common expedient in the traveling wave tube art for keeping the electron flow cylindrical is to immerse the beam path in a magnetic field in which the magnetic lines are parallel to the longitudinal direction of electron flow. In a common form of such magnetic focusing, usually termed Brillouin type focusing, the electron gun is enclosed in a magnetic shield, and the electrons are caused to spiral as they enter the region of longitudinal magnetic field from the shielded region. There results an inward or focusing force per charge proportional to the product of the angular velocity and the longitudinal magnetic field, or effectively the square of the magnetic field. This inward force is adjusted to counterbalance exactly the sum of outward mutually repulsive forces of the electrons (the so-called space charge forces) and the outward centrifugal force of the spiraling electrons. If in addition to satisfying the condition along the region of magnetic field, the electron beam is made to enter this magnetic field region with zero radial velocity, it will travel without spreading.

However, both because of the relatively long length of the electron path and because of the large space charge forces found in a beam of high density, it is found in practice that the auxiliary equipment necessary to provide a magnetic field of sufficient strength and uniformity is often heavy and bulky, being many times the weight and size of the traveling wave tube alone. For obvious reasons, it is desirable to minimize the size and weight of this auxiliary equipment, and the present invention is directed towards this end.

Accordingly, the principal object of the present invention is to effect economies in the requirements of the magnetic field necessary for good magnetic focusing of a stream of charged particles.

The present invention relates to a system of magnetic focusing in which the intensity of the magnetic field varies periodically with distance along the path of flow rather than being constant therealong.

Analysis, of which a more detailed description follows, has revealed that an essentially non-diverging beam may be obtained if the R. M. S. value of a periodic longi-

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tudinal magnetic field in the vicinity of the beam has the same magnitude as the uniform axial field characteristic of Brillouin focusing. It is obvious that for a given average field value, a larger R. M. S. field value results if the field is localized in a succession of relatively short regions instead of being uniform over a relatively long region. Accordingly, the necessary value of R. M. S. field necessary for a non-diverging beam can be achieved with a minimum of driving magnetomotive force by concentrating the longitudinal magnetic field along a periodic series of short gaps along the path of flow.

A usual expedient for achieving the desired longitudinal magnetic field is to surround the tube envelope with a solenoid which when energized establishes an axial magnetic field which immerses the path of electron flow.

In accordance with the present invention, economies in the driving magnetomotive force necessary are achieved by suitably shielding the electron path from the solenoid field along much of its length and localizing the field to a succession of unshielded regions and arranging to have the magnetic field reverse direction at each unshielded region. In an illustrative embodiment of the invention, an annular structure of a material of low reluctance such as soft iron surrounds the electron path, the structure having an outer cylindrical surface which is continuous for forming a low reluctance magnetic path and an inner cylindrical surface which is provided with a regular succession of apertures surrounding the path of flow. A succession of solenoids is wound in the interior of the annular frame for forming a succession of magnetic fields which leak out at the apertures in the inner cylindrical surface for creating regions of longitudinal magnetic fields along the adjacent portions of the electron path, successive solenoids being oppositely wound whereby the direction of the field reverses with successive regions. In particular, there are developed optimum relationships for the length, spacing and intensity of these longitudinal magnetic field regions.

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

Fig. 1 shows an electron beam system which utilizes a time-constant spatially alternating magnetic field to focus the beam;

Fig. 2 shows a traveling wave tube which utilizes the electron beam system of Fig. 1 in accordance with the invention;

Fig. 3 shows a traveling wave tube which utilizes an electron beam system which provides a unidirectional magnetic field which is varied periodically in intensity; and

Figs. 4A through 4C and 5 through 8 are plots which will be useful in explaining the principles of the invention.

In the electron beam system 10 shown in Fig. 1, an evacuated envelope 11 of a suitable non-magnetic material such as glass houses the electron beam. At one end of the envelope, an electron gun 12 serves as the source of a solid beam of electrons. Although an electron gun customarily includes an electron emissive cathode, a beam focusing electrode, and an accelerating electrode system, for purposes of simplicity, the electron gun is shown schematically merely as a cathode. At the opposite end of the envelope a target electrode 13 serves to collect the spent electrons at the end of their path. Intermediate the electron source 12 and target electrode 13, provision is made for accelerating the electron beam. In the case of a traveling wave tube, an interaction circuit is provided therebetween which is maintained at an appropriate positive D. C. potential with respect to the electron source. In the system shown, an electrode member is disposed along the path of flow in the form of a

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resistive coating 14 on the inner surface of the envelope for providing an accelerating field.

The focusing of the electron beam is achieved by a succession of regions of longitudinal magnetic field along the path. To achieve the desired succession of magnetic regions, the solenoids 15 are spaced apart along and with their axis coinciding with the path of flow. Each solenoid 15 is surrounded by a magnetic shield 16 which serves as a flux guide and is open only along a short gap 17 adjacent the path of flow where the magnetic field escapes into the path of flow for creating a region of longitudinal magnetic field. The spacing of the gaps is adjusted in accordance with the principles set forth in the analysis which follows hereinafter. Alternatively, the arrangement may be viewed as comprising an annular frame member 16 of a material having a high permeability such as soft iron for serving as a low reluctance magnetic path for which the driving magnetomotive force is provided by the plurality of solenoids 15 spaced apart within the annular interior of the frame member. The frame member is closed except for a succession of cylindrical gaps 17 along its inner surface which permit leakage of the magnetic field to adjacent regions of the electron path. The successive solenoids are separated by a succession of transverse magnetic disks 18 which isolate the separate solenoids to make feasible the reversal of the direction of longitudinal magnetic field along successive gaps by a reversal of the direction of current flow through successive solenoids. By reversing the direction of the magnetic field along successive regions there can be achieved a substantially sinusoidal variation of magnetic intensity along the path of flow. Such a magnetic field distribution lends itself to the analysis which follows:

It is assumed that, (a) the magnetic field B is axially symmetric and uniform over the beam cross-section, i. e.,

$$B_z = B(z)$$

where z is measured in the direction of longitudinal flow. Moreover, for simplicity B_z will hereinafter be designated by B. (b) the electric field E due to space charge acts only in a radial direction r, i. e.,

$$E = E_r$$

The Lagrangian for an electron in an electric and magnetic field is given by

$$L = \frac{m}{2} (\dot{r}^2 + r^2 \dot{\theta}^2 + \dot{z}^2) + e(v \cdot A) - eV \quad (1)$$

where A is the magnetic vector potential, V the electric potential, and e the charge of an electron. For the assumed conditions,

$$A = A_\theta = \frac{Br}{2}$$

For the condition of no magnetic field at the cathode one obtains,

$$\dot{\theta} = -\frac{1}{2}\eta B \quad (2)$$

where η is the charge mass ratio of an electron. Using Equation 2 the expression for r derived from the Lagrangian is,

$$\ddot{r} + \frac{B^2 \eta^2}{4} r - \eta \frac{\partial V}{\partial r} = 0 \quad (3)$$

For an electron at the edge of the beam,

$$\frac{\partial V}{\partial r} = \frac{r_0^2 \rho}{2\epsilon r}$$

where r_0 is the beam radius at the entrance of the focusing structure and ρ is the charge density per unit volume which is assumed constant across the beam. Equation 3 now becomes,

$$\ddot{r} + \frac{B^2 \eta^2}{4} r - \frac{\eta r_0^2 \rho}{2\epsilon r} = 0 \quad (4)$$

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Now if there be defined B_0 as the peak value of magnetic field at the axis, L as the magnet period (equal to twice the mean distance between gaps or solenoids),

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

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

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

$$z = u_0 t$$

$$\sigma = \frac{r}{r_0}$$

where u_0 is the beam velocity, which is assumed to be constant. Rewriting Equation 4

$$\ddot{\sigma} + \left(\frac{B\eta}{2}\right)^2 \sigma - \frac{\omega_p^2}{2} \frac{1}{\sigma} = 0 \quad (5)$$

For the focusing structure shown in Fig. 1 the substantially sinusoidal magnetic field B at the axis is very nearly given by,

$$B = B_0 \cos \frac{2\pi z}{L}$$

Using this value of B, Equation 5 becomes

$$\ddot{\sigma} + \frac{1}{2} \left(\frac{\omega_L}{\omega}\right)^2 (1 + \cos 2T) \sigma - \frac{1}{2} \frac{\omega_p^2}{\omega} \frac{1}{\sigma} = 0 \quad (6)$$

where T is equal to ωt and $\dot{\sigma}$ is equal to

$$\frac{d^2 \sigma}{dT^2}$$

For convenience let,

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

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

Then Equation 6 becomes

$$\ddot{\sigma} + \alpha (1 + \cos 2T) \sigma - \beta \frac{1}{\sigma} = 0 \quad (7)$$

This non-linear differential equation can be solved for values of α and β of interest to the study of practical traveling wave tubes.

For convenience it was assumed that the electrons were injected with no radial velocity at the point T equal to 0, i. e., at a point where the magnetic field was a maximum. In practice this condition can be realized by adjusting the position of the electron gun with respect to the first longitudinal magnetic field gap or by suitable electrostatic focusing near the gun.

Figs. 4A through 4C show plots of the beam radius as a function of the distance along the path of flow z for various values of the parameter α with β held constant. For a given focusing structure and a given value of beam velocity α is proportional to the square of the peak magnetic field (B_0^2) and β is proportional to the beam current I_0 , and therefore varying α is equivalent to varying the peak magnetic field B_0 . With a particular value of magnetic field the perturbations of the beam radius are seen to be a minimum (Fig. 4B) and this is the so-called optimum field. For higher values of peak magnetic field B_0 the average radius of the beam is decreased (Fig. 4C) and for lower values of B_0 it is increased (Fig. 4A).

The optimum values of α (or magnetic field) are plotted as a function of β (or space charge) in Fig. 5. For small values of β ($\beta < 0.2$) the optimum value of α is approximately equal to β . As β is increased the optimum value of α gets progressively larger than β (it should also be noted that the mean radius of the beam is getting progressively smaller). More important, however, is the fact that the ripples in the beam radius get progressively larger until for a value of $\beta \geq 6$ the beam

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radius diverges to a value greater than twice its initial value which is assumed to be larger than the maximum value to be permitted irrespective of the value of α . When α and β are expressed in terms of familiar tube constants one obtains,

$$\beta \sim K \left(\frac{L}{d} \right)^2$$

$$\alpha \sim \frac{B_0^2 L^2}{V_0}$$

where L is twice the gap spacing, d is the beam diameter, V_0 is twice the beam voltage, B_0 is the peak magnetic field, and K is the beam perveance. It is evident that given a particular traveling wave tube, for β to be less than 0.6 (and consequently a beam confined to less than twice the initial diameter) it is preferable to adjust L (the solenoid spacing) since this is the only parameter not associated with the physical constants of the tube.

For small values of β the required value for α was found to be equal to β for minimum perturbation of the beam radius. This value of α corresponds to a peak magnetic field (B_0) equal to $\sqrt{2}$ times the field required for Brillouin focusing. However, since this is a sinusoidal varying field, one should compare the R. M. S. value of this field with the Brillouin field, in which case the two are equal. For higher values of β the mean diameter of the beam for minimum perturbation was significantly reduced below r_0 (as is evident from Fig. 4B). If the mean radius is used in computing the required Brillouin field, the two schemes of focusing will again be found to be equivalent with respect to R. M. S. fields within the accuracy of the computation. Therefore, it appears that axially symmetric periodic magnetic focusing requires the same total magnetic energy in the vicinity of the beam as does Brillouin focusing, but it makes possible a reduction in total magnetomotive driving force needed.

Unlike the case of the uniformed solenoid, the focusing cannot be improved by increasing the magnetic field strength well beyond the theoretical required value. Instead one encounters regions of magnetic field strength which cause the beam to diverge to the enclosing envelope and therefore for good focusing the field must lie within certain well defined regions. A good insight into the mechanism of this phenomenon can be obtained from the "Butterfly Diagram" (Fig. 6) which shows the stable and unstable regions of the Mathieu equation.

In a consideration of Equation 7, it can be seen that the first two terms comprise Mathieu's differential equation while the last term is due to the space charge forces of the electrons. An analysis of Mathieu's equation can be found in a book entitled "Theory and Applications of Mathieu Functions" by H. W. MacLachlan published by the Oxford University Press (1947). If the solution to the homogeneous equation without space charge (Mathieu's equation) diverges, then it is reasonable to suppose that the addition of the space charge term will not restore stability. (However, the converse is not necessarily true, i. e., if the homogeneous part is stable the complete solution is not necessarily stable.) From Equation 7 the constants a and q of the standard form of Mathieu's equation becomes respectively 1 and 1/2 and therefore describe a straight line on the stability chart (Fig. 6). (Also shown is the line corresponding to the case where the solenoids are wound so that the field of each is in the same direction.) This line intersects the boundaries of the stable and unstable regions at points which define the values of

$$\frac{1}{2} \left(\frac{\omega L}{\omega} \right)^2$$

(the constant α which separate the pass and stop bands of periodic focusing.

The case of "aiding fields" is represented by a broken

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line of greater slope. This arises from the slightly different equation for r applicable to this case.

$$\ddot{r} + \left(\frac{1}{1+\Delta} \right)^2 \left(\frac{\omega L}{\omega} \right)^2 \left[\left(1 + \frac{\Delta^2}{2} \right) + 2\Delta \cos 2T + \frac{\Delta^2}{2} \cos 4T \right] r - \frac{1}{2} \left(\frac{\omega_p}{\omega} \right)^2 \frac{1}{r} = 0 \quad (8)$$

where the magnetic field varies along the beam path as,

$$B = \frac{B_0}{1+\Delta} (1 + \Delta \cos 2T)$$

For a particular experimental focusing structure Δ was measured to be 1/3, so Equation 8 becomes

$$\ddot{r} + .562 \left(\frac{\omega L}{\omega} \right)^2 [1.055 + .667 \cos 2T + .055 \cos 4T] r - \frac{1}{2} \left(\frac{\omega_p}{\omega} \right)^2 \frac{1}{r} = 0$$

Ignoring the $\cos 4T$ term, and rewriting in terms of the previous constants α and β , for "Aiding Fields," Equation 8 becomes

$$\ddot{r} + 1.12\alpha [1.055 + .667 \cos 2T] r - \beta \frac{1}{r} = 0 \quad (9)$$

The case of aiding fields is, however, of less practical interest.

It will be noted from Fig. 6 that the stop bands for aiding fields should be narrower with respect to the parameter α than in the case of opposed fields. Fig. 7 shows the collector current measured plotted against the solenoid current of an experimental arrangement. For convenience of comparison the first theoretical stop bands, obtained from the Mathieu stability plot, for the two cases of aiding and opposed fields are shown on the graph. The continuous line represents the case of opposing fields, the broken line the case of aiding fields. Very close agreement between these theoretical stop bands and measured stop bands lends support to the argument for using the stability diagram.

A simplified analysis which can be carried out is to assume that along the path of flow the regions of longitudinal magnetic field are short compared to the distance separating them, so that the succession of focusing fields may be regarded as a series of thin converging lenses. Then if the beam is started in such a manner that it is cylindrical midway between two adjacent lenses, and if the lenses are chosen of the right strength, the flow will be cylindrical between the next two lenses. The converging effect of the lenses is on the average just balanced out by the diverging effect of the space charge between the lenses, and the electron beam flow is identical between each successive pair of lenses. By inserting the quantitative expressions for the diverging effect of the space charge given in Section 9.2 (pages 147 through 152) of my book entitled "Theory and Design of Electron Beams," published by D. Van Nostrand Company, Incorporated, New York (1949), it can be shown that for non-divergent flow it is important that

$$174 \frac{I^{1/2}}{V^{3/4}} \frac{z}{r_0} < 2.16$$

where z is the spacing of successive lenses, r_0 is the beam radius at the lenses, I is the current in amperes of the beam, and V is the accelerating voltage acting on the beam. Additionally, it can be shown that the convergence C of the lens required for this result is such that

$$C = - \frac{2R_0' Z}{L}$$

where Z is the parameter measuring distance given by

$$174 \frac{I^{1/2}}{V^{3/4}} \frac{z}{r_0}$$

and the R_0' corresponding to a given Z can be found

from the curve shown in Fig. 8 where R_0' is plotted as a function of Z . Here it can be seen that no values of R_0' exists for which Z is greater than 2.16. For values of Z smaller than this, there are two possible values of R_0' , one for which $-R_0'$ is less than .92 corresponding to a very weak lens and a large minimum beam radius, the other for which $-R_0'$ is greater than .92 corresponding to a strong lens and a small minimum beam radius.

In the traveling wave amplifier 20 shown in Fig. 2, an envelope 21 of a non-magnetic material such as glass houses various tube elements. Many of the details whose need will be obvious to a worker in the tube art have not been shown. Alternatively, it is possible to employ an envelope of a magnetic material such as kovar if the envelope is made so thin as to become magnetically saturated so readily as to little reduce the magnetic field in the interior of the envelope. At the two opposite ends of the envelope are positioned an electron source 22 and a target electrode 23. The electron source is an electron gun comprising an electron emissive cathode 24, a beam forming electrode 25A and an accelerating electrode 25B for forming an electron beam which is projected along the elongated portion of the envelope to the target 23 which serves as the collector of the spent electrons. Disposed along the path of flow is a helically coiled conductor, a plurality of operating wavelengths long, which serves both as the interaction circuit for propagating a slow electromagnetic wave in coupling relation with the electron beam and also as an electrode for accelerating the electron beam.

The helix 26 is joined at opposite ends to an input coupling strip 27 by an impedance matching section 29 and to an output coupling strip 28 by an impedance matching section 30. The matching sections 29 and 30 are simply extensions of the conductor 26 in which the pitch of the helix is gradually increased. An input wave is applied to the upstream end of the helix interaction circuit by way of input wave guide coupling connection 31 and the output wave is abstracted at the downstream end by way of output wave guide coupling connection 32. Each of the wave guide coupling connections 31 and 32 is a section of rectangular wave guide which has a pair of opposite side walls 31A, 31B and 32A, 32B apertured for passage therethrough of the tube envelope and which has a closed end 31C, 32C and an open end by which it can be connected into a wave guide system. Each of the input and output coupling strips 27 and 28 is supported in its corresponding wave guide coupling connection. Input waves are applied to the input wave guide coupling connection 31 to have a mode of propagation having an electric field direction parallel to the coupling strip 27. In this way, an electromagnetic wave is introduced into the helix interaction circuit for travel therealong in coupling relation with the electron beam. The electron gun is aligned to form a solid cylindrical beam for projection coaxially through the helix. For accelerating the electron beam, the helix is maintained by suitable lead-in connections not shown at a potential which is positive with respect to that on the cathode 24 and approximately equal to that on the target 23. For efficient operation, it is important that the electron flow be substantially parallel to the axis of the helix 26 whereby a minimum of electrons will be lost in striking the conductor. Accordingly, it is desirable to introduce some focusing of the electron beam in order to counteract the transverse space charge forces which tend to make the beam diverge. The description hitherto has been of a conventional form of traveling wave tube essentially of the kind described in United States Patent No. 2,575,383 which issued to L. M. Field on November 20, 1951.

In accordance with a preferred embodiment of the invention, each of a succession of solenoids 33 are spaced apart along the path of flow. Each solenoid is enclosed within a magnetic shield or flux guide 34, which is open

only along a short gap 35 adjacent the path of electron flow where the magnetic field escapes into the path of flow for creating a region of longitudinal magnetic field. The current through the windings of successive solenoids is adjusted to introduce a reversal in the direction of longitudinal magnetic field set up across successive gaps 35. It is these successive regions of longitudinal magnetic field that effect the desired focusing.

It is generally desirable to minimize the disturbing effect of the input and output wave guides 31 and 32 on the periodicity of the regions of longitudinal magnetic field along the whole length of path flow. To this end, the aperture side walls 31A, 31B, 32A and 32B of each of wave guide connections 31 and 32 are made of a material of high permeability while the other pairs of side walls together with the end closures 31C and 32C are made of a non-magnetic material such as copper. Magnetic flux producing means are bridged across the two pairs of apertured side walls 31A, 31B and 32A, 32B. These magnetic means are illustrated in the embodiment of Fig. 2 as the electromagnets 37 and 38. The side walls 31B and 32B are provided with projecting sleeves 39 and 40 which closely surround portions of the glass envelope 21 for forming with side walls 31A and 32A gaps 41 and 42, respectively, similar to the air gaps 35 along the magnetic shield 34. By choosing the electromagnets 37 and 38 of appropriate strength, the region of periodically varying longitudinal magnetic field can be extended along the path of electron flow past the two wave guide connections. In some instances it may be desirable to taper each of the wave guides 31 and 32 to provide a wall separation in the direction of electron flow which results in minimum disturbance of the periodicity of the longitudinal magnetic field. To insure the desired condition of minimum beam radius at a point half-way between the first two periodic regions of longitudinal magnetic field, it is generally advantageous to add a magnetic lens, here the magnetic field provided by the solenoid 43, in conjunction with the electrode focusing system of the electron gun. This, together with a suitable choice of gap periodicity and solenoid strength in accordance with the analysis set forth above, makes possible projection of the beam throughout the length of the helix with a minimum of lost electrons.

Fig. 3 shows a traveling wave tube similar to that shown in Fig. 2 with which is associated a focusing system which provides an array of unidirectional longitudinal field regions. For convenience the same reference numerals used in designating elements of the traveling wave tube shown in Fig. 2 are employed here. The focusing system shown in Fig. 3 comprises essentially a single solenoid 52 which provides the magnetomotive driving force for the succession of regions of longitudinal field along the path of flow. In the present instance, it is assumed that the drift regions of low magnetic field which separate the regions of high magnetic field are long so that it is feasible to allow those portions of the electron path corresponding to travel within the input and output wave guides 53 and 54 serve as drift spaces. To this end, it may be desirable to taper these wave guides in the direction of electron flow to reduce the wall spacing in the region of electron traversal. Under such conditions, it will be advantageous to have the wave guides 53 and 54 be entirely of a material of high permeability to provide magnetic shielding of the regions they enclose, and to have the solenoid 52 extend between the wave guides 53 and 54. Alternatively, if desired, the periodic regions of longitudinal magnetic field can be extended along the path of flow past the wave guides by utilizing the wave guides in a manner to provide regions of high longitudinal magnetic field therein as described in connection with Fig. 2.

To confine the magnetic field to periodic intervals along the path of flow, a succession of cylindrical sleeves 55 of a material of high permeability are disposed around

the envelope 21 for serving as flux guides, and there is formed a succession of air gaps 56 along the path of flow across which are set up longitudinal components of magnetic field. It is characteristic of this arrangement that the direction of the longitudinal magnetic field is the same in successive air gaps so that the applicable analysis is that of the "fields aiding" case. Additionally, a cylindrical jacket 57 of high permeability surrounds the outside of the solenoid for serving as a low reluctance flux guide therealong.

As is indicated by the analysis by concentrating most of the magnetic energy provided by the solenoid to a series of relatively short gaps along the path of flow, there is enhanced the efficient utilization of the driving magnetomotive force provided, and, accordingly, the size and power of the solenoid necessary for a given degree of focusing can be less than for the conventional Brillouin-type focusing.

In my copending application Serial No. 351,983, filed April 29, 1953, there is described a focusing system which employs permanent magnets to achieve along the path of flow a succession of regions of longitudinal magnetic fields characterized in that the direction of the magnetic field reverses with succeeding regions.

What is claimed is:

1. In a traveling wave tube, an electron source and a target electrode defining therealong a path of electron flow, electrode means disposed along the path of flow for accelerating the electron stream, a plurality of identical solenoids disposed along the path of flow at equal distances, adjacent solenoids being in field opposing relation, and a succession of identical annular permeable members, each forming a low reluctance path around a solenoid which is open at equal distances along an annular region adjacent to and surrounding the path of flow for establishing longitudinal magnetic flux along the corresponding region of the electron path, the successive uniform regions of magnetic flux serving as successive identical converging lenses having a convergence sufficient for overcoming the space charge divergence between successive regions.

2. In a traveling wave tube, an electron source and a target defining therealong a path of electron flow, a helical conductor along the path of flow for accelerating the electron stream and for propagating waves for interaction with said flow, a succession of identical solenoids disposed along and surrounding successive regions of the path of electron flow at equal distances, adjacent solenoids being in field opposing relation, and a succession of identical permeable members, each enclosing a solenoid for forming a path of low magnetic reluctance therearound and having an annular aperture in the surface adjacent the path of electron flow for allowing penetration of the path of electron flow by the magnetic field.

3. In a traveling wave tube, means forming a path of electron flow, a wave circuit for propagating a slow wave for interaction with the electron flow, a wave guide connected to the upstream end of the wave circuit having a pair of permeable opposite walls, magnetic means for establishing a magnetic field along the path of flow between the pair of walls, a succession of identical solenoids disposed along and surrounding successive regions of the path of electron flow at equal distances, adjacent solenoids being in field opposing relation, and a succession of identical permeable members, each enclosing a different solenoid and having an annular aperture adja-

cent the path of electron flow for allowing penetration of the path of electron flow by the magnetic field.

4. In a traveling wave tube, an electron source and collector electrode defining therebetween a path of electron flow, an interaction circuit for propagating a slow electromagnetic wave in field coupling relation with said electron flow, a succession of identical solenoids disposed along and surrounding the electron path at equal distances, adjacent solenoids being in field opposing relation, and a succession of annular shielding means enclosing the succession of solenoids, said shielding means comprising annular metallic members having high permeability resulting in low magnetic reluctance paths, each shielding means being apertured through its center and thereby aligned coaxially and positioned uniformly along and adjacent the axis of the tube envelope, the side of said shielding means adjacent the path of electron flow having an opening defining a succession of equal spaced gaps along the axis of electron flow.

5. A traveling wave tube comprising an envelope, an electron source and collector electrode at opposite ends of said envelope and defining therebetween a path of electron flow, an interaction circuit for propagating a slow electromagnetic wave in field coupling relation with said electron flow, a succession of identical solenoids disposed along and surrounding the electron path at equal distances, adjacent solenoids being in field opposing relation, and magnetic shielding means encompassing said solenoids except for a succession of gaps along the path of said electron flow, said gaps being of equal lengths, the distances between adjacent gaps being equal, and one gap being associated with each of said solenoids.

6. A traveling wave tube comprising an evacuated envelope, means for forming a cylindrical beam of electrons for flow axially through said envelope, an interaction circuit for propagating a slow electromagnetic wave in field coupling relation with said beam, and means for maintaining the electron beam cylindrical and of substantially uniform diameter during its progression past said interaction circuit, said means comprising a succession of identical pole pieces spaced equal distances apart along the path of said flow, and a plurality of substantially identical magnet means interposed between adjacent pole pieces, each of said pole pieces being common to like poles of two adjacent magnet means and each adjacent pair of said pole pieces defining a gap of the same length as the other of said gaps, whereby said pole pieces and magnet means provide a longitudinal region of periodic spatially alternating magnetic field along the axis of the electron beam.

7. A traveling wave tube in accordance with claim 6 wherein said pole pieces are cylinders of a magnetic material positioned external to said envelope and adjacent thereto.

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