

Aug. 12, 1958

J. R. PIERCE

2,847,607

MAGNETIC FOCUSING SYSTEM

Filed April 29, 1953

4 Sheets-Sheet 1

FIG. 1

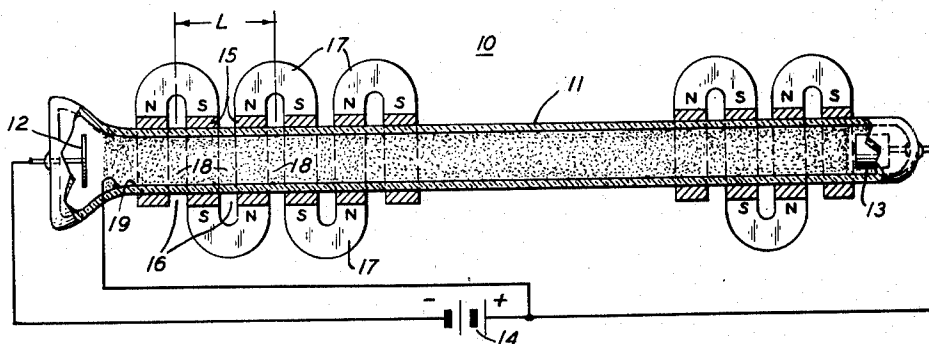


FIG. 2

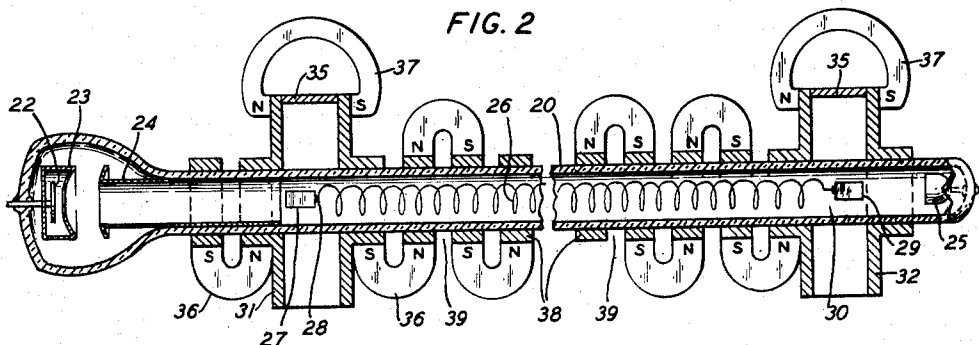


FIG. 3

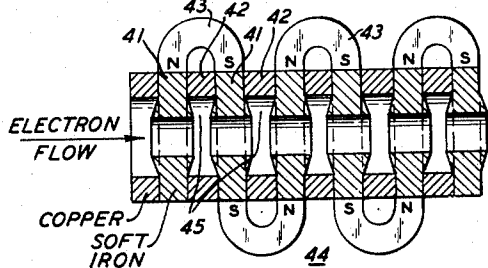


FIG. 4

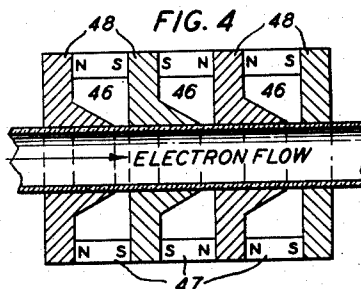


FIG. 5

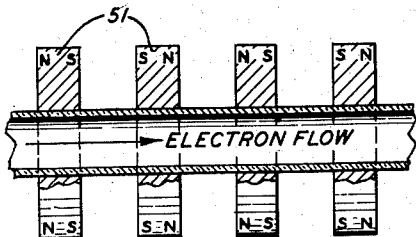
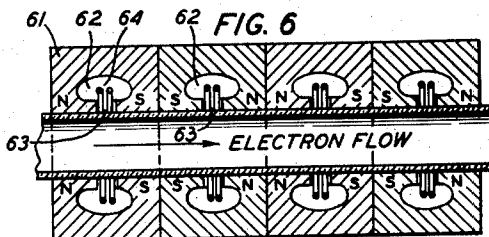


FIG. 6



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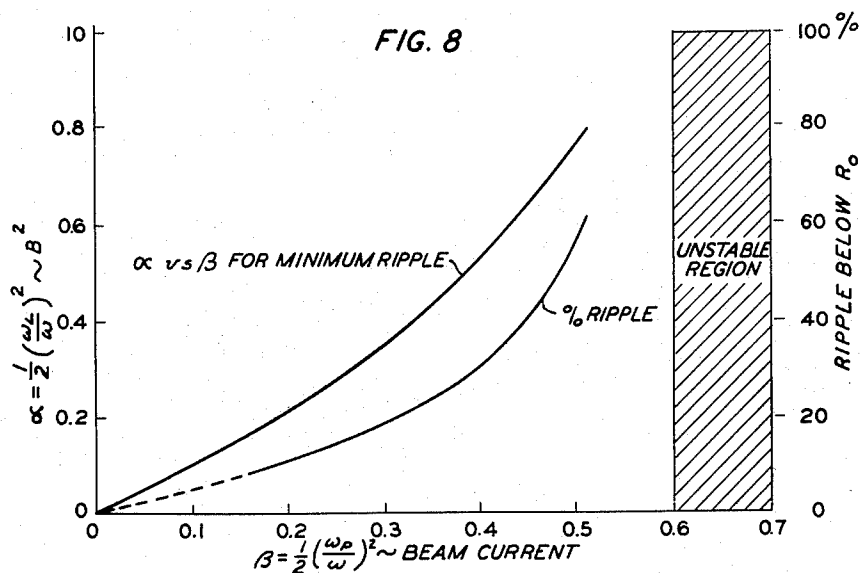
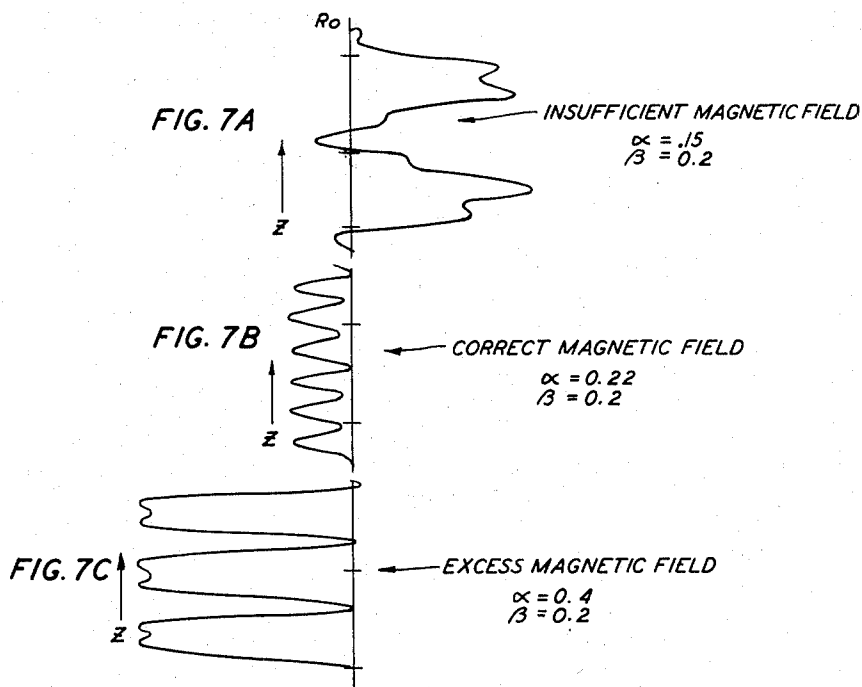
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MAGNETIC FOCUSING SYSTEM

Filed April 29, 1953

4 Sheets-Sheet 2



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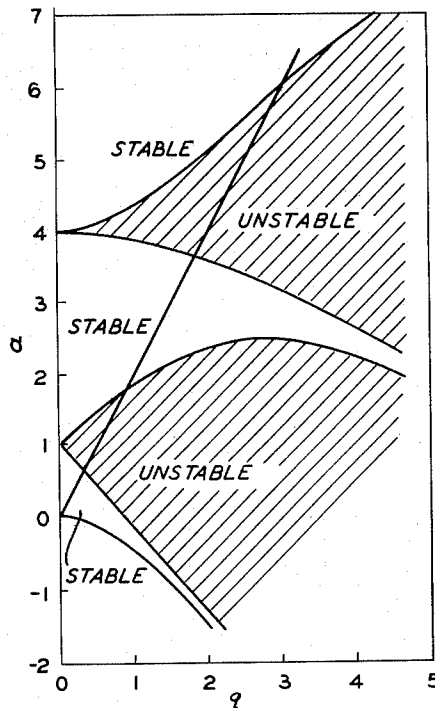
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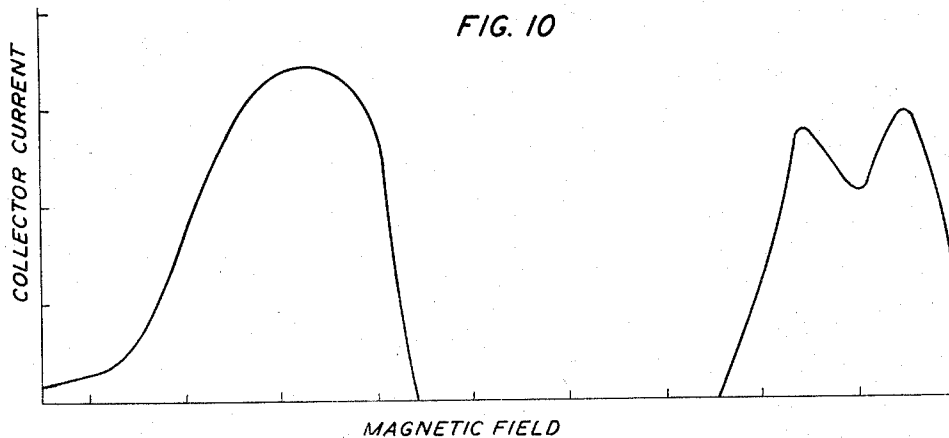
4 Sheets-Sheet 3

FIG. 9



MATHIEU FUNCTION
STABILITY PLOT OF
 $\frac{d^2b}{dT^2} + (a + 2q \cos 2T)b = 0$
WHERE $a = \frac{1}{2} \left(\frac{\omega_z}{\omega} \right)^2$, $q = \frac{1}{4} \left(\frac{\omega_z}{\omega} \right)^2$

FIG. 10



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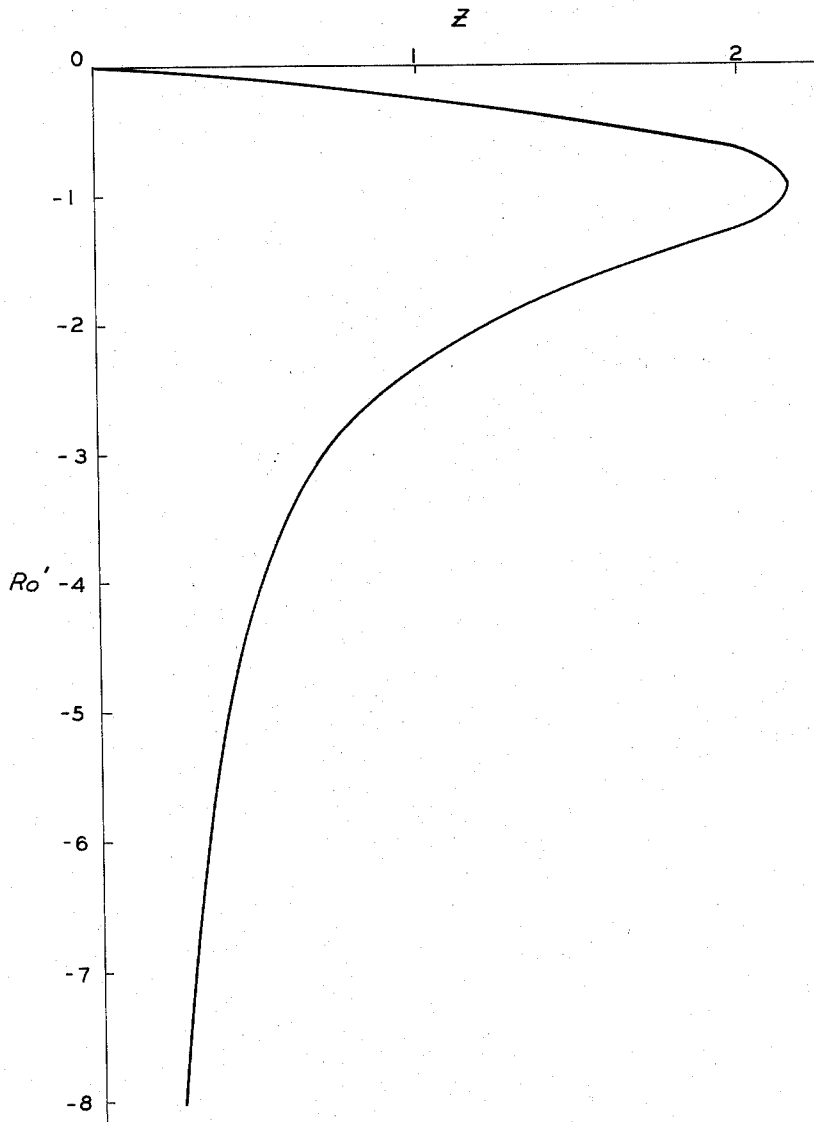
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MAGNETIC FOCUSING SYSTEM

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4 Sheets-Sheet 4

FIG. II



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1

2,847,607

MAGNETIC FOCUSING SYSTEM

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Application April 29, 1953, Serial No. 351,983

6 Claims. (Cl. 315—3.5)

This invention relates to systems for focusing beams of charged particles, and more particularly to systems where an electron beam is collimated by magnetic fields for travel over a relatively long path as is characteristic of many forms of cathode ray devices, such as, for example, traveling wave tubes.

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

A more specific object of the invention is to effect economies in the magnetic field necessary for good magnetic focusing of an electron beam in a traveling wave tube to the end that there results a saving in the size and weight of the equipment used for such focusing.

In a traveling wave tube, an electron stream is made to interact with a traveling electromagnetic 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 electrons strike the interaction circuit and to confine the electrons to regions of high signal fields. To minimize transverse components set up by space charge effects, it is the usual practice to set up a uniform longitudinal magnetic field along the path of electron flow. This magnetic field is generally achieved either by the use of permanent magnets or external solenoids.

Hitherto, it has been common practice to employ Brillouin type focusing with high density electron beams. In focusing of this type, 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. The angular velocity of each electron is proportional to the difference in magnetic flux encountered in going from the shielded region into the field region. The inward or focusing force per charge is 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 (generally described as the space charge forces) and the outward centrifugal force of the spiraling electrons. If, in addition to satisfying this condition along the magnetic field region, the electron beam is caused to enter the magnetic field region initially 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 existing in an electron stream of high density, it is found in practice that the solenoids or permanent magnets necessary to provide a satisfactory uniform longitudinal magnetic field are often large 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 focusing equipment, and the present invention is directed to this end.

The present invention achieves this end by employing

2

along the path of flow a succession of regions of longitudinal magnetic field characterized in that the direction of this field reverses in successive regions.

Analysis, of which a more detailed description follows hereinafter, has revealed that an essentially non-diverging beam may be obtained if the R. M. S. value of the longitudinal 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 concentrated in a succession of relatively short regions instead of being uniform over a relatively long region. Accordingly, a high R. M. S. value of longitudinal magnetic field in the vicinity of the beam, important for good focusing, 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 beam path. For the case where the magnetic flux is provided by a solenoid, periodic focusing in this way permits an overall decrease in the magnetomotive driving force of the solenoid necessary. In my copending application Serial No. 351,984, filed April 29, 1953, now Patent 2,841,739, issued July 1, 1958, there are described focusing arrangements of this kind utilizing solenoids. Where permanent magnets are utilized to create the desired magnetic flux, a succession of longitudinal magnetic sections provides even more marked advantages over Brillouin type uniform field focusing. First, a periodic field system of this kind can be made as long as desired by adding magnets without the fields of the added magnets reducing the fields of magnets already present. Also, the weight of the magnetic material necessary will be considerably less for the periodic field system since, unlike the uniform field permanent magnet system for which the field must be broad in order to be uniform, no extra flux needs to be set up merely to insure uniformity of field along the path of flow. Moreover, in a succession of regions in which the field alternates in direction, the field strength falls off away from the axis more rapidly than in a succession of regions in which the field is of constant direction, and hence such a spatially alternating field stores less total energy because it extends over a smaller volume. Since the magnet weight is governed by the total stored energy, this factor permits a reduction thereof.

In a preferred embodiment of the invention, a succession of hollow cylinders of a permeable material such as Permalloy or soft iron are disposed for surrounding spaced portions of the electron path. Then a succession of small permanent magnets are bridged across successive cylinders for forming a series of converging magnetic lenses which establish longitudinal magnetic fields of substantially circular symmetry along portions of the electron path corresponding to the gaps formed between successive cylinders. The pole faces of the permanent magnets are oriented to introduce a reversal of the longitudinal magnetic field across portions of the electron path corresponding to successive gaps so that the magnetic field will fall off sharply with distance away from the electron path.

Various other illustrative embodiments will be described herein, each of which is characterized as establishing along the path of flow a succession of regions of longitudinal magnetic field, the direction of the magnetic field reversing with successive regions.

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

Fig. 1 shows in schematic form a longitudinal cross section of an electron beam system in accordance with the invention;

Fig. 2 shows in longitudinal cross section a helix-type traveling wave tube embodying the electron beam system shown in Fig. 1;

Fig. 3 shows in longitudinal cross section an interaction circuit portion of a traveling wave tube in which a focusing system in accordance with the invention is incorporated into the interaction circuit;

Figs. 4 through 6 are longitudinal cross sections of various modifications of focusing systems in accordance with the invention; and

Figs. 7A through 7C, and 8 through 11 are curves which are useful in an exposition of the principles of the invention.

Referring now more particularly to the drawings, Fig. 1 illustrates schematically an electron beam system 10 in accordance with the invention suitable for incorporation in apparatus utilizing a relatively long electron beam, such as a traveling wave tube. At opposite ends of an evacuated elongated envelope 11 which, for example, is of glass or a suitable non-magnetic metal such as copper, are positioned a source of a solid beam of electrons 12 and a target 13. The source of electrons 12 generally will be an electron gun which includes an electron-emissive cathode surface, 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 path, and accordingly is maintained at a suitable potential positive with respect to the cathode of the electron source 12 by means of a voltage source 14. An electrode member which is kept at a positive potential with respect to the cathode of the electron gun is disposed along the path of flow for providing an accelerating field. In a traveling wave tube, the interaction circuit will generally serve as such an electrode member. In the electron beam system shown, a non-magnetic conductive coating 19 is applied to the inner surface of the elongated portion of the envelope which is maintained at a positive potential with respect to the cathode of the electron gun by voltage source 14 for providing the accelerating field. For maintaining the electron flow substantially cylindrical (i. e. having in appreciable transverse components), a succession of identical tubular cylinders 15 of a material having a high permeability, such as, for example, soft iron, are disposed coaxial with the path of electron flow around the elongated portion of the tube envelope for serving as flux guides. Successive cylinders are spaced apart leaving gaps 16 of uniform length between adjacent cylinders. A succession of identical U-shaped permanent magnets 17 are disposed along the path of electron flow, for convenience of illustration alternate magnets being shown disposed on the same side of the electron path, each successive magnet being bridged across a successive gap 16 and having each one of its two pole faces flush with a different one of two adjacent cylinders. Successive magnets are reversed in sense, so that only like poles are common to each of the cylinders. Accordingly, alternate cylinders are flush with like poles, adjacent cylinders are flush with unlike poles, as is shown. Effectively, the succession of cylinders serve as a succession of oppositely poled pole pieces.

As a result of this arrangement of magnets, there results along the path of electron flow a succession of regions 18, each corresponding to a gap 16 between adjacent cylinders, where there exists a longitudinal magnetic field of substantially circular symmetry and the direction of this longitudinal magnetic field reverses along successive regions. By such a succession of regions of time-constant spatially alternating longitudinal magnetic field, the electron beam may be focused.

Each pair of adjacent cylinders and its associated magnet may be viewed as a magnetic circuit which is closed by way of its air gap. Successive magnetic circuits are arranged to have their air gaps aligned along the path of electron flow and oriented to have the flux across suc-

cessive air gaps reverse in direction. It is apparent that the relative circumferential position of successive magnets is unimportant if the reluctance of the cylinders is negligibly low. For purposes of illustration, it is convenient to position successive magnets 180° apart circumferentially around the path as is shown in Fig. 1, but, in practice, to achieve a high degree of circular symmetry it may be advantageous to dispose two or more magnets circumferentially about each pair of adjacent cylinders or to make the magnets of toroidal or cylindrical form.

Before examining in more detail specific embodiments incorporating electron beam systems in accordance with the invention, it seems appropriate to analyze with some detail the basic arrangement shown in Fig. 1. This analysis is for the case of a solid electron beam but it can be extended to the case of tubular beams.

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

$$B_z = B(z)$$

(B_z will be written simply as B hereinafter) (b) the electric field E due to space charge acts only in a radial direction, i. e.,

$$E = E_r$$

The Lagrangian for an electron of radius *r* 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 no magnetic field at the cathode there results,

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

where η is the charge mass ratio of the electron. From 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 of the electron stream, assumed constant over the beam cross section structure. Equation 3 now becomes,

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

Let us define B₀ as the peak value of magnetic field at the axis, and L as the magnet period (equal to twice the distance between magnets). For convenience, let us define

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

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

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

$$z = u_0 t$$

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

5

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

$$\ddot{\sigma} + \left(\frac{B_0}{2}\right)^2 \sigma - \frac{\omega p^2}{2} \frac{1}{\sigma} = 0 \quad (5)$$

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

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

Using this value of B,

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

where, $T = \omega t$ and

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

For convenience let,

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

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

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

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 $T=0$, i. e., at a point where the magnetic field was a maximum. In practice this condition is realized by adjusting the position of the electron gun with respect to the first lens or by adjusting electrostatic focusing electrodes near the gun.

Figures 7A through 7C show plots of the beam radius as a function of 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 total D.-C. current in the beam 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. 7B) and this is the so-called optimum field. For higher values of B_0 the average radius of the beam is decreased (Fig. 7C) and for lower values of B_0 it is increased (Fig. 7A).

The optimum values of α (or magnetic field) are plotted as a function of β (or beam current) in Fig. 8. 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 $\beta \geq 0.6$ the beam radius diverges to more than twice its initial radius which for the present can be assumed to be the maximum divergence tolerable 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 magnet spacing, d is the beam diameter, V_0 is the beam accelerating 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

6

than twice the initial diameter) it is convenient to adjust L (the magnet spacing) since this is the only parameter not associated with the physical constants of the tube.

For small values of β of the required value for α is seen 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 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 Figure 7B). 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 computer curves. Therefore, axially symmetric periodic magnetic focusing requires the same total magnetic energy in the vicinity of beam as does Brillouin focusing. However, when the magnetic energy is to be supplied by a permanent magnet, periodic focusing increases many times the efficiency possible, and consequently permits use of a considerable reduction in the amount of magnetic energy necessary to be provided initially.

However, unlike the case of the uniform magnetic field, in the case of a periodic magnetic field the focusing cannot be improved by increasing the magnetic field strength well beyond the theoretical required value. Instead there are encountered regions of magnetic field strength which cause the beam to diverge 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" (Figure 9) which shows the stable and unstable regions of the Mathieu equation.

A consideration of Equation 7 shows that the first two terms comprise Mathieu's differential equation while the last term is due to the space charge forces of the electrons. A detailed analysis of this differential equation is found in a book entitled "Theory and Applications of Mathieu Functions" by H. W. MacLachlan, 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 become respectively 1 and $\frac{1}{2}$ and therefore describe a straight line on the stability chart (Figure 9). 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 a) which separate the pass and stop bands of periodic focusing.

The curve of Fig. 10 illustrates the relationship of collector current which was measured as a function of the magnetic strength of the magnets for a fixed magnet spacing and a constant beam current of an arrangement of the kind described in Fig. 1 and illustrates graphically the phenomenon of pass bands and stop bands predicted by the analysis.

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 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 for the results stated the convergence C of the lens required 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 graph of Fig. 11 where R_0' is plotted as a function of Z . Here it can be seen that no values of R_0' exist 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.

Fig. 2 illustrates how a typical helix-type traveling wave tube, for example, of the kind described in United States Patent 2,575,383 which issued on November 20, 1951 to L. M. Field can be adapted for use with an electron beam system in accordance with the invention. In the interest of simplicity, the traveling wave tube is shown in schematic form, many of the specific tube details being omitted. However, reference can be had to the above-identified Field patent for a more detailed description of a typical helix-type traveling wave tube. The various tube elements are enclosed in a non-magnetic envelope 20. Alternatively, it is possible to utilize an envelope of a magnetic material such as kovar so long as it is made sufficiently thin as to become magnetically saturated without seriously reducing the magnetic field. At one end to serve as a source of electrons there is positioned an electron gun which comprises an electron emissive cathode 22, and an electrode system for shaping and focusing the electrons emitted into a beam including a beam forming electrode 23 and an accelerating anode 24. At the opposite end of the envelope, a collector 25 is positioned in target relation with the electron gun. Disposed along the path of electron flow is a helically coiled conductor 26, a plurality of operating wavelengths long, which serves as the interaction circuit for propagating a slow electromagnetic wave in coupling relation with the electron beam and 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 28 and to an output coupling strip 29 by an impedance matching section 30. These matching sections 28 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 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 apertured for passage therethrough of the tube envelope, and which has a closed end and

an open end by which it can be connected into a wave guide transmission system. Each of the input and output coupling strips 27 and 29 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 vector parallel to the coupling strip 27. In this way, an electromagnetic wave is introduced into the interaction circuit for travel therealong in a coupling relationship with the electron beam. The electron gun forms a solid cylindrical electron beam for projection coaxially through the helix. For accelerating the electron beam longitudinally, the helical conductor is maintained by suitable lead-in connections (not shown) at a potential which is positive with respect to that of the cathode 22 and which may be approximately the same as that of the collector 25 or substantially lower. 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 is lost in striking the conductor. Accordingly, it is desirable to introduce some focusing of the electron beam in order to counteract the radial space charge forces which tend to make the beam diverge.

In accordance with an embodiment of the invention, each of a succession of cylinders 38 of a material having a high permeability, such as soft iron, Permalloy, or one of the ferrites, is disposed around the tube envelope spaced apart along the axis in the region of electron flow for forming a succession of gaps 39 between adjacent cylinders. In the region of the input and output wave guide coupling connections 31 and 32, special precautions must be taken. To minimize the discontinuities to be introduced at these regions, it is desirable that the two side walls of each of the wave guides 31 and 32 which are apertured for the passage of the tube envelope also be of material of high permeability while the other two side walls and the end closures 35 of each be of a non-magnetic metal such as copper. In this way, each of the apertured side walls serves as a separate pole piece and the space between these walls serves as another gap.

Across each of the gaps 39 there is bridged a permanent magnet 36 which, for example, can be of the horseshoe type, having its pole faces flush with an adjacent pair of cylinders. Again, it is convenient for purposes of assembly and illustration to dispose successive magnets on opposite sides of the envelope. In accordance with a characteristic feature of the invention, successive magnets are oriented in opposite senses whereby the direction of the longitudinal magnetic field across successive regions of the electron path corresponding to gaps 39 between cylinders is reversed. Permanent magnets 37 are similarly bridged across the two apertured side walls of each of the two coupling connections 31 and 32 in accordance with the practice of treating each of these apertured side walls as pole pieces. It may be that, because the spacing between these side walls is, because of transmission considerations, preferably different from the optimum spacing between pairs of regular cylinders, the size of each of permanent magnets 36 may be proportionately different from that of permanent magnets 37. Alternatively, it may be desirable to taper the wave guides 31 and 32 to provide a wall separation in the direction of flow more nearly equal than desired for the gap separation 39 between adjacent cylinders 38.

The various parameters, such as gap spacing and magnetic intensities, of an electron beam system of this kind are adjusted in accordance with the principles set forth in connection with the detailed analysis of the arrangement shown in Fig. 1.

Moreover, an electron beam system of this kind can similarly be incorporated into various other forms of traveling wave tubes. In particular, in some forms, elements of the focusing structure can be incorporated as part of the interaction circuit. For example, Fig. 3 shows a fragment of traveling wave tube utilizing an

interaction circuit of this kind. A regular succession of annular rings, adjacent rings 41 and 42 being alternately of a magnetic metal such as soft iron and a non-magnetic metal such as copper, are stacked together to form a cylindrical wave guide structure 44 through which is projected an electron stream. Each ring has substantially the same outer diameter, but alternate iron rings 41 have a smaller inner diameter whereby such rings project further into the hollow of the cylindrical wave guide and are closer to the electron flow. Additionally, it may be advantageous to taper outwardly the innermost ends of such rings for narrowing the air gaps 45 therebetween adjacent the path of flow. There consequently results a corrugated wave guide which is a well known form of slow wave interaction circuit suitable for incorporation into traveling wave tubes. In accordance with the principles of the invention, a succession of permanent magnets 43 is disposed along the interaction circuit, each magnet having its pole faces flush with a pair of magnetic rings, successive magnets being reversed in sense. In this way there is created along the path of electron flow a succession of regions of longitudinal magnetic field corresponding to the air gaps 45, the direction of the magnetic field reversing along successive regions. Various other slow wave circuits can be devised of this kind in which portions are of suitable magnetic material for serving as flux guides in magnetic focusing systems operating in accordance with the spirit of the invention.

Various other magnet arrangements are possible for instrumenting the principles of the invention. By way of example, several other embodiments of electron beam systems are shown in Figs. 4, 5 and 6.

In the arrangement of Fig. 4, a succession of annular cylinders 43 of material having a high permeability are disposed along the path of electron flow for serving as pole pieces and spaced apart for forming a succession of gaps 46. A series of bar magnets 47 is disposed across the successive gaps, the magnets across adjacent gaps being reversed in sense whereby there results along the path of electron flow a succession of regions of longitudinal magnetic field corresponding to successive gaps, the direction of the longitudinal magnetic field reversing with successive sections. To increase the circular symmetry it may be desirable to substitute for the bar magnets 47 annular cylindrical magnets magnetized in an axial direction.

In the arrangement of Fig. 5, a succession of annular cylindrical magnets 51 magnetized in an axial direction are spaced apart along the path of electron flow, adjacent magnets being reversed in polarity. Here, again there results along the path of electron flow a succession of regions of longitudinal magnetic field, the direction of the longitudinal field reversing with successive regions.

Fig. 6 shows still another possible arrangement. A succession of annular sections 61 of material suitable for being permanently magnetized, such as Alnico, is disposed in contiguous relationship along the path of flow. Each section is a tubular circular cylinder whose inner surface is grooved to form an annular air gap 62 surrounding and having an opening 63 along a relatively smaller region into the electron path. There consequently results a regular series of openings 63 along the electron path. A few turns of wire 64 suitable for carrying large currents are wound in each of the gaps 62. Then, after the various sections are firmly positioned in place, a direct current is passed through the wires 64 for permanently magnetizing the various sections to the desired intensity. The direction of the current in the turns in the various gaps is adjusted so that successive sections are magnetized in opposite senses as illustrated by the polarities shown in Fig. 6. As a consequence, there results along the electron path a succession of regions of longitudinal magnetic fields, corresponding to successive openings 63, the direction of the magnetic field reversing with each successive region. In arrangements

of this kind, the optimum magnetic field intensity for a given spacing for the successive magnets and a given beam current can be arrived at conveniently by adjusting the amplitude of the magnetizing current through wires 64 for maximum collector current. By magnetizing in this way after assembly there is avoided the possibility that the intensity of the field of the magnets will be changed away from the desired value in the assembly process as a result of forcing like poles of adjacent magnets into close proximity. Alternatively, however, it is possible to assemble in the first instance a plurality of individual permanent magnets of the configuration shown and so to avoid the need for subsequent magnetizing.

It can be seen from the foregoing description that the various embodiments described are merely illustrative of the principles of the general invention. Various other arrangements can be devised by a worker skilled in the art without departing from the spirit and scope of the invention. For example, the desired succession of longitudinal magnetic field regions with the direction alternating with successive regions can be derived by a quadrupole magnetic structure of the kind described in copending application Serial No. 351,977 filed April 29, 1953, by P. P. Cioffi, now Patent 2,844,754, issued July 22, 1958. Additionally, as described in the Cioffi application, it may be advantageous to provide flux guiding means for aligning the magnetic flux in successive gaps.

Moreover, in a copending application Serial No. 351,874, filed April 29, 1953 by J. T. Mendel there are described arrangements for better adapting the principles of the present invention to the focusing of hollow electron beams. Alternatively, arrangements can be devised in which the two poles of each of a series of permanent magnets are associated with other than adjacent pairs of pole pieces.

What is claimed is:

1. In combination an electron source and target electrode defining therebetween a path of electron flow, a helical conductor disposed along the path of flow for accelerating the electron beam and for propagating electromagnetic waves for interaction with the stream, a succession of cylinders of high permeability material disposed around and spaced apart along the path of flow, input and output wave guide sections disposed along the path of flow in coupling relation to the input and output ends of the helical conductor, a pair of opposite side walls of each wave guide section being apertured for passage therethrough of the electron flow and being of a high permeability material, and a succession of permanent magnets disposed along the path of flow for bridging across successive cylinders and said apertured side walls of said wave guide sections for forming along the path of flow a succession of regions of longitudinal magnetic field, the direction of the field reversing with successive regions.

2. 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 comprising a plurality of substantially U-shaped permanent magnets having poles abutting adjacent of said pole piece cylinders 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.

3. 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, said pole pieces forming said interaction circuit, 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 field along the axis of the electron beam.

4. 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, said pole pieces comprising annular cylinders having extending nose portions axial of said envelope, and a plurality of substantially identical magnet means interposed between adjacent pole pieces, said magnet means comprising permanent magnets positioned axially of said envelope and extending between adjacent of said annular cylinders, 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 provided a longitudinal region of periodic spatially alternating magnetic field along the axis of the electron beam.

5. In a traveling wave tube, an evacuated envelope, means for forming a uniform cylindrical electron beam for flow axially through said envelope, an interaction circuit extending within said envelope parallel to the electron beam for propagating a slow electromagnetic wave in coupling relation with the electron beam, and means for overcoming space charge forces in said beam and maintaining the electron flow cylindrical and of substantially constant diameter in its passage past said interaction

circuit, said means comprising a plurality of identical tubular cylinders of material having a high permeability spaced uniformly apart and coaxially with the path of electron flow, and a plurality of identical permanent magnets, each extending between two successive cylinders, said cylinders constituting pole pieces and each pole piece serving as a common bridging point for like poles of adjacent permanent magnets, successive magnets thereby being reversed in sense, and alternate cylinders being of the same magnetic polarity, the succession of cylinders serving as a succession of oppositely poled pole pieces forming a longitudinal region of periodic spatially alternating magnetic field sinusoidal in effect along the axis of the electron beam.

6. In a traveling wave tube, an evacuated envelope, means forming a cylindrical beam for flow axially through said envelope, a conductive member extending within said envelope parallel to the electron beam for propagating a slow electromagnetic wave in coupling relation with the electron beam and establishing an electrostatic field for accelerating the electron beam, and means for overcoming space charge forces in said beam and maintaining the electron flow cylindrical in its passage past said conductive member comprising at least four pole pieces spaced apart along the beam path and at least three permanent magnets disposed along the path of flow external to the envelope, each magnet extending between a pair of adjacent pole pieces, successive magnets being reversed in polarity whereby adjacent pole pieces are oppositely poled.

References Cited in the file of this patent

UNITED STATES PATENTS

2,200,039	Nicoll	May 7, 1940
2,218,725	Schroeder	Oct. 22, 1940
2,233,264	Marton	Feb. 25, 1941
2,259,994	Boersch et al.	Oct. 21, 1941
2,296,355	Levin	Sept. 22, 1942
2,300,052	Lindenblad	Oct. 27, 1942
2,305,884	Litton	Dec. 22, 1942
2,369,796	Ramberg	Feb. 20, 1945
2,418,349	Hillier et al.	Apr. 1, 1947
2,503,173	Reisner	Apr. 4, 1950
2,640,162	Espenschied et al.	May 26, 1953
2,741,718	Wang	Apr. 10, 1956

OTHER REFERENCES

Article by E. D. Courant et al., pages 1190-1196, Phys. Rev. for December 1952.