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2,867,745

PERIODIC MAGNETIC FOCUSING SYSTEM

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FIG. 1

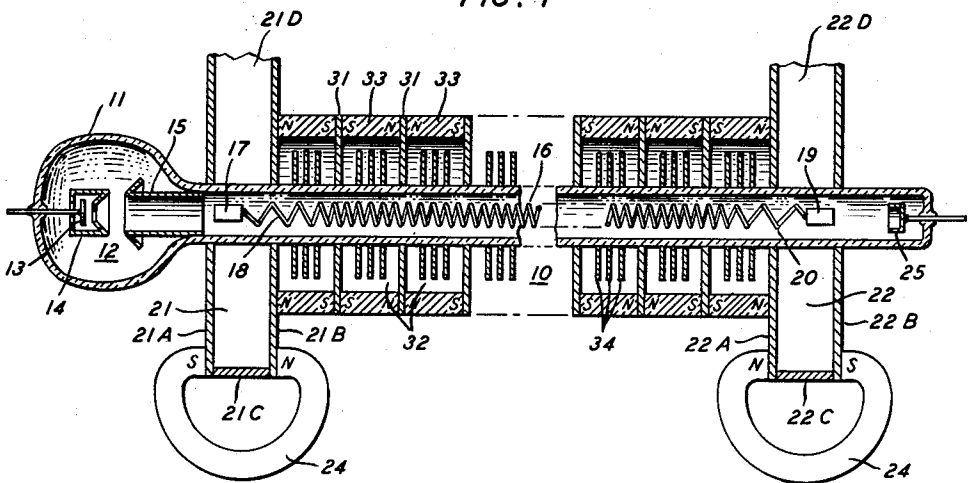


FIG. 2

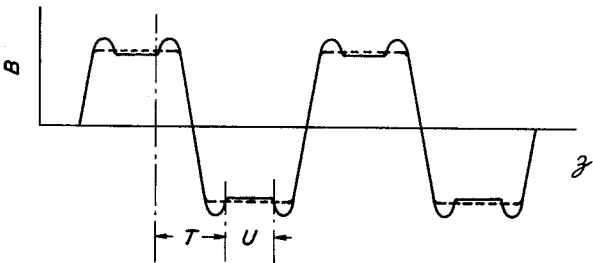


FIG. 3

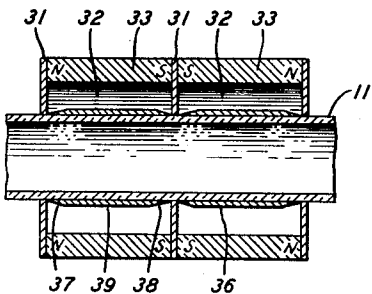
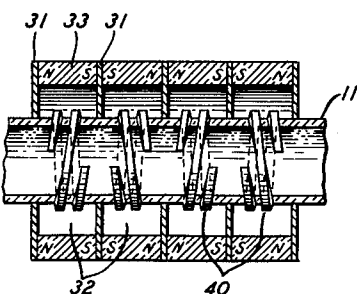


FIG. 4



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PERIODIC MAGNETIC FOCUSING SYSTEM

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10 Claims. (Cl. 315—3.5)

This invention relates to periodic focusing arrangements which utilize a succession of regions of spatially alternating time-constant axially symmetric longitudinal magnetic field to focus a beam of charged particles.

The principles of periodic focusing are set forth in my U. S. Patent 2,847,607, issued August 12, 1958. In a typical focusing arrangement of this kind, annular magnetic elements suitable for serving as pole pieces are spaced apart along and surrounding a longitudinal path of flow of an electron beam. Permanent magnets are then utilized to pole successive pole pieces oppositely whereby there is established along the path of flow a periodic succession of regions of longitudinal magnetic field, characterized in that the direction of the field is reversed in successive regions. As is there pointed out, it is found that as the magnetic period is changed or as the magnetic strength is increased the focusing exhibits successive pass and stop bands, i. e., successive regions of good and bad focusing.

An important advantage of periodic focusing arrangements of this kind is the much improved magnet efficiency provided over uniform field permanent magnet focusing. It is found that the improved efficiency makes possible good focusing in this way with magnets a small fraction of the size and weight needed for uniform field focusing.

Hitherto it had been thought most advantageous to operate at the pass band corresponding to the shortest magnetic period both since this resulted in the smallest ripple in the electron beam diameter and so provided the highest beam transmission efficiencies, and since it permitted the maximum saving in magnet weight and size.

However, when periodic focusing principles are employed to focus the electron beam in a traveling wave tube (a device which utilizes the interaction between a traveling electromagnetic wave and an electron beam over a relatively long path to secure gain to the wave) it is often found desirable to have magnetic periods which are relatively long, i. e., long relative to the magnetic period corresponding to operation in the pass band requiring the shortest magnetic period but still short relative to the length of the path of electron flow. It is thought that a magnetic period of from one-half to one-tenth the length of the electron path will usually be desirable. Among other considerations, in traveling wave tubes long magnetic periods permit ease of fabrication and assembly, facilitating the introduction of wave guide coupling connections for applying and abstracting wave energy to the tube and minimizing the number of magnets and pole pieces necessary. Additionally, long magnetic periods make it possible to utilize conveniently the longitudinal magnetic field in successive regions to bias magnetically ferrite elements which may be inserted along the path of flow to provide unidirectional attenuation to minimize the tendency towards self-oscillation which is characteristic of such tubes. This will be described in greater detail below.

A long magnetic period can be used consistently with the principles of periodic focusing by operation in one

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of the higher pass bands. However, in operation with long magnetic periods, it is particularly important to minimize ripples in the electron beam diameter. The presence of transition regions, resulting from the periodic reversals of the direction of the longitudinal magnetic field, in which the field strength is lower than that required for good focusing, has a strong tendency to introduce ripples in the electron beam diameter. When the magnetic period is low, these ripples can generally be kept small easily by the proper choice of the peak magnet field, but when the magnetic period is long special precautions appear necessary lest the beam transmission efficiency be seriously impaired.

A primary object of the present invention is to minimize the deleterious effect of transition regions in periodic magnetic focusing arrangements.

A related object is the better to adapt periodic magnetic focusing techniques for use in traveling wave tubes in which relatively long magnetic periods are desirable.

To this end, the invention provides a periodic magnetic focusing system which establishes along the path of electron flow a succession of regions of spatially alternating time-constant longitudinal magnetic field characterized in that along each of these regions the strength of the magnetic field is higher near the two ends than therebetween. By peaking the magnetic field strength before each reversal in direction, the mean square of the field strength across each of the transition areas (the peaked field strength portions being considered as part of the transition area) can be made substantially equal to the square of the field strength along the intermediate portions of relatively uniform strength of each successive region. Various specific arrangements will be described hereinafter which will peak the magnetic field intensity before each reversal in field direction as is desired. Of those to be described in detail a common characteristic is the positioning adjacent to the path of flow of permeable means which selectively shunt magnetic flux from the path of flow, whereby along the path of flow the strength of the magnetic field is greatest immediately before and after reversals in the direction of the field. Alternatively, it is possible to vary the magnetic field strength along the path of flow in a similar pattern by properly shaping the successive pole pieces between which is established the longitudinal magnetic field. However, this latter technique ordinarily will prove less convenient than the insertion of shunting means.

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

Fig. 1 shows a helix-type traveling wave tube which employs a periodic magnetic focusing system in accordance with the invention;

Fig. 2 shows the magnetic field intensity variation along a portion of the path of flow of the tube shown in Fig. 1; and

Figs. 3 and 4 show fragmentary portions of alternative forms of periodic focusing systems in accordance with the invention for utilization with the tube shown in Fig. 1.

Referring now more particularly to the drawings, Fig. 1 illustrates schematically a traveling wave tube 10 of the kind well known in the art which utilizes a periodic focusing system for keeping its electron beam aligned with the tube axis.

The various tube elements are enclosed in an evacuated envelope 11. The envelope is, for example, of glass or a suitable non-magnetic metal such as copper, or even a magnetic material such as Kovar so long as it is made sufficiently thin so as to become magnetically saturated so readily that it does not seriously reduce the magnetic focusing field along the path of flow. At opposite ends

of the envelope are positioned an electron gun 12 which serves as the source of an electron beam and a target or collector electrode 25. The electron gun and collector are aligned to provide a longitudinal path of flow along the tube axis. The electron gun includes an electron-emissive cathode surface 13, an electrode system 14 for controlling the intensity of electron emission and forming the electrons into a well-defined cylindrical beam and an accelerating anode 15 for giving the electrons a longitudinal velocity suited for interaction with the signal wave in the manner characteristic of traveling wave tube operation. Disposed along the path of flow is a helically coiled conductor 16, a plurality of operating wave lengths long, which serves as interaction circuit for propagating a slow electromagnetic wave in coupled relation with the electron beam.

The helix 16 is joined at opposite ends to an input coupling strip 17 by an impedance matching section 18 and to an output coupling strip 19 by an impedance matching section 20. These matching sections 18 and 20 are extensions of the conductor 16 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 21 and the output wave is abstracted at the downstream end by way of output wave guide coupling connection 22. Each of the wave guide coupling connections 21 and 22 is a section of rectangular wave guide which has a pair of opposite side walls, 21A, 21B and 22A, 22B, apertured for passage therethrough of the tube envelope, and which has a closed end 21C, 22C, and an open end 21D, 22D, by which it can be connected into a wave guide transmission system. Each of the input and output coupling strips 17 and 19 is supported in its corresponding wave guide connection. Input waves are applied to the input wave guide connection 21 to have a mode of propagation having an electric field vector parallel to the coupling strip 17. 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 cylindrical electron beam for projection coaxially through the helix. For accelerating the electron beam longitudinally, the helical conductor 16 is maintained by suitable lead-in connections (not shown) at a potential which is positive with respect to that of the cathode 13 and which may be approximately the same as that of the collector 25 or may be substantially lower. For efficient operation, it is important that the electron flow be substantially parallel to the axis of the helix 16 whereby a minimum number of electrons are lost in striking the conductor. For this purpose it is usual to provide magnetic focusing of the electron beam to counteract the radial space charge forces in the beam which tend to make it diverge.

The description hitherto has been of a conventional helix-type traveling wave tube. The present invention is directed in its principal application to an improved permanent magnet periodic focusing system for use with such a tube.

In accordance with an illustrative embodiment of the invention, each of a succession of annular disk members 31 of material which is magnetically soft, i. e., highly permeable, such as soft iron, Permalloy, or one of the ferrites, is disposed around the tube envelope spaced apart along the tube axis for forming a succession of gaps 32 therebetween. The separation of these members determines a distance which is one half the magnetic period so this spacing should be appropriately chosen. Generally, it will be desirable to choose a magnetic period of from one half to one tenth the length of the path of the electron flow. These members 31 serve as a series of pole pieces along the path of flow between which will be set up regions of longitudinal magnetic field. To minimize any discontinuities introduced by the input and output wave guide connections,

the two side walls 21A, 21B and 22A, 22B of the wave guides 21 and 22 which are apertured for passage therethrough of the tube envelope also are of a magnetically soft conductor so that these walls may simultaneously serve as pole pieces. It may be desirable in some cases, to taper the wave guides so that the spacing between side walls at the point of insertion of the tube envelope corresponds to that desired between successive pole pieces. The unapertured side walls of the wave guides, as well as the end closures 21C, 22C, are of a non-magnetic conductor such as copper to avoid shunting the flux to be set between the apertured side walls.

In accordance with a characteristic of periodic magnetic focusing principles, successive pole pieces must be oppositely poled whereby there results along the tube axis a spatially alternating magnetic field. One convenient arrangement for achieving the desired polarities is illustrated. It comprises bridging successive pole pieces 31 by annular cylindrical permanent magnets 33 magnetized longitudinally, successive permanent magnets being reversed in sense as shown. The annular magnets 33 advantageously have an inner diameter which is large relative to the inner diameter of the annular pole pieces so that there are formed annular gaps 32 between successive pole pieces in the region between the tube envelope 11 and the cylindrical magnets 33. The outer diameter of the magnets advantageously is equal to that of the pole pieces whereby a smooth outer surface is formed along the major portion of the tube length. Moreover, consistent with the purpose of minimizing the discontinuities introduced by the wave guide input and output connections, at each of the wave guide connections 21 and 22 a permanent horseshoe-shaped magnet 24 is bridged between the two apertured side walls 21A, 21B and 22A, 22B thereof which serve as pole pieces and its size is chosen to provide a magnetic field strength along that portion of the tube axis therebetween, corresponding to that desired along those portions of the tube axis between successive pole pieces.

As has been stated above, one of the primary purposes of the invention is to make possible good focusing, consistent with periodic focusing principles, with relatively long magnetic periods. In the analysis set forth in my above-mentioned patent where it is assumed that the field intensity variation is sinusoidal, it is shown that one of the conditions for stable flow can be represented by a Mathieu function stability plot which is characterized by a succession of stable pass and unstable stop regions. It is found that when the field intensity variation is in the form of a square wave, the conditions for stable flow are similarly characterized by pass and stop regions. To utilize long magnetic periods stably, it is desirable to operate in one of the higher pass regions. An effective upper limit exists, however, on the length of the magnetic period since the ripple on the beam tends to increase with longer magnetic periods and it is generally desirable to limit the ripple on the electron beam so that the maximum beam radius is less than twice the initial beam radius. These various conditions are analyzed in considerable detail in my afore-mentioned patent, and for the various design considerations applicable to the design of a periodic magnetic focusing system reference can be made thereto.

The principal improvement of the present invention is the increasing of the strength of the longitudinal component of magnetic field along the tube axis in the regions near the pole pieces relative to the intermediate regions. This effectively minimizes the increase in ripple on the beam which is occasioned by an increase in the magnetic period of the spatially alternating field, and operation in the higher pass bands is made more attractive. In the plot of Fig. 2 there is illustrated as the solid line the desired variation in the magnetic field strength B along the path of flow. The magnetic intensity B is plotted as the ordinate with the distance along the tube axis z as

the abscissa. For the sake of comparison the field variation which would be provided by the focusing structure described in my above-mentioned patent is shown as the broken line. It can be seen that it is desired to peak the magnetic field intensity preliminary to and subsequent to each reversal in direction. The end sought is to have the mean square field in the transition region, designated in the plot as T, substantially equal to the square of the field along the region, designated in the plot as U, of substantially uniform field strength. The points of zero field along the tube axis correspond to points along the tube axis opposite the centers of the successive pole pieces, and one half the magnetic period corresponds to the distance between corresponding points on successive pole pieces. It is generally desirable to minimize the length of the transition region T, and more particularly to minimize the distance along which the magnetic field strength is very low. To this end, it is advantageous to make the pole pieces as thin as possible without having them become magnetically saturated.

To achieve the field strength variation illustrated, the arrangement shown in Fig. 1 utilizes a succession of thin permeable annular disks 34, or washers, with several spaced apart along and surrounding the path of flow in each of the regions 32 between successive pole pieces, the spacing from washer-to-washer in each region being less than the spacing between washer and pole pieces. The presence of such permeable washers serves to shunt a portion of the magnetic field from the path of flow. This shunting effect is enhanced the closer the washer spacing. Accordingly, because of the distribution described the field strength will have the desired variation along the path of flow, being higher along the portions corresponding to the ends of each region 32 where there is a wide washer-to-pole piece spacing than along the portions corresponding to the intermediate portion of each region 32 where there is a close washer-to-washer spacing.

In Fig. 3 there is shown a portion of a modified periodic focusing system in accordance with the invention also for use with the traveling wave tube shown in Fig. 1. As above, there is positioned around the tube envelope 11 a succession of annular permeable elements 31 which serve as pole pieces spaced apart along the path of flow by the gaps 32 and associated therewith is the succession of permanent magnets 33 which polarize successive pole pieces oppositely for achieving along the path of flow a succession of longitudinal field regions characterized by a reversal of field direction with successive regions. In this instance to shape the field strength variation along the path of flow as is desired in accordance with the principles of the present invention, a succession of thin walled cylinders 36 of permeable material are positioned closely surrounding the tube envelope in the successive gaps 32 between pole pieces for serving as flux guides. The wall thickness of each cylinder is sufficiently small to become readily magnetically saturated so that the magnetic field intensity along the path of flow is not too considerably reduced thereby. Additionally, to provide the desired selective shunting effect on the magnetic flux along the electron path the wall thickness of each cylinder 36 is less at its two end portions 37, 38 than the intermediate portion 39 therebetween whereby more of the flux is diverted from the path of flow along portions thereof corresponding to this intermediate portion 39 than along portions thereof corresponding to the thinner end portions 37, 38. It should be evident that the greater the difference in wall thickness of the end portions and the intermediate portions the greater the differential shunting effect. For the largest differential effect, the end portions 37, 38 may be eliminated thereafter leaving only a short section of cylinder in each gap 32 spaced apart a predetermined distance from the two pole pieces defining the ends of each gap.

It should be further evident that by making the tube envelope of a permeable material such as Kovar, the en-

velope itself may be made to serve the function of the succession of cylinders for achieving the desired field strength variation along the electron path. For use in this way, the thickness of the permeable envelope should be made less at regions adjacent the pole pieces than along the intermediate regions between pole pieces.

The present invention has another important advantage in that it facilitates the solution of another problem associated with the operation of traveling wave tubes. This is the problem of minimizing the undesirable effects arising from reflections resulting from mismatches at the input and output coupling connections to the tube and from irregularities along the interaction circuit. The usual remedy for such effects is the insertion along the interaction circuit of dissipative material to absorb such reflected wave energy. In particular, in a copending application Serial No. 362,177 filed June 17, 1953 of R. Kompfner and H. Suhl it is taught that reflected waves traveling in the direction from the output connection back to the input connection can be selectively attenuated by the insertion distributed along the path of flow of ferrite material which is appropriately biased magnetically. In particular, it is pointed out that in a helix-type traveling wave tube selective attenuation of the kind desired can be had by surrounding the helix interaction curve with a cylindrical ferrite element which is biased in a circumferential state of magnetization, and further that a helical section of ferrite placed in a longitudinal magnetic field will become biased in a state of circumferential magnetization and so will be suited for use in achieving the desired selective attenuation.

Fig. 4 shows a portion of a periodic focusing system in accordance with the invention for use with the tube shown in Fig. 1 which is modified for use with selective attenuation techniques of the kind just described. A plurality of helical ferrite sections 40 are disposed around the tube envelope 11 along the path of electron flow. To provide the circumferential magnetic bias needed for operation as unidirectional attenuation, each ferrite section is positioned in a region 32 of longitudinal field between successive pole pieces 31, the longitudinal field inducing a circumferential field in each helical ferrite section. Because the directivity of the attenuation properties of these ferrite elements depends on the direction of the biasing circumferential magnetic field, and since the direction of the longitudinal magnetic field in the successive regions between pole pieces reverses as is characteristic of periodic magnetic focusing, reversing the direction of the circumferential field set up in the helical ferrite elements, special precautions must be taken to have the direction of high attenuation the same for each ferrite section. In the arrangement shown, successive helical ferrite sections in successive gaps 32 are made to have their pitches in opposite senses to compensate for the reversal in direction of the biasing longitudinal fields. Alternatively, successive helical ferrite sections might be of materials having different characteristics to the same end, or ferrite elements may be inserted only in alternate gaps.

In the usual selective attenuation ferrite arrangements, the degree of discrimination between the two directions is related to the length along the wave path of the selective attenuation elements. For large discriminations, a relatively long length of ferrite material is desirable. It can be appreciated that it would be preferable from the viewpoint of ease of fabrication and assembly to minimize the number of separate helical ferrite sections necessary in the arrangement shown in Fig. 4 at the expense of increasing the length of each helical section. To this end, it is desirable that the magnetic period provided by the periodic focusing structure be long. As has been discussed above, with long magnetic periods it is important to peak the magnetic field strength before each reversal in the direction of the magnetic field. In operation, it is found that the helical ferrite sections serve as flux guides.

in the manner described for the flux guides used in the arrangement shown in Fig. 3, having a shunting effect on the magnetic flux along the path of electron flow. To provide the desired variation in field strength along the path of flow, the helical ferrite sections are positioned to start and end in from the pole pieces. As a result along the path of flow there is little shunting of the magnetic flux in the portions adjacent the pole pieces and the field strength there is higher than along the intermediate portions. Alternatively, the cross-sectional area of the helical ferrite sections may be decreased at each end for the same purpose in the manner analogous to variations in the wall thickness of the cylindrical flux guides shown in Fig. 3.

It is to be understood that the various embodiments which have been described are merely illustrative of the principles of the invention. Various other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention. For example, it should be possible to approximate the desired field strength distribution along the path of flow by properly shaping the pole pieces. Moreover, although the invention has been described with particular reference to incorporation in helix-type traveling wave tubes, the applications thereof are not so limited. The invention may be utilized in any apparatus where it is desired to focus a beam of charged particles over a relatively long path.

What is claimed is:

1. In combination, an envelope, an electron source and a target spaced apart within said envelope for defining therebetween a longitudinal path of electron flow, a succession of annular permeable elements uniformly spaced apart along and surrounding the path of electron flow for serving as a succession of pole pieces, and a permanent magnet structure for polarizing successive pole pieces oppositely for establishing a continuous succession of spatially alternating focusing fields along the path of flow, and magnetically permeable means closely surrounding the envelope and disposed along the path of flow between successive pole pieces for maintaining along the path of flow the strength of the magnetic field at values higher at portions corresponding to regions adjacent the pole pieces than at portions corresponding to regions intermediate the pole pieces.

2. In combination, an envelope, an electron source and a target spaced apart within said envelope for defining therebetween a longitudinal path of electron flow, magnetic means closely surrounding the envelope and disposed uniformly along the path of flow for establishing therealong a continuous succession of regions of longitudinal magnetic field, the direction of the magnetic field reversing in successive regions, and means for peaking the intensity of the longitudinal magnetic field along the path of flow immediately before and after each reversal in the direction of the magnetic field.

3. In combination, an envelope, an electron source and a target electrode spaced apart within said envelope for defining therebetween a longitudinal path of flow, uniformly spaced means including a permanent magnet structure for establishing along the path of flow a continuous succession of regions of longitudinal magnetic field, the direction of the magnetic field reversing with each successive region, and magnetically permeable means closely surrounding the envelope for reducing the strength of the magnetic field along the path of flow in the intermediate portions of each region whereby the strength of the magnetic field is higher near the ends of each region than along said intermediate portions.

4. In combination, an electron source and a target electrode defining therebetween a path of electron flow and means for focusing the electron beam along this path of flow comprising uniformly spaced means for establishing along said path of flow a continuous succession of spatially alternating time-constant magnetic fields characterized in

that the intensity of the magnetic field is at a peak along short regions adjacent the regions of reversal in direction of the magnetic field.

5. In combination, an envelope, an electron source and a target electrode spaced apart within said envelope for defining therebetween a path of electron flow, a succession of thin pole pieces positioned to closely surround the envelope and uniformly spaced apart along the path of flow, permanent magnet means for biasing successive pole pieces oppositely for establishing a continuous succession of time-constant spatially alternating magnetic fields along the path of flow, and a plurality of magnetically permeable elements surrounding the envelope and spaced apart along the path of flow between each pair of successive pole pieces, characterized in that element-to-element spacing is smaller than the element-to-pole spacing.

6. In combination, an electron source and a target electrode for defining therebetween a path of electron flow, a helical conductor positioned along said path of flow for propagating a traveling wave for interaction with the electron flow, a plurality of pole pieces spaced apart along the path of flow and surrounding the helical conductor, a succession of permeable helical ferrite elements positioned along the path of flow, successive ferrite elements being interposed between and spaced from successive pole pieces, the pitch of adjacent ferrite elements of the succession being of opposite sense, and permanent magnet means for polarizing successive pole pieces oppositely and for maintaining a circumferential magnetic bias in the ferrite elements thereby providing nonreciprocal attenuation for a wave passing along said slow wave structure.

7. In combination, an evacuated envelope, an electron source and a target electrode spaced apart in said envelope for defining therebetween a path of electron flow, a helical conductor for propagating an electromagnetic wave for interaction with the electron flow, a succession of helical ferrite elements having a magnetic permeability greater than one positioned to surround the envelope, a succession of pole pieces positioned along the path of flow, each pole piece of said succession interposed between and spaced from successive ferrite elements, and magnetic means for polarizing successive pole pieces oppositely and for maintaining a circumferential magnetic bias in said helical ferrite element.

8. In combination, an evacuated envelope, two electrodes spaced apart in said envelope for defining therebetween a path of electron flow, means for propagating electromagnetic wave energy in coupling relation with the electron flow, and means for focusing said electron flow and for providing nonreciprocal attenuation to the propagating electromagnetic wave energy, said means comprising a plurality of magnetically permeable ferrite windings positioned to surround the path of electron flow and arranged in spaced succession along the length of said electron path, a succession of pole pieces interleaved with the succession of ferrite windings such that the pole pieces and windings are positioned alternately in spaced succession along the path of flow, and magnetic means for maintaining a circumferential magnetic bias in the ferrite windings and for polarizing adjacent pole pieces oppositely, whereby the magnetic focusing field will be spatially alternating along the path of flow and have greater magnetic intensity in the region adjacent to the pole pieces than in the region of said ferrite windings positioned between adjacent pole pieces.

9. A periodic focusing arrangement comprising a plurality of annular pole pieces uniformly positioned in spaced succession along a common axis, magnetic means for polarizing adjacent pole pieces of the succession oppositely for establishing a continuous succession of time-constant spatial alternating fields and magnetically permeable means interposed in the region between adjacent pole pieces and spaced apart therefrom for modifying the field along the common axis such that the average of the mean

square of the field intensity along the axis in the region of the transition between successive half-cycles of the spatially alternating field is approximately equal to the square of the field intensity along said axis between these transition regions.

10. In a traveling wave tube comprising an evacuated envelope, an electron source and a target in said envelope for defining therebetween a path of electron flow, a slow wave transmission circuit for propagating wave energy in coupling proximity to said electron flow, a plurality of annular magnetically permeable elements arranged in a uniformly spaced succession along said envelope and surrounding said envelope, alternate elements serving as pole pieces and having an inside diameter substantially equal to the outside diameter of the envelope and magnetic means for maintaining pole pieces oppositely polarized for forming a continuous succession of spatially alternating magnetic fields along the electron path having

a greater field intensity in the region adjacent the pole pieces than in the region intermediate successive pole pieces.

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