

Feb. 16, 1960

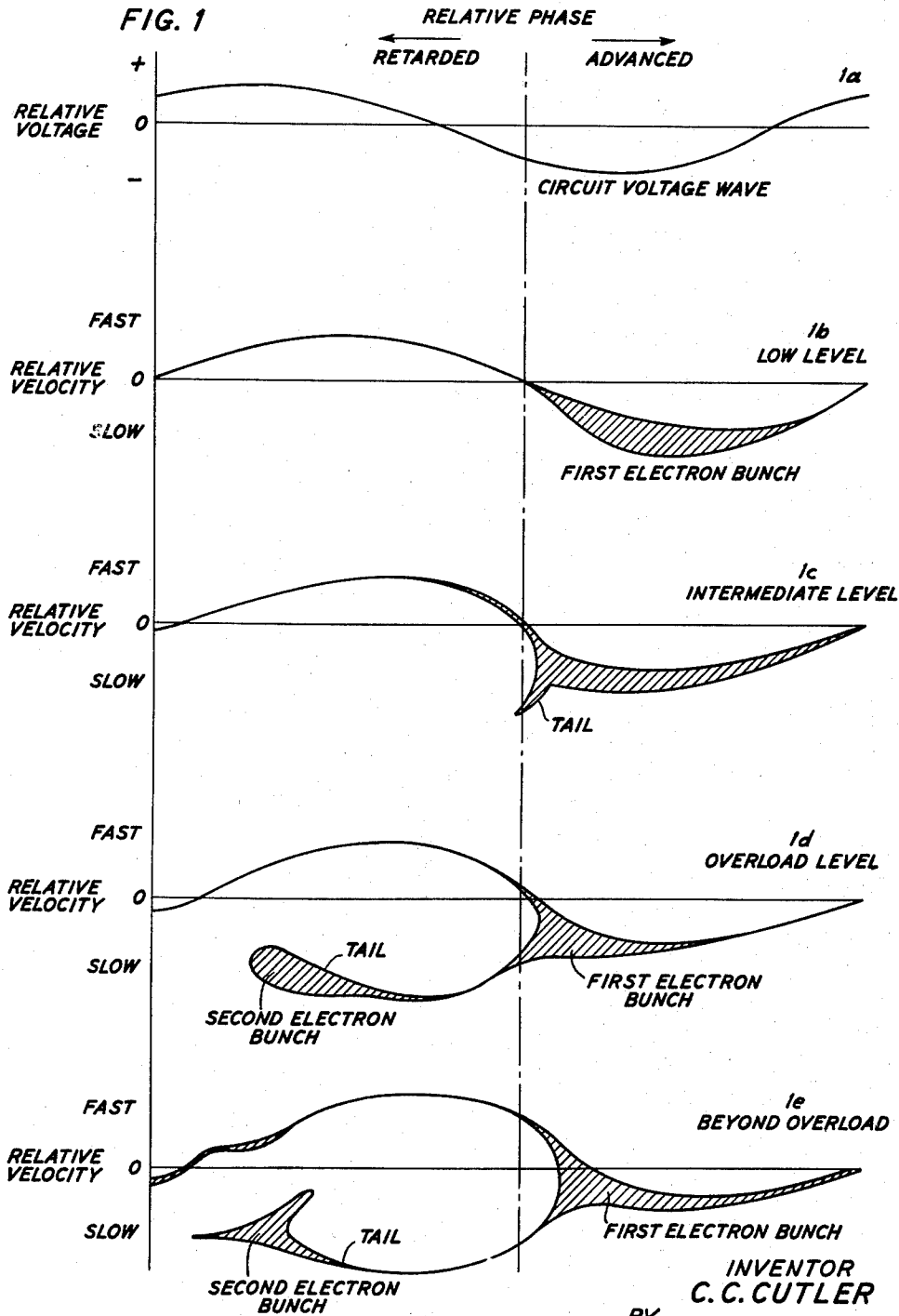
C. C. CUTLER
TRAVELING WAVE TUBE

2,925,519

Filed Aug. 26, 1954

5 Sheets-Sheet 1

FIG. 1



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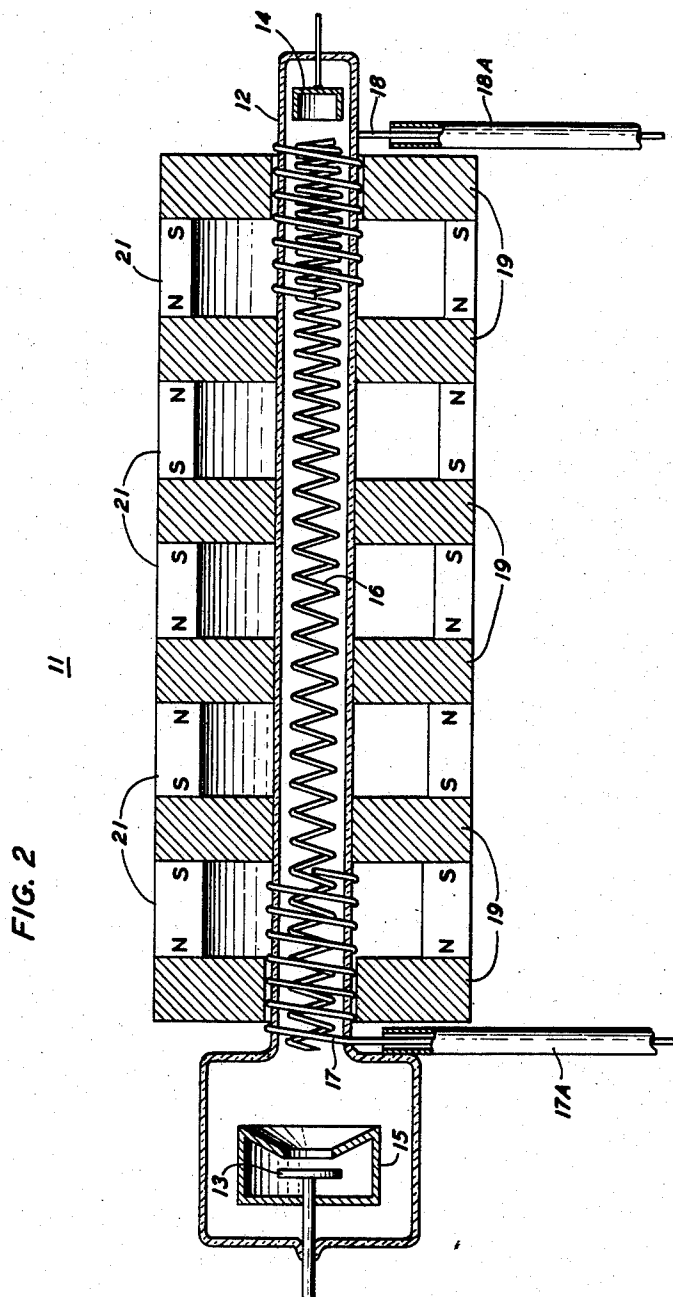
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FIG. 3

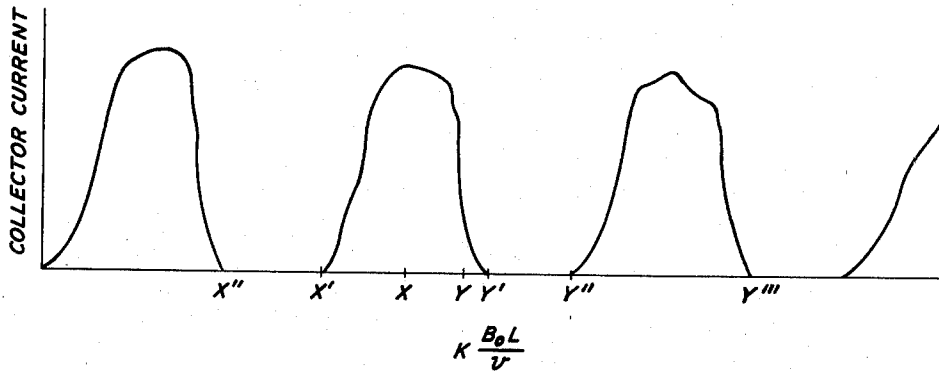


FIG. 4

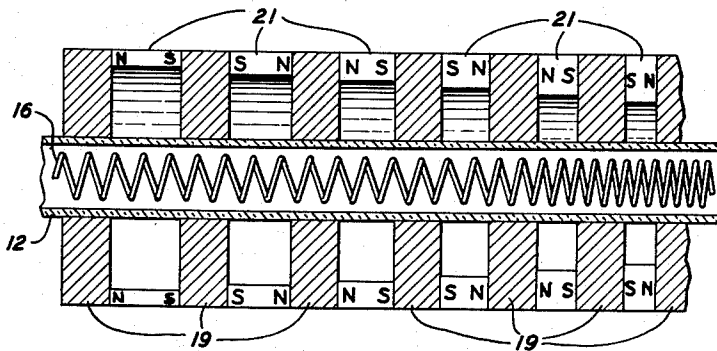
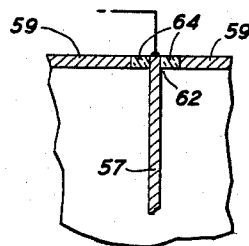


FIG. 7



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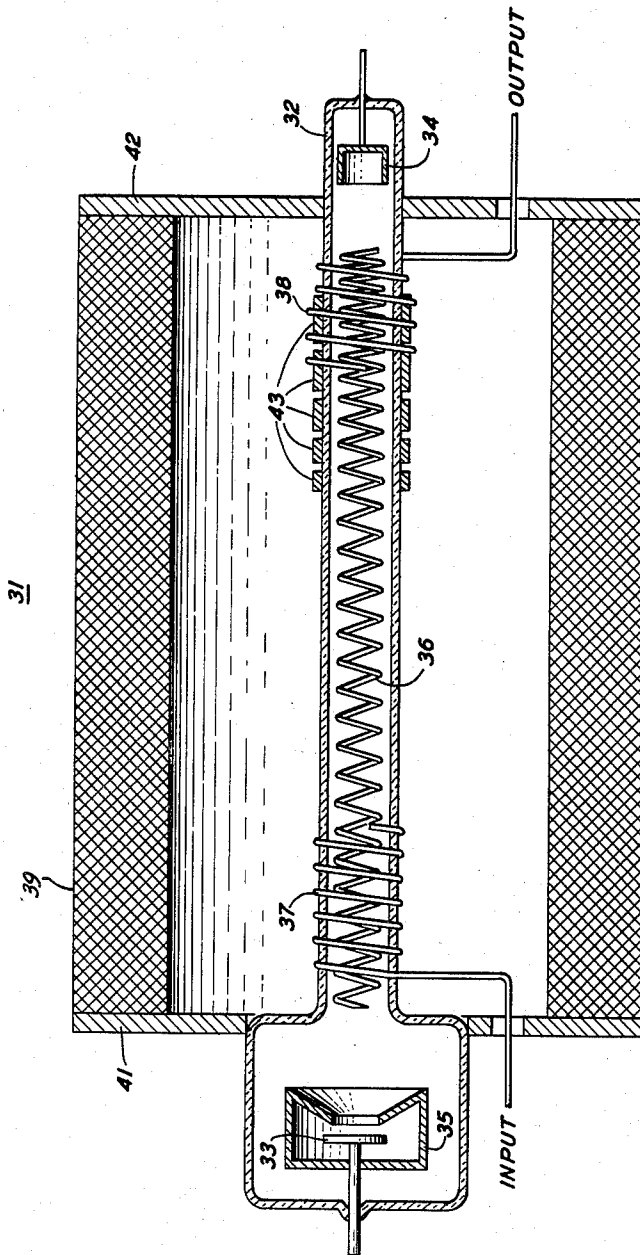
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FIG. 5



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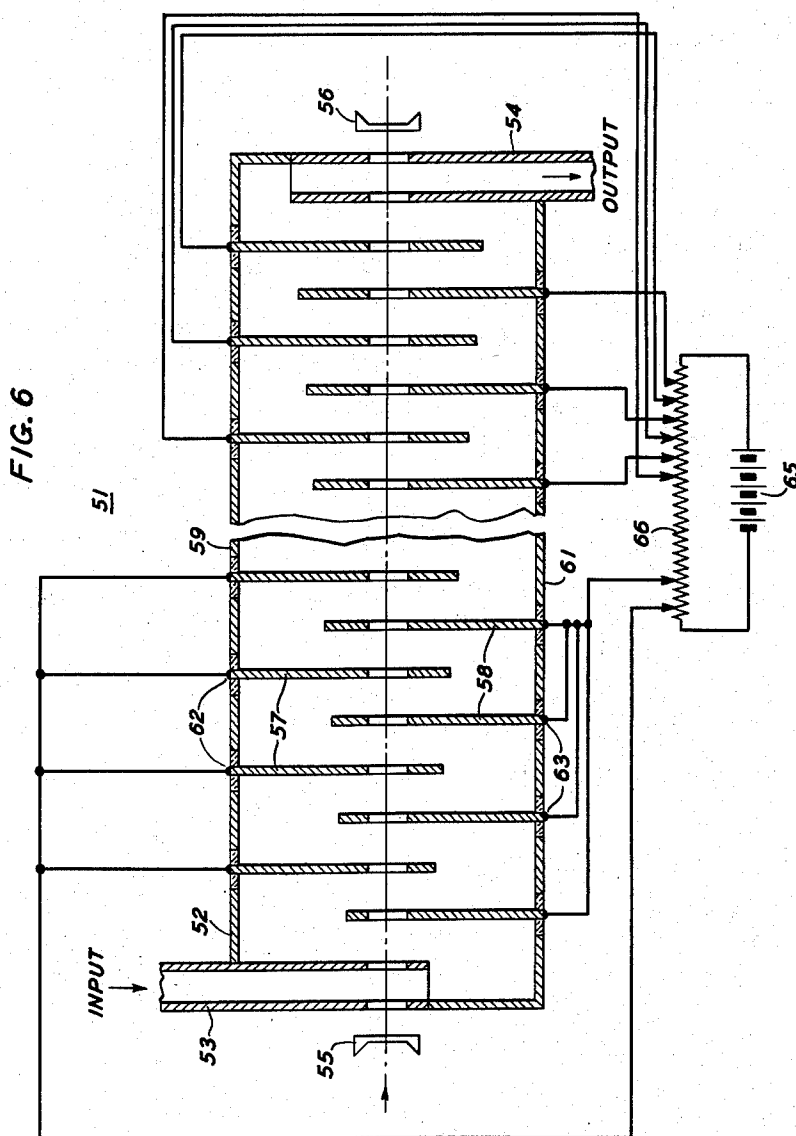
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2,925,519

TRAVELING WAVE TUBE

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Application August 26, 1954, Serial No. 452,247

26 Claims. (Cl. 315—3.6)

This invention relates to devices which utilize the interaction between an electron beam and a traveling electromagnetic wave over a distance equal to a plurality of operating wavelengths. Such devices are now commonly described as traveling wave tubes and have heretofore been characterized by decreasing efficiency at high signal levels.

It is an object of this invention to increase the efficiency of a traveling wave tube.

More specifically, it is an object of this invention to increase the efficiency of a traveling wave tube by means of velocity sorting of the electrons in the beam which may be advantageously accomplished by modifications in the focusing of the beam.

In a traveling wave tube, the electron stream is projected closely past an interaction circuit along which the signal wave is propagating. For efficient operation, it is generally important to keep the electron flow cylindrical (i.e., to have no net divergence or convergence) both to avoid having electrons strike the interaction circuit and to confine the electrons to regions of high signal fields. To minimize the space charge transverse components of force upon the electrons within the beam, it is the usual practice to set up a uniform longitudinal magnetic field along the path of electron flow. This magnetic field has generally been achieved by the use of either permanent magnets or solenoidal magnets external of the tube.

Moreover, the usual manner for achieving such a uniform longitudinal field has been 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 the mutually repulsive outward 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 down the length of the tube, to be collected by a collector electrode at the far end of the tube.

If, at the same time, an electromagnetic wave is introduced into the wave propagating circuit which is contiguous to the electron beam along the length of the tube in a manner such that there is a component of electric field of the wave which is parallel to the electron beam, interaction between the wave and the beam

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will take place. Such interaction takes the form both of extraction of energy from the electron beam by the wave, and extraction of energy from the wave by the beam. Over a plurality of operating wavelengths, there will be more energy extracted from the beam than is returned to it, resulting in a net decrease in energy content of the beam and reflected by a decrease in the average velocity of the electrons in the beam and a net increase in the amplitude of the wave. During the interaction, the energy extracted from the wave by the beam will serve to accelerate some of the electrons in the beam, while the extraction of energy from the beam by the wave results in a deceleration of some of the electrons in the beam. This interaction thus superimposes on the D.-C. velocity of the beam an A.-C. velocity component and results in bunches in the beam of high electron density interposed between regions of low electron density. At the output end, this A.-C. velocity component still exists, but the average velocity of the beam is decreased as a natural result of the net loss of energy from the beam.

In practice, it has been found that traveling wave tubes exhibit the phenomenon of overloading, that is, with an increase in input level of the wave the output of the tube increases substantially linearly up to a point, and then begins to level off until another point is reached where a further increase in input level gives no further increase in output. This latter point is the overload point of the tube. In some cases, a further increase in input level results in an actual decrease in output. As a result, the efficiency of a traveling wave tube reaches a maximum as the overload region is approached, and beyond the overload region, the efficiency decreases. In a preferred embodiment of the invention, a succession of magnetic pole pieces are spaced uniformly along the major portion of the length of the tube and are joined together by permanent magnets in a manner such that alternate pole pieces will be of opposite polarity. Such an arrangement has the effect of imparting a uniform periodicity to the magnetic focusing field. For reasons which will be more fully explained hereinafter, along a portion of the path of flow the strength of each successive focusing region is made to differ from adjacent focusing regions by using permanent magnets of different strength. In addition, for fullest realization of the benefits made possible by the elimination of undesirable electrons, the velocity of propagation characteristic of the traveling wave circuit is made to change in a particular manner along the length of the tube.

Various other illustrative embodiments will be described herein, each of which is characterized as establishing along the path of flow a periodic focusing field, in which a variation is imparted to the focusing effect of the field by varying any one of several parameters upon which the focusing effect depends.

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

Fig. 1 is a series of curves pictorially representing the behavior of electrons in the beam for various levels of signal;

Fig. 2 is a sectional view of a traveling wave tube embodying my invention;

Fig. 3 is a plot of collector current versus the focusing parameters in a periodic focus traveling wave tube, showing the higher order pass and stop bands;

Fig. 4 is a sectional view of another focusing arrangement for a traveling wave tube embodying my invention;

Fig. 5 is a sectional view of still another tube embodying my invention;

Fig. 6 is a sectional view of a tube embodying my invention wherein electrostatic focusing is used, and;

Fig. 7 is a view showing the connection of the plates to the walls of the tube of Fig. 6.

Detailed study and measurements of the operation of a typical traveling wave tube, the results of which are shown in Figs. 1(a) through 1(e), have yielded an explanation of the tube behavior in the overload range and beyond, including for the first time an insight into the specific phenomenon of overloading resulting in decreasing output. The present invention to a large extent is based upon the utilization of the results of such study to effect modifications in the beam focusing arrangement and interaction circuit of a traveling wave tube to compensate for overloading.

Figure 1(a) represents the voltage wave in the wave propagating circuit, which, for simplicity's sake, is shown as sinusoidal. If this wave corresponds to a low level input signal, and a beam of electrons is directed along the wave propagation circuit for interaction with the wave, at regions well along the wave circuit a velocity modulation of electrons within the beam takes place. This velocity modulation is pictured in Fig. 1(b), wherein the ordinate represents velocity, and the abscissa represents phase. The origin on the ordinate scale represents the average or D.-C. velocity of the electron beam. The curve of Fig. 1(b) represents the distribution of electrons within the beam relative to the phase of the traveling wave, and the velocities of the electrons at any given phase angle. It can be seen in Fig. 1(b) that there is a pronounced grouping of electrons at a velocity less than the average or D.-C. velocity, as represented by the large shaded area on the distribution curve, and in a phase relationship with the voltage wave to give up energy thereto. This grouping or bunching of the slowed up electrons as diagrammed illustrates the interaction phenomenon. In this case, substantially all of the electrons in the main bunch are in the proper phase relationship with the wave to give up their energy thereto, and the giving up of energy results in a slowing down and bunching at this particular phase angle. If, instead of a signal of a low input level, a signal of an intermediate level is introduced into the wave circuit, the resulting velocity distribution of the electrons will be as shown in Fig. 1(c). The shaded area which represents a bunch of slow electrons which have lost energy to the traveling wave begins to develop a "tail" which represents a group of still slower electrons. This phenomenon is caused by the fact that space charge forces within the bunch act to repel slow electrons at the rear of the bunch, decreasing their velocity still further. Inasmuch as these last electrons are traveling at a velocity which is less than the velocity of the bunch, they begin to fall back in phase relative to the voltage wave, to which they still give up energy, and, as a consequence, the "tail" at the rear of the main bunch forms. When the input level of the signal is raised to the overload value, a velocity distribution of the nature shown in Fig. 1(d) will occur within the beam. At overload, it can be seen that the "tail," which was beginning to develop at the intermediate input level, has developed to the extent that there are now two discrete bunches of slow electrons, the first bunch being in phase with the wave and the second bunch having fallen back in phase until its phase relationship with the wave is such that energy is extracted from the wave. This results in acceleration of the electrons within this second bunch and the upturning end of the "tail" shown in Fig. 1(d) is a graphic illustration of this phenomenon. The reason for the leveling off of the gain at overload can now be understood. The electrons in the second bunch are in a position to absorb energy from the wave as quickly as energy is given up to the wave by electrons in the first bunch. In addition, this absorption of energy from the wave acts to reduce the velocity of the wave and decrease its amplitude until

which then spills over into the accelerating region. Fig. 1(e) represents the velocity distribution in the beam for a signal of input level beyond overload. The electrons in the second bunch, which absorb energy from the wave, commence to speed up, and hence advance in phase. However, a portion of the electrons in this bunch, because of the repulsion effect of space charge forces, continue to fall back in phase relative to the wave.

It can be seen by a study of Figs. 1(a) through 1(e) that for a signal of any input level, there is a large group of electrons which stays in the proper phase relationship with the traveling wave for giving up energy to the wave. The decreasing gain and efficiency with increasing input level is directly attributable to the formation of one or more groups of electrons which have fallen out of phase with the wave to the extent that energy is extracted from the wave. It is therefore necessary, for efficient operation of the tube, that the formation of these secondary groups of electrons be prevented or that such groups be eliminated before their full detrimental effects are realized.

The present invention achieves these ends by eliminating or expelling from the electron beam the slow electrons which tend to form these secondary groups before the groups are formed, with the net result both that the only electrons remaining in the beam are those which will continue to transfer energy to the wave and that there will be substantially no extraction of energy from the wave by secondary groups.

Such elimination of the undesirable slow electrons is realized in accordance with the invention by making use of a focusing arrangement which acts upon electrons within the beam selectively to focus or defocus them, depending upon their velocity. More particularly, such focusing action is preferably obtained by the use of an arrangement which provides a succession of alternately stronger and weaker focusing regions. Such a succession of alternately stronger and weaker focusing regions may be advantageously achieved by use of periodic focusing. A detailed description and analysis of magnetic periodic focusing may be found in the copending applications of J. R. Pierce, Ser. No. 351,983, filed April 29, 1953, now United States Patent 2,847,607, issued August 12, 1958, and Ser. No. 351,984, filed April 29, 1953, now United States Patent 2,841,739, issued July 1, 1958. However, a brief description of this type of focusing will be given here to facilitate an understanding of the present invention. It is to be understood that while the principles of the invention will be set forth with greatest particularity in its application to magnetic focusing, the invention is equally applicable to other types of focusing, such as electrostatic, as will be described briefly hereinafter, and accordingly applicant does not intend to limit himself to magnetic focusing alone.

Analysis has revealed that an essentially non-diverging beam may be obtained if the R.M.S. (root mean square) 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. 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. Assuming that along the length of the tube, that is, the path of flow, the regions of longitudinal magnetic field are short compared to the distance separating them, the succession of focusing fields may be regarded as a series of thin converging lenses. 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 between the lenses, and the electron beam flow is identical between each pair of lenses. However, unlike the case of a uniform magnetic field, in the periodic field the focusing cannot be improved by increasing the magnetic field strength beyond the theoretical required value. Instead, there are encountered regions of magnetic field strength which cause the beam to diverge. For a given magnetic field strength, the velocity of an electron within the beam determines whether that particular electron is focused or defocused. Defocused electrons, if the amount of defocusing is sufficient, may be completely expelled from the beam. This difference in behavior of electrons within the beam under the influence of a periodic magnetic field gives rise to "pass" bands, that is, for a given magnetic field a range of velocities where the electrons will be focused, and "stop" bands, where, for the same magnetic field, there is a range of velocities where the electrons will be defocused.

The present invention makes use of this phenomenon, in a manner which will be more fully explained hereinafter, to eliminate from the electron beam those electrons in the beam which have fallen back in phase from the group of electrons which are giving up their energy to the wave, thus preventing them from extracting energy from the wave. Moreover, the elimination of these electrons from the beam makes possible the realization of the advantages to be gained from varying the propagation characteristic of the wave circuit to maintain synchronism between the beams and the wave. Heretofore, these advantages have been recognized but their realization has never been completely successful.

Turning now of Fig. 2, there is illustrated schematically a traveling wave tube 11 embodying the principles of the invention. Located at opposite ends of an evacuated elongated envelope 12 which, for example, is of glass or any suitable non-magnetic material, or of magnetic material which will saturate readily, are a source of a solid beam of electrons 13 and a target or collector electrode 14. The electron source 13 is shown schematically and will, in general, consist of an electron emissive cathode, a heater unit, an intensity control element, and an electrode arrangement 15 for shaping and accelerating the beam. The target 14 serves as a collector of electrons and is, accordingly, maintained at a suitable potential positive with respect to the electron emissive cathode of the source 13 by means of suitable lead-in connections from a voltage source, not here shown. In conventional traveling wave tubes an electrode member maintained at a positive potential with respect to the cathode of the source is disposed along the path of flow for providing an accelerating field. In most traveling wave tubes, the interaction circuit itself serves as such an electrode. In the tube of Fig. 2, the interaction circuit comprises a helically coiled conductor 16, a plurality of operating wavelengths long, which serves as a propagating circuit for electromagnetic waves. The pitch of the helix determines the velocity with which the wave propagates down the length of the tube, and this pitch is adjusted to propagate the wave in coupling relationship with the electron beam. In addition, the helical interaction circuit 16, in the embodiment here shown, serves as an accelerating electrode for the electron beam and so is maintained at a suitably positive potential with respect to the cathode of the electron gun.

At each end, the helix 16 is connected to an external transmission line by suitable coupling. As shown, at the input end, the coupling means comprises the helix 13 wound in a sense opposite to that of the helix 16 and surrounding the tube envelope along a region overlapping the input end of the helix 16. The end of the helix 17 adjacent the end of the helix 16 is connected to the inner conductor of the coaxial line 17A which forms the external transmission line leading to the signal source and its opposite end is terminated to be substantially reflect-

tionless. Coupled helix arrangements of this kind are described more fully in copending application Serial No. 360,579, filed June 9, 1953, by R. Kompfner, now United States Patent 2,834,908, issued May 13, 1958. At the output end, energy is transferred from the helix 16 to an external transmission line 18A, for utilization in a manner analogous to that described for the input end. Various other arrangements for coupling to and from a helix interaction circuit may be substituted. It is understood also that while the interaction circuit is shown as a helix 16, it may take any one of a number of forms well known to those skilled in the art, such as, for example, a wave guide having serrated or ridged walls.

Disposed along the path of flow, and uniformly spaced from each other, are a plurality of annular pole pieces 19 of material having a high magnetic permeability. A series of bar magnets 21 is disposed across successive gaps between the pole pieces, 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 fields, the direction of the magnetic fields reversing with each successive region. For reasons which will be explained hereinafter, in the embodiment here shown, with progress toward the output end, each succeeding region of magnetic field is made weaker than the preceding region over an output end portion of the path of flow. This is accomplished by using progressively weaker bar magnets 21. This is illustrated here by depicting successive magnets along the output end portion as of increasingly smaller cross-section.

In the aforementioned Pierce patents, the phenomena of "stop" and "pass" bands in conjunction with periodic focusing are discussed at length. It is there shown that these phenomena depend upon the parameters of magnetic field strength, periodicity of the magnetic field, and the accelerating voltage or velocity of the electrons in the beam. In Fig. 3 there is shown a graph of the pass and stop bands for a typical periodic focusing system, wherein the fraction of the current initially in the beam which reaches the collector is plotted against the term

$$K \frac{B_0 L}{v}$$

which may be arbitrarily designated as the periodic focusing parameter, B_0 representing a measure of the magnetic field, L representing the separation of the pole pieces, v representing the average electron velocity, and K is a constant for a given tube. It can be seen from a study of Fig. 3, that if an arbitrary point x on the abscissa is selected, a decrease in magnetic field strength or a decrease in the separation of the pole pieces results in a shifting of the point x to the left. Conversely, an increase in the value of either of these two parameters shifts the point to the right. On the other hand, an increase in velocity of electrons within the beam shifts the point to the left, while a decrease shifts it to the right. If a traveling wave tube of the type shown in Fig. 2 is operated at the point x with the collector current as indicated at that point, a change in one of the parameters will cause a change in focusing effect and a corresponding change in collector current. If, for example, there is a decrease in magnetic field strength of sufficient magnitude, the operating point becomes x' . At the point x' , the current reaching the collector has dropped to zero, or, in other words substantially all of the electrons are defocused at this point. Further decrease in magnetic field brings no increase in collector current until operating point x'' is reached at which point current again begins to reach the collector. The interval between x' and x'' is designated a stop band, since it represents a range wherein substantially all of the electrons are defocused so that none reaches the collector. Conversely, the ranges where significant current reaches the collector are designated as pass bands, inasmuch as at least some electrons are focused. Those electrons which are defocused are expelled from the beam and collected by the interaction circuit, the walls of the tube, or

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suitable electrodes placed along the tube for that purpose.

If a periodic focus traveling wave tube is operated with the values of B_0 , L and v such that the major portion of the in-phase electrons, which have velocities approximating v are focused to the extent indicated at point Y, and the signal input level is in the overload region, those electrons at the rear of the first bunch of electrons, which are decelerated as shown and explained in conjunction with Fig. 1(d), fall within the stop band $Y'-Y''$. Thus those electrons to which is attributed the overload behavior are defocused and expelled from the beam. The operating point Y is so chosen that either the tendency of the electrons to form a "tail" as overload is approached is prevented in its inception, or the "tail" is allowed to form to some extent so that the last measure of utility is had from those electrons, but the formation of the second group of electrons is prevented by defocusing the electrons as their velocity decreases to within a certain range.

As the first group of electrons, which is advantageously phased with the wave, moves down the tube toward the collector, the velocity of the electrons within the group gradually decreases as they give up their energy to the wave, with the result that these electrons tend to approach a stop band, i.e., point Y shifts to the right in Fig. 3. At the same time, the electrons toward the rear of the bunch have a still greater decreased velocity, due to the space charge effects as discussed earlier, and hence they approach a pass band ($Y'''-Y''''$). If these tendencies are allowed to go unchecked, there occurs at some point along the flow path a defocusing of the desirable electrons and a focusing of the undesirable ones. The present invention corrects these tendencies by varying at least one of the three focusing parameters with progress along the path of flow in a manner to maintain the operating point of the system continually in a fixed position relative to the stop and pass bands, so that the properly phased electrons remain focused throughout their travel down the tube while the improperly phased electrons become defocused.

In the embodiment illustrated in Fig. 2, the strength of the magnetic field is decreased in each succeeding focusing region, while the spacing of the fields is maintained constant. The decreased strength may be simply achieved by decreasing the cross section of each succeeding magnet, or alternatively, it may be achieved by decreasing the magnetization of each succeeding magnet. By properly choosing the value of the magnetic field for each focusing region, the net effect is to keep the operating point for the undesirable electrons within a stop band throughout the interaction length of the tube. The amount of change in magnetic field necessary for this purpose varies in greater or lesser degree depending upon such things as beam density and radius which determine the space charge forces.

During interaction between the beam and the wave, the giving up of energy to the wave by the main or first group of electrons results in these electrons slowing down, as was pointed out in the foregoing. If the propagation velocity characteristic of the wave circuit is constant, so that the wave propagates with a uniform velocity along the interaction circuit, the synchronism between the wave and the beam decreases at the output end where the velocity of the main useful bunch has decreased. In accordance with another feature of the present invention, the wave and the beam are maintained in coupling relation along substantially the entire length of the wave circuit by imparting to the output end portion of the wave circuit a decreasing velocity characteristic with progress towards the output end.

In the embodiment of Fig. 2, the helical interaction circuit is varied in pitch along the output end of the tube, the pitch decreasing toward the output end. Since the propagation characteristic of the circuit varies as the pitch, a decrease in pitch results in a decrease in the velocity of a wave propagating along the circuit. By

properly decreasing the pitch, the wave is made to stay in proper phase relationship with the beam as the beam decreases in average velocity.

It has been suggested hitherto that the efficiency of a traveling wave tube may be improved by providing for a reduction in the propagation velocity of the wave near the output end of the interaction circuit to compensate for the reduced average velocity of the beam there. However, in practice, heretofore, the method has never been really successful, especially in the overload range. The analysis set forth in connection with Fig. 1 of the overload phenomenon makes it possible to understand now why such methods have not succeeded as expected.

Where there exists energy abstracting electron bunches in the beam in addition to energy imparting electron bunches, changes in the propagating characteristics of the interaction circuit to enhance the efficiency of wave interaction with such energy imparting bunches concurrently results in increasing the effect of the energy abstracting electron bunches so that little net gain results. Where, however, as in the present invention, the energy abstracting electron bunches can be eliminated, the full advantages of varying the wave velocity to maintain synchronism with the beam can be realized even for signal levels within and beyond the usual overload range.

In the embodiment shown in Fig. 2, the magnetic focusing fields are created by permanent magnets. Other means, such as solenoidal magnetic means, may be used in place of the permanent magnets, in which case the control over the strength of the magnetic focusing fields is maintained by controlling the current in each winding or solenoid or the number of effective turns in each solenoid, or both. Such an arrangement is within the scope of the present invention, as are other arrangements of similar nature.

In Brillouin type focusing, when the electron velocity decreases as a result of interaction, an increase in the focusing fields is sometimes necessary to counteract the increased radial effect of the space charge forces which occur with reduced velocity and bunching. A thorough discussion of Brillouin type focusing and the several phenomena associated therewith, including the foregoing, may be found in "Theory and Design of Electron Beams," by J. R. Pierce, D. Van Nostrand Company, Inc. Under such conditions, the decrease in velocity requires an increase in focusing field, but, as explained earlier, the decreased velocity also requires a decreased field in order to maintain the operating point properly placed relative to the pass and stop bands. The present invention remedies the apparent anomaly by varying the spacing between the focusing regions (the parameter designated by the letter L in Fig. 3) to maintain the operating point properly positioned with respect to the pass and stop bands, and varying the strength of the magnetic field to counteract for the increased radial space charge effects. In Fig. 4 there is illustrated a short section of the interaction path of a tube embodying these principles. For simplicity's sake, the elements in Fig. 4 which are the same as elements in Fig. 2 are designated by the same reference numerals. In Fig. 4, the strength of the magnets is made to increase along a downstream portion of the length of the tube with distance toward the output end to give a periodic focusing arrangement of gradually increasing strength. The spacing between each of the focusing regions is decreased toward the output end sufficiently to maintain the proper stop and pass band positioning as explained in the foregoing. Such an arrangement thus permits varying the magnetic fields to correct for one condition of operation and varying the spacing to correct for a second condition of operation. As was the case in connection with Fig. 2, other suitable means may be used to vary the strength of the focusing fields, including the use of solenoids and the like.

While the foregoing discussion and embodiments have been somewhat generalized as to the portion of the inter-

action path affected by the varying focusing fields or changing periodicity, measurements have shown that the overload effects discussed in connection with Fig. 1 are more pronounced in the last half of the path of travel of the beam. Thus, it is usually not necessary to introduce any variations in the focusing until the beam is in the last portion of its path of travel, where there has been a substantial decrease in energy content in the beam. In Fig. 5 is shown an embodiment of the principles of the invention wherein the variations in the focusing effect are introduced in the tube near the output end only. In Fig. 5 is shown a traveling wave tube 31 having an elongated evacuated envelope 32, at opposite ends of which are located an electron beam source 33 and a target or collector electrode 34. The electron beam source 33 has associated therewith an electrode arrangement 35 for shaping the electron beam. A helically coiled conductor 36 serves as the wave propagating circuit and is coupled at its ends to an impedance matching input coupler 37 and an impedance matching output coupler 38 which may take any one of a number of suitable forms including the coupling arrangements mentioned in connection with Fig. 2. A longitudinal magnetic focusing field is supplied by a magnetic member 39 which may be a permanent magnet or a solenoid arrangement, and which has mounted at its ends pole pieces 41 and 42 of suitable magnetic material. Disposed along the path of flow, toward the output end of the tube is a series of cylindrical rings 43 of magnetic material which surround the helix 36. These rings 43 of magnetic material act as shunts for the magnetic field, and hence have the effect of imparting to the field periodic non-uniformities. By varying the spacing between the rings, or varying the width of the rings, the parameter L of Fig. 3 may be varied to correspond to variations in the velocity of the electrons in the beam to maintain the operating point in the proper relationship to the pass and stop bands.

The foregoing illustrative embodiments have all utilized magnetic focusing. However, as previously indicated, the principles of the invention are applicable to various other types of focusing arrangements, such as electrostatic focusing. The principles of electrostatic focus tubes are clearly set forth in the copending United States patent application Serial No. 364,242, filed June 26, 1953, by P. K. Tien, now United States Patent 2,834,908, issued May 13, 1958. In such an arrangement, electric lines of force are set up between successive electrodes disposed along the beam path, successive electrodes being of opposite polarity with respect to the mean potential between adjacent electrodes. Such an arrangement presents to the electron beam a periodic electric field which acts to focus the electrons in the beam in a manner similar to the periodic magnetic field of the preceding embodiments. Thus variations in the potential difference between adjacent electrodes and variations in the spacing of the electrodes cause the focusing regions to act upon the beam in the same or similar manner that variations in the magnetic field strength and in the periodicity of the magnetic focusing regions act upon the beam in a magnetic focusing arrangement.

In Fig. 6 there is shown by way of example for purposes of illustration solely a schematic diagram of a traveling wave tube 51 using periodic electrostatic means for focusing the electron beam. Tube 51 comprises a wave guiding circuit 52 which is, for example, a hollow wave guide of rectangular cross section which is folded back and forth upon itself in serpentine fashion, in the manner shown and described in the copending United States patent application Serial 250,093, filed October 6, 1951, of C. C. Cutler, now United States Patent 2,810,854, issued October 22, 1957. Wave energy is supplied at the input end 53 which may, for example, be a continuation by way of a pressure-tight window, not shown, of a conventional rectangular wave guide.

In like manner, wave energy is extracted from the tube at the output end 54 through a similar connection to a conventional rectangular wave guide. A source 55 of an electron beam is located adjacent the input end of the wave circuit and oriented to direct an electron stream along the tube transversely of the folds in the wave guide. The source 55 is shown schematically and may take any one of a number of forms suitable for use in an electrostatic focusing tube, such as the electron gun structure shown and described in the aforementioned Tien application. A collector electrode 56 is positioned at the output end of the tube in target relation to the electron gun 55 for collecting the spent electrons at the end of their travel. The folds of the wave guide are formed by a plurality of plates 57, 57 and 58, 58 which are of a suitable conducting material, such as copper, extending from opposite walls 59 and 61, respectively, in an interdigital pattern. The walls 59 and 61 are of conducting material. Each of the plates 57, 57 is capacitively connected to the wall 59 by a condenser 62 and each of the plates 58, 58 is capacitively connected to the wall 61 by a condenser 63. The capacitive connection makes possible D.-C. isolation of the various plates so that different voltages may be applied to successive plates to achieve electrostatic focusing. The capacitive connections 62 and 63 may be made in any suitable way, such as, for example, by the structure shown in Fig. 7, wherein each plate 57 is separated from the wall 59 by a suitable dielectric material 64, such as mica. By keeping these capacitive connections thin, the radio frequency properties of the wave circuit are unaffected. A suitable voltage source 65 and a voltage dividing resistor 66 supply the necessary potentials for application to the plates 57, 57 and 58, 58. Coupling with the electron beam is achieved by slotting or boring the plates to permit passage of the beam through the plates and the regions between.

As was the case with magnetic periodic focusing, the phenomenon of overloading and consequent reduction in efficiency can be substantially overcome by varying the strength of the focusing fields along the interaction path. In the arrangement of Fig. 6, a uniform potential difference is maintained between adjacent plates over a portion of the path length. As the electrons within the beam spend their energy, the velocity variation becomes more pronounced. As pointed out in the foregoing, the velocity variations become more serious along the last half of the interaction circuit. The plates 57, 57 and 58, 58 are maintained at progressively decreasing potentials toward the output end over the last portion of the circuit to counteract the effects of the decreasing electron velocity, thus maintaining the operating point of the beam in proper relationship with the stop and pass bands in accordance with the principles of the invention as set forth.

The decreasing electron velocity makes necessary a gradual decrease in the wave velocity from input to output. In the embodiment of Fig. 6, the path length of the wave propagation circuit is increased by making successive plates 57 and 58 longer than the preceding ones, thus effectively slowing down the wave by causing it to traverse longer transverse paths for given increments of axial travel down the tube.

While the principles of the present invention have been set forth with greatest particularity as applied to the specific structures herein disclosed, it is obvious that these principles are equally applicable to many other arrangements and embodiments wherein control over various portions of the focusing system can be had, and to other arrangements which, by their nature, permit velocity sorting of the electrons.

In addition, while the foregoing disclosure has been largely devoted to the improvement of the efficiency of traveling wave tubes, the principles of the invention lend themselves readily to other applications wherein velocity

sorting of electrons in the beam is utilized to provide selective amplitude discrimination, such as, for example, in copending United States patent application Serial No. 452,248, filed August 26, 1954, the principles of velocity sorting are used in signal limiting, expanding, and slicing.

What is claimed is:

1. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting in electrons in the beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising means disposed along the path of electron flow for at least a portion thereof for establishing a succession of dissimilar, spaced focusing regions therealong, the product of the focusing field strength within the regions and the spacing of the regions decreasing over a distance of at least three successive regions in the direction of beam travel, said slow wave circuit having a nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along that portion of the slow wave circuit where the interaction takes place.

2. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting in electrons in the beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising a plurality of means disposed along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the spacing between successive ones of said means being different whereby improperly phased electrons are defocused, the spacing decreasing over a distance of at least three successive regions in the direction of beam travel.

3. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting in electrons in the beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising a plurality of means disposed along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the spacing between successive ones of said means being different whereby improperly phased electrons are defocused, the spacing decreasing over a distance of at least three successive regions in the direction of beam travel, said slow wave circuit having a nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along that portion of the slow wave circuit where the interaction takes place.

4. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting in electrons in the beam becoming

improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising means disposed along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the magnitude of the focusing fields in each focusing region being different from the others whereby improperly phased electrons are defocused, the magnitude of said fields decreasing over at least three successive regions in the direction of beam travel.

5. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting in electrons in the beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising means disposed along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the magnitude of the focusing fields in each focusing region being different from the others whereby improperly phased electrons are defocused, the magnitude of said fields decreasing over at least three successive regions in the direction of beam travel, said slow wave circuit having a nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along that portion of the slow wave circuit where the interaction takes place.

6. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting from the electron beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising a plurality of means disposed along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the spacing between successive ones of said means being different, the spacing decreasing over at least three successive regions in the direction of beam travel, and the magnitude of the focusing field in each of said focusing regions being different from the others whereby improperly phased electrons are defocused.

7. An electron discharge device comprising a slow wave circuit and an electron beam source for projecting an electron beam along said slow wave circuit in coupling relation thereto for cumulative interaction with a high frequency wave propagating on said circuit, the interaction resulting from the electron beam becoming improperly phased for cumulative interaction with the wave over at least a portion of the length of the slow wave circuit in the region of interaction and in a net slowing down of the beam, means for defocusing the improperly phased electrons despite changes in the net beam velocity comprising a plurality of means deposited along the path of electron flow for at least a portion thereof for establishing a succession of spaced focusing regions therealong, the spacing between successive ones of said means being different, the spacing decreasing over at least three successive regions in the direction of beam travel, and the magnitude of the focusing field in each of said focusing regions being different from the others whereby improperly phased electrons are defocused, said slow wave circuit having a nonuniform propagation characteristic for

maintaining the wave and the beam in synchronism along that portion of the slow wave circuit where the interaction takes place.

8. An electronic device comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit at one end thereof, output coupling means coupled to said circuit at the other end thereof, and means for establishing dissimilar spaced focusing regions along at least a portion of the path of electron flow, the focusing effect of said focusing regions being governed in part by the parameters B_0 and L , where B_0 is a measure of the strength of the focusing fields and L is a measure of the spacing of the spaced regions, said means comprising a plurality of spaced means, successive spaced means being related to vary at least one of the parameters B_0 and L along at least a portion of the path of electron flow over three or more successive ones of said focusing regions such that the product of B_0 and L decreases in the direction of electron flow.

9. An electronic device comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, said circuit having a nonuniform propagation characteristic, input coupling means coupled to said circuit at one end thereof, output coupling means coupled to said circuit at the other end thereof, and means for establishing dissimilar spaced focusing regions along at least a portion of the path of electron flow, the focusing effect of said focusing regions being governed in part by the parameters B_0 and L , where B_0 is a measure of the strength of the focusing fields and L is a measure of the spacing of the spaced regions, said means comprising a plurality of spaced means, successive spaced means being related to vary at least one of the parameters B_0 and L along at least a portion of the path of electron flow over three or more successive ones of said focusing regions such that the product of B_0 and L decreases in the direction of electron flow.

10. An electronic device as claimed in claim 9 in which the spacing between successive ones of said plurality of spaced means varies over at least a portion of the path of electron flow.

11. An electronic device as claimed in claim 9 in which the strength of the focusing fields established by the plurality of means varies over at least a portion of the path of electron flow.

12. The improvement as claimed in claim 3 wherein the spacing between successive ones of said means decreases toward the output end of the slow wave circuit.

13. The improvement as claimed in claim 4 wherein the means comprises magnetic members for establishing periodic magnetic focusing regions.

14. The improvement as claimed in claim 4 wherein the means comprises electrodes for establishing periodic electrostatic focusing regions.

15. The improvement as claimed in claim 5 wherein the magnitudes of the focusing fields decrease toward the output end of that portion of the slow wave circuit where interaction between the beam and the wave takes place.

16. The improvement as claimed in claim 5 wherein the means comprises magnetic members for establishing periodic magnetic focusing regions.

17. The improvement as claimed in claim 5 wherein the means comprises electrodes for establishing periodic electrostatic focusing regions.

18. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, and means

for focusing the electron beam comprising a plurality of differently spaced elements establishing a series of focusing regions extending axially of the tube for at least a portion thereof, the difference in spacing between the elements decreasing in the direction of beam travel and causing a predetermined difference in the focusing effect of the focusing regions, the spacing between any pair of adjacent elements being greater than the spacing between the succeeding pair of adjacent elements in the direction of beam travel.

19. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, and means for establishing a series of focusing regions of varied strength extending axially of the tube for at least a portion thereof for focusing the electron beam, said means comprising a plurality of equally spaced elements, the difference in strength of the several focusing regions decreasing in the direction of beam travel in such a manner that both adjacent and alternate ones of said focusing regions are of different strength causing a predetermined difference in the focusing effect of the focusing regions.

20. A traveling wave tube amplifier as claimed in claim 19 in which the means for focusing the electron beam comprises a plurality of magnetic elements establishing a plurality of magnetic focusing regions.

21. A traveling wave tube amplifier as claimed in claim 19 in which the means for focusing the electron beam comprises a plurality of electrodes establishing a series of electrostatic focusing regions.

22. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, and means for focusing the electron beam comprising a plurality of equally spaced elements of different sizes establishing a series of dissimilar focusing regions extending axially of the tube for at least a portion thereof, alternate ones of said elements decreasing in size toward the collector electrode, the difference in size of the several elements causing a predetermined difference in the focusing effect of the focusing regions.

23. An electron discharge device as claimed in claim 1 wherein said means for defocusing improperly phased electrons comprises a plurality of spaced magnetic shunt rings extending axially of the tube for at least a portion thereof establishing a series of periodic focusing regions each of said shunt rings differing in width from the others whereby there is established a predetermined difference in the focusing effect of the focusing regions.

24. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, means for focusing the electron beam comprising a plurality of differently spaced elements establishing a series of focusing regions extending axially of the tube for at least a portion thereof, the difference in spacing between the elements decreasing in the direction of beam travel in such a manner that the spacing between any pair of adjacent elements is greater than the spacing between the succeeding pair of adjacent elements in the direction of beam travel causing a predetermined difference in the focusing effect of the focusing regions, and an interaction circuit for propagating a traveling wave having a

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nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along the interaction circuit.

25. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, means for establishing a series of focusing regions of varied strength extending axially of the tube for at least a portion thereof for focusing the electron beam comprising a plurality of equally spaced elements, the difference in strength of the several regions causing a predetermined difference in the focusing effect thereof, the strength of alternate ones of the several regions decreasing toward the output coupling means, and an interaction circuit for propagating a traveling wave having a nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along the interaction circuit.

26. A traveling wave tube amplifier comprising, in combination, means including an electron gun and a collector electrode for forming and projecting an electron beam, a wave propagation circuit between said gun and said collector, input coupling means coupled to said circuit adjacent the electron gun, output coupling means coupled to said circuit adjacent the collector, means for focusing the electron beam comprising a plurality of equally spaced elements of different sizes establishing a

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series of dissimilar focusing regions extending axially of the tube for at least a portion thereof, alternate ones of said elements decreasing in size toward the collector electrode, the difference in size of the several elements causing a predetermined difference in the focusing effect of the focusing regions, and an interaction circuit for propagating a traveling wave having a nonuniform propagation characteristic for maintaining the wave and the beam in synchronism along the interaction circuit.

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