Jan. 31, 1967 J. E. ORR 3,302,126

COLLECTOR ARRANGEMENT FOR COLLECTING UNFAVORABLY PHASE FOCUSED ELECTRONS

Original Filed April 5, 1962 3 Sheets-Sheet 1

FIG. 1

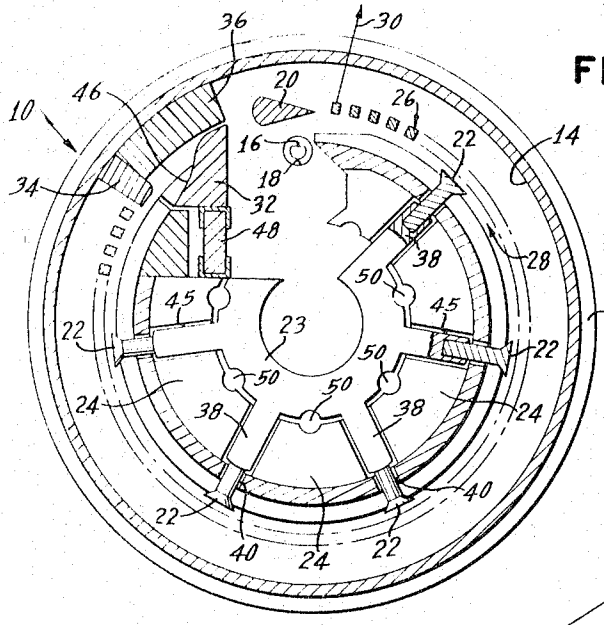
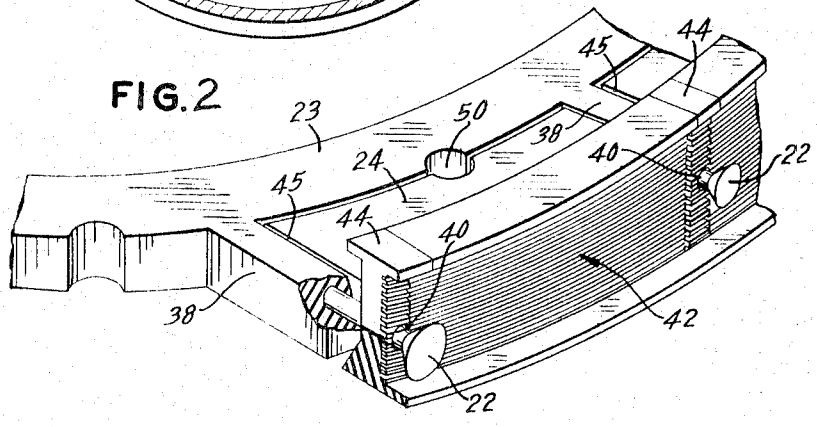


FIG. 2



INVENTOR.
JAMES E. ORR
BY Ronald W Barry
ATTORNEYS

Jan. 31, 1967 J. E. ORR 3,302,126

COLLECTOR ARRANGEMENT FOR COLLECTING UNFAVORABLY PHASE FOCUSED ELECTRONS

Original Filed April 5, 1962 3 Sheets-Sheet 2

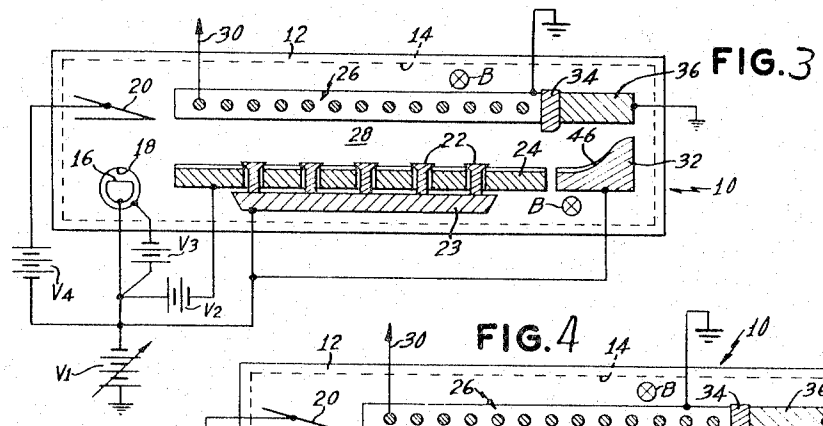


FIG. 3

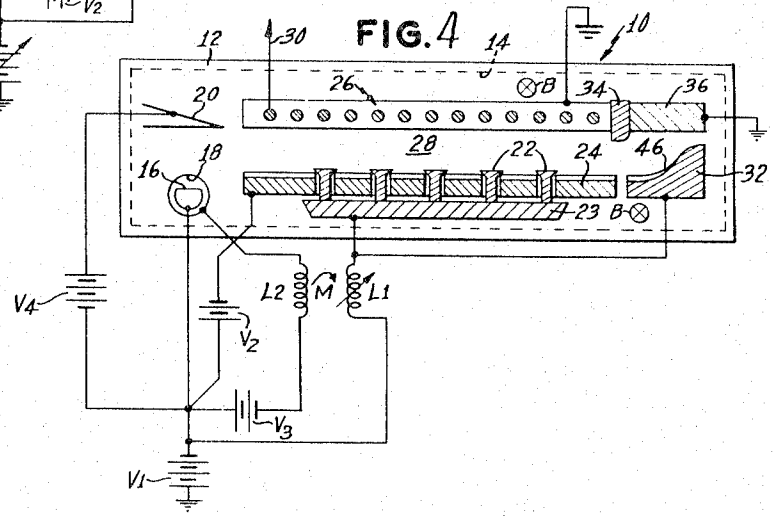


FIG. 4

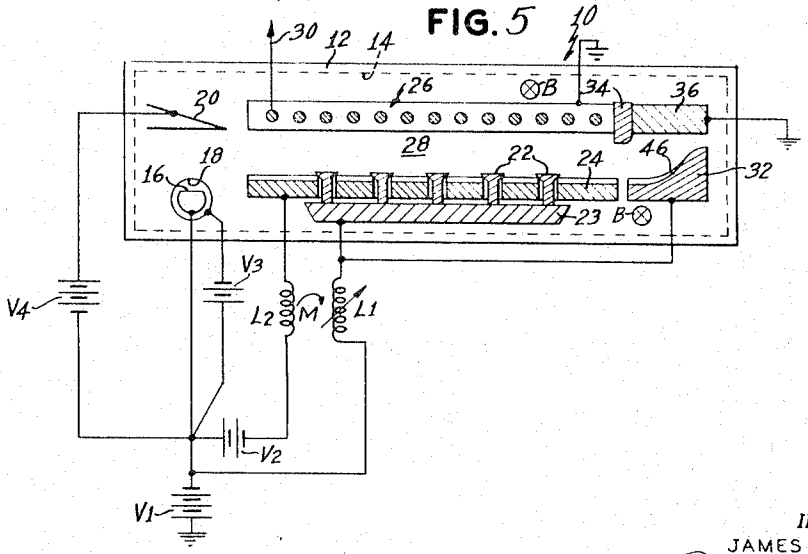


FIG. 5

INVENTOR.
JAMES E. ORR
BY Ronald W. Reagan
ATTORNEYS

Jan. 31, 1967 J. E. ORR 3,302,126

COLLECTOR ARRANGEMENT FOR COLLECTING UNFAVORABLY PHASE FOCUSED ELECTRONS

Original Filed April 5, 1962 3 Sheets-Sheet 3

FIG. 6

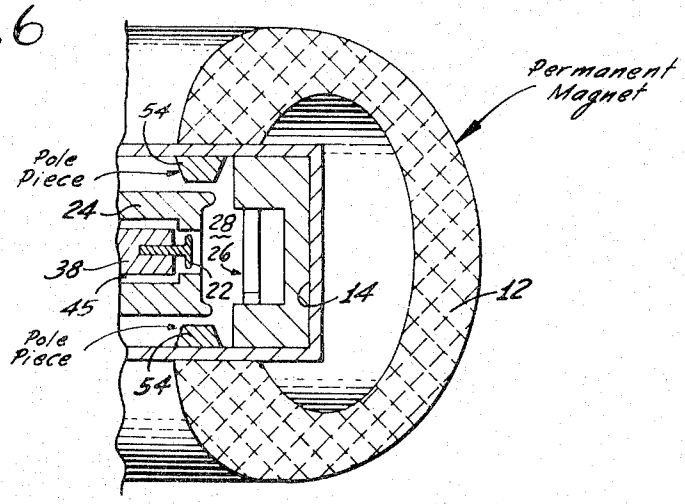
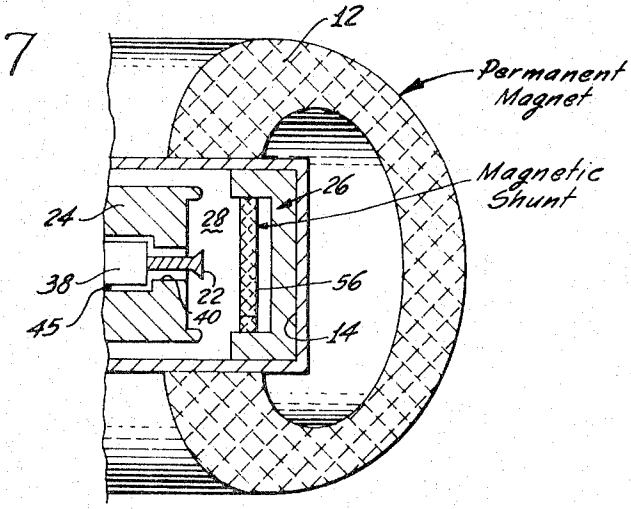


FIG. 7



INVENTOR
JAMES E. ORR

By Ronald W. Reagan

ATTORNEY

United States Patent Office 3,302,126
Patented Jan. 31, 1967

3,302,126

COLLECTOR ARRANGEMENT FOR COLLECTING UNFAVORABLY PHASE FOCUSED ELECTRONS

James E. Orr, Redwood City, Calif., assignor to Litton Precision Products, Inc., San Carlos, Calif., a corporation of Delaware

Continuation of application Ser. No. 185,270, Apr. 5, 1962. This application Nov. 8, 1963, Ser. No. 322,342
8 Claims. (Cl. 331—82)

This application is a continuation of my application Serial No. 185,270, filed April 5, 1962, now abandoned.

This invention relates to improved electron tubes, and more particularly to improved electron collection arrangements for crossed electric and magnetic field travelling wave devices, for enhancing the efficiency of operation of such devices.

Conventional microwave crossed field travelling wave tubes, such as forward wave amplifier or backward wave oscillator tubes, for example, typically include an evacuated envelope and an electron gun disposed within the envelope for producing an electron beam directed along a predetermined path, which may be circular or linear. The envelope also encloses a slow-wave structure which extends along the path of the electrons to permit interaction between the electron beam and any electromagnetic wave propagating along the slow wave structure. A sole electrode is normally positioned along the electron path concentrically with or parallel to the slow-wave structure, and a collector electrode is provided at the remote end of the interaction region for collecting the electrons of the beam and for dissipating their kinetic energy as they impinge upon the collector electrode.

As the electron beam travels through the interaction region in coupling relationship with the electromagnetic wave propagating in the slow-wave structure, energy is transferred from the beam to the electromagnetic wave. During the process of exchange of energy between electromagnetic wave and electron beam, some of the electrons strike the sole electrode and are collected. The electrons which impinge upon the sole electrode have kinetic energy which is dissipated as heat and therefore wasted. The remaining electrons are either collected on the slow-wave structure or continue along to the exit end of the interaction region where they are collected by the collector electrode. The collector electrode may be designed to provide an enlarged surface over which the electrons may be dispersed to prevent a concentrated beam of electrons from impinging upon a small surface area. Avoidance of electron concentration on the surface of the collector electrode is primarily intended to minimize or eliminate damage which could result from excessive heat produced in the collector, due to the kinetic energy of the impinging electrons. The kinetic energy of the electrons which impinge upon the collector is converted into heat and must be removed by a suitable cooling apparatus. This kinetic energy is therefore wasted without enhancing the efficiency of operation of the device.

The slow-wave structure of such devices is conventionally maintained at ground potential and the cathode in the electron gun and the sole electrode are conventionally maintained at relatively high negative voltages, thus being at relatively high potentials for a negatively charged electron. When the electron beam enters the interaction region, the individual electrons of the beam have a substantially uniform kinetic energy, which is a function of the accelerating field in the electron gun, and a potential energy which is a function of the electrostatic potential of the location in which the beam is injected into the interaction region.

As is well known to those skilled in the art, an electron in a crossed field seeks to travel at a velocity equal to

E/B where E represents the intensity of the electrostatic field and B represents the intensity of the magnetic field. In practice, the electron guns used in such devices are designed to supply electrons having as near this velocity as possible, so that a maximum number of electrons traverses the length of the interaction region when there is no interaction between the electrons and any electromagnetic wave being propagated on the slow-wave structure.

When an electromagnetic wave having a phase velocity substantially equal to the velocity of the electron beam is being propagated on the slow-wave structure, an injected electron may enter the interaction region at a time at which the electrical field component of the wave tends either to draw the electrons towards the slow-wave structure or to force the electron nearer the sole electrode. Since the slow-wave structure is being maintained at ground potential, as was previously mentioned, those electrons which are attracted to the slow-wave structure find themselves in a region of lower potential and give up a portion of their energy to the electromagnetic wave. Some electrons actually strike the slow-wave structure, thus being collected, and give up all their potential energy to the wave. The kinetic energy of these electrons is dissipated as heat in the slow-wave structure.

This energy transfer from the electron beam to the electromagnetic field may be viewed in either of two ways. In the first of these, the crossed fields may be thought to attempt to maintain the electrons at a uniform velocity, and as the electron is drawn by the wave into a region of lower potential, that portion of the potential energy of the electron greater than that of the region of lower potential into which it enters is delivered to the electromagnetic wave. In the second of these, the electron may be considered to interact with the travelling wave and deliver a portion of its kinetic energy to the wave. This results in a decrease of velocity of the electron and the slowed electron is drawn by the electrostatic field closer to the slow-wave structure, since the influence of the magnetic field on the slower electron is reduced. In so doing the electron moves into a region of lower potential and is immediately accelerated by the electrostatic field through which it has fallen back to its original velocity, but it is now in a region of lower potential. This energy transfer occurs repeatedly until the electron finally strikes the slow-wave structure or leaves the interaction region.

Conversely, those electrons which enter the interaction region in a region of an electric field which tends to force the electrons away from the slow-wave structure and towards the sole electrode are driven into an area of higher potential. These electrons must extract energy from the wave in order that they may take on a higher potential energy themselves.

Those electrons which are attracted toward the slow-wave structure, thereby delivering energy to the travelling wave, are termed favorably focused electrons, while those which are attracted to the sole electrode, thereby extracting energy from the travelling wave, are termed unfavorably focused electrons. The possibly that an electron will be a favorably focused electron is the same as that it will be an unfavorably focused electron. However, the favorably focused electrons tend to be drawn more and more into the electromagnetic wave and thus continue to deliver their potential energy to the wave, while the unfavorably focused electrons are driven away from the electromagnetic wave and tend to take less and less energy from the wave as they approach the sole electrode. There is thus a net transfer of energy from the electron beam to the electromagnetic wave and by proper choice of design parameters, such crossed field devices may be made into either amplifiers or oscillators.

To date no known apparatus has been proposed to remove the unfavorably bunched electrons from the beam as the electrons travel through the interaction space. The need for greater efficiency and increased gain in crossed field devices has led in the present invention to the development of an electron collection system for crossed field devices wherein certain electrons from the beam are collected to enhance the gain and efficiency of the tube. These improvements are, in part, due to the demands of airborne applications for higher gains and efficiencies, in order to increase the power capabilities of crossed field amplifiers and oscillators, while maintaining their small size and weight.

The present invention overcomes the foregoing enumerated and other limitations of the prior are electron collection arrangements by providing an improved electron collection arrangement which enhances the overall operational efficiency of crossed field travelling wave devices, while providing higher power and maintaining smaller size and weight. In accordance with an illustrative embodiment of the present invention, there is provided an electron collection arrangement for collecting the unfavorably phase focused portion of the electron beam as it passes through the interaction space and the remainder at the remote end of the interaction space of an electron discharge device. The collector arrangement includes a plurality of collector elements disposed in sequentially spaced relationship along the interaction space for collecting the unfavorably phase focused electrons. These plurality of collector electrodes may be projecting above or be recessed below the surface of an associated sole electrode concentric with the interaction space. A terminal collector electrode arrangement at the remote end of the interaction region collects all electrons leaving the interaction region.

More particularly, in one embodiment of the invention, the elemental collector electrodes disposed along the interaction region may be in the form of relatively small pins, each having an enlarged head, which are maintained at cathode potential. The pins are supported by independent means, since they must be electrically insulated from the sole electrode. The pins are exposed to the electron beam along its path through the interaction space. These elemental collector electrodes preferably project into the interaction region to a point which substantially corresponds to the equipotential line of cathode potential between the slow wave circuit and the sole electrode of the device.

The preselected configuration of collector electrodes depends upon the rate at which unfavorable electron bunches are formed and the ability of each collector to dissipate the heat produced by the impinging electrons. In the case of a tube which operates at a fixed electric field in the interaction space, such as a crossed field amplifier, the configuration of collectors may be coincident with cusps of resultant cycloidal electron path.

In another illustrative embodiment of the invention, the elemental collector electrodes may be recessed below the circumferential surface of the sole electrode. In this embodiment, the recessed elemental collector electrodes are disposed away from the interaction space, so as to provide a distortion in the distribution of the electric field within the interaction space in the vicinity of the elemental collector electrodes. The distortion of the electric field causes the unfavorably focused electrons to follow the equipotential lines whereby they are collected on the recessed collector electrodes at reduced velocities.

It has been determined that the novel elemental collector electrodes may project into the interaction space when the tube is operated at lower power levels, while at higher power levels it is desirable to remove them from the direct path of the electron beam in the interaction space. For example, it has been discovered that when a device is operated at X-band frequencies (8,000–12,000 mc.) and with a beam current of more than fifty (50) milliamperes,

it is advantageous to have the elemental electrodes in a recessed position to avoid their melting.

In accordance with yet another illustrative embodiment of the invention, the current developed by the collected electrons is applied to produce modulating potentials either on the grid electrode, the accelerator electrode, or the sole electrode of the tube. More specifically, the elemental collector electrodes and the terminal collector electrode are connected in series with a first inductance to form a resonant circuit which is, in turn, in series with the cathode. An internal capacitance created by the relative spacing between the elemental collector electrodes, the sole electrode and slow-wave structure, and the capacitance between the terminal collector electrode and the conventional collector electrode determine the capacitance of the resonant circuit. The first inductance, which may be either internal or external, is in series with the foregoing internal capacitance, forming a resonant combination in the cathode circuit. The frequency of oscillation of the resulting resonant circuit depends upon the capacitance resulting from the relative space relationships of the aforementioned elements of the tube and the inductance selected to be included in the circuit. A second inductance is connected in series with either the grid or sole electrode in which a modulating current is induced. Thus, the radio frequency (RF) current developed in the resonant circuit by recirculating the recovered electrons produces a current in the grid or sole circuit corresponding to the RF current to produce amplitude modulation or frequency modulation, respectively.

According to another illustrative embodiment of the invention, the magnetic field traversing the interaction space adjacent to the sole electrode and extending a predetermined distance therefrom is significantly increased in the region of the elemental collector electrodes to enable the electrons near an elemental collector electrode to be collected more readily. More particularly, a pair of pole pieces are disposed on either side of the interaction space for concentrating the path of magnetic flux lines in the region adjacent the sole electrode and the elemental collector electrodes. These pole pieces may have a cross-sectional configuration in the form of a trapezoid and be disposed about the interaction space so that the magnetic flux lines are concentrated more in the region adjacent the sole. In the foregoing manner, the magnetic field adjacent the slow-wave structure is significantly less strong than that adjacent the sole.

A reduction in the effects of the flux lines which traverse the interaction space adjacent the slow-wave circuit may also be achieved by utilizing another arrangement which includes periodically spacing magnetic shunts in the vicinity of the slow-wave structure. More specifically, the elements of the slow-wave structure may be the periodically spaced shunts. With this arrangement, the magnetic flux lines traversing the interaction space in the vicinity of the slow-wave structure where the shunts may be employed tend to flow readily through the shunts which offer a path of less reluctance than through free space in the interaction region. Consequently, the flux lines in the interaction space near the magnetic shunts are significantly less dense than they are in the corresponding region adjacent the sole electrode and the elemental collector electrode. Thus, this arrangement creates a condition which causes the defocused electrons near the sole to be attracted more readily to the elemental collector electrodes adjacent the sole electrode, where the magnetic field is strongest.

It is therefore an object of the invention to provide an electron collection arrangement for a crossed field travelling wave tube wherein the unfavorably focused electrons of the beam are removed from the beam, thereby increasing the gain of the travelling wave tube.

It will be readily appreciated that the unfavorably focused electrons, in extracting electromagnetic wave

energy from the travelling wave, reduce the gain and power output of the device and thus reduce the efficiency of the device.

It is therefore another object of the invention to provide an electron collection arrangement to increase the efficiency of a travelling wave device by recovering the unfavorably phase focused portio of the electron beam at cathode potential as the electrons travel through the interaction region and thus avoid excessive heat energy losses, and thus enhancing the efficiency of the device.

Still another object of the invention is to provide an electrode collection arrangement for a crossed field travelling wave tube wherein the electrodes are subjected to less heat from electrons impinging thereon.

Yet another object of the invention is to provide an electron collection arrangement for a crossed field travelling wave tube whereby the electron beam of the tube is amplitude-modulated by the current resulting from the collection arrangement.

An additional object of the invention is to provide an electron collection arrangement for a crossed field travelling wave tube whereby the electron beam of the tube is frequency-modulated by the current from the collector structure.

A further object of the invention is to provide an arrangement which makes the transverse magnetic field more concentrated in the vicinity of the sole electrode and the elemental collector electrodes to provide more effective electron collection.

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

In the drawings:

FIG. 1 is a schematic plan view, partly in cross-section, of a crossed field travelling wave tube having an electron collection arrangement in accordance with the present invention;

FIG. 2 is a fragmentary isometric view, partly in cross-section, of a sole electrode support member and collector electrode elements shown in FIG. 1;

FIG. 3 is a schematical diagram illustrating the manner in which the various voltage potentials are imposed upon the electron collection arrangement of the crossed field travelling wave tube of FIG. 1, in accordance with the present invention;

FIG. 4 is a schematic diagram illustrating the manner in which the crossed field travelling wave tube of FIG. 1 may be employed to provide amplitude modulation of the electron beam of the tube;

FIG. 5 is a schematic diagram illustrating the manner in which the crossed field travelling wave tube of FIG. 1 may be employed to provide frequency modulation of the electron beam of the tube by sole modulation.

FIG. 6 is a diagrammatic view, partly in cross-section, of a crossed field travelling wave tube illustrating the manner in which a pair of permanent magnetic pole pieces may be employed to concentrate the magnetic flux lines in a preselected region as they traverse the interaction space, in accordance with the present invention; and

FIG. 7 is a diagrammatic view, partly in cross-section, of a crossed field travelling wave tube illustrating the manner in which interdigital elements made of magnetic material may be employed to distort the magnetic field lines in the vicinity of the slow-wave structure, in accordance with the present invention.

With reference now to the drawings, wherein the same reference characters designate like or corresponding parts throughout the several views, there is shown in FIG. 1 a schematic plan view of a crossed field travelling wave tube, generally designated 10, which has an associated steady biasing magnetic field illustrated by one of two pole pieces of a permanent magnet designated 12. The tube shown in FIG. 1 is a backward wave oscillator tube, and the several embodiments of the invention will be described in connection with this type of tube. It should be expressly understood that the invention is not limited to backward wave oscillator tubes, but may be employed in connection with other types of crossed field travelling wave tubes, such as forward wave amplifiers.

As shown in FIG. 1, the oscillator includes a vacuum envelope 14 for housing the elements of the device, a cathode 16 and a grid electrode 18 circumjacent the cathode for producing an electron beam, an accelerator electrode 20 adjacent the cathode and grid, and forming therewith an electron gun for the oscillator. In accordance with the present invention, the tube also includes a plurality of collector electrode elements 22 supported by a support member 23 and electrically insulated from a sole electrode 24 which has one end adjacent the electron gun region and one end remote therefrom. The slow-wave structure 26 may be of any design suitable for forming an interaction space with the sole electrode and for extracting microwave energy from an electron beam, such as an interdigital delay line. The slow-wave structure or circuit is concentric with the sole electrode, forming an electron and electromagnetic wave interaction space 28 therebetween. In addition, the tube includes an output means 30, which may be of any design suitable for extracting microwave energy from the slow-wave structure and coupling it to an external load, a depressed collector electrode 32 disposed at the remote end of the sole electrode, an attenuator 34 disposed at the termination end of the slow-wave structure, and a conventional electron collector electrode 36 adjacent the attenuator in opposed space relationship with respect to the depressed collector electrode 32. Depressed collector electrode 32 is supported by insulator 48, which allows a separate electrical potential to be applied to depressed collector electrode 32.

Considering now the specific elements of the device of FIG. 1, the slow-wave structure 26 is disposed concentrically with respect to the sole electrode 24 to form an interaction space 28 therebetween. The detailed construction of the sole electrode 24, the collector electrode elements 22, and the collector electrode element support member 23 may be understood more readily by referring to FIG. 2, which is an enlarged fragmentary view of the structure shown in FIG. 1.

As shown in FIG. 2, each of the collector electrode elements 22 has a slender pin-like configuration with an enlarged flat-top head. These pin-like collector elements are connected to the support member 23 by means of rectangular elements 38 which extend radially with respect to the sole electrode. Each collector electrode element 22 passes through an aperture 40 formed in the body of the sole, and projects a preselected distance into the interaction space 28 between the sole and slow-wave structure as shown in FIG. 1. The distance to which the collector electrodes project beyond the ridged surface designated 42 of the sole 24 will be discussed in greater detail below. The sole includes a number of T-shaped plug elements 44 corresponding to the number of collector elements 22, which enable the collector elements to be readily connected to the support member 23 during the fabrication process of the tube. Both support member 23 and collector electrode elements 22 are electrically insulated from sole electrode 24 by a slight separation 45 therebetween. The assembly of support member 23 and collector electrodes 22 is fixedly positioned with respect to sole 24, which is also fixedly positioned, thereby enabling them to be held in electrically insulated, spaced relationship with one another.

As shown in FIGS. 1 and 2, there are a plurality of apertures 50 formed between sole 24 and support member

23, through which appropriate support mounting posts (not shown) pass for supporting and insulating the two members. In this manner, various potentials may be imposed upon the elements of the tube.

The electrical potentials imposed upon the various electrodes of the tube can best be described with reference to FIGS. 3, 4, and 5. As shown in the schematic diagram of FIG. 3, for purposes of simplicity, the vacuum envelope 14 is indicated by a dashed line rectangle, instead of the actually circular arrangement, while the magnet bias is indicated by a solid line rectangle and the encircled crosses designated B representing the magnetic field set up by the permanent magnet 12. The remainder of the tube is substantially as indicated in FIG. 1. The voltage imposed upon collector electrodes 22, depressed collector electrode 32 and cathode 16, designated V_1, is a variable source, while the voltages imposed upon sole 24, grid 18 and accelerator 20, designated V_2, V_3 and V_4, respectively, are fixed. This arrangement enables the potential of the cathode 16, collector electrodes 22 and depressed collector electrode 32 to be varied with respect to the slow-wave structure 26 and conventional collector 36, which are at ground potential. It should be noted at this point that either the voltage V_2 or V_3 could be made variable in lieu of V_1 to provide sole modulation for frequency modulation or to provide grid modulation for amplitude modulation, respectively.

It may be noted that the depressed collector 32 and collector electrodes 22 are at about the same negative potential, with respect to ground, as cathode 16. It can be readily seen that electrons collected by the collector elements 22 and the depressed collector 32 are recirculated directly through the cathode circuit and require no input energy from V_1 to return to the cathode 16, as is the case for electrons collected on ground potential surfaces such as slow-wave structure 26 and conventional collector electrode 36. Thus, it will be appreciated by those versed in the microwave tube art that such an arrangement will greatly enhance the efficiency of operation of the tube.

The positive terminal of cathode voltage source V_1 is connected to ground along with collector 36, attentuator 34 and slow-wave structure 26. The accelerator 20 is held at a positive potential with respect to the cathode by the voltage source V_4 and grid 18 is held at a negative potential with respect to the cathode by the voltage source V_3.

Consider now the electrical operation of the crossed field backward wave oscillator tube in which there is provided a collection arrangement having a plurality of spaced collector electrodes confronting the interaction space all of which are maintained substantially at cathode potential as taught in the present invention. Operation of this tube according to this illustrative embodiment is based upon the interaction which will occur between the electron beam and the electromagnetic energy wave propagating in the slow-wave structure in backward direction. In accordance with this feature of the invention, emphasis is placed upon the collection of electrons by the arrangement to provide enhanced efficiency through the removal of unfavorably phase focused electrons and the recovery of energy otherwise lost in the conventional prior art collection arrangements.

In operation, cathode 16 is activated to provide a source of electrons which are drawn therefrom under the influence of the positive potential V_4 applied to the accelerator electrode 20. As the electrons leave cathode 16 under the influence of both electric and magnetic fields in the gun region, they follow a cycloidal path. At the peak of the cycloid the electrons are injected into the interaction space 28 between the sole 24 and slow-wave structure 26. As the electrons traverse the length of the interaction space 28 in tight coupling relationship with the electromagnetic wave propagating in the slow-wave interdigital structure 26, many of the electrons of the beam become favorably phase focused, while many others become unfavorably focused. As was previously mentioned, the electrons which tend to give up energy to the electromagnetic wave are said to be favorably focused and move closer and closer to the slow-wave structure, giving up more and more energy until they are collected on the slow-wave structure or leave the interaction region, while the unfavorably focused electrons take energy from the electromagnetic wave and move away from the slow-wave structure toward the sole electrode in a manner well known in the prior art.

As the unfavorably focused electrons approach sole 24, the majority of them is collected by the collector electrodes 22 which are disposed along the interaction space at positions where bunches of unfavorably phase focused electrons approach the sole electrode. A few of the electrons do reach the sole, but only an insignificant number. The remaining electrons which have been collected neither by slow-wave structure 26, nor sole 24 nor collector electrodes 22 pass from the interaction space 28 into the collector region between the opposing depressed collector electrode 32 and conventional collector 36, and are collected therein. Details of the electron collection process in such a depressed collector arrangement are described in my co-pending application Serial No. 322,330, filed November 8, 1963, also a continuation of my aforesaid application Serial No. 185,270, filed April 5, 1962.

Consider now the advantages which are derived through the use of the novel arrangement of electron collection electrodes in accordance with the teachings of the invention as far as described hereinabove. From an electrical point of view, the electrons which impinge upon the collectors of the arrangement provide a source of energy that is fed back into the tube system to increase the overall efficiency thereof. Next, the removal of the unfavorably focused electrons from the electron beam significantly reduces or eliminates the amount of energy taken by the unfavorably focused electrons from the electromagnetic wave propagating in the slow-wave structure, thereby increasing the magnitude of the electromagnetic wave available for interaction with the favorably focused electrons. The availability of stronger electromagnetic fields, in turn, increases the gain, and thus the efficiency of tubes employing the arrangement taught by the invention. In practice, it has been found that the efficiency of backward wave oscillator tubes may be increased more than twenty-five percent, and it can be demonstrated that the gain of forward wave amplifiers may be increased by more than 5 db.

Another advantage rises from the removal of the unfavorably focused electrons. It is well known by those versed in the travelling wave tube art that unfavorably focused electrons have random motions and velocities, and this, in general, accounts for the major microwave noise generated by a tube. Thus, the present method of removing these unfavorably focused electrons substantially reduces or eliminates the microwave noise of the tube normally produced by random motion of the electrons.

Other embodiments of the invention are shown in FIGS. 4 and 5. As shown in FIG. 4, an external inductance coil L_1 is connected in series with the collector electrodes 22 and depressed collector electrode 32 to provide a series resonance circuit. A second external inductance coil L_2 is connected in series with the grid electrode 18 and voltage source V_2 and is coupled to L_1 for mutual induction. As electrons are recovered by collector electrodes 22 and depressed collector electrode 32, the voltage oscillations produced by them are fed back into the cathode circuit.

The frequency at which the grid electrode 18 is modulated to provide amplitude modulation of the electron beam is determined by the frequency of oscillation in the resonant circuit consisting of the external inductance coil L_1 and the internal capacitance of the tube which exists between the elements of the collection arrangement, at one side, and both the sole electrode 24 and the slow-wave structure 26 at the other side. As shown in FIG. 4,

coil L_1 may be a variable inductance so that the frequency of oscillation of the series resonant circuit may be varied.

Referring now to FIG. 5, there is shown another embodiment of the invention. The circuit arrangement shown in FIG. 5 is different from that shown in FIG. 4 in that the inductance coil L_2 is connected in series with the sole electrode **24** and voltage source V_2. With this arrangement, the current induced in coil L_2 from coil L_1 tends to modulate the sole electrode **24** thereby to produce frequency modulation of the electron beam.

The foregoing unique circuit arrangement, wherein the crossed field traveling wave tube is utilized, provides several advantages over those of the prior art. The first advantage arises from the fact that the tube can be made self-oscillatory with the use of extremely simple and inexpensive components, such as inductance coils L_1 and L_2. Thus, there is provided a device which may be readily adapted to provide frequency or amplitude modulation, thereby eliminating the need for the conventional prior art modulation system. The prior art systems have the disadvantage of being relatively expensive, complicated and cumbersome.

In addition to the foregoing advantage, the arrangement for frequency modulation shown in FIG. 5 also has the capability of generating noise within the tube at very high frequency modulation rates. In certain airborne applications, it is extremely desirable to have travelling wave tubes with the capabilities of the present invention, to avoid the size and weight often associated with prior art airborne equipments.

It has been found that the basic concepts herein set forth may be employed in a crossed field travelling wave tube to provide the advantages discussed hereinabove. For example, it has been found that a backward wave oscillator tube having the advantages set forth may be realized from a tube in which the slow-wave structure is spaced from the sole by about 0.117 inch, and the spacing between the slow-wave structure and the collector electrode elements is in the range of 0.033 to 0.045 inch. In addition, the spacing between the conventional collector electrode **36** and the depressed electrode **32** is tapered, the greatest separation adjacent the interaction space being about 0.254 inch and the smallest separation remote from the interaction space being about 0.020 inch. The spacing between the collector electrodes **22** and the sole electrode **24** or the slow-wave structure **26** will be determined by the value of the capacitance desired in each case.

Further enhancement of the electron collection process may be achieved through the use of a modified steady biasing magnetic field as shown in FIG. 6. In FIG. 6, there is shown a permanent magnet **12** to provide a steady biasing magnetic field producing magnetic flux lines which traverse the interaction space **28**, perpendicular to the path of the electron beam. A plurality of pole pieces **54** are disposed in opposed spaced relationship on either side of the interaction space **28** adjacent the collector electrodes **22**. The opposed faces of the pole pieces **54** may be circular, square or rectangular, for specific examples. As shown, pole pieces **54** may have a trapezoidal cross section which tends to concentrate the magnetic flux lines in the vicinity of the sole electrode **24** at the elemental collector electrodes **22**. In this manner, the magnetic flux in the vicinity of the electrodes **22** is significantly greater than it is in the vicinity of the slow-wave structure.

There is also shown in FIG. 6 the arrangement whereby the surfaces of collector electrodes **22** are positioned beneath the surface of sole electrode **24**. Thus, the electric field intensity in the localized regions around collector electrodes **22** is substantially less than the electric field intensity in other portions of the interaction region, since the spacing between collector electrodes **22** and slow-wave structure **26** is greater than that between sole electrode **24** and slow-wave structure **26** and the potential difference between collector electrodes **22** and slow-wave structure **26** is less than that between sole electrode **24** and slow-wave structure **26**. This reduction in electric field intensity and the previously described increase in magnetic field intensity in this region results in a substantially lower E/B ratio. As is well known to those skilled in the art, the velocity of an electron in a crossed field seeks to become E/B, and thus the electrons collected on collector electrodes **22** are collected at a reduced velocity, and thus a reduced kinetic energy.

Also, the localized increase in magnetic field intensity deflects unfavorably focused electrons downward into the collector electrodes **22** even though the unfavorably focused electrons may not yet have reached this level in the other portions of the interaction region.

It is again noted that the collector electrodes **22** in FIG. 6 are positioned beneath the surface of sole electrode **24**, whereas in the other shown embodiments the electrodes **22** are projected into the interaction region **28**. If no disturbance in the electric field intensity in this region is desired, the collector electrodes **22** may project into the interaction region **28** a sufficient distance such that their surface falls along the equipotential line of cathode potential. However, in higher powered devices, it is desirable to lower the surface of the collector electrodes **22**, sometimes even to the extent shown in FIG. 6, such that these surfaces are positioned beneath the surface of sole electrode **24**. This not only decreased the electric field intensity in these regions, thereby providing for collection at lower electron velocity, but also removes the edges of collector electrodes **22** from the direct path of the electron beam which in a high-powered device may melt the collector electrons **22**.

A modification of the distribution of the magnetic flux in the interaction space may be accomplished in a manner different from that discussed in connection with FIG. 6. With reference to FIG. 7, there is shown a diagrammatic view, partly in cross-section, of a portion of a crossed field travelling wave tube in accordance with another embodiment of the present invention. In this embodiment of the invention, the slow-wave structure **26** has one or more interdigital elements **56** which are of a magnetic material, such as high purity iron, for example, disposed in preselected positions along the slow-wave structure. As shown in the drawing, these interdigital elements are disposed opposite the collector electrodes **22** and tend to significantly reduce the concentration of magnetic flux lines in the vicinity of the slow-wave structure.

In the embodiment of FIG. 7, the magnetic material of which the interdigital elements are made provides a shunting path for the magnetic flux line. Thus, the magnetic flux lines which normally traverse the interaction space parallel to the interdigital elements of the slow-wave structure are distorted in the region adjacent the slow-wave structure such that they are bent closer to the interdigital elements **56**.

In each of the embodiments of FIGS. 6 and 7, a localized magnetic field gradient adjacent the collector electrodes **22** is produced, with a strong magnetic field near the collector electrodes **22** and weaker magnetic fields elsewhere. Defocused electrons, near the collector electrodes, are therefore subjected to a relatively strong magnetic field and are directed toward the collector electrodes. The total magnetic field to which properly focused electrons are subjected, however, is somewhat weaker, and they are held in their proper trajectories adjacent the slow-wave structure.

While the crossed field travelling wave tube of the invention has been described with reference to only one particular configuration of collector electrode elements **22**, it will be understood that various modifications could be made in the construction and configuration thereof without departing from the spirit and scope of the invention. Thus, by way of example, but not of limitation, the collector electrode elements **22** could have a T-

shaped or an inverted U-shaped configuration. In particular, the cross bar section of the T or the section of the U connecting the two parallel legs thereof could project into the interaction space in the same manner as the enlarged flat round heads of the elements 22 shown in the drawing. Furthermore, each collector electrode may have a different spacing with respect to the slow-wave structure and the sole electrode. In some instances, successive collector electrodes may be spaced closer to the slow-wave structure than the preceding electrode. In addition to the mechanical modifications which may be made, it is possible to amplitude modulate the tube of FIG. 4 by connecting an inductance in series with the accelerator voltage V_4 in a manner similar to that discussed in connection with FIGS. 5 and 6. Accordingly, it is to be understood that the foregoing description shall be interpreted only as illustrative of the invention, and that the appended claims be accorded as broad interpretation as is consistent with the basic concepts herein taught.

What is claimed as new is:

1. In a crossed field travelling wave electron discharge device, a slow-wave structure, a sole electrode disposed adjacent said slow-wave structure and spaced therefrom to form an interaction space therebetween, means including a cathode for producing and directing an electron beam along said interaction space, means for providing a magnetic field transverse to the path of the beam along said interaction space, a plurality of collector electrodes disposed along said interaction space and projecting through said sole electrode to remove unfavorably focused electrons and to recover energy from said electrons, and means for maintaining said collector electrodes at a potential substantially equal to that of said cathode, whereby the gain and efficiency of said electron discharge device is increased.

2. A crossed field travelling wave electron discharge device, comprising means including a cathode for producing and directing a beam of electrons through an interaction space, a slow-wave structure disposed about said electron beam, a sole electrode disposed co-extensively with said slow-wave structure and spaced therefrom to form said interaction space therebetween, means for providing a magnetic field with flux lines threading transverse to the path of the beam along the length of said interaction space, an electron collector arrangement comprising a plurality of collector electrodes supported by a support member and electrically insulated from said sole electrode in sequentially spaced relationship along said interaction space to project from said sole into said interaction space toward said slow-wave structure to permit the removal of unfavorably focused electrons from said beam, each of said collector electrodes being spaced substantially the same distance from said slow-wave structure, a terminal collector electrode having a curved surface disposed at the end of said interaction space remote from said cathode and oriented along the path of said electron beam, and means for maintaining said terminal collector electrode and said plurality of collector electrodes at a potential substantially that of said cathode to enhance the efficiency of the device.

3. In combination, a travelling wave electron discharge device including a slow-wave structure, a sole electrode extending generally parallel to and spaced from said slow-wave structure and forming an interaction space therebetween, an electron gun including a cathode, a grid electrode and an accelerator electrode for producing and directing an electron beam between the sole and slow-wave structure, a plurality of collector electrodes extending into said interaction space to recover electrons from said electron beam, means for maintaining said collector electrodes at a potential substantially equal to that of said cathode, and means including a resonant circuit element in series with said cathode and said collector arrangement for producing radio frequency current from the recirculation of the electrons recovered from said beam, and for modulating said electron beam at said radio frequency.

4. In combination, a travelling wave electron discharge device including a slow-wave structure, a sole electrode extending generally parallel to and spaced from said slow-wave structure and forming an interaction space therebetween, means including a cathode and a grid electrode for producing and directing an electron beam between said sole electrode and said slow-wave structure, an electron collector arrangement including a plurality of electrodes extending into said interaction space and a terminal collector electrode disposed at one end of said interaction space to recover said electrons from said electron beam, means for maintaining said collector arrangement at a potential substantially that of said cathode, means including a resonant circuit element in series with said cathode and said collector arrangement for producing radio frequency current from the recirculation of the electrons recovered from said beam, and means for coupling said radio frequency current to said grid electrode to produce amplitude modulation of said electron beam.

5. In combination, a travelling wave electron discharge device including a slow wave structure, a sole electrode extending generally parallel to and spaced from said slow wave structure and forming an interaction space therebetween, means including a cathode and a grid electrode for producing and directing an electron beam between said sole electrode and said slow-wave structure, an electron collector arrangement including a plurality of electrodes extending into said interaction space and a terminal collector electrode disposed at one end of said interaction space to recover electrons from said electron beam, means for maintaining said collector arrangement at a potential substantially that of said cathode, means including a resonant circuit element in series with said cathode and said collector arrangement for producing radio frequency current from the recirculation of the electrons recovered from said beam, and means for coupling said radio frequency current to the sole electrode to produce frequency modulation of said electron beam.

6. In a crossed field travelling wave electron discharge device, a slow-wave structure, means including a cathode for producing and directing an electron beam along said slow-wave structure, means for providing a magnetic field with flux lines threading transverse to the path of the electron beam, said means including a plurality of pole pieces disposed in opposed spaced relationship on either side of said electron beam at preselected points thereof, a plurality of collector electrodes disposed along said electron beam to remove unfavorably focused electrons and to recover energy from said electrons, and means for maintaining said collector electrodes at a potential substantially equal to that of said cathode, whereby the gain and efficiency of said electron discharge device is increased.

7. In a crossed field travelling wave electron discharge device, a slow-wave structure, a sole electrode disposed coextensive with said slow-wave structure and spaced therefrom forming an interaction space therebetween, means for establishing an electric field having an intensity E in said interaction space, means including a cathode for producing and directing a beam of electrons through the interaction space, a plurality of collector electrodes disposed along said interaction space in a preselected space relationship with one another, means for providing a magnetic field having an intensity B with flux lines threading transverse to the path of the beam along the length of said interaction space, and means to decrease the ratio E/B adjacent said collector electrodes to thereby increase the forces which cause the electrons to be collected on said collector electrodes and decrease the velocity at which the electrons impinge upon said collector electrodes.

8. In a crossed field travelling wave electron discharge

device, an interdigital slow-wave structure including a plurality of interdigital elements for introducing a delay in an electromagnetic wave propagating in said structure, means for producing a magnetic shunting path at periodically spaced points along said slow-wave structure, said means including at least some of said interdigital elements being made of a magnetic material disposed at each of said periodically spaced points, means for providing a magnetic field with flux lines threading transverse to the path of the beam along said interaction space, a plurality of collector electrodes disposed along said interaction space and recessed therefrom to remove unfavorably focused electrons and to recover energy from said electrons, and means for maintaining said collector electrodes at a potential substantially equal to that of said cathode, whereby the gain and efficiency of said electron discharge device is increased.

References Cited by the Examiner

UNITED STATES PATENTS

2,687,777	8/1954	Warnecke et al.	315—3.6 X
2,702,370	2/1955	Lerbs	332—13
2,844,797	7/1958	Dench	332—25
2,976,455	3/1961	Birdsall et al.	315—393 X
3,073,991	1/1963	Osepchuk	315—39.3
3,098,979	7/1963	Ashley et al.	332—58 X

OTHER REFERENCES

IBM Technical Disclosure Bulletin, vol. 3, No. 10, March 1961, Communication with Broad-Band Microwave Oscillator, by Rumble.

HERMAN KARL SAALBACH, *Primary Examiner.*

S. CHATMON, JR., *Assistant Examiner.*