Aug. 24, 1954 C. E. RICH ET AL 2,687,490

HIGH-FREQUENCY BEAM TUBE DEVICE

Filed Sept. 22, 1949

4 Sheets-Sheet 1

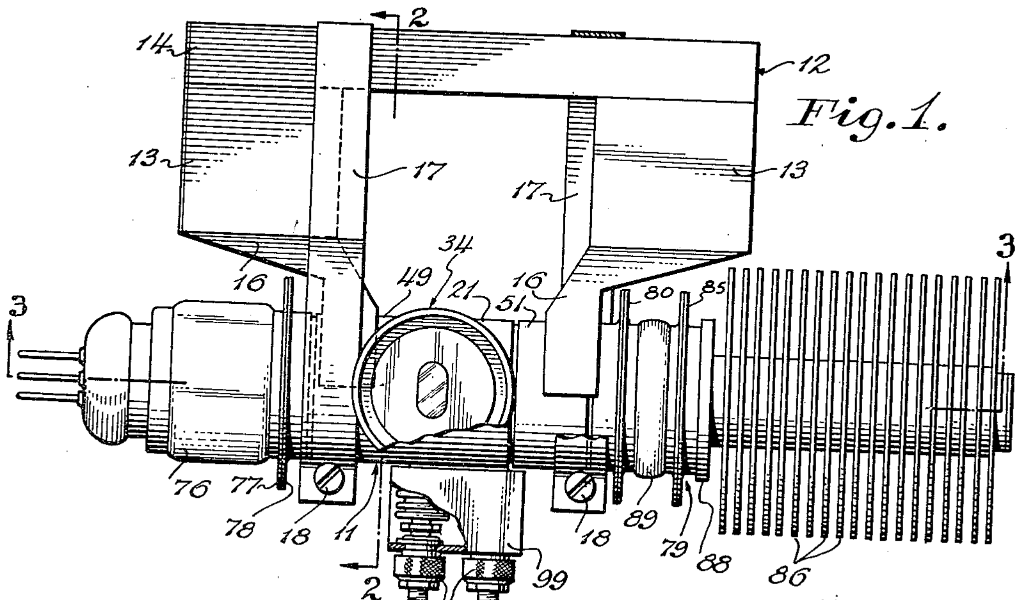


Fig. 1.

Fig. 4.

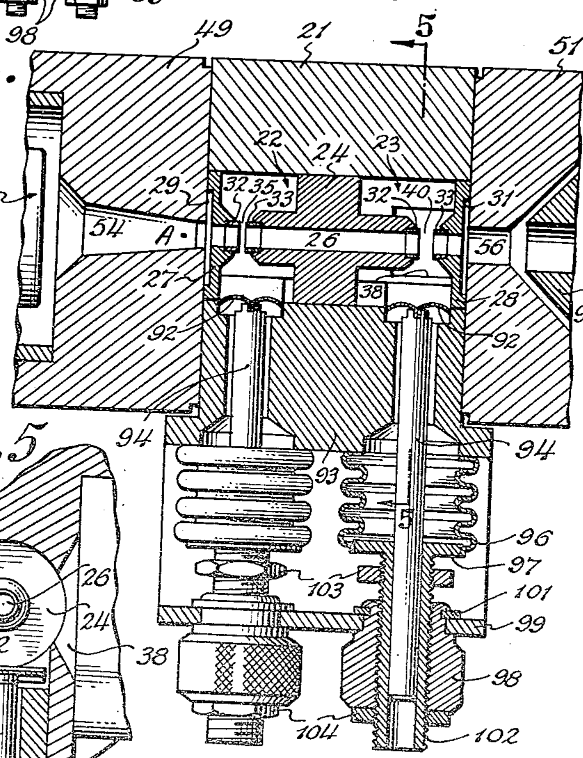


Fig. 2.

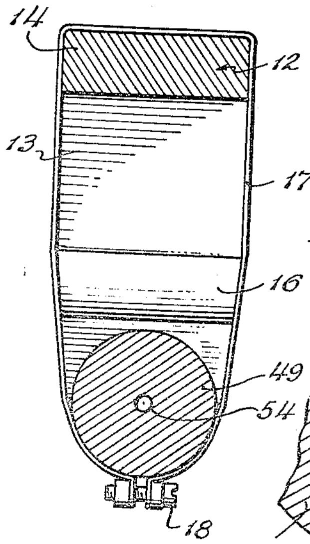
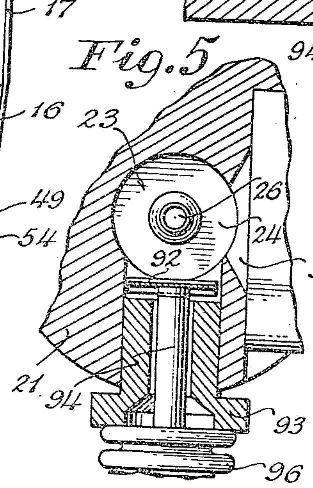


Fig. 5



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HIGH-FREQUENCY BEAM TUBE DEVICE

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4 Sheets-Sheet 2

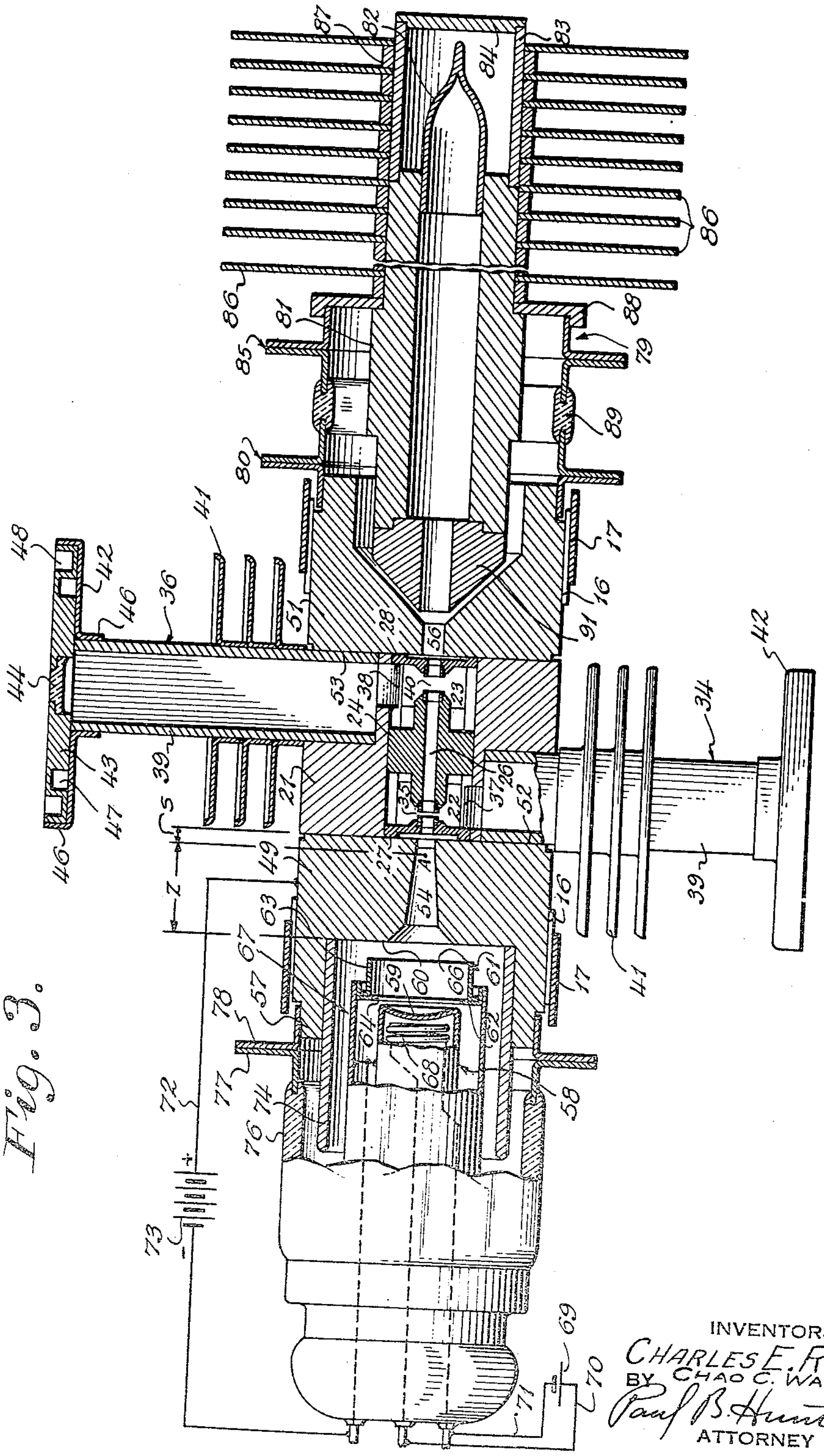

Fig. 3.

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HIGH-FREQUENCY BEAM TUBE DEVICE

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Fig. 6.

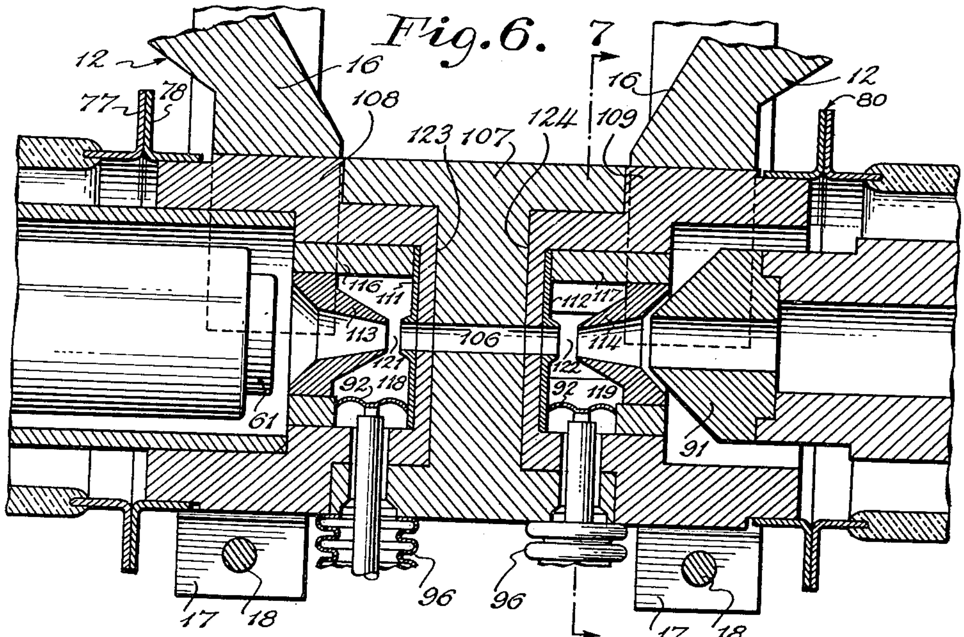
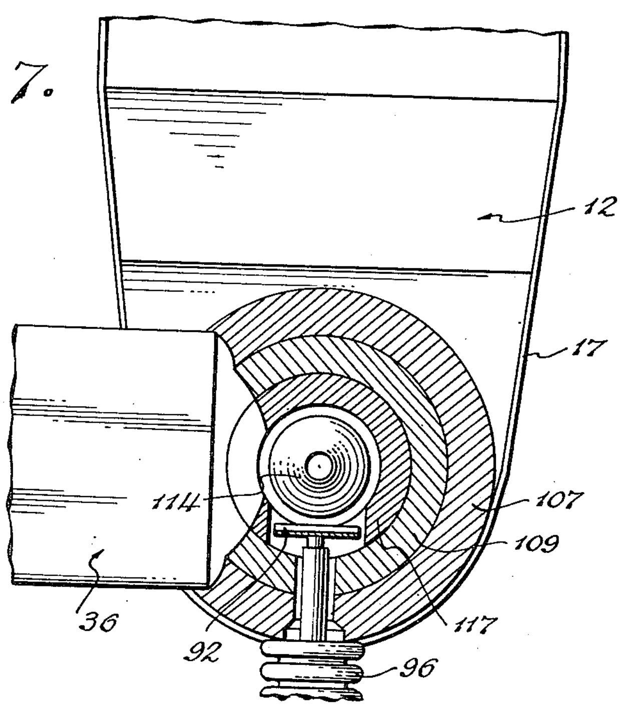


Fig. 7.



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HIGH-FREQUENCY BEAM TUBE DEVICE

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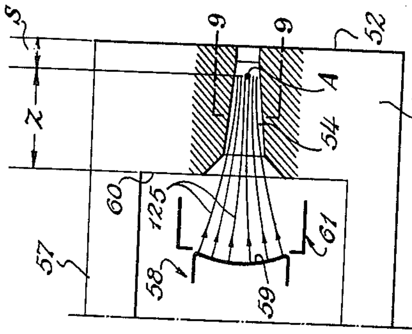

Fig. 8.

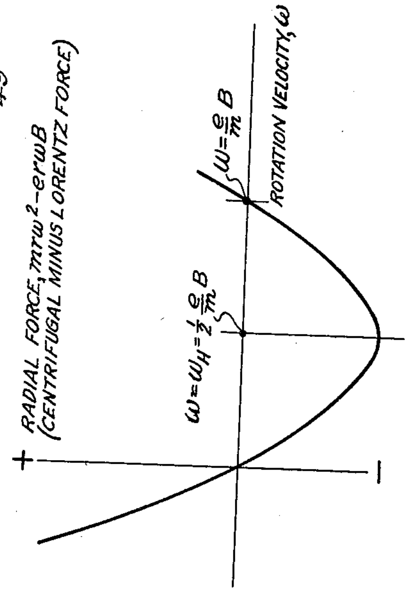

Fig. 10.

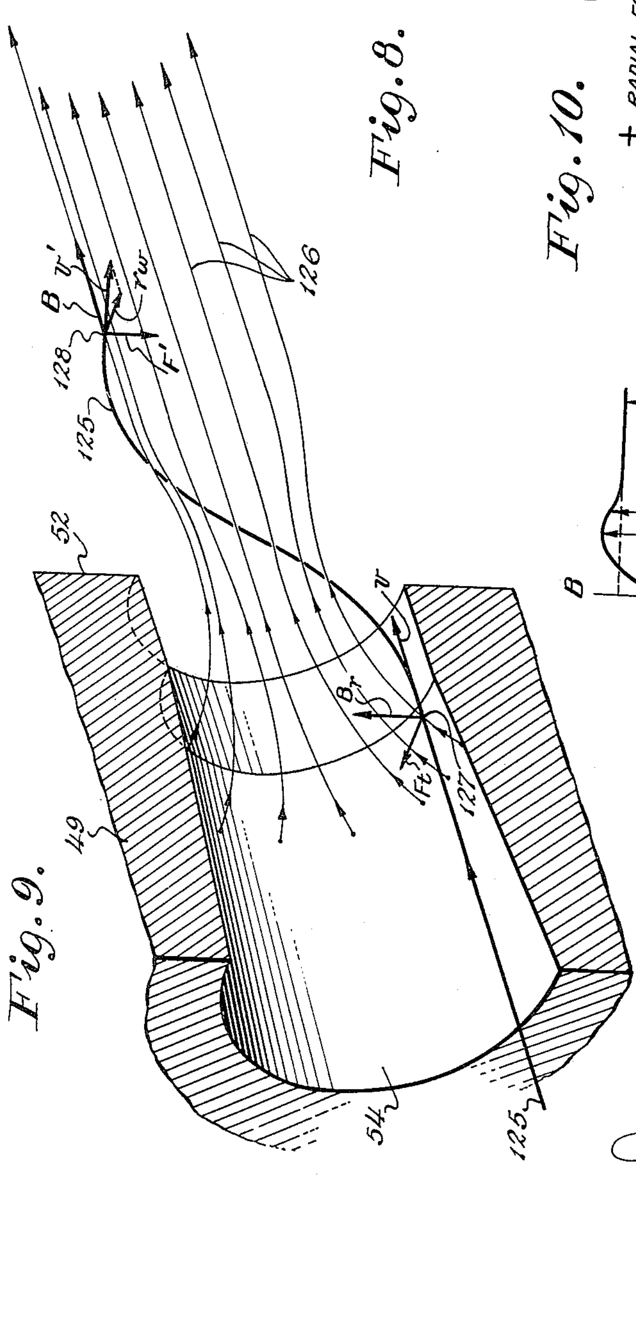

Fig. 9.

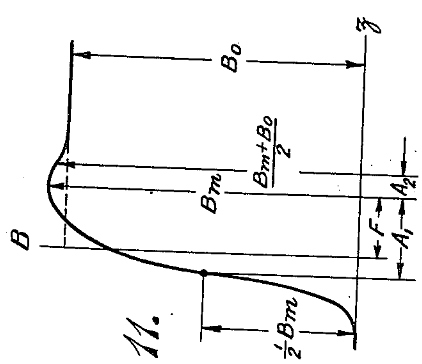

Fig. 11.

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UNITED STATES PATENT OFFICE

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HIGH-FREQUENCY BEAM TUBE DEVICE

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Application September 22, 1949, Serial No. 117,187

12 Claims. (Cl. 315—6)

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This invention relates to electron discharge devices and more particularly, to the use of magnetic focusing in such devices.

For certain types of electron tubes, it is desirable to provide an electron beam with a small diameter for a considerable length. It is not very difficult to accomplish this result where the electron beam density involved is not large, such as in the case of a cathode ray tube or electron microscope, in which the repulsion forces between electrons are negligible. The electron optics employed in such electron discharge devices are based on a consideration of the trajectories of individual electrons without taking into account the presence of the other electrons. Usually, in such devices electrostatic means of control are sufficient to confine the electron beam to desired paths.

In order to provide a high-powered velocity modulation device it is necessary to employ a relatively large electron beam current. At the same time, the electron beam must have a relatively small diameter to obtain suitable beam-field interaction to yield satisfactory efficiency and gain. In such tubes, the electron beams are generally confined within a unipotential cylinder or hollow conductor so that no electrostatic field can be employed to counteract space charge repulsion. According to the present invention, in order to overcome the tendency for the electron beam to diffuse an axially-directed magnetic field is provided.

Some attempts have been made in velocity modulation devices, such as klystrons, to employ the principle that an electron beam tends to follow magnetic lines of force. Such resulting devices are frequently equipped with a coil surrounding the drift space to prevent the electron beam impinging upon the drift tube walls. Other such devices include coils arranged around the resonators to cause the electron beam to converge at a focal point in the vicinity of the resonator gaps. In such arrangements crossover of the electrons is a typical occurrence, giving rise to undesirable electron trajectories. Where the electrons are made to converge toward the resonator gaps, the drift tube is customarily formed with an extremely tapered configuration. Such drift tube shapes are not consistent with optimum klystron tube operation.

Other arrangements for controlling electron trajectories in klystron devices include the provision of a magnetic field of suitable configuration extending from behind the cathode to beyond the output resonator gap. With high-powered

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operation involving an extremely high-density electron beam it is advisable to employ an electron-emitting surface having an area greatly in excess of the ultimate cross-sectional area of the electron beam. Consequently, the electrons emanating from the cathode surface must be made to converge. If magnetic lines of force are used to obtain the desired paths for the electrons throughout their entire transit in the device, the magnetic means become complicated and bulky. Moreover, in an exceedingly high-powered device the strength of the required magnetic field to achieve the desired electron trajectories becomes prohibitive.

If the advantages associated with a high-density electron beam are to be realized, it is advisable to eliminate the use of grids whenever possible. With the removal of grids the loss of beam current through direct interception thereby and the dissipation of heat developed from such interception is eliminated.

According to the present invention a gridless extremely high-power tube structure is provided wherein an axially-directed magnetic field extends through the drift tube and consequently confines electrons in those regions to a beam having a cylindrical envelope of substantially uniform cross section along the tube axis. Moreover, the pole pieces associated with the magnetic circuit are included as integral parts of the tube structure and also serve to define a portion of the vacuum envelope of the tube structure.

To suitably shape the electron beam prior to its entrance into the magnetic field electrostatic focusing means are provided. In application 81,480 entitled "Charged Particle Beam Forming Apparatus" in the name of Chao Wang, filed March 15, 1949, now Patent No. 2,564,743, a non-magnetic focusing arrangement is described similar to that shown herein and suitable for forming a beam configuration for cooperation with the magnetic means of the instant invention.

While the structure of the instant invention has been employed satisfactorily for continuous wave operation, it has been found particularly suitable for pulsed operation at an operating frequency of the order of 10,000 megacycles per second yielding a peak power output well in excess of 5 kilowatts. In the case of pulsed operation, using pulses of the order of .5 microsecond, ion focusing is not available to assist in shaping the beam. Moreover, the loss of beam current by direct interception militates against the use of grids to an extent even greater than in the case of continuous wave operation. In all high-powered operation, and particularly in producing high-powered oscillatory pulses, the problem of the dissipation of heat becomes exceedingly important. This is particularly the case in providing oscillations of high amplitude having a wavelength of the order of 3 cm. which necessarily involves physically small tube parts owing to frequency considerations.

An object of the present invention is to provide an improved high frequency electron discharge device with magnetic focusing.

A further object lies in the provision of an improved electron beam producing means utilizing electrostatic and magnetic controls.

A still further object is to provide an ultra-high-frequency velocity modulation electron discharge device capable of delivering exceedingly large magnitudes of power.

Another object lies in the provision of magnetic focusing in a velocity modulation device with the pole pieces of a magnetic circuit constituting integral parts of the device.

A still further object is to provide a compact, rugged and high-powered electron tube employing magnetic focusing.

Another object is to provide a high-power ultra-high-frequency electron tube suitable for pulsed operation.

Other objects and advantages will become apparent from the specification, taken in connection with the accompanying drawings, wherein the invention is embodied in concrete form.

In the drawings,

Fig. 1 is a view, partially in cross-section, of an electron discharge device of the present invention;

Fig. 2 is a view, partially in cross-section, taken along line 2—2 of Fig. 1;

Fig. 3 is a view, mainly in cross-section, taken along line 3—3 of Fig. 1;

Fig. 4 is a cross-sectional view of a part of Fig. 1, particularly useful for showing the novel frequency controlling arrangement;

Fig. 5 is a view, partially in cross-section, taken along line 5—5 of Fig. 4;

Fig. 6 is a view, mainly in cross-section, of a modification of a part of the device of Fig. 1;

Fig. 7 is a view, mainly in cross-section, taken along line 7—7 of Fig. 6;

Fig. 8 is a partially schematic view of the electron gun structure of the device shown in Fig. 3, and illustrates the trajectories of a few of the electrons of the electrostatically focused portion of the electron beam between the cathode 58 and the point A in hole piece 49;

Fig. 9 is an enlarged perspective view of a portion of the pole piece 49 shown in Figs. 3 and 8, taken along line 9—9 of Fig. 8 and shows the path followed by an electron therein and beyond the pole piece 49 under the influence of the beam-controlling magnetic field, space charge repulsion, and centrifugal forces;

Fig. 10 is a graph showing the relationship between the radial forces and the rotational velocity of an electron in a magnetic field; and

Fig. 11 is a typical plot of the magnetic field strength as a function of axial position in the vicinity of a magnetic pole piece such as 49 in the tube of Fig. 3.

Similar characters of reference are employed in all of the above figures to indicate corresponding parts.

Referring to Figs. 1 and 2, an evacuated electron discharge device or tube 11 is provided with an external magnetic circuit, such as permanent magnet 12 suitably positioned relative to the tube 11 for providing a magnetic field extending parallel to the longitudinal axis of the tube 11 throughout the central region of the tube 11. The magnet 12 is constituted of blocks 13 of highly magnetic material, such as Alnico V, a steel bar 14, and steel cradles 16. Cradles 16 are formed to cooperate with the exterior walls of tube 11 and partially surround magnetic pole pieces which are included as integral parts of the tube 11. Metallic straps 17 extend around the blocks 13, bar 14, cradles 16 and tube 11 and are each joined by means of a screw 18. The parts constituting tube 11 may be more readily described in connection with Fig. 3. While separate parts have been employed to form the external permanent magnet 12 for convenience in fabrication, it is of course understood that a single structure composed of highly magnetic material might be employed. This would have the advantage of a more compact external magnet structure.

Referring to Fig. 3, a metallic block 21, suitably apertured, serves to define a portion of the wall surfaces of two electromagnetic field defining means, such as cavity resonators 22, 23. Supported by the block 21 is a hollow tubular member 24, the ends of which also serve to define a portion of the wall surface of the cavity resonators 22, 23. The surface of the aperture of tubular member 24 forms the wall of a drift tube or drift space 26. Apertured discs 27, 28 are arranged at opposite ends of the tubular member 24 and spaced therefrom to provide end walls for the resonant cavities 22, 23, respectively. The shape of the discs 27, 28 and the ends of tubular member 24 is such as to provide each of the resonators 22, 23 with a doubly-reentrant configuration. Annular slots 29, 31 (see Fig. 4) are provided adjacent the resonators 22, 23, respectively, to permit the discs 27, 28 to be suitably bowed, thereby facilitating the pretuning of the resonators 22, 23. The block 21, tubular member 24 and discs 27, 28 are preferably made of copper or a copper-plated material to provide highly conductive wall surfaces for the resonators 22, 23.

Gap defining means, such as thin walled sleeves 32, 33, are concentric about the longitudinal axis of the tube 11. The sleeves 32, 33 are preferably made of a material having a high melting point and readily machinable, such as molybdenum. The sleeves may be seen more clearly in Fig. 4. By providing the sleeves 32, 33 with a thin wall, for instance of the order of 0.005 inch, a relatively small surface area is presented by the ends of the sleeves 32, 33 to electrons which may impinge thereon, thus minimizing secondary electron emission.

Coupling means 34, 36 are employed for introducing electromagnetic energy into the cavity resonator 22 and coupling energy from the cavity resonator 23, respectively. Windows 37, 38 are provided in the block 21 of suitable dimensions to effect an impedance match between the resonators 22, 23 and the coupling means 34, 36, respectively. Each of the coupling means 34, 36 are shown formed of a rectangular cross-section wave guide 39 provided with cooling fins 41 and an end flange 42 suitable for supporting the window frame 43, which in turn contains the glass window 44. Inasmuch as the vacuum envelope of the tube 11 is constituted in part of the glass window 44, the frame 43, and the end flange 42, these parts are joined in vacuum-tight connections.

For instance, along the lip 46 of the end flange 42 an atomic hydrogen weld may be employed to join the lip 46 of the end flange 42 to the window frame 43. In order to thermally isolate the glass window 44 from heat developed during such welding or other joining operations, the outer portion of the frame 43 is formed with annular slots 47, 43 to provide a relatively long heat flow path. In addition, the configuration of the outer portion of the frame 43 serves to mechanically isolate the glass window 44 from jarring of the outer portions of the end flange 42 and frame 43.

Located on either side of the resonators 22, 23 are magnetic means, such as pole pieces 49, 51, respectively, made preferably of soft iron. It has been found advisable to provide the pole pieces 49, 51 with substantially planar pole faces 52, 53, respectively. The pole faces 52, 53 are preferably disposed substantially at right angles to the longitudinal axis of the tube 11 in order to obtain a more uniform magnetic field. By tapering the pole pieces 49, 51, such as providing the pole faces 52, 53 with a frusto-conical configuration, it is possible to minimize stray or leakage fluxes. However, unless extreme care is used in thus shaping the pole pieces 49, 51, a non-uniform magnetic field may result. The pole pieces 49, 51 are formed with aligned apertures 54, 56, respectively, through which an electron beam may pass. For shielding purposes pole piece 49 is provided with an outer annular extension 57. Pole pieces 49, 51 serve to provide an axially-directed magnetic field with magnetic lines of force extending through the gaps 35, 40 of the resonators 22, 23, respectively, which are defined by the sleeves 32, 33, as well as through the drift tube 26 when the pole pieces 49, 51 are suitably energized by an external magnetic source, i. e. by the permanent magnet 12 above described.

By applying a positive potential to the pole piece 49 relative to the cathode 58, electrons may be accelerated. Thus, an anode is provided by the pole piece 49 with an anode plane 60 formed by the surface of the pole piece 49 adjacent the cathode 58 and arranged at right angles to the axis of the tube 11. As discussed above, the pole pieces 49, 51 may be tapered. Under such conditions, the inner portion of the pole piece 49 adjacent the aperture 54 may be formed with a frusto-conical shape.

Cathode 58 is similar to that disclosed in Patent No. 2,564,743, referred to hereinabove. The cathode 58 is provided with an electron-emitting surface 59, which is spherically-concave about the longitudinal axis of the tube 11. In order to provide rectilinear motion of electrons emanating from the surface 59, field forming means, such as focusing electrode 61, is arranged around the path of the electron beam. The electrode 61 is formed of a disc 62 and a cylinder 63 which are supported by support 67. The disc 62 is centrally-apertured to provide a first line conductor or edge 64 spaced from the surface 59 and of greater diameter than the surface 59. The end of cylinder 63 most remote from the surface 59 provides a second line conductor or edge 66, which has a diameter greater than that of edge 64 and is positioned at a greater distance from the surface 59 than the first edge 64. When the surface 59 is suitably energized by the heater 68 which is connected to battery 69 by means of leads 70, 71, electrons emanate from the cathode. By applying a positive potential to the pole piece 49 relative to the cathode 58 by means of a suitable source of potential, such as battery 73 and lead 72, electrons emanating from the surface 59 are accelerated towards the anode plane 60. Such electrons are electrostatically controlled by the edges 64, 66 provided by disc 62 and cylinder 63, respectively.

The extension 57 of the pole piece 49, previously referred to, serves to isolate the cathode 58 and the field forming means, including the edges 64, 66, from the magnetic field.

While it is not essential for the operation of the device, it has been found preferable to provide an iron skirt 74 surrounding the cathode 58. This skirt 74 is supported by the extension 57 of the pole piece 49 and prevents the formation of metallic deposits on the inner surface of glass bell 76. Such deposits might give rise to undesirable arcing and/or disturb the electric field.

The extension 57 of pole piece 49 is joined to the glass bell 76 by means of flanged tubular members 77, 78, which are connected in a vacuum-tight manner to preserve the internal vacuum of the tube 11.

To collect electrons after their passage through the resonators, an electron collector 79 is positioned behind the catcher resonator 23. The collector 79 is constituted of a tubular member 81 having a metallic bell 82 at one end thereof, which is formed from a thin-walled cylindrical tubular member, preferably of copper, and pinched at one end after the tube 11 is evacuated, the other end of bell 82 being connected in a vacuum-tight manner to the tubular member 81. A further tubular member 83, provided with an end plate 84, is connected to the tubular member 81 and surrounds a portion of the metallic bell 82. Around the tubular members 81, 83 are positioned cooling fins 86 which are suitably disposed by means of spacing rings 87. The tubular member 81 of the collector 79 is connected to the pole piece 51 by apertured disc 88, glass ring 89, and sets of flanged tubular members 80 and 85, with all of the connections being made in a vacuum-tight manner.

An apertured end member 91 is provided at the end of tubular member 81 adjacent the pole piece 51. It has been found advisable to employ a relatively small diameter aperture for the end member 91 in order to prevent the formation of a virtual cathode in this part of the structure.

In operation, a beam of electrons is projected successively through the gap 35, the drift tube 26, and the gap 40. While the electron beam is under the influence of the electromagnetic field of resonator 22, the electrons are subjected to velocity variations, resulting in a velocity-modulated beam. In passing through the drift tube 26 the velocity-varied beam becomes grouped or bunched by reason of the faster moving electrons overtaking the slower electrons to give rise to a density-modulated beam. This density-modulated beam traverses the gap 40 of the output resonator 23 where electromagnetic energy is extracted from the beam to sustain oscillations in this resonator 23. After such extraction of energy the beam passes through the aperture 56 of the pole piece 51 to the electron collector 79.

Electromagnetic energy is introduced into the buncher resonator 22 by way of coupling means 34. The input waveform after amplification is transmitted from the output resonator 23 by way of coupling means 36.

In the event that pulse operation is desired, the accelerating voltage may be systematically applied to the tube 11. In such case, battery 73 may be replaced by a pulse generator capable of delivering a large negative pulse of suitable magnitude and repetition rate, thereby providing an oscillatory high frequency output pulse through coupling means 36.

In order to provide an electron beam for projection through the gaps 35, 40 of sufficient density for high powered operation, it has been found advisable to employ a cathode emitting surface 59 having considerably greater area than the ultimate cross-sectional area of the electron beam. In the event that the emitting surface 59 was substantially the same area as the electron beam, the emitting surface 59 would be unable to supply the requisite electron density for a sufficient length of time to provide a practical and useful cathode 58 for high-powered operation.

As discussed in the above-mentioned Patent No. 2,564,743, rectilinear motion of electrons emanating from a substantially spherically-concave emitting surface may be obtained. By reason of field forming means, such as focusing electrode 61, substantially rectilinear motion of electrons is obtained between the emitting surface 59 to a point almost extending to the anode plane 60. The potential distribution along the boundary of the beam is designed to follow radii of the spherical-concave surface 59. Accordingly, along the beam boundary in the cathode region there is no tendency for the electrons to deviate from rectilinear paths owing to the fact that the potential distribution outside the beam is similar to the potential distribution existing inside the beam. Stated somewhat differently, the field forming means including the focusing electrode 61 are effective for providing, in the presence of complete space charge, a zero voltage gradient normal to the edge of the electron beam.

Where a smoother grid is included in the anode plane 60, the equipotential lines existing near the anode plane 60 may be maintained more readily as concentric circles. However, when such a smoother grid is omitted, as is the case with the instant structure in order to minimize electron beam interception by such a grid, a special problem is presented by reason of the distortion of the equipotential lines in the vicinity of the anode plane 60. Such distortion tends to diverge the electron beam before it reaches the anode plane 60. As a consequence, the anode aperture 54 is of greater diameter than would ordinarily be required in order to prevent beam interception by the anode or pole piece 49.

The focusing electrode 61, which is electrically connected to the cathode 58 and consequently maintained at the same potential, is effective for shaping the electron beam in the manner indicated substantially through electrostatic means. After the beam passes into the aperture 54 of the pole piece 49, the electrons at some point in their transit are directed in paths which are parallel to the longitudinal axis of the tube 11. This point represents the axial location at which the electrostatically focused beam converges to a minimum diameter, the electrons thereat having no radial components of velocity with respect to the beam axis. It may be considered for design purposes that a parallel electron beam enters the magnetic field at the point A which is located a distance of one radius from the pole face 52. The radius here involved is that of the aperture 54 in the plane of the pole face 52.

While it is possible to shape the electron beam in the manner indicated by arranging the magnetic field to thread the cathode 58, such an arrangement involves a complicated structure for providing a suitable magnetic field to achieve the desired electron paths. Accordingly, in order to simplify the cathode structure 58 it has been found advisable to shape the beam through electrostatic means, taking precautions to prevent magnetic flux from penetrating the cathode 58. For instance, the extension 57 of the pole 49 comprises magnetic flux modifying means to isolate the cathode region from undesirable magnetic lines of force.

The electrons of the beam in their transit from the plane including the point A through the input gap 35, drift tube 26 and output gap 40 tend to be directed in helical paths having substantially constant diameters within a beam envelope extending parallel to the longitudinal axis of the tube 11 owing to the influence of magnetic focusing provided by the pole pieces 49, 51 suitably energized by the permanent magnet 12. This condition exists despite the fact that with a high-density beam the space charge forces tending to separate the electrons forming the beam are exceedingly large. Were the magnetic restraining means omitted, a large portion of the beam current would be intercepted by the adjacent structure of the tube 11. With the velocity variations impressed upon the electrons by the electromagnetic field existing in the resonator 22, the electrons become grouped in the drift tube 26, giving rise to greater electron concentrations. The magnetic focusing tends to maintain the beam envelope substantially uniform and parallel to the tube axis prior to and after the formation of the greater electrons concentrations, thereby minimizing transverse debunching.

Thus, in a first region under the influence of electrostatic field forming means such as electrode 61 and the anode plane 60, electrons originally converge to a focal point in the vicinity of the anode plane 60 and then tend to assume parallel paths. In a second region beyond the pole face 52 the beam envelope is maintained substantially uniform and parallel to the tube axis by reason of the axially-directed magnetic field which tends to counteract space charge repulsion forces. In an intermediate region located within the aperture 54, the electron paths change from converging to parallel trajectories. Theoretically, until the beam arrives at a plane, including the point A and positioned at right angles to the axis of the tube 11, electrons are acted upon only by electrostatic means. After passing the plane including the point A, which plane is the effective plane of entrance of the beam into the magnetic field, the electrons are controlled only by magnetic means and follow helical paths having constant diameters. In practice, owing to fringing field effects this exact condition is difficult to realize.

Where dealing with a high density electron beam, space charge repulsion force may seriously impair the output power and gain of a velocity modulation electron discharge device. Owing to such space charge effect, transverse debunching as well as longitudinal debunching may occur. As a consequence, the density of the electron groups passing through the gap of the output resonator, such as gap 40, is reduced. By virtue of the present invention, the cross-sectional area of the electron beam throughout its passage through the gaps 35, 40 and drift tube 26 tends to be maintained constant.

In order to obtain a sufficiently high coefficient of coupling to the cavity resonators 22, 23, it is advisable that the diameter of the gaps 35, 40 be slightly greater than the diameter of the beam passing therethrough. In the case of gridless gap coupling, the outer regions of the electron beam will be more tightly coupled to the resonators 22, 23 than the central portion of the beam. In addition, there is less longitudinal debunching in the part of the beam adjacent the wall of the drift tube 26. Therefore, the outer region of the beam manifests a greater degree of modulation than the central region of the beam. In view of the fact that it is the outer portion of the beam that is lost due to transverse debunching and imperfect focusing, extreme care must be taken with regard to these factors.

Generally speaking, it has been found possible to obtain a magnetically restrained beam of prescribed shape if two factors are chosen properly. One is the angle between the edge of the beam and the axis of the tube 11 at the entrance of the beam into the magnetic field, which is conveniently taken as the point A. The other is the radius of the beam at the point A relative to the magnitudes of the accelerating voltage and the magnetic field. By altering the axial position of the electron gun structure comprising the emitting surface 59, the focusing electrode 61, and the anode plane 60 relative to the surface 52 of the pole piece 49, a change may be made to occur in the position at which the electrons of the beam have no radial components of velocity relative to the effective plane where the electrons enter the magnetic field. This results in a modification of the trajectories of the electrons of the beam relative to the axis of tube 11 at the point A.

In general, it is desirable that the electrons be moving parallel to the axis of the tube 11 at the time they reach point A. This is illustrated in Fig. 8 where the electron gun structure and typical electron paths 125 are schematically illustrated. The electron paths 125 are convergent from emitting surface 59 and become parallel at point A where the beam has a minimum diameter. A slight deviation from this condition may be tolerated, however, without seriously impairing the operating characteristics of the tube 11.

In Fig. 9, the heavy solid line 125 represents the path of one electron, of the electron paths 125 in Fig. 8, at the edge or boundary of the beam. The thin solid lines 126 represent magnetic lines of force, but only a few typical lines are shown in Fig. 9. It is assumed that the pole piece 49 in Fig. 9 is polarized as a north pole. The lines 126 in Fig. 9 may be considered to indicate approximately average or median lines in the field.

As the electron enters the field, in the vicinity of the point 127, it is moving originally with a velocity v in a straight line parallel to the longitudinal axis of the tube 11. Point 127 is included in a transverse plane through point A shown in Figs. 3 and 8. Owing to the outward fringing of the field in the aperture 54, there is a radially inward magnetic field component B_r at this point. The electron, being a charged particle, is acted upon as it crosses the field B_r by the so-called Lorentz force F_t which is at right angles to both the velocity v and the field component B_r. This force accelerates the electron in the direction of the arrow F_t in Fig. 9, giving it an angular velocity of rotation about the axis. As the electron crosses all of the fringing flux, this velocity is increased to a certain value ω which depends upon the initial velocity v and the total amount of flux which is crossed.

The rotational component of velocity of the electron causes it to continue to cross the magnetic flux lines in the uniform portion of the magnetic field. At the point 128, for example, the electron is moving at the velocity v', and crossing the field B with a transverse component of velocity $r\omega$, where r is the radial distance of the electron from its axis of rotation. This produces a radially inward Lorentz force $F'=er\omega B$, where e is the charge on the electron.

The electron is subject also to a radially outward centrifugal force of $mr\omega^2$, where m is the mass of the electron. Thus the net inward force available to overcome the space charge repulsion force is the difference between the centrifugal and Lorentz forces, and is a function both of angular velocity and magnetic field strength B. Fig. 10 shows how the radial force, considered positive in the outward direction, varies as a function of velocity with a given field strength B. It is apparent that this force is negative (i. e. inward) between the limits of $\omega=0$ and

$$\omega=\frac{e}{m}B$$

and has a maximum negative value when

$$\omega=\frac{1}{2}\frac{e}{m}B$$

Thus, the magnetic field is most effective in producing inward force for overcoming space charge repulsion when the angular velocity is

$$\omega_H=\frac{1}{2}\frac{e}{m}B$$

It can be shown that the angular velocity ω_H is obtained when the electron crosses, in the region of fringing flux, all of the flux which lies between its path and the axis in the uniform field region. Since this requires the least magnetic field to maintain the electron in a path of constant radius, it is the mode of operation which is preferred. It is possible, however, to maintain the desired electron paths with angular velocities other than ω_H, providing a stronger field is used.

The foregoing discussion relates to an "edge" electron, i. e. one at the boundary of the beam. Other electrons, nearer the axis of the beam are subject to similar forces. They cross less flux in the vicinity of the aperture 54 and have a lower transverse velocity $r\omega$ in the uniform field, but are subject to less total space charge force and less centrifugal force, so they follow paths similar to those of the edge electrons, but at smaller radii.

In designing a tube like that of Fig. 3 to operate as described, one of the principal problems is to determine the proper axial distance between the electron gun 58 and the pole face 52 to make the electron beam enter the magnetic field in the required manner. The electron gun, comprising the cathode 58, focusing electrode 61, and the anode plane 60 may be designed as described in the aforementioned Patent No. 2,564,743 to produce a beam of a predetermined radius a, with the electrons moving in substantially parallel rectilinear paths, at a point A which is an axial distance Z from some reference point such as the anode plane 60, in the absence of magnetic field. The point A will be inside the aperture 54, a certain distance S from the face 52 of the pole piece 49. When this distance S is found, the axial distance $Z+S$ between anode plane 60 and the pole face 52 shown in Figs. 3 and 8 is known.

The distance S can be found empirically from a curve of magnetic flux density as a function of axial position in the vicinity of the aperture **54**. Fig. 11 shows a typical plot of the axial flux density B as a function of axial distance z from the plane of a substantially planar pole face such as **52** of pole piece **49** shown in Fig. 9. B_0 represents the flux density in the uniform field region remote from the pole face, the plane of pole face **52** being indicated by ordinate B in Fig. 11. Near the aperture **54**, the lines of force crowd together to terminate on the edge and interior of the aperture, as shown in Fig. 9, and the flux density has a maximum value B_m at a distance F from the pole face and ordinate B. Inside the aperture to the left of ordinate B in Fig. 11 (where z is negative) the flux density falls off rapidly with increase in z. Curves like that of Fig. 11 may be obtained by actual measurement of the field, or may be analytically determined from the pole piece configuration.

To further understand the field plot shown in Fig. 11, consider a pole piece with no aperture therein and having a planar pole face. A plot of the magnetic field distribution along the z axis would be constant all the way up to the pole face, as shown by the dotted lines in Fig. 11. Suppose such a pole piece contained an aperture therethrough having some given diameter. The lines of force originally terminating on the pole face when there was no aperture, must terminate on new surfaces. Some of the lines of force will terminate inside the aperture, and some will crowd themselves with the rest of the lines of force on the pole face. The net result is to change the field distribution so that the axial magnetic field plot is changed to the solid curve in Fig. 11. Usually there will be a maximum magnetic field point close to the pole face due to the crowding together of lines of force in front of the pole face, as is shown in Fig. 9 and indicated by B_m in Fig. 11. The lines of force decrease to the uniform value of B_0 to the right of the maximum point, and decrease rapidly to zero in the aperture to the left of this maximum point as shown in Fig. 11.

As shown in Fig. 11, A_1 is the distance to the left of the point of maximum flux B_m, where the flux is $\frac{1}{2}B_m$. A_2 is the distance to the right of the point of maximum flux where the flux is $\frac{1}{2}(B_m+B_0)$. It is assumed that the strength of the magnetic flux decreases approximately parabolically from the point of maximum flux B_m to a point where the flux is $\frac{1}{2}B_m$, and decreases approximately parabolically from the point of maximum flux B_m to a point where the flux is $\frac{1}{2}(B_m+B_0)$. The point A which lies in the effective entrance plane of the electron beam into the magnetic field should be placed a distance Δz to the left of the point of maximum flux B_m:

$$\Delta z=[A_1\eta 2+A_2(\eta-1)(\eta+3)]\frac{\pi}{4}$$

where

$$\eta=\frac{B_m}{B_0}$$

Since B_m is at the distance F to the right of the pole face **52**, the distance S in Figs. 3 and 8 can be found by: $S=\Delta z-F$, the distance S being of the order of the radius of aperture **54** in the plane of pole face **52**; and the distance from the anode plane **60** to the plane of the pole face **52** will be:

$$Z+\Delta z-F$$

All of the constants A_1, A_2, F, and η depend on the degree of saturation of the pole face around the tip of the aperture opening, the diameter of the opening and shape of the tip, and the diameter and shape of the pole face. The pole face can be planar or frusto-conical as mentioned above, or any suitable configuration.

Generally speaking, if a larger magnitude of accelerating potential is employed, it is necessary to provide a stronger magnetic field. For instance, when the accelerating potential is changed from 12 to 17 kilovolts, it has been found that the magnetic field must be increased from 1200 to 1390 gausses in order to maintain the percentage of beam current passing to the collector **79** at a maximum. Where introducing relatively large magnitudes of electromagnetic energy into the resonant cavity **22**, it has been found advisable to increase the strength of the magnetic field in order to overcome transverse debunching which accompanies modulation.

While the percentage of the beam current reaching the collector **79** is an important factor in the operation of the tube **11**, the shape of the electron beam is a prime consideration. If the beam is allowed to converge even slightly at any point along the drift tube **26**, the debunching forces increase very rapidly with a resultant loss in gain. From a consideration of transverse debunching which causes a non-magnetically focused beam to diffuse as a square of the drift distance, it is considered good practice from a design standpoint to make the drift distance or length of drift tube **26** less than optimum value. With magnetic focusing the transverse debunching tends to be suppressed.

In employing an axial magnetic field in order to obtain a suitable configuration for the electron beam care must be taken to prevent multipactor effect from reducing the gain and output power of the device. With a high-density electron beam, some electrons may deviate from the desired trajectories despite magnetic focusing. When primary electrons impinge upon the surfaces of the resonator **22, 23**, secondary electrons may be set free. If the secondary electrons traverse the gap **35, 40** in a time corresponding to a half-cycle of the radio frequency field maintained therein, they may impinge upon the opposed surfaces of the resonators **22, 23** to set free additional secondary electrons. These electrons may be in proper phase to move with the radio frequency field across the gap **35, 40** during the next half-cycle. Thus, a condition may arise wherein a spurious electron cloud fluctuates back and forth across the resonator gap **35, 40** in phase with the radio frequency energy. Such a condition results in extraction of energy from the field by such electrons.

It has been found that with magnetic focusing multipactor effect becomes more pronounced. A tentative explanation for this condition follows: Ordinarily, in the absence of magnetic focusing, secondary emitted electrons tend to follow the radio frequency field lines extending through the gap **35, 40** of the resonator **22, 23**. Such field lines are of unequal length, resulting in secondary electrons following trajectories having different lengths, which minimize the possibility of resonance occurring. However, with an axially-directed magnetic field, the electrons tend to follow rectilinear trajectories so that the secondary electrons will tend to move in similar-length paths with similar transit times. Such a condition will more readily give rise to multipactor effect.

Accordingly, in the design of the tube **11**, care must be taken to avoid the multipactor effect which seriously limits the gain and output power of the device. It has been found that by the inclusion of the sleeves 32, 33 for defining the electron-permeable gaps 35, 40 of the resonators 22, 23, multipactor effect is substantially eliminated. With thin walls used for the sleeves 32, 33, as discussed above, the area presented by the ends of the sleeves 32, 33 to electrons deviating from desired paths, is relatively small, thereby reducing the magnitude of secondary electron emission from this source.

In addition, it has been found advisable to employ different internal diameters for each of the sleeves 32, 33 defining each of the resonator gaps 35, 40. In other words, the gap 35 of the buncher resonator 22 may be formed with sleeves having different internal diameters. For instance, with a device suitable for sustaining oscillations having a wavelength of the order of 3 cm. and with an ultimate beam diameter of approximately 0.084 inch, the sleeves 32, 33 forming the entrance and exit apertures of the gap 35 may be provided with internal diameters of 0.100 and 0.125 inch respectively. The sleeves 32, 33 forming the electron permeable gap 40 of the catcher resonator 23 may be constituted in a similar manner. If desired, all of the sleeves defining the gaps 35, 40 may be provided with different internal diameters.

Referring to Fig. 4, there is shown a novel tuning arrangement for varying the resonant frequency of the resonators 22, 23. Side wall 92 of the resonators 22, 23 is provided with a doubly bowed configuration and rigidly attached to the block 93 along two edges thereof. As may be seen more clearly in Fig. 5, the side wall 92 along its other two edges is unconnected. The wall 92, which is preferably made of copper or a copper-plated material to provide a highly conductive surface, is folded back along its middle portion and rigidly connected to a slot in the end of shaft 94. Thus, longitudinal movement of this shaft 94 permits the middle portion of the side wall 92 to move back and forth to alter the resonant frequency of the resonators 22, 23.

The shaft 94 is partially surrounded by bellows 96 having an apertured end wall 97 rigidly connected to the shaft 94. One end of the bellows 96 is rigidly connected to the block 93. The connections of the shaft 94, end wall 97, bellows 96 and block 93 are all vacuum-tight to preserve the internal vacuum of the tube 11. A knurled ring 98 supported by plate 99 and ring 101 is effective for permitting axial movement of the apertured screw portion 102 of the end wall 97. Nuts 103, 104, when suitably soldered to the apertured screw portion 102, limit the axial movement of the shaft 94.

It will be noted that the side wall 92 is rigidly secured to the means including block 93 defining the cavity resonators 22, 23 along two of its edges. The wall 92 along its other edges is spaced from but almost in contact with the cavity resonators 22, 23. By such an arrangement, the wall 92 does not serve to define a portion of the vacuum envelope of the tube 11, other means including bellows 96 positioned beyond wall 92 being effective for performing this function. With the wall 92 partially disconnected from the block 21, it is possible to subject the wall 92 to greater movement by means of shaft 94 to vary the frequency of resonators 22, 23 over a wider range without damaging or impairing the functioning of the wall 92 through strain or a permanent set. By partially securing the wall 92 to the resonators 22, 23, spurious fluctuations of the position of the wall 92 owing to vibration or similar causes are minimized. This is particularly advantageous during tuning of the resonators 22, 23, affording a smoother variation of resonant frequency as a function of the angular position of the knurled ring 98. Undesirable changes in the values of "Q" of the resonators 22, 23 are substantially eliminated.

While wall 92 has been shown secured to block 93, which is preferably made of copper or a copper-plated material to provide highly conductive surfaces, it is apparent that the wall 92 need not be directly connected to the means defining the cavity resonators 22, 23. For instance, such a connection could be conveniently made to structure located adjacent the means defining the resonators 22, 23. In addition, while the wall 92 has been shown as fastened to the block 93 along two of its edges, it will be understood that a suitable connection could be made at any point of the wall 92.

Referring to Fig. 6, there is shown another embodiment of the instant invention in which the magnetic means which are provided as integral parts of the electron discharge device are arranged to direct magnetic lines of flux substantially only through the drift space region. A drift tube 106 is formed by a suitably apertured metallic block 107. Magnetic focusing means, such as pole pieces 108, 109, when suitably energized by an external magnetic circuit, such as permanent magnet 12, are effective for providing the desired magnetic field configuration. The pole pieces 108, 109 are formed to cooperate with the metallic block 107 and are arranged to surround apertured discs 111, 112, resonator poles 113, 114, side walls 92 and annular members 116, 117, thereby forming cavity resonators 118, 119, respectively. If desired, an annular slot may be provided between the discs 111, 112 and the pole pieces 108, 109, respectively, to permit bowing of the discs 111, 112 in order to facilitate pretuning of the resonators 118, 119, respectively. The apertured discs 111, 112, the resonator poles 113, 114, annular members 116, 117, side walls 92, are preferably made of copper or a copper-plated material to provide highly conductive surfaces for the resonators 118, 119, respectively.

The operation of the device of Fig. 6 is similar to that previously described in connection with Figs. 1 through 5, with the exception that the axially-directed magnetic field extends substantially only through the drift tube 106. By preventing the presence of magnetic lines of flux in the region of the gaps 121, 122 of the resonators 118, 119, respectively, difficulties with multipactor effect are substantially eliminated. It will be noted that the gaps 121, 122 are defined by the opposed ends of resonator pole 113 and apertured disc 111 and by the opposed ends of resonator pole 114 and apertured disc 112, respectively. It has been found unnecessary to define the gaps 121, 122 by means of special sleeves such as the sleeves 31, 33 previously described, although such sleeves may be included if desired.

The external magnetic circuit, constituted of permanent magnet 12, is coupled to the pole pieces 108, 109 at a place remote from the pole faces 123, 124 of the pole faces 108, 109, respectively. This is similar to the magnetic coupling arrangement employed in connection with the device of Figs. 1–5. With this type of coupling a more uniform magnetic field is obtained.

While a permanent magnet 12 has been shown for energizing the pole pieces 49, 51 and 108, 109, an electromagnet circuit might be employed for this purpose. Furthermore, if desired, the external magnet 12 might be omitted. In such case, the pole pieces 49, 51 and 108, 109 could be formed of highly magnetic material.

It is apparent that in any electron discharge device in which it is desired to employ a high-density electron beam, the instant invention will be useful. For instance, it is particularly effective for providing a high-density electron beam for use in travelling wave amplifiers.

While the instant invention has been described in connection with a two-resonator velocity-modulation electron discharge device operating as an amplifier, it is of course understood that the invention may be embodied in other types of apparatus. For instance, either single, plural or multi-electromagnetic field defining means or resonant chamber means suitably disposed for interaction with an electron beam may be provided with the magnetic electron beam directing means of the instant application. More particularly, three or more aligned resonators cooperating with magnetic means, such as pole pieces 49, 51, provide a highly useful device. The present structure may also be modified to form a high frequency generator. A feedback coupling loop may be arranged between the input and output resonators 2, 23 or 118, 119 to provide a structure suitable for sustaining oscillations to provide a high-powered electromagnetic generator. If desired, the frequency of the output resonator 23 or 119 may be selected as a harmonic of the frequency of the input resonator 22 or 118 to provide a frequency multiplication device. In addition, the instant invention may be employed in a single resonator velocity-modulation device or reflex klystrons, as well as in travelling wave velocity-modulation devices.

It is apparent that many changes could be made in the construction of the devices of Figs. 1–7 and that many apparently widely different embodiments of this invention could be made without departing from the scope thereof. For instance, while the instant magnetic focusing arrangement is particularly suitable for cooperating with electrostatic electron controlling means, the magnetic means is effective in itself for directing electrons in desired trajectories. As discussed above, the instant invention may be included in any electron discharge device in which it is desirable to maintain electrons in desired trajectories. Accordingly, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. High frequency beam tube apparatus, comprising an electron gun including cathode and electrostatic focusing means supported within an evacuated envelope, said electron gun comprising means for producing and directing an electron beam which converges to a minimum diameter at a predetermined location spaced from said cathode along a path within said envelope, magnetic beam controlling means adjacent said path for maintaining the diameter of said beam substantially constant along a region beyond said location, said magnetic beam controlling means comprising means for directing lines of magnetic force which curve into the path of said beam within said envelope in the

vicinity of said predetermined location and extend substantially axially along said path and said region, said magnetic beam controlling means including electron permeable magnetic pole piece means adjacent said location and positioned along said path relative to said location to make the effective plane of entrance of said beam into the curved lines of magnetic force substantially coincident along said axis with said location at which said beam converges to a minimum diameter, and magnetic flux modifying means in the vicinity of said electron gun for isolating said cathode from undesirable magnetic lines of force, whereby said beam along said region beyond said location has a substantially uniform diameter of the order of said minimum diameter.

2. High frequency beam tube apparatus, comprising an electron gun including cathode and electrostatic focusing means supported within an evacuated envelope, said electron gun comprising means for producing and directing a beam of electrons along an axis within said envelope wherein the electrons of said beam have substantially zero radial components of velocity with respect to said axis at a predetermined location therealong from said cathode, and magnetic beam controlling means adjacent said axis for maintaining the diameter of said beam substantially constant along a region beyond said location, said magnetic beam controlling means comprising means for directing lines of magnetic force which curve into the path of said beam within said envelope in the vicinity of said predetermined location and extend longitudinally along said axis and said region, said magnetic beam controlling means including apertured pole piece means positioned along said axis in the vicinity of said location at which the electrons of said beam have substantially zero radial components of velocity, the end of said aperture at the face of said pole piece means most remote from said electron gun being spaced along said axis from said location by a distance of the order of the radius of the aperture at said face to make the effective plane of entrance of said beam into the curved lines of magnetic force substantially coincident along said axis with said predetermined location at which the electrons of said beam have substantially zero radial components of velocity, whereby said beam along said region beyond said location has a substantially uniform diameter.

3. High frequency beam tube apparatus as defined in claim 2, and further including magnetic flux modifying means in the vicinity of said electron gun for isolating said cathode from undesired lines of magnetic force.

4. An ultra-high-frequency electron discharge device comprising an electron emitter, anode means cooperating therewith for producing an electron beam, magnetic means coupled to said beam for confining said beam to a desired path, at least a portion of said magnetic means forming said anode means, and electromagnetic energy field defining means coupled to said beam in energy exchanging relation.

5. An ultra-high-frequency electron discharge device as defined in claim 4, and further including electrostatic focusing means adjacent said emitter and spaced from said anode means, said magnetic means including magnetic pole piece means having an electron permeable aperture therethrough along the path of said electron beam, said electron emitter including a con-

cave emitting surface, said electrostatic focusing and anode means comprising means for making said electron beam converge from said concave emitting surface to a minimum diameter at a predetermined location within said aperture, said one end of said aperture being separated from said location by a distance of the order of the radius of said aperture at said one end thereof, whereby the diameter of said electron beam beyond said pole piece is substantially uniform along the axis of said beam.

6. Ultra-high-frequency apparatus, comprising a source of electrons and a magnetic member having an aperture registering with the path of said electrons, said member having an inner planar portion disposed substantially perpendicularly to said path, said member having an outer portion extending substantially parallel to said path and in the direction of said electron source, anode means, said anode means being formed substantially by said planar portion, and magnetic shielding means, said shielding means being provided substantially by said outer portion.

7. Ultra-high-frequency apparatus as defined in claim 6, wherein electrostatic focusing means are included adjacent said source of electrons and spaced from the planar portion of said magnetic member, said source of electrons and said electrostatic focusing and anode means comprising means for producing and directing an electron beam which converges from said source to a minimum diameter at a predetermined location within the aperture of said magnetic member.

8. Ultra-high-frequency velocity modulation apparatus, comprising first and second cavity resonator means having electron-permeable gaps, drift tube means extending between said gaps, an anode means including said anode for projecting electrons through said gaps and said drift tube means, and magnetic means including pole pieces for confining said electrons traversing said drift tube means to a substantially rectilinear beam, a portion of one of said pole pieces forming said anode.

9. Ultra-high-frequency velocity modulation apparatus as defined in claim 8, wherein said means for projecting electrons includes cathode and electrostatic focusing means spaced from said anode for producing and directing an electron beam having substantially zero radial components of velocity with respect to the axis of said apparatus at a predetermined location within an electron permeable region through said one of said pole pieces.

10. A velocity modulation device comprising an electron source, two spaced magnetic pole pieces, a portion of one of said pole pieces comprising anode means, the source and pole pieces including said anode means being aligned along an axis, resonant chamber means having electron-permeable gaps aligned along said axis, the pole pieces being positioned adjacent the resonant chamber means and having apertures therethrough aligned along said axis and registering with said gaps, and a drift tube aligned with said gaps and positioned between said pole pieces.

11. A velocity modulation device as defined in claim 10, wherein the aperture in said one of said pole pieces is tapered along said axis, the larger end of said aperture being closer to said electron source than the smaller end of said aperture, and further including focusing means adjacent said electron source and spaced from said anode means for directing an electron beam which converges from said electron source to a minimum diameter at a predetermined location within said tapered aperture, the smaller end of said aperture being spaced from said location along said axis by a distance of the order of the radius of said aperture at the smaller end thereof to make the effective plane of entrance of said beam into fringing lines of magnetic flux produced in the vicinity of said one of said pole pieces substantially coincident along said axis with said location, whereby the diameter of said electron beam is substantially uniform beyond said one of said pole pieces along said axis.

12. In an evacuated ultra-high-frequency velocity modulation electron discharge device having an axis, a cathode having an electron-emissive surface, a disc having an aperture aligned with and positioned along said axis, a cylinder aligned along said axis and having its inner edge most remote from said cathode disposed in spaced relationship to the aperture of said disc, resonant chamber means having electron-permeable regions, said regions being aligned along said axis, drift tube means positioned between said regions and aligned along said axis, two magnetic mutually spaced pole pieces adjacent said chamber means, each of said pole pieces being apertured along said axis and defining a portion of the vacuum envelope of the device, and a permanent magnet having its arms magnetically coupled to said pole pieces respectively at regions thereof remote from the faces of said pole pieces.

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