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EFFICIENT HIGH POWER BEAM TUBE EMPLOYING A FLY-TRAP BEAM COLLECTOR HAVING A FOCUS ELECTRODE STRUCTURE AT THE MOUTH THEREOF

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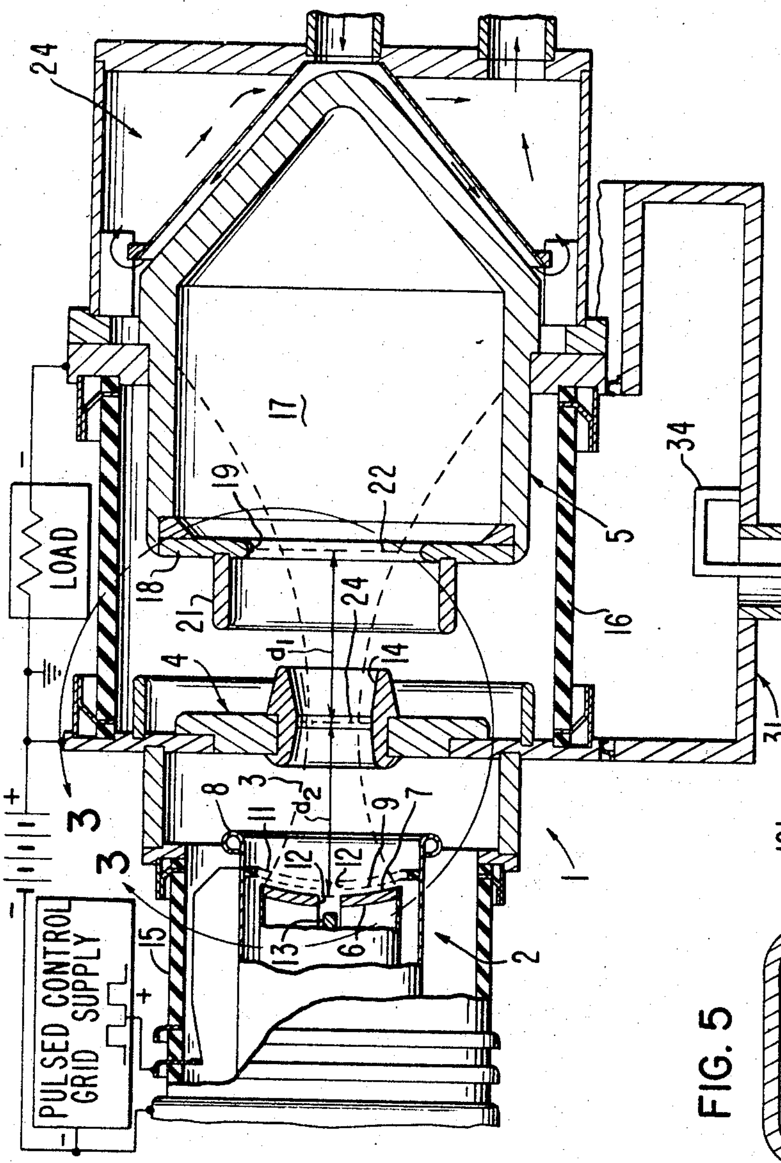

FIG. 1

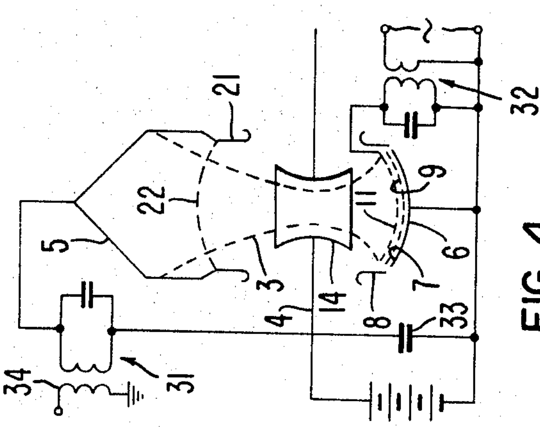

FIG. 4

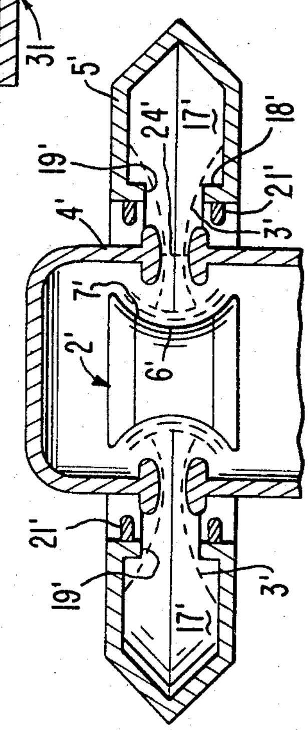

FIG. 5

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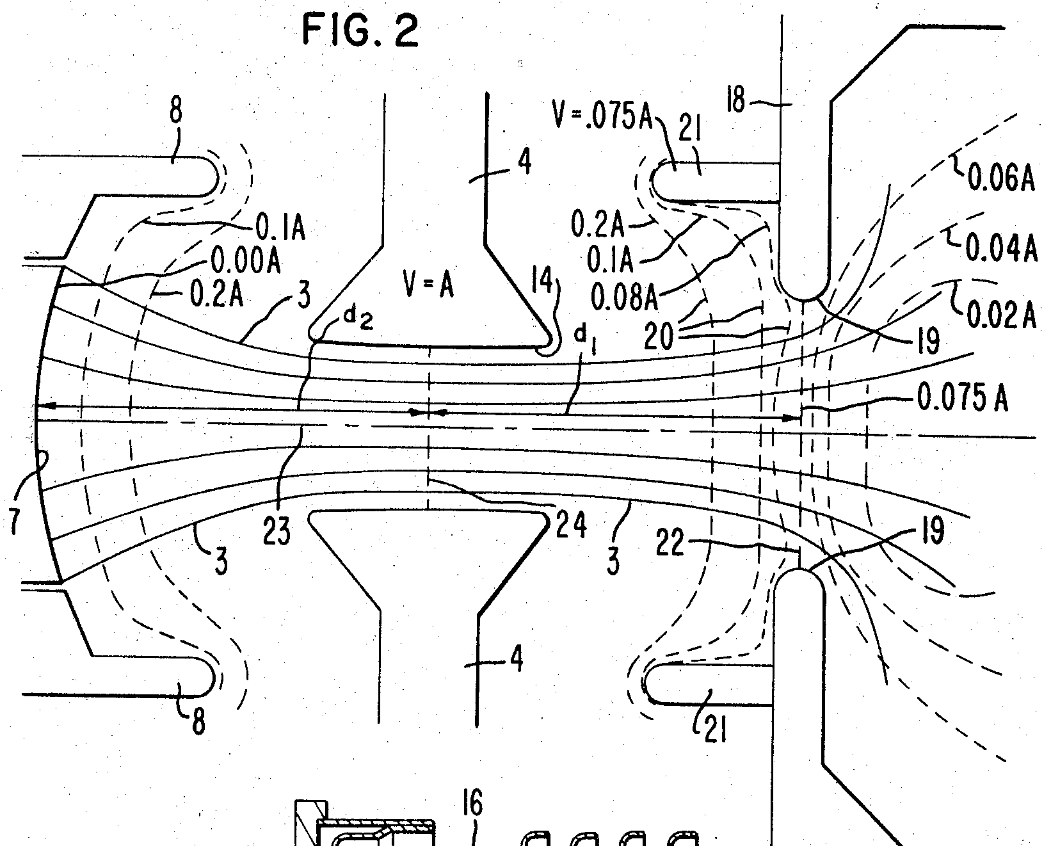
FIG. 2



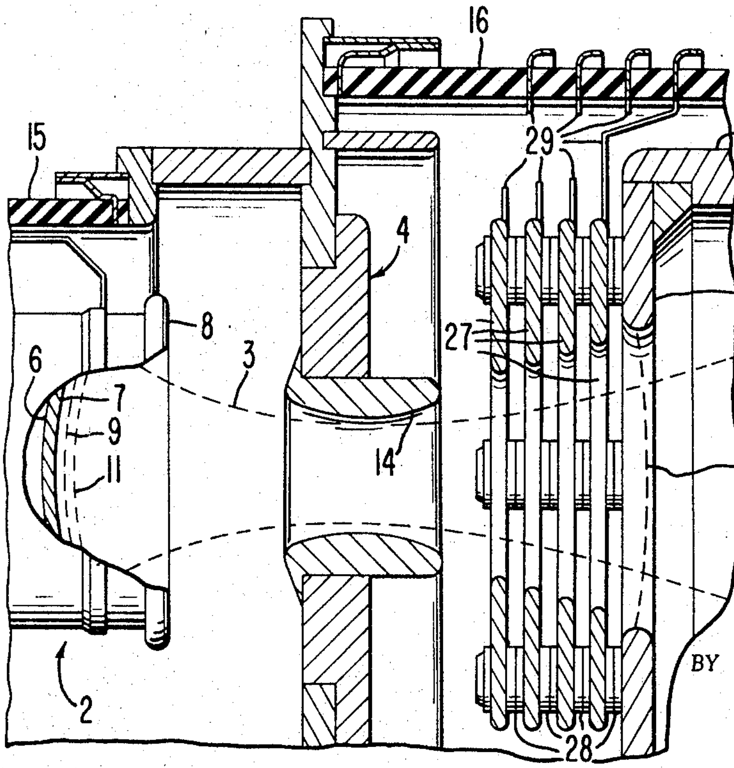


FIG. 3

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EFFICIENT HIGH POWER BEAM TUBE EMPLOYING A FLY-TRAP BEAM COLLECTOR HAVING A FOCUS ELECTRODE STRUCTURE AT THE MOUTH THEREOF

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ABSTRACT OF THE DISCLOSURE

An improved beam tube is disclosed. The beam tube includes a beam accelerating electrode and a fly-trap collector for collecting the beam. A beam focus electrode structure is disposed at the mouth of the fly-trap collector in the intervening space between the mouth of the collector and the accelerating electrode. The focus electrode focuses the beam in the deceleration space preceding the mouth of the collector to maintain a condition of laminar flow of the electrons, whereby extremely high tube efficiencies are obtained in excess of 95% at beam voltages in excess of 10's of kilovolts and at power levels on the order of megawatts or more. Beam tubes of the present invention, may be linear or circular in configuration.

Heretofore, certain beam tubes have been proposed as efficient switch tubes. Such tubes have employed a depressed collector and a suppressor grid to collect secondary electrons emitted from the collector. Efficiencies on the order of 97% have been shown to be possible. However, the power level of this type of tube is limited due to the fact that the suppressor grid intercepts a significant amount of the beam current during the turn-on and turn-off periods of the beam which are of finite duration. Due to the fragile nature of the suppressor grid the grid could not be adequately cooled. Such a tube is described in an article by D. A. Dunn, et al., entitled "Axially-Symmetric Space-Charge Flow in a Decelerating Space," Proceedings of the Fourth International Congress on Microwave Tubes, The Hague, Holland.

In the present invention, the tube includes a Pierce-type electron gun either of an axial or radial geometry for forming the electron beam. A non-intercepting control grid, preferably of a double aligned mesh type, provides a mμ of on the order of 30 to 50. The grid provides relatively low voltage control without significantly perturbing the laminar electron flow of the beam. The beam is collected within a fly-trap collector having a beam focusing electrode structure at the mouth thereof for focusing the beam in the decelerating space preceding the mouth of the fly-trap collector. Such a collector permits collection of almost the total cathode current by maintaining essentially laminar flow of the electrons in the beam decelerating space when the collector is operated at a potential of 1–5% of the accelerating electrode potential. The laminar flow and proper shaping of the equipotentials in the decelerating region and at the mouth of the collector prevents setting up of excessive space charge depressions in the beam in the deceleration region. The fly-trap design prevents secondary electrons emitted from the collector surfaces from flowing back down the beam path to the accelerating anode and avoids the power handling limitations of the prior art.

In one embodiment of the present invention, the tube is a linear beam tube with the spacing from the cathode to the midplane of the accelerating electrode being about equal to the spacing from the collector equipotential surface, at the fly-trap mouth, to the midplane of the accelerating anode, whereby efficient and stable operation of the tube is obtained.

In another embodiment of the present invention, the tube is a radial beam tube with the beam directed radially outwardly from a central cathode emitter, whereby the power handling capability of the tube is greatly extended while obtaining the advantages of efficient operation.

In both of the aforementioned embodiments, a radio frequency resonant circuit may be connected between the accelerating electrode and the collector electrode. A signal to be amplified is applied to the control grid to modulate the beam. The modulated beam excites the radio frequency resonant circuit. The special beam optics in the decelerating region of the beam permit the collector potential to swing nearly to the cathode potential without reflecting electrons to the accelertaing electrode, thereby obtaining efficient R.F. operation.

The principal object of the present invention is the provision of an improved high power beam tube.

One feature of the present invention is the provision of a beam tube having an electron gun comprising a cathode emitter, focus electrode, and accelerating electrode to produce a laminar beam, and a fly-trap collector with the provision of a beam-focusing structure at the mouth of the fly-trap collector for focusing the beam for laminar flow in the beam decelerating region between the accelerating electrode and the beam collector structure, whereby an efficient high power beam tube is obtained.

Another feature of the present invention is the same as the preceding feature wherein the beam-focusing structure is a structure surrounding the beam intermediate the accelerating electrode and the fly-trap entrance of the beam collector, such focusing structure being shaped to form a series of beam decelerating equipotential surfaces over the decelerating region of the beam path which are inwardly dished toward the collector mouth, whereby the beam is permitted to expand in the direction transverse to its path into the collector while maintaining laminar flow of the beam.

Another feature of the present invention is the same as any one or more of the preceding features wherein the beam-focusing structure, in the decelerating region of the beam, includes one or more electrodes operating at a potential or potentials different from the potentials applied to the accelerating electrode and the collector electrode, whereby focusing of the beam is facilitated.

Another feature of the present invention is the same as any one or more of the preceding features wherein the beam tube is a linear beam tube with the cathode to accelerating electrode spacing being about equal to the spacing between the accelerating electrode and the collector and with the beam optics arranged to produce a convergent and divergent laminar flow of electrons which is axially symmetric about the midplane of the accelerating electrode, whereby an efficiency and stable high power linear beam tube is obtained.

Another feature of the present invention is the same as any one or more of the preceding features including a control grid structure formed by a double grid assembly closely spaced to the cathode with the apertures in the two grids in alignment and with the grid adjacent the cathode being operated at cathode potential, whereby high mu control of the beam is obtained without disrupting the laminar electron flow of the beam and without intercepting the beam.

Another feature of the present invention is the same as any one or more of the preceding features wherein the accelerating electrode contains a non-intercepting beam passageway therethrough having a length greater than the minimum characteristic transverse dimension of the passageway, whereby the accelerating electrode serves as an effective electrical screen between the collector and control grid to prevent R.F. feedback when the tube is used as an R.F. generator or to prevent unwanted grid current during the transient switching periods when used as a switch tube.

Another feature of the present invention is the same as any one or more of the preceding features wherein a control grid and cathode electrode are centrally apertured to permit positive ions generated within the tube and flowing down the center of the electron beam to pass through the grid and cathode to a target structure, preferably made of a getter material, to prevent damage to the grid or cathode and to permit getter pumping within the tube.

Another feature of the present invention is the same as any one or more of the preceding features wherein the tube includes an electron emitter having an emitting surface inwardly dished of the emitter, and the beam-focusing electrode structure, in the beam decelerating region, is formed and arranged to shape the electric fields of the collector such that the collector equipotential surface at the collector mouth approximates a mirror image of the dished electron emitter surface to preserve the laminar flow of electrons into the collector, whereby unwanted reflection of electron current to the accelerating anode is prevented to obtain enhanced efficiency.

Another feature of the present invention is the same as any one or more of the preceding features including the provision of a resonant circuit connected between the accelerating electrode and the fly-trap collector for generating an output R.F. signal, whereby an efficient source of R.F. energy is obtained.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

FIGURE 1 is a longitudinal sectional view, partly in elevation, of an electron beam tube of the present invention,

FIGURE 2 is a potential and beam trajectory plot for an electron tube of the type depicted in FIGURE 1,

FIGURE 3 is a longitudinal sectional view of an alternative embodiment of a portion of the structure of FIGURE 1 delineated by line 3—3,

FIGURE 4 is a schematic line diagram of a radio frequency tube embodying features of the present invention, and

FIGURE 5 is a schematic diagram of a radial tube geometry incorporating features of the present invention.

Referring now to FIGURE 1 there is shown the beam tube **1** of the present invention. The tube includes a Pierce-type gun assembly **2** at one end of the tube **1** for projecting a beam of electrons **3** through an accelerating anode electrode **4** to a fly-trap type beam collector **5**.

The electron gun **2** includes a cathode emitter **6** having an inwardly dished emissive surface **7** facing the accelerating electrode **4**. The emitter surface **7** is preferably spherically shaped and constitutes a section of a sphere of relatively large radius. A cylindrical beam focus electrode **8** coaxially surrounds the outer periphery of the cathode emitter **6** and projects toward the accelerating electrode **4**.

A pair of mesh grids **9** and **11** are closely spaced to the emitting surface **7** and are shaped to conform to the spherical shape of the emitting surface **7**. The grids **9** and **11** are carried from the focus electrode **8** and are insulated from each other and from the focus electrode to permit independent operating potentials to be applied thereto. The grids **9** and **11** are spaced apart by a few millimeters and have their grid openings in alignment to minimize grid interception of beam current and such as not to disturb the laminar flow of the trajectories of the electrons of the beam. The grid **9** which is closest to the cathode emitter, as of 0.030" spacing, is preferably operated at cathode emitter potential, whereas the grid **11** facing the accelerating electrode **4** is pulsed with a potential which is a small fraction, as of $\frac{1}{30}$ or $\frac{1}{50}$, of the accelerating potential for controlling the flow of electrons from the emitter **6** through the accelerating electrode **4**. In a preferred embodiment, the double grid structures are formed by electric discharge machining.

Grids **9** and **11** and the cathode emitter **6** preferably include a central aperture **12** in axial alignment with the center of the electron beam **3** to permit positive ions and reflected electrons to pass therethrough without interception by the grids or emitting surface **7**. A target electrode **13** is coaxially disposed of the aperture **12** in the cathode emitter **6** to collect the positive ions. The target electrode **13** is preferably made of a getter material, such as titanium, for gettering the ions and other residual gasses within the tube **1**. The target **13** can function both as a bulk getter and as a sputter-type getter. Getter material sputtered from the target **13** by energetic positive ions is deposited on the anode **4** and other surfaces within the tube to provide gettering surfaces.

The accelerating electrode **4**, as of copper, includes a central beam passageway **14** of circular cross section and of smaller diameter than the cathode **6**. The beam passageway **14** is preferably longer than its diameter to provide an effective electric shield between the control grids **9** and **11** and the collector electrode **5**. This shielding is beneficial in preventing transient voltages from being coupled from the collector electrode **5** to the control grid **11** during transient switching periods of the tube **1**, when operated as a switch tube. When the tube **1** is operated as a radio frequency (R.F.) amplifier it prevents coupling of R.F. voltages from the output circuit to the control grid circuit which could otherwise lead to instabilities and oscillations of the tube.

A cylindrical high voltage insulator assembly **15** holds off the high voltages applied between cathode **6** and accelerating electrode **4** and, in addition, permits certain of the various independent electron gun assembly potentials to be applied to various electrodes thereof. A similar cylindrical high voltage insulator **16** is sealed between the accelerating electrode **4** and the beam collector electrode structure **5** to form a portion of the tube's vacuum envelope and to permit the collector **5** to operate at a depressed potential nearly equal to the cathode emitter potential, whereby the forward conduction potential drop of the tube **1** is but a small percentage, as of 1% to 10%, of the accelerating electrode potential.

The beam collector structure **5** includes a beam collecting cavity portion **17** for collecting the beam on the interior surfaces thereof and a centrally apertured wall **18** defining a beam entrance passageway **19** which is of constricted cross sectional area compared to the collector portion **17** to prevent escape of secondary electrons from the collector back toward the accelerating electrode **4**. A tubular conductive beam focus member **21** projects from the collector wall **18** toward the accelerating electrode **4** for shaping the equipotential surfaces at the beam entrance passageway **19** and in the decelerating region immediately preceding the passageway **19**. The beam focus member **21** and the beam entrance passageway **19** are, in a preferred embodiment, dimensioned to produce an equipotential surface **22** across the beam entrance passageway **19** at the potential of the depressed collector structure **5** which, in the presence of space charge, is preferably shaped to approximate a symmetrical mirror image of the inwardly dished emitter surface **7** of the cathode emitter **6**. In addition, the beam focus electrode **21** is shaped to produce a series of equipotential surfaces **20** across the beam path (as shown in the potential plot of FIGURE 2) which are generally mirror images of the equipotential surfaces in the beam path on the beam accelerating side of the accelerating electrode **4**. In this manner, the electrons of the beam at the beam edge, in the decelerating region, experience an inwardly-directed force opposite to the outwardly-directed force on such electrons produced by space charge within the beam. The ratio of these forces is chosen to provide a beam which expands as a desired function of axial distance, while preserving laminarity of flow as far as possible.

In addition, the distance d_1 taken along the beam axis **23** from the equipotential surface **22** to a middle transverse plane **24** of the accelerating passageway **14** is preferably equal to the distance d_2 from the cathode emitter surface **7** to the midplane **24**. In this manner, the beam **3** converges and diverges axially symmetrically about the midplane **24** of the anode to preserve the laminar electron flow in the deceleration region between the accelerating electrode **4** and the depressed collector electrode **5**. Departures from laminar electron flow represent a spread in the velocities of the electrons of the beam **3** and results in collection of some of the electrons at higher velocities than desired, thereby contributing to inefficiencies in operation of the tube **1**.

In operation, the tube **1** of FIGURE 1 is an efficient switch tube. When operated as a switch tube **1** the cathode **6** and first grid **9** are operated at cathode potential, as of 10 to 200 kv., negative relative to the accelerating electrode **4** which is grounded. The collector electrode **5** is operated at ground potential in the "off" condition. To turn the tube **1** on the second control grid **11** is switched to a potential positive with respect to the cathode **6** by an amount which is roughly equal to the accelerating electrode-to-cathode electrode potential divided by the mu of the control grid. Because the resulting beam current flows through the load resistor of suitable value the collector electrode **5** is switched to a potential which is but a small percentage of the cathode-to-accelerating electrode potential, as of less than 10% of that potential, and preferably less than 2% of the accelerating electrode potential. With proper design of the tube for laminar electron flow and symmetrical beam convergence and divergence into the collector **5**, as above described, 98% of the beam current can be expected to be collected at 1% of the accelerating electrode potential. This will yield an accelerating electrode dissipation of 2% of the power in the load and a collector dissipation of 1% for a switch tube efficiency of 97% in the "on" condition. This is typical for an axially symmetrical structure with a beam permeance of 1×10^{-6}. The accelerating electrode **4** and collector electrode **5** are conveniently cooled by circulating a liquid coolant therethrough. A coolant jacket is depicted at **26** for cooling the collector structure **5**.

Referring now to FIGURE 3 there is shown an alternative embodiment of the tube **1** of the present invention. In this embodiment, the tube **1** is essentially identical to that of FIGURE 1 except that the beam focusing structure **21**, which projected toward the accelerating electrode **4** from the collector wall **18**, is replaced by a plurality of centrally apertured conductive disks **27** separated by insulator **28** and carried from the collector wall **18**. Independant operating potentials are applied to the disks **27** via leads **29** which pass through the high voltage insulator assembly **16**. By applying the proper potentials to the beam focus electrodes **27** relative to the collector potential, the electric equipotentials **20** and **22** are properly shaped as previously described, thereby preserving laminar electron flow in the decelerating region between accelerator **4** and collector **5** to obtain optimum depressed collector operation and, thus, tube efficiency.

Referring now to FIGURE 1 there is shown a radio frequency alternative embodiment of the present inventino. In this case, a cavity resonator structure **31**, only partially shown, is connected between the accelerating electrode **4** and the collector electrode **5** externally of the tube's vacuum envelope. For this case, the load is replaced by the resonator **31** in the manner as depicted in the schematic diagram of FIGURE 4.

A second resonator **32**, not shown in FIGURE 1, which is tuned to the same frequency as the output resonator **31**, is connected between the second control grid **11** and the cathode emitter **6**. A by-pass capacitor **33** is connected between the accelerating electrode **4** and the cathode **6**. An R.F. signal to be amplified, at the resonant frequency of the output resonator, is coupled into the input resonator **32** to produce an R.F. voltage between the second grid **11** and the cathode **6**. During the positive excursions of this voltage, beam current pulses will flow to the collector **5**. These pulses of beam current will excite the output resonator **31**. Amplified output R.F. energy is extracted from the ouput resonator **31** via coupling loop **34** and fed to a suitable utilization device or load, as shown.

The tube of FIGURES 1 and 4 which is adapted for R.F. operation will provide an efficient source of R.F. power up to several megawatts of R.F. power at frequencies up to several hundred mHz.

Referring now to FIGURE 5 there is shown an alternative embodiment of the present invention. In this embodiment, the tube is designed to have cylindrical symmetry and to operate with a radial flow of electrons **3'** from an axially disposed electron gun **2'** to a coaxially disposed surrounding collector structure **5'** with beam focus structure **21'**. The accelerating electrode **4'** is cylindrical and the axially disposed cathode emitter **6'** has an inwardly dished emitting surface **7'** forming a surface of revolution. The collector structure **5'** includes a hollow annular cavity **17'** for collecting the beam. The inner wall **18'** of the annular collector **5'** includes an annular beam passageway **19'** defining the mouth of the collector. An annular beam focus structure **21'** projects toward the accelerating electrode **4'** at the mouth of the collector **5'**.

The focus structure **21'** is formed and arranged so that it shapes the equipotentials in the decelerating region of the beam path **3'** to produce a series of equipotential surfaces at and preceding the mouth of the collector which are dished inwardly toward the collector structure. Such equipotential surfaces are shaped like the surfaces **20** and **22** of FIGURE 2 except that such surfaces are surfaces of revolution about the central axis of the tube rather than spherical surfaces as employed in the linear beam tubes of FIGURES 1–4. As in the embodiment of FIGURE 1, the electrodes **6'**, **4'**, **5'** and **21'** are dimensioned and shaped to provide a converging and diverging electron beam **3'** about the mid-cylindrical surface **24'** of the accelerating electrode **4'**.

The radial beam tube of FIGURE 5, which employs a radial beam **3'**, has certain advantages over the linear beam tube of FIGURE 1. More particularly, a higher beam current is obtainable because of the larger emitting surface **7'**. Secondly, due to the expanding cross sectional area of the beam **3'** as it nears the collector **5'**, the space charge density will be reduced to permit the collector potential to more nearly equal the cathode potential without reflecting electrons, thereby increasing the efficiency and lowering the forward potential drop of the tube in the "on" condition. The radial version of FIGURE 5 should permit a thirty fold, or greater, increase in peak beam current and power switched for a given supply voltage, the increase being limited only by the physical size (dia.) of the structure. The radial tube version of FIGURE 5 may also incorporate an output resonator for operation as an R.F. power tube.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, 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. A beam tube apparatus including, means forming a cathode electrode having an emitting surface for supplying copious electron emission, means forming an accelerating electrode spaced from said cathode electrode for accelerating electrons emitted from said cathode through a beam passageway in said accelerating electrode, said beam passageway in said accelerator having a smaller cross sectional area that the emissive surface of said cathode emitter, means forming a beam collector electrode structure spaced from said accelerating electrode for collecting the beam after passage through the beam passageway in said accelerating electrode, said collector structure being of the fly-trap type characterized by having a beam-collecting cavity portion with means forming a constricted beam entrance defining a mouth portion of said collector which opens into said beam collecting cavity of larger dimensions, said constricted beam entrance mouth portion serving to inhibit the escape of secondary electrons from said beam collecting cavity back toward said accelerating electrode, the improvement comprising, means forming an electric beam focus structure disposed at said mouth portion of said collector and in the intervening space between said mouth portion and said beam accelerating electrode for shaping the decelerating electric field equipotentials in the decelerating region of the beam path leading into said collector, and said beam focus structure being shaped and arranged to produce a series of electric equipotential surfaces across the beam path in between said accelerating electrode and said collector which in the presence of the beam are inwardly dished toward said collector and which series of equipotentials includes an equipotential at collector potential extending across said mouth portion of said collector, whereby approximately laminar flow of the electrons of the beam into said collector is obtained to provide efficient operation of the tube.

2. The apparatus of claim **1** including, means forming a control grid structure disposed adjacent said cathode and disposed sufficiently closer to said cathode than said accelerating electrode to provide a mu of at least 10.

3. The apparatus of claim **1** wherein the tube apparatus is a linear beam tube and the spacing from said cathode to said accelerating electrode's equipotential surface at the potential of said accelerating electrode on the beam path is approximately equal to the spacing between said accelerating electrode's equipotential surface on the beam path and said collector electrode's equipotential surface at the potential of said collector electrode on the beam path to produce a beam of electrons which converges through said accelerating electrode and diverges from said accelerating electrode into said beam collector with the near axial symmetry on opposite sides of the midpoint of said accelerating electrode.

4. The apparatus of claim **2** wherein said control grid structure is of the double grid type having a first grid structure disposed adjacent said cathode electrode and connected electrically to said cathode electrode to operate at the same electrical potential, and having a second grid structure disposed adjacent said first grid structure on the side facing said accelerating anode with its grid openings in axial alignment with the grid openings of said first grid, the spacing between said first and second grid structures being only a small fraction of the spacing between said cathode and said accelerating electrode, and means for applying a control potential to said second grid structure independently of the potential applied to said first grid structure, whereby control of the beam is obtained without intercepting beam current and without substantially perturbing the laminar flow of the electrons in the beam.

5. The apparatus of claim **2** wherein, the beam passageway in said accelerating electrode has a length taken in the direction of the beam which is greater than the smallest dimension of the beam passageway in said accelerating electrode taken in the direction normal to the direction of the beam, whereby the accelerating electrode provides an effective electrical shield between said collector electrode and said control grid electrode to prevent electrical coupling therebetween.

6. The apparatus of claim **2** wherein, said control grid electrode structure is centrally apertured in alignment with the center of the beam to permit positive ions and reflected electrons to pass therethrough without interception by said grid structure to prevent overheating of said grid structure.

7. The apparatus of claim **6** wherein, said cathode electrode includes a central aperture in alignment with the center of the beam to permit positive ions to pass therethrough to prevent ion bombardment of the electron emissive surface of said cathode electrode.

8. The apparatus of claim **1** wherein, said cathode electrode has an electron emissive surface facing said accelerating electrode which is dished inwardly of said cathode electrode, and said focus structure at said mouth of said collector being shaped to provide an equipotential surface at collector potential which extends across said mouth portion of said collector and which equipotential surface approximates the shape of the inwardly dished surface of said cathode electrode without substantial bowing thereof toward said accelerating electrode when said collector electrode is operated at a potential less than 10% of the full beam potential applied to said accelerating electrode and above cathode potential, whereby substantially all of the beam current is collected by said collector without producing an appreciable flow of electrons from said collector electrode back toward said accelerating electrode.

9. The apparatus of claim **8** wherein, said focus structure for providing the aforementioned collector electrode equipotential surface shape is an electrode structure insulated from said accelerating electrode and said collector electrode for operation with at least one electrical potential different than that of said collector electrode.

10. The apparatus of claim **2** including, means for simultaneously pulsing the potential of said control grid positive with respect to said cathode emitter and for pulsing the potential of said collector negative with respect to said accelerating electrode to provide an efficient switch tube apparatus.

11. The apparatus of claim **2** including, means forming a radio frequency resonator conductively connected between said accelerating electrode and said collector electrode for operation at the same D.C. potential as said accelerating electrode and said collector electrode but for establishing different radio frequency potentials therebetween whereby an efficient source of radio frequency power is obtained when said control grid electrode is excited with a radio frequency potential at the resonant frequency of said radio frequency resonator.

12. The apparatus of claim **1** wherein said cathode emitter, said accelerating electrode and said collector electrode structure are all concentrically disposed with respect to each other, and the electron beam passes radially outwardly from said cathode emitter to said collector electrode structure, whereby the power handling capacity of the tube is greatly increased.

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