

Aug. 7, 1945.

R. V. L. HARTLEY
ELECTRON DISCHARGE DEVICE

2,381,539

Filed March 28, 1941

3 Sheets-Sheet 1

FIG. 1

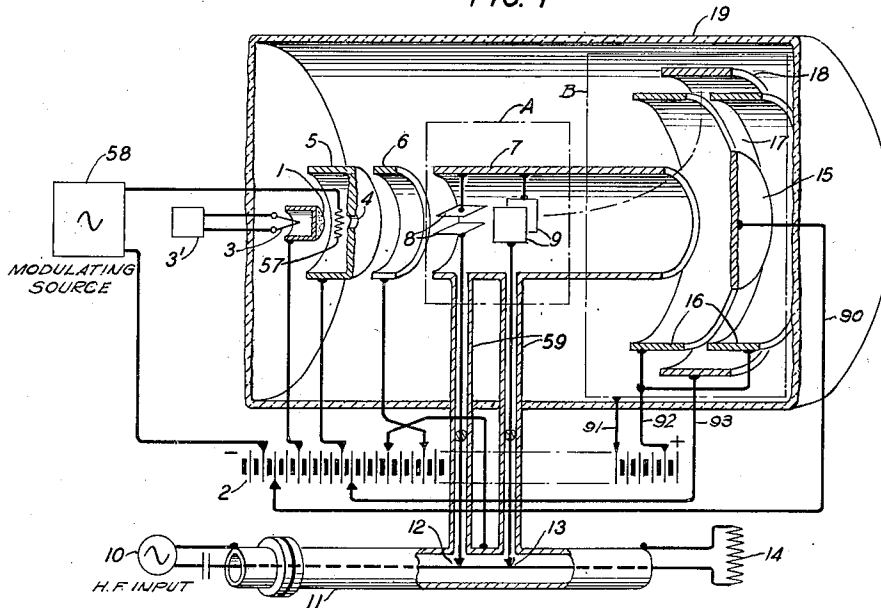


FIG. 2

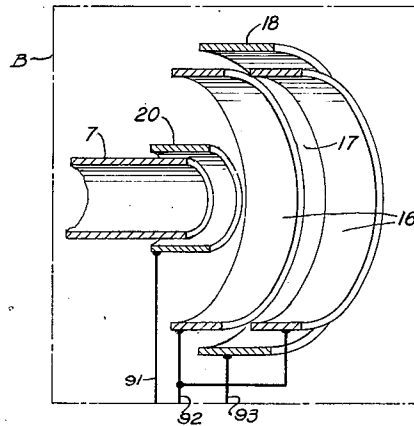
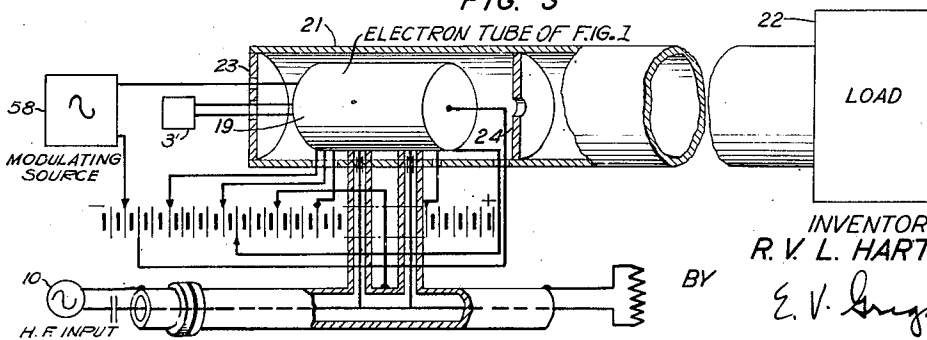


FIG. 3



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FIG. 4

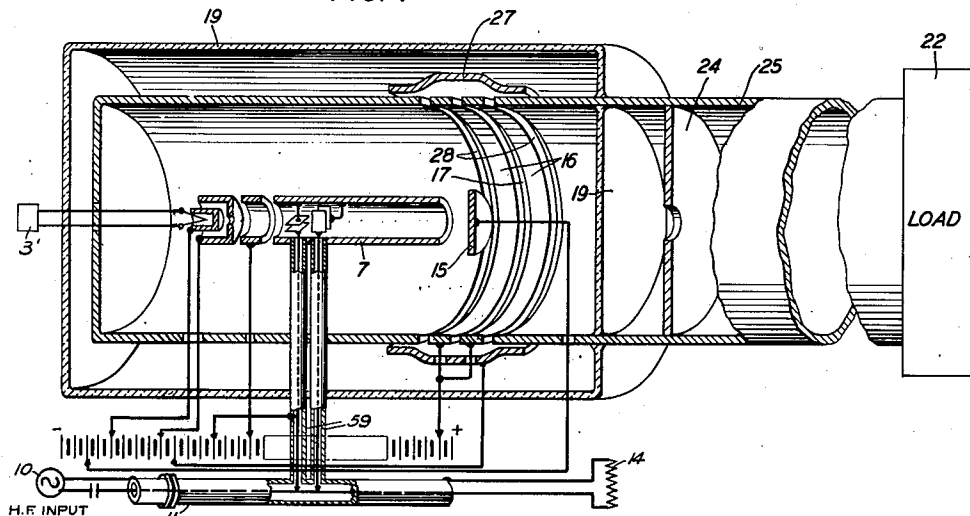


FIG. 5

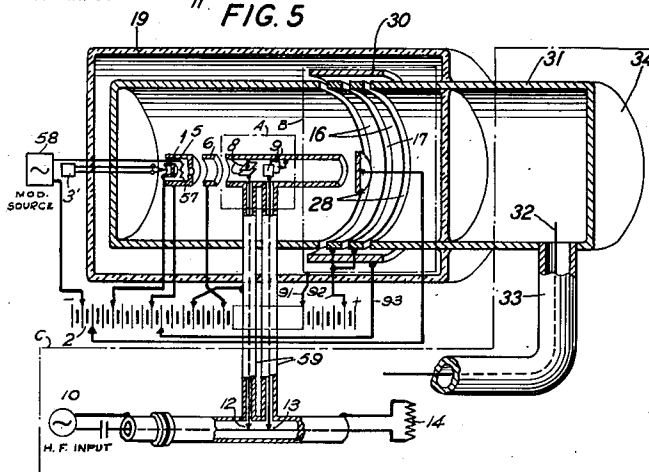


FIG. 6

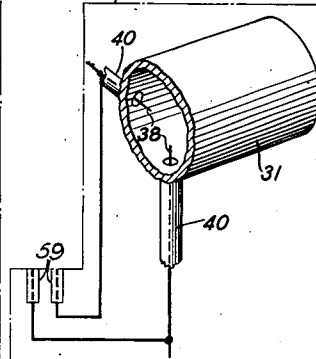


FIG. 7

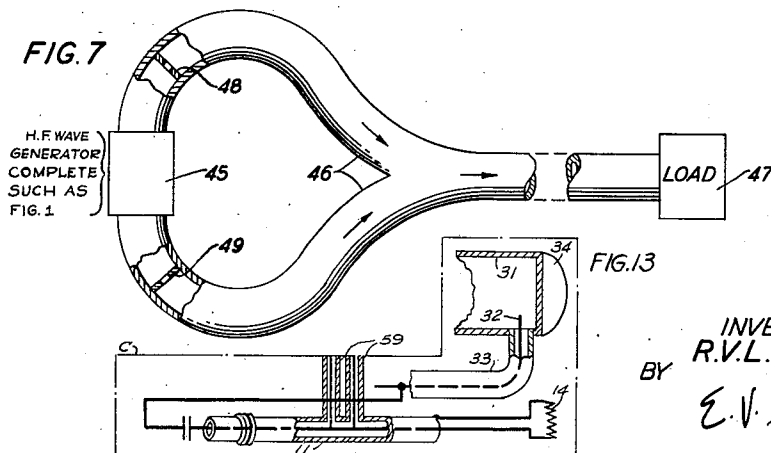
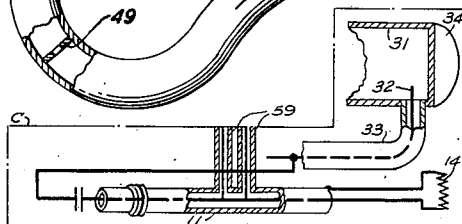


FIG. 13



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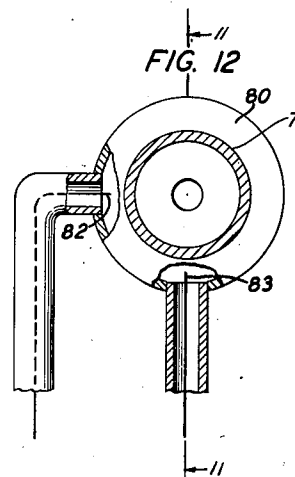
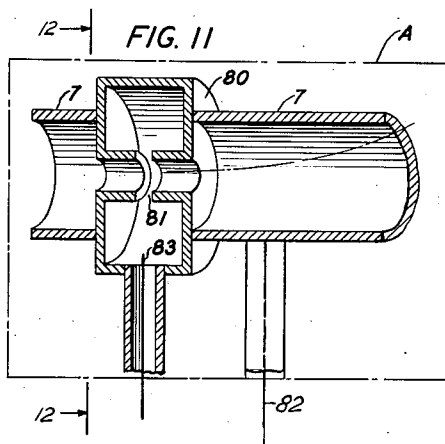
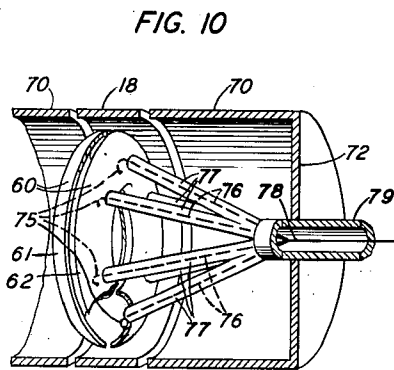
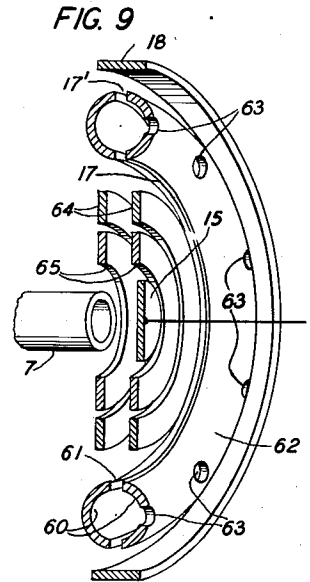
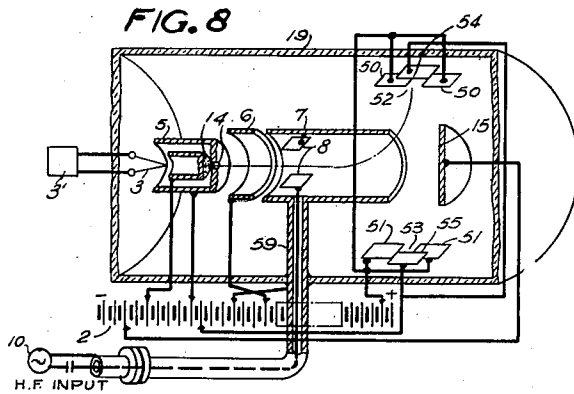
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ELECTRON DISCHARGE DEVICE

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3 Sheets-Sheet 3



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2,381,539

ELECTRON DISCHARGE DEVICE

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Application March 28, 1941, Serial No. 385,629

30 Claims. (Cl. 315-5)

This invention relates to methods of generating amplifying, modulating, and radiating ultra-high frequency waves, and to circuits including space current devices adapted for carrying out these and other operations.

In most prior art devices of the space current type for generating ultra-high frequency waves, the space current delivers energy to the generated waves at a rate which varies during the cycle, instead of delivering energy to the wave at a constant rate. For example, in the case of waves generated in accordance with the velocity variation principle, the space current delivers energy in spurts of a duration not exceeding one-half a cycle of the generated wave. Similarly, in various forms of generators, the space current delivers energy impulsively, rather than a constant flow.

Because of the irregular transmission of energy by the space current, considerably higher space current voltages are required during intervals when energy is being supplied for the generation of waves of given power than would be the case if there were no irregularity. The relatively high voltage needed in any event for producing the space current, even without the irregularity of conversion of space current energy into the desired waves, results in relatively large losses of energy as well as transients and other objectionable phenomena at the anode, due to the high velocity of the electrons when striking the anode, and this difficulty is greatly increased by the irregular energy conversion. Because of the heat produced by the electron impacts, the power output of a given size of device is definitely limited by overheating and the accompanying destruction of the anode and adjacent parts of the generating device. Similar difficulties are experienced in various other ways because of the spasmodic, rather than continuous conversion of energy, in somewhat the same way that a reciprocating engine involves difficulties not experienced with a turbine.

Another serious problem from the standpoint of engineering and economics when converting space current energy into desired wave energy, particularly at ultra-high frequencies, is the complication of providing suitable transmission and coupling circuits between the electrodes of the space current device and the output terminals.

Some of the objects of the present invention are to reduce or avoid the above-mentioned difficulties, in whole or in part; to establish an efficient and convenient energy transfer relation between a beam of electrons and an electromagnetic wave field; to generate, modulate, amplify,

or radiate high frequency wave energy in a simplified manner and with improved efficiency; to convert direct current energy into ultra-high frequency wave energy at a constant rate rather than at a variable rate during each cycle; to provide efficient space current devices and circuits of relatively simple construction for accomplishing any of the above-mentioned objectives; to distribute electron impact losses and so reduce heating at the anode; to provide a source of ultra-high frequency waves particularly adapted for transmission to wave guides; and to generate waves of exceptionally high frequency and power.

In accordance with one specific illustration of an ultra-high frequency generator to be described, a continuous direct current, consisting of a beam of high velocity electrons, is cyclically deflected at an ultra-high frequency by rotating the beam about an axis substantially normal to the beam, like a single spoke in a rotating wheel, thereby generating and directly radiating a circularly polarized output wave in the direction of the axis around which the beam rotates.

One form of space current device adapted for this operation, may include a gun from which an electron beam is projected axially through an accelerating cylinder coaxial with the gun and containing polyphase deflector plates for deflecting the beam in a path which rotates around the gun axis. A retarding electrode outside the electron exit end of the cylinder, has such a potential and position that the electrons lose their velocity axially of the cylinder before reaching the retarding electrode. The electrons at a position in the beam after losing their velocity axially of the cylinder then constitute a continuously rotating virtual cathode of the general dimensions of the beam. Concentric with this cathode are one or more accelerating electrodes, preferably a pair of short cylinder electrodes of relatively large radius for highly accelerating the electrons from the virtual cathode radially outward toward a slot between the pair. Concentric with the slot and radially outside it is an anode for collecting the spent electrons.

Rotation of that part of the electron beam projected from the virtual cathode by the pair of accelerating electrodes, causes that part of the beam to radiate electromagnetic waves of the frequency of rotation. The relation of the radiated wave to the beam of electrons producing it, is such that the direction of the electric field of the wave at the beam, moves substantially in synchronism with the direction of the electron flow in the beam, the resulting reaction of the electric field of the wave on the beam being such as to

oppose and reduce the velocity of the electrons to a maximum degree, thereby causing the electric field of the wave to continuously absorb energy directly from the beam throughout each cycle, and at a substantially constant rate throughout each cycle. A wave guide or other form of load may be arranged to receive the radiated wave and by making the load resonant the opposing field is enhanced and the absorbed energy increased. After the electrons have transferred to the radiated wave, a part of their energy of propulsion, they are collected at the anode. A relatively small increment of positive potential over that of the cathode is employed at the anode to further retard the electrons before their capture and so minimize the energy losses and heating from electron impact on the anode. Local heating of the anode is further minimized due to the fact that the electron impacts are cyclically distributed over the anode surface. A plane polarized wave may be directly generated in a similar manner in a modified form of device in which the beam of electrons is cyclically deflected through preferably 180 degrees, so that the beam vibrates back and forth between two pairs of accelerating plates.

Modulation of the generated wave may be accomplished by applying the modulating wave to a grid for varying the amount of current in the electron stream while generating the ultra-high frequency waves. Amplification of a modulated ultra-high frequency carrier wave may be obtained by utilizing a relatively thick beam from the electron gun and so producing a disc-like space current stream, diffusing radially outward as a sheet from the position of the virtual cathode, and deflecting in a rotating path the virtual cathode at the center of the disc by means of a rotating field excited by the modulated carrier waves. Amplification may also be obtained by producing a beam of electrons and rotating the beam at the carrier frequency in the plane normal to the wave axis through rotation of the virtual cathode as previously described, while effective length of the rotating beam is varied in accordance with the modulations of the carrier waves, the rotation of the virtual cathode being caused by the carrier waves and the radii of rotation being determined by the modulation.

In one modification, very high frequency waves are produced in a toroid, formed like a pipe bent into a continuous ring, the toroid being divided into two identical rings by a slot where the radial plane of the toroid intersects the pipe. The toroid is placed so that its slot is concentric with the virtual cathode rotating at ultra-high frequency. The toroid is made highly positive to project the beam of electrons at high velocity through the slot. The ultra-high frequency of rotation of the beam is such relatively to the dimensions of the toroid that harmonics of the frequency of rotation are generated within the pipe and circulate progressively around within the pipe. The resulting radiations may be transmitted from the pipe through equally spaced windows in one of the halves of the toroid, so that the resulting effect of all of the windows together is like that of an antenna array concentrating the total radiation in a desired direction, as, for example, into a wave guide.

These and other features and objects of the invention will be understood by reference to the following detailed description of certain illustrative forms in connection with the accompanying drawings.

In the drawings:

Fig. 1 is a schematic diagram showing in partial axial section an ultra-high frequency wave generator of the space current type;

Fig. 2 is a diagram showing a different electrode arrangement for the Fig. 1 device;

Fig. 3 is a diagram showing how the Fig. 1 device may be inserted within a wave guide;

Fig. 4 is a diagram showing how the wave guide of Fig. 3 may be made a part of the Fig. 1 device;

Fig. 5 shows a modification of the Fig. 4 arrangement employing an electrostatic probe;

Fig. 6 is a diagram of an arrangement of probes for deriving a two-phase current from a circularly polarized wave;

Fig. 7 is a diagram showing an arrangement for merging two oppositely directed waves into a unidirectional wave;

Fig. 8 is a diagram showing a modification of Fig. 1, using flat accelerating and collecting electrodes for producing a plane polarized wave;

Fig. 9 is a diagram of a modified embodiment for producing waves of a frequency harmonic to a fundamental of high or ultra-high frequency;

Fig. 10 is a diagram showing a modification of Fig. 9, employing an array of probes for leading off the generated harmonic waves;

Figs. 11 and 12 show two views of a cavity deflector for use in place of deflecting plates as illustrated in Fig. 1 for deflecting the electron beam leaving the cathode; and

Fig. 13 shows a modification of Fig. 5 wherein the device is made self-excited by exciting the input with a feedback connection from the output circuit rather than from an external high frequency input source.

In Fig. 1 the cathode 1 is adjustably connected with a point near the negative end of the battery or other source of direct current energy 2. The element 3, heated by the source 3', causes cathode 1 to emit electrons which are projected through the beam defining aperture 4 on the axis of gun electrode 5, and then successively through the positively charged accelerating electrodes 6 and 7 of hollow cylindrical form, coaxial with electrode 5. The positive potentials of electrodes 5, 6, 7, are adjusted individually by a separate tap on source 2 for each electrode. Electrodes 6 and 7 have much higher positive potentials than electrode 5, and electrode 6 is usually made more positive than electrode 7 to provide with electrode 7 a converging lens in order to focus or concentrate the beam at a suitable point remote from cathode 1.

A pair of plate electrodes 8 for deflecting the electron stream in a vertical plane and another pair 9 at right angles thereto for deflecting the stream in a horizontal plane, are provided in well-known manner for connection with a two-phase source of waves derived from the source of high frequency excitation of the device, to cyclically deflect the stream in a path which rotates continuously about the gun axis, once for each cycle of the wave. One electrode of each pair 8, 9, is connected by way of cylinder 7 and the outer conductors of the coaxial cables 59 with a single adjustable tap on source 2 and with a terminal on the outer conductor of the coaxial cable 11 common to the two phases, the other electrode of each pair 8, 9, being connected respectively, by the inner conductors of the coaxial cables 59, with the other terminals of the two-phase source which differ in phase by 90 degrees. The amount of deflection of the beam

and the length of the cylinder 7 are so chosen that the beam emerges from the cylinder near the periphery thereof but without striking it.

A convenient two-phase supply consists of a single phase source 10 of ultra-high frequency waves connected with a coaxial cable 11, the outer conductor of which forms the terminal common to the two phases, while the inner conductor is provided with two adjustable taps 12 and 13, differing in phase by 90 degrees. The cable is terminated with a surge impedance 14, for preventing reflection of waves back toward the source 10. Any other suitable form of two-phase source may be supplied in place of that shown. It will be understood that the leads from points 11, 12, 13, to plates 8, 9, should be of such length that they do not introduce any departure from the desired phase quadrature relation between the waves on plates 8 and 9.

An alternative to the two pairs of plate electrodes for deflecting the beam of the electron gun is an electrical resonator placed near the cathode end of the cylinder 7 in place of the plate electrodes as shown at 8 and 9 in Fig. 1. This resonator may be of the cylindrical reentrant type, as illustrated in Figs. 11 and 12. Fig. 11 is a modification of the portion of Fig. 1 included within the dotted line A and may be substituted for that portion in Fig. 1 or the similar portion in Fig. 4 or Fig. 5. Fig. 12 is a view at right angles to the view of Fig. 11 to indicate clearly a method of excitation of the resonator. The resonator, 80, must be constructed of electrically conducting material and be dimensioned to support within it at the frequency of excitation of the device a circularly polarized wave such that the electric lines of force extend in diametric directions. Such a circularly polarized wave produces a rotating electric field which extends through the gap 81 into the path of the electron beam. The rotating field acts upon the electron beam traversing it to deflect the beam and rotate it cyclically in the same manner as the beam in a cathode ray tube is rotated by two pairs of plate electrodes energized in phase quadrature as illustrated in Fig. 1. The circularly polarized wave may be induced in the deflecting resonator by means of probes 82 and 83 spaced 90 degrees apart around the periphery of the resonator as shown in Fig. 12 and energized in phase quadrature from the excitation source, for example, in the same manner as the plates 8 and 9 are connected to source 10 through taps 12 and 13 in Fig. 1. This type of deflector may be employed in any embodiment of the invention where circular deflection of the electron beam is desired. The same general type of resonator deflector may be used to obtain deflections back and forth in a single plane, such as obtained with a single pair of deflecting plates and illustrated in Fig. 8, by producing in the resonator a plane polarized wave, rather than one circularly polarized by energizing it from a single phase source as may be done utilizing only a single probe, such as 83 alone.

The circular retarding electrode 15 of disc form, normal to and coaxial with the axis of gun 5, is positioned near to but spaced slightly beyond the end of electrode 7 through which the electron beam is projected, and is connected through an adjustable tap with source 2 at a point polarizing the electrode at a sufficiently negative potential with respect to cathode 1, to make all the electrons in the beam lose their axial velocity before reaching electrode 15. The motion of electrons along the gun axis toward electrode 15 is thus completely stopped, so that the beam is abruptly

deflected or bent into a path positioned approximately in a radial plane of the gun axis, between electrodes 7 and 15, without suppressing the deflections of the beam radial to the axis. The electron beam, at the place where it loses its axial velocity, thus constitutes in effect a continuously rotating virtual cathode, having an emission surface area equal to the cross-section of the beam, the plane of rotation being normal to the gun axis around which the cathode rotates at the ultra high frequency.

A hollow cylindrical accelerating electrode 16, of substantially larger radius than that of electrodes 7 and 15 and the virtual cathode, is preferably divided into two parts, constituting a pair of axially short rings, separated by a narrow slot 17, extending continuously around between the rings, concentrically with the point on the gun axis around which the virtual cathode rotates. Electrodes 16 are connected together to have the same potential and have an adjustable tap on source 2 for charging them to a sufficiently high positive potential to draw all the electrons radially out from the virtual cathode and accelerate them toward and through the slot 17, and to cause the electrons to traverse the radial distance in a small fraction of the period of the ultra high frequency wave to be generated. The direction of the radius taken by a particular electron, is determined by the position at which the electron emerges from cylinder 7, and hence depends on the phase of the wave which deflects the beam. The radial beam therefore rotates once for each cycle of the deflecting wave. It will be seen that the energy of radial motion of the electrons in the beam is derived practically entirely from the source of direct current 2, and not from the deflecting wave.

The cylindrical electrode 18, disposed radially outside the slot 17, serves as an anode to terminate the electron stream, the anode having an adjustable tap connection on source 2 for polarizing the electrode with just sufficient positive potential to capture all the electrons passing through slot 17, the potential of electrode 18 being considerably less positive than rings 16. An envelope 19 of suitable insulating material, such as glass of low dielectric loss, is provided around the electrodes of the device for maintaining a suitably high vacuum for operation of the device.

The electron beam rotating in the radial plane about the axis of rotation which is the axis of the device, generates a circularly polarized electromagnetic wave which may be propagated along the axis of rotation and normal to the plane of rotation.

Since the electric field of the wave generated by the beam is in phase with the beam, it reacts on the electrons in the beam in directions opposing their radial outward flow, thus slowing their radial velocity and increasing the intensity of the electric field. The direct current energy of the beam is thus converted directly into radiated ultra high frequency wave energy.

The high frequency energy thus drawn from the electron beam is proportional within limits to the strength of the high frequency electric field by which the motion of the electrons in the beam is opposed, or, in other words to the impedance of the load coupled to the electron beam. If the high frequency energy is radiated directly into free space the load impedance is low and the energy transferred will be relatively small. Consequently, it is desirable to utilize a resonator in which a standing wave may be produced to

enhance the strength of the high frequency electric field where it interacts with the electron beam thus increasing the impedance of the load and allowing more energy to be given up by the beam to the high frequency wave with which the field is associated.

In order that the electric field of an electromagnetic wave may serve effectively at the rotating electron beam, as a means for increasing the radiation from the beam, it is necessary only that the beam rotate concentrically with the electric field of the wave, that the beam and the electric field rotations be of the same frequency, and that the beam and field be phased so that the field opposes the radially outward motion of the electrons. Under these conditions, all of the electrons traverse the maximum voltage developed across the load. Since all of the electrons traverse substantially the same retarding field, they reach the end of their radial path with the same velocity, and therefore may be retarded and captured at low velocity by the same increment of positive potential above the potential of the cathode 1.

The intensity of the generated high frequency electric field may be enhanced, as previously suggested, for example, by reflection of the generated wave back on the beam in proper phase, as where the generator is enclosed within a wave guide, to be referred to in more detail in connection with Figs. 3 and 4. In any event, the load should be so coupled with the generator of Fig. 1, that the electrons of the rotating beam traverse the electric field of the load before reaching the slot 17.

The potential of electrode 6 is preferably adjusted so that the electrons come to a focus or are concentrated at a point near the slot 17, so that the electrons may readily pass through the slot. Since the potentials of cathode 1, accelerating electrodes 6, 7 and 16, anode 18, and retarding electrode 15, are substantially constant, the flow of direct current energy into the electromagnetic wave is continuous throughout the cycle of rotation, the energy flow being at a substantially constant rate throughout the cycle of the ultra high frequency wave, as contrasted with the spurts of energy of maximum duration of one-half a cycle in generators of the velocity variation type. It is therefore possible to employ a minimum voltage for driving the space current through the device to produce a given amount of output power, as compared with prior devices wherein undesirably large spurts of energy are required in order to produce the same power averaged over the cycle. Since all of the electrons approach the anode 18 with the same velocity, they may be brought more nearly to rest before striking the anode than they can in devices where the velocity of the used electrons varies over the cycle, so that dissipation of energy at the anode is kept to a minimum and the heating of the anode may be made relatively small. The problem of dissipating the heat is further relieved by the fact that the place of impact of the electrons is continually moving away from the most heated spot, while the total heat radiating area is relatively large. Because of the simplified problem of heat dissipation, larger electron currents and higher voltages may be used than in devices having a fixed point of electron impact.

Since the circuits employed may be of the efficient resonant cavity type and the transfer of energy from the electron beam to the high frequency circuit is continuous throughout each high

frequency cycle, a very high efficiency of conversion of direct current energy into ultra high frequency wave energy is achieved.

In case it is found difficult to provide a lead to the retarding electrode 15 in such a position that the lead does not lie parallel to the electric field of the wave being radiated, the disc 15 may be replaced by a hollow cylinder retarding electrode 20, as shown in Fig. 2. The cylinder 20 is positioned radially just outside of the deflection cylinder 7 to expose the electron stream to such a force, as a result of the positive charge on cylinder 20, that the electrons lose all the axial velocity with which they emerge from cylinder 7. Fig. 2 is a modification of the portion of Fig. 1 included within the dotted line B and may be substituted for that portion in Fig. 1 or in the similar portion of Figs. 4 or 5. Also in Fig. 8 or Fig. 9 an electrode such as 20 may be used instead of electrode 15. It will be noted that Fig. 1 shows an unused battery lead 91. When the Fig. 2 modification of Fig. 1 is used this lead connects to electrode 20 of Fig. 2 and then since there is no electrode 15 the lead 90 formerly connecting to 15 is unused. This changing of leads when electrode 20 is substituted for electrode 15 is necessary because 15 is negatively charged and 20 must be positively charged (more so than tube 7).

Fig. 3 shows a wave guide 21 in the form of a pipe within which the space current device 19 of the type shown in Fig. 1, may be placed coaxially of the pipe, to transmit ultra high frequency waves through the pipe to load 22, the radius of the pipe 21 being such that the frequency range of transmission of the pipe coincides with the frequency range of waves to be radiated by the generator 19. Since the radiation produced by device 19 is bidirectional along the axis of the device, one end of pipe 21 may be closed by a radial reflector 23, so positioned on the axis of device 19 that the reflected wave reaches the radially flowing part of the electron stream in device 19 in phase with the wave being radiated directly by the stream, thus providing a unidirectional transmission characteristic of correspondingly increased energy. The iris diaphragm 24 is positioned to the right of the radially flowing part of the electron stream as the reflector 23 is to the left of it to form a resonant chamber between 23 and 24, such as to produce an intense high frequency field for interaction with the electron stream. The coupling between this resonant chamber and the portion of guide leading to the load 22 is determined by the size of the opening in the diaphragm 24. Therefore, the iris diaphragm and the resonant chamber together form an impedance transforming element between the electron stream and the wave guide on the opposite side of the diaphragm.

The circularly polarized wave generated in and radiated by the device 19 in guide 21, is of the H_1 type, characterized by the fact that the electric component of the wave oscillates along a diameter of the pipe through which the wave is transmitted, there being no electric component of the wave axially of the pipe. The circularly polarized wave generated by the device 19, may be looked upon as being a combination of two H_1 type of waves, each of the waves being plane polarized and propagated in the same direction in such phase relation that one may be considered to have its electric component displaced 90 degrees around the propagation axis from the corresponding electric component of the other wave.

The combination of the two H_1 waves, assuming for the moment that there is no reflected wave, takes the form of a circularly polarized wave in which the combined electric component at any one point on the propagation axis is of constant intensity and rotates around the propagation axis with the same direction of rotation as the beam of electrons which produced the wave. When the radiated wave is reflected back on itself, in a resonant chamber, and attenuation may be neglected, the resulting standing waves are characterized by different values of the combined electric component at points along the axis of wave propagation in the chamber between alternate loops and nodes, the combined component at any one point on the axis remaining of constant value and rotating about the axis at that point in the same direction as the rotation of the electron beam. By utilizing reflection and resonance effects accompanying reflection in a resonant chamber or cavity, very intense electric fields may be produced in phase with the rotating electron beam, so that an efficient and continuous transfer of energy may be made to take place from the direct current of the beam to the high frequency wave radiated to the load.

Fig. 4 shows the wave guide 25 in which the accelerating electrodes 16 form a part of the pipe 25. The envelope 19 surrounds the electrodes and encloses one end of the guide, the guide being sealed to the envelope 19 by well-known methods of sealing a metal tube passing through a vacuum sealing wall. Electrodes 16 are separated axially from the walls of pipe 25 by narrow slots 28 for purposes of insulation, but may otherwise be looked upon as being a continuation of pipe 25. Anode 27 is shown with a slightly smaller diameter at the edges of the cylinder than in the central portion thereof, in order to reduce the gap between anode 27 and pipe 25, and the leakage of radiated wave energy which might otherwise occur. The elements 25 and 27 are radially spaced apart slightly to provide suitable insulation space therebetween. The circuit and general operation of the Fig. 4 device is similar to that of Fig. 3. However, the modulating source 58, grid 57 and the connections thereto are omitted from Fig. 4 to simplify the figure.

Fig. 5 shows a slight modification of Fig. 4, in which the anode 30 is made of smaller radius than anode 27 in Fig. 4, so that the gap between anode 30 and pipe 31 may be made suitably small without varying the radius of cylinder 30 along the axis. An electrostatic pick-up probe 32, extending from within the pipe 31, forms the inner conductor of a coaxial cable 32, 33, for transmitting ultra high frequency waves from the guide to some desired load, and may be utilized in place of the source 10 in Fig. 1, for maintaining rotation of the electron beam. The probe 32 and cable 33 may thus constitute a feedback circuit, causing the device to operate as a self-excited oscillation generator. Fig. 13 is a modification of the portion of Fig. 5 included within the dotted line C which may be substituted for that portion of Fig. 5 to show such a feedback connection for operating the device as a self-excited oscillation generator. If desired, the reflector 34, disposed radially of pipe 31, may be provided to close one end of the pipe at such a position that the enclosed space becomes a resonant chamber for increasing the intensity of the electric field at the rotating electron beam, the field being in phase with the beam. When reflector 34 is used, the

probe 32 is preferably placed at a voltage loop in the pipe chamber 31.

Fig. 6 is an alternative modification of the portion of Fig. 5 included within the dotted line C which may be substituted for that portion of Fig. 5 to show operation of the device as a self-excited oscillation generator. In Fig. 6 the pair of electrostatic probes 38, are positioned in the same radial plane in pipe 31, but are angularly disposed 90 degrees apart around the axis of the pipe, and thus constitute with pipe 31, a source of two-phase current. The probes 38 are brought out from pipe 31, as the inner conductors of the coaxial cables 40, and may be connected respectively, with one of the electrodes of each pair 8, 9, of Fig. 1, as a substitute for source 10 and tap connections 12, 13. The outer conductors of cables 40 provide the common connection of conductor 11 for the other electrode of each pair 8, 9, in Fig. 1.

Fig. 7 shows a space current device 45, similar to Fig. 1, having a separate wave guide 46 connected with each end thereof. The guides 46 are curved around to join each other at a position where the phases of the waves in the two guides 46 are the same, so that the bidirectionally radiated waves coming from generator 45 of the Fig. 1 type, are combined into a single unidirectional wave which is transmitted to the load 47. The iris diaphragms 48 and 49 are positioned from the radial electron stream in device 45 and from each other to form a resonant chamber between 48 and 49 and to produce an intense high frequency field for interaction with the electron stream as has been described previously in connection with Fig. 3.

Fig. 8 shows a modification of Fig. 1 for directly producing a plane polarized wave of the H_1 type, instead of a circularly polarized wave produced by the Fig. 1 device. The figure is to indicate the variations from Fig. 1 and in operation the showing of Fig. 8 would be enclosed in a resonant cavity or wave guide portion as illustrated in Figs. 3, 4 and 5. The modulating source 58, grid 57 and the connections thereto are omitted to simplify the figure. The pair of cylindrical electrodes 16 of Fig. 1 are replaced by two pairs of flat plate electrodes 50 and 51. Electrodes 50 are adapted to accelerate the electron beam in a vertically upward direction, while electrodes 51 are adapted to accelerate the beam in a vertically downward direction. The electrodes 50 are separated by a slot 52, and the electrodes 51 by a slot 53, the slots 52, 53 corresponding in function and location with the slot 17 of Fig. 1. The cylindrical accelerating electrodes 6, 7, and the retarding disc electrode 15 are coaxial with gun electrode 5, as in Fig. 1. A flat plate electrode 54 is positioned radially outside the slot 52, and a similar flat plate electrode 55 is positioned radially outside of slot 53, electrodes 54 and 55 serving as anode for collecting the spent electrons passing through slots 52 and 53, respectively. A single pair of deflecting plates 8, is provided for oscillating the electron beam back and forth in a vertical plane, alternately to anodes 54 and 55, thereby generating a plane polarized wave of the H_1 type. When operating the Fig. 8 device to react on a plane polarized wave, the beam should be made to deflect in phase with the electric field of the wave, so that the field of the wave opposes the flow of electrons in the beam. It will be seen that the efficiency of the generator of the plane polarized wave type, shown in Fig. 8 will be less than that of the rotating beam

type of generator as shown in Fig. 1 since in the Fig. 8 device, some of the electrons will flow when the field of the load is zero, while only a very few electrons will flow when the field of the load is at the maximum value.

For the purpose of modulating the wave generated by the device of any of the figures described above, the magnitude of the electron stream may be varied in accordance with the modulating wave by means of a grid 57, preferably located near the cathode 1, for example between the electrodes 1 and 5, as shown in Fig. 1. The modulating wave from the source 58, is impressed between the grid 57 and cathode 1, by way of an adjustable tap on source 2 for polarizing the grid negatively with respect to cathode 1.

For the purpose of amplifying a wave which is already modulated, as in a repeater, the electron stream in Fig. 1 may be adjusted to an unfocused condition, so that in the absence of a deflecting potential on the plates 8, 9, the stream is diffused uniformly outward from the axis of the electrode 7 into a radial plane passing through the slot 17. The electrons emerging from cylinder 7 therefore spread over a circular area normal to the gun axis, as a uniform sheet which contributes no energy to the load in the absence of a variable deflecting potential on plates 8, 9. A modulated carrier wave applied as a deflecting wave to the plates 8, 9, then causes the place, where the electrons enter this circular area of the electron path, to rotate about the gun axis with a varying radius, thereby unbalancing the radial stream in accordance with each cycle of the carrier wave and the modulations thereof. As a consequence of the unbalanced components of the radial electron stream, which have the effect of rotating around the gun axis at the wave frequency rate, an electromagnetic wave of corresponding frequency is radiated along the axis of the device with amplified energy, as compared with the relatively small energy required to cause the center of the stream to rotate about the axis.

Another method of amplifying a modulated carrier wave, is to focus the electron beam as described in connection with Fig. 1, and to apply such large deflecting potentials to the plates 8, 9, that the stream of electrons emerges from cylinder 7 at a distance from the axis of the cylinder which is a considerable fraction of the radius of the pipe through which the waves are to be transmitted. Variations in the amplitude of the deflecting waves, corresponding with the modulations thereof, then cause the rotating radial beam to traverse a varying fraction of the field of the load, and so give up correspondingly variable amounts of energy to the load, the energy thus given up representing an amplification of the original wave.

Fig. 9 shows an arrangement of electrodes adapted for substitution in the device of Fig. 1 to permit the generation of waves which are harmonic to the frequency of rotation of the electron beam. The pair of ring electrodes 16 of Fig. 1, are replaced by a toroid 60 in the form of a metallic pipe bent into a continuous ring, concentric with the center of the rotating virtual cathode between electrodes 7 and 15. The toroid is interposed in the path of the radial beam of electrons, and has a circumferential slot 17, 17', where the radial plane of the toroid intersects the pipe, thus dividing the toroid into two rings 61, 62, disposed respectively on opposite sides of the plane of rotation of the electron beam. The electron beam is projected radially through the

slot in response to a high positive accelerating potential applied to the toroid through an adjustable tap on the source 2, as in the case of the rings 16, Fig. 1. The anode 18 collects the spent electrons as in Fig. 1.

In order that a plane polarized wave of the H₁ type may be set up to progressively circulate along the pipe of the toroid within the cavity of the pipe, the plane of the electric vector being parallel to the toroid, the frequency of such a wave should be high enough for the wave to be transmitted effectively by the pipe. Furthermore, the length of the pipe and the mean circumference of the toroid, should be made equal to an integral number of wave lengths of such a wave. The electrons passing through the slot 17, 17', of the pipe oppose the direction of the field of the waves set up in the pipe. By adjusting the frequency of rotation of the electron beam in the plane passing through the slot, so that the point of transit of the electrons rotates with the same speed as the wave travels in the pipe, the electrons will always pass through a point where they give up a maximum amount of energy to the wave. The frequency of the field at any point in the pipe will be a multiple of the high frequency or ultra high frequency of rotation of the electron beam, and is determined by the number of wave lengths measured around the pipe. The electron beam in this manner can support a whole series of waves whose frequencies are in harmonic relation to the high frequency of rotation of the beam.

In order to select a desired one of the resulting harmonics and to suppress others, the energy to be withdrawn from the pipe is removed at properly selected points thereon. For example, in order to obtain an output wave having a frequency ten times that of the beam rotation frequency, ten points equally spaced around the toroid 60, are provided with circular holes 63, serving as openings through which desired energy may escape in the form of radiation or preferably through which probes may be inserted to remove the desired energy through coupling with the high frequency field within the toroid. Undesired harmonics adjacent to those being selected, are in such phase relation relatively to the openings that destructive interference takes place to oppose their transmission.

Any tendency to generate frequencies much below the desired harmonic, may be counteracted also by making the cut-off frequency of the toroid pipe only slightly lower than the desired frequency. The electrons in the beam should be accelerated to such a high velocity that they traverse the diameter of the pipe in a small fraction of the period of the desired harmonic wave.

By means of the Fig. 9 modification, the beam may be rotated at a high frequency below the ultra high frequency range to generate ultra high frequency waves as harmonics of the beam rotation frequency, or the beam may be rotated at an ultra high frequency to generate much higher frequency waves, not readily obtainable by the usual types of generators. One of the advantages of the Fig. 9 form of generator is that no metallic parts other than for coupling probes are required within the resonant chamber of the pipe.

A pair of flat focusing rings 64, of smaller radius than toroid 60, and another pair of similar rings 65 of smaller radius than rings 64, may be provided if desired, to improve the concentration of the beam and to direct it more effectively to pass through the slot 17, 17'. The rings in each pair

64, 65, are coaxial with cylinder 7 and are symmetrically disposed on opposite sides of and close to the radial path of rotation of the electron beam. Each of the rings 64, 65, has an adjustable tap connection (not shown) with source 2, to charge the rings positively at potentials which are intermediate between those of electrodes 7 and 60, the rings 65 being more positive than rings 64 when the adjustment of the beam calls for an electron lens system adapted to converge the beam toward the slot 17, 17'. It will be understood that the rings 64, 65, need not be provided unless improved focusing of the beam is desired.

High frequency energy radiated through the holes 63 may be directed into a resonant wave guide or cavity by placing the device coaxially in the guide or cavity as illustrated for the Fig. 1 device in Figs. 4 and 5. In the preferred method of removing high frequency power from the toroid where it is not desired to use the holes 63, Fig. 9, as a means for directly radiating the output waves, the holes 63 may be utilized for the insertion of or be replaced by probes 75, Fig. 10, located at points selected similarly to the holes 63 around the toroid ring 62 and projecting into the space within the toroid. The probes 75 are connected by the central conductors 76 of coaxial lines 77, of equal electrical length, with the central conductor 78 of the coaxial cable 79 which transmits the desired waves combined in phase with each other from all the probes.

Various other forms and modifications of the methods and apparatus specifically described herein by way of illustration, will be apparent to those skilled in the art, and it is intended that the invention be not limited to these specific examples, but only by the scope of the claims.

What is claimed is:

1. The method which consists in producing a beam of electrons; cyclically deflecting the beam at high frequency without substantially affecting the components of electron velocity in the direction of the axis of the undeflected beam; substantially suppressing at a position along the path of the deflected beam the components of electron velocity in the direction of the axis of the undeflected beam without developing substantial electron velocity components in the opposite axial direction, while supplying direct current energy to the beam in directions and amount tending to substantially increase the components of electron velocity directed substantially radially about the axis of the undeflected beam; and utilizing the high frequency energy radiated from the beam by virtue of its cyclic variations in position.

2. The method which consists in producing a beam of electrons; cyclically deflecting the beam at high frequency without substantially affecting the components of electron velocity in the direction of the axis of the undeflected beam; substantially suppressing at a position along the path of the deflected beam the components of electron velocity in the direction of the axis of the undeflected beam without developing substantial electron velocity components in the opposite axial direction, leaving the components of electron velocity directed substantially radially about the extended axis of the undeflected beam, so that the cyclic high frequency deflections of the beam cause it to follow radially directed paths with its radial direction varying cyclically in accord with the deflections and causing similar cyclic variations in the flow of electrons in each radial path; supplying direct current energy to the beam in directions and amount tending to increase the

velocity of the electrons in the said substantially radial directions; and utilizing the high frequency energy generated by virtue of the cyclic variations in the flow of electrons in each radial path.

3. The method which consists in producing a beam of electrons, cyclically deflecting the beam at high frequency such that the beam rotates in substantially a plane completely around an axis, while supplying direct current energy to the beam in directions and amount tending to substantially increase the velocity of electrons along the beam, subjecting the cyclically rotating beam to a substantially synchronously moving electric field in phase with the beam, and utilizing energy transmitted to the electric field by the electrons in the beam in overcoming the opposition of said electric field.

4. The method which consists in producing a beam of electrons, cyclically deflecting the beam at high frequency without substantially affecting the components of electron velocity in the direction of the axis of the undeflected beam while supplying direct current energy to the beam in directions and amount tending to substantially increase the velocity of electrons along the beam in the directions of deflection, reflecting waves radiated by the beam back to the deflected beam at the place of radiation in phase with the waves being radiated, and utilizing the resulting waves.

5. The method which consists in transferring direct current energy to a beam of electrons, rotating said beam at a wave radiation frequency such that the rotating path of the beam is the generatrix of a substantially plane surface, and utilizing the resulting waves radiated by the beam.

6. The method which consists in transferring direct current energy to a beam of electrons, rotating said beam at a wave radiation frequency such that the rotating path of the beam is the generatrix of a substantially plane surface, combining into a single wave the waves radiated in opposite directions along the axis of rotation of the electron beam, and utilizing the resulting combined waves.

7. The method of amplifying modulated ultra high frequency carrier waves, which consists in producing a virtual source of electrons, producing a stream of electrons flowing radially outward from said source in a path of disc-like form having the source of electrons initially at the center of the disc, collecting the electrons at the edge of the disc-like path, deflecting in accord with said modulated carrier waves the position of said source in said disc in a generally circular path so that the source revolves around its initial position in accordance with said modulated waves with a radius varying with the degree of modulation, and utilizing the resulting amplified ultra high frequency waves radiated as a consequence of the unbalancing and rotation of the disc-like stream of electrons due to the deflection of the virtual electron source in accordance with the modulated waves.

8. In combination, means for producing a beam of electrons, means for cyclically deflecting the beam at high frequency without substantially affecting the components of electron velocity in the direction of the axis of the undeflected beam, means for substantially suppressing at a position along the path of the deflected beam the components of electron velocity in the direction of the axis of the undeflected beam without developing substantial electron velocity components in the opposite axial direction, means for sup-

plying direct current energy to the beam in directions and amount tending to substantially increase the remaining components of electron velocity, directed substantially radially about the axis of the undeflected beam, and means for utilizing the high frequency energy radiated from the beam by virtue of its cyclic variations in position.

9. The combination specified in claim 8, in which the cyclic deflection consists of a rotation so that the beam path generates a conical surface.

10. In combination, means for producing a beam of high velocity electrons, means for cyclically deflecting the beam at high frequency such that it rotates in substantially a plane completely around an axis, means for producing an electric field at the beam which moves synchronously in phase with the beam, and means for utilizing energy radiated by the electrons in the beam in overcoming the opposition of said electric field.

11. In combination, means for producing a beam of high velocity electrons, means for cyclically deflecting the beam at high frequency so that the beam path generates a surface of revolution, means comprising a substantially closed hollow body resonator for reflecting high frequency waves radiated by the beam back to the beam in phase with the waves being radiated, and means for utilizing the resulting high frequency waves.

12. In combination, means for producing a beam of high velocity electrons, means for cyclically rotating said beam at a wave radiation frequency such that the rotating path of the beam is the generatrix of a substantially plane surface to produce radiations propagated in opposite directions, and means for combining said oppositely directed radiations.

13. In combination, a direct current circuit, a wave transmission line for waves of a given frequency, and means for converting direct current energy from said circuit into a beam of high velocity electrons rotating at said given frequency around the axis of propagation of the wave transmission line.

14. In combination, a space current device having an evacuated envelope, an electron emitter, electrodes for projecting a beam of electrons from said emitter along the axis thereof, plates disposed on opposite sides of the beam path and excited by an alternating voltage for cyclically deflecting the beam in a path having the axis of the emitter at the center thereof, an electrode remote from the emitter suitably charged for substantially stopping the motion of the electrons of the beam in the direction of said axis before they reach said electrode and at a place remote from said emitter without suppressing said deflections of the beam, electrode means disposed radially outward an appreciable distance from said stopping place suitably charged for accelerating the beam radially outward at high velocity, and an anode for collecting the electrons in the vicinity of said accelerating electrode.

15. The combination specified in claim 14, in which the accelerating electrode means is highly charged at a positive potential with respect to the emitter while the electron collecting anode is charged to a less positive potential than the accelerating electrode.

16. In combination, a space discharge device having an evacuated envelope, an electron gun, deflecting means arranged to rotate the stream of electrons therefrom about the axis of the gun,

an electron retarding electrode located in front of and on the axis of the gun and suitably charged to substantially stop the axial motion of the electrons in said stream before reaching the retarding electrode without stopping the deflections of the stream, accelerating electrode means disposed about the axis of the gun for increasing the radial velocity of the electron stream, and electron collecting electrode means so disposed and so charged as to terminate the path of the electron stream.

17. The combination specified in claim 16, in which the collecting electrode means arranged to capture the electrons in the vicinity of the accelerating electrode means is less positive with respect to the emitter than said accelerating means.

18. In combination, an electron emitter, means for projecting a beam of electrons from said emitter, means for deflecting the beam in a path rotating around the axis of the undeflected beam, means remote from the emitter for bending the forward end of the beam into a path approximately in a plane normal to said axis, means for transmitting energy to the beam in said plane to exert a force tending to increase the velocity of the electrons in the beam, and means for collecting the electrons in said beam in a zone coaxial with said axis and spaced a substantial distance radially outward from the place where the beam is bent into its path in said plane.

19. In a space current device having an evacuated envelope, a cathode electrode for supplying electrons to a beam, an electron beam accelerating electrode of cylindrical form through which the beam is to be projected, a pair of plates disposed on opposite sides of the beam path and suitable if electrically charged for deflecting the beam in one plane and a pair of plates disposed on opposite sides of the beam path oriented around the path at right angles to the orientation of the first said pair of plate electrodes and suitable if electrically charged for deflecting the beam in a plane at right angles to said first plane, said plates being near the beam entrance end of said cylindrical electrode, an electron beam retarding electrode of circular form spaced beyond but near the beam exit end of the cylindrical electrode, a pair of axially short ring electrodes of greater radius than said accelerating and retarding electrodes and having an electron path therebetween consisting of a narrow slot extending continuously around between the rings, said slot being concentric with the space near the beam exit end of said cylindrical electrode, means adapted to be energized to direct the electron beam through said slot, and an annular electrode radially outside said slot for collecting the electrons passing through the slot, said electrodes being in coaxial relation with each other.

20. In a space current device having an evacuated envelope, means for producing a virtual cathode revolving at a predetermined frequency in a path lying substantially in a plane, a pair of annular electron accelerating electrodes generally parallel to the said plane and separated axially by a circumferential slot which includes the said plane and is concentric with said virtual cathode, the said slot being such as to permit passage therethrough of a beam of electrons accelerated by said annular electrodes radially outward from the virtual cathode toward said slot, and an annular anode radially outside of said slot for collecting electrons passing through the slot.

21. In an amplifier for modulated ultra high

frequency waves, means for producing a virtual electron source movable within a plane about an axis passing at right angles through a predetermined point in the plane, annular electrode means for accelerating a stream of electrons radially outward in said plane from said virtual source, an annular anode coaxial with said annular accelerating means for collecting electrons in the vicinity of said accelerating means, and means for moving the position of said virtual source in said plane in a path whereby the source revolves around said predetermined point in accordance with said modulated ultra high frequency carrier waves whereby the electron stream is caused to radiate modulated ultra high frequency waves in amplified form in the direction of said axis.

22. In combination, an electron emitter, means for projecting a beam of electrons from said emitter, an electrically resonant cavity deflector arranged to produce a cyclically varying electric field in the path of the electron beam in a manner to cyclically deflect the beam in a path having the axis of the undeflected beam at the center thereof, an electrode remote from the emitter suitably charged for substantially stopping the motion of the electrons of the beam in the direction of said axis before they reach said electrode and at a place remote from said emitter without suppressing the deflections of the beam, electrode means disposed radially outward from said axis an appreciable distance from said stopping place for accelerating the beam radially outward, and an anode for collecting the electrons in the vicinity of said accelerating electrode.

23. In combination, an electron emitter, means for projecting a stream of electrons from said emitter, means for cyclically deflecting the stream in a path having the axis of the undeflected stream at the center thereof, means remote from the emitter for substantially stopping the motion of the electrons in the stream in the direction of said axis without stopping the deflections of the stream, accelerating electrode means disposed about the said axis for increasing the velocity of the electron stream in the directions of the deflections after said substantial stoppage of the axial motion, electron collecting electrode means so disposed as to terminate the path of the electron stream, and a substantially closed electrically resonant system arranged to impress a high frequency electric field, produced from the energy of the resonator, upon at least a portion of the path of the deflected electron stream whereby high frequency energy is radiated by the electron stream to the electric field and thus transferred from the electron stream to the resonator.

24. The combination according to claim 23 in which the frequency to which the resonant system is turned is the same as that of the cyclic deflections of the electron stream.

25. The combination according to claim 23 in which the frequency to which the resonant system is tuned is harmonically related to the frequency of the cyclic deflections of the electron stream.

26. The combination according to claim 23 in which the arrangement of the electrical resonant system with respect to the path of the deflected electron stream is such that the high frequency electric field impressed upon the path is the field substantially at the place of a loop in the standing wave pattern of the field produced from the energy of the resonator whereby the electron stream encounters maximum high frequency load impedance.

27. In combination, an electron emitter, means for projecting a stream of electrons from said emitter, means for cyclically deflecting the stream in a path having the axis of the undeflected stream at the center thereof, means remote from the emitter for substantially stopping the motion of the electrons in the stream in the direction of said axis without stopping the deflections of the stream, accelerating electrode means disposed about the said axis for increasing the velocity of the electron stream in the directions of the deflections after said substantial stoppage of the axial motion, electron collecting electrode means to terminate the path of the electron stream, a substantially closed electrically resonant system arranged to impress a high frequency electric field, produced from the energy of the resonator, upon at least a portion of the path of the deflected electron stream whereby high frequency energy is radiated by the electron stream to the electric field, and a load circuit arranged to receive high frequency energy so radiated through an impedance transforming element.

28. The method which consists in producing a beam of electrons; cyclically deflecting the beam at high frequency with a rotary motion so that its rotating deflected path generates a conical surface; substantially suppressing at a position along the path of the deflected beam the components of electron velocity in the direction of the axis of the undeflected beam without developing substantial electron velocity components in the opposite axial direction, while supplying direct current energy to the beam in directions and amount tending to substantially increase the components of electron velocity directed substantially radially about the axis of the undeflected beam; and utilizing the high frequency energy radiated from the beam by virtue of its cyclic variations in position.

29. The method which consists in producing a beam of electrons; cyclically deflecting the beam at high frequency with a rotary motion so that its rotating deflected path generates a conical surface; substantially suppressing at a position along the path of the deflected beam the components of electron velocity in the direction of the axis of the undeflected beam without developing substantial electron velocity components in the opposite axial direction, leaving the components of electron velocity directed substantially radially about the extended axis of the undeflected beam, so that the cyclic high frequency deflections of the beam cause it to follow radially directed paths with its radial direction varying cyclically in accord with the deflections and causing similar cyclic variations in the flow of electrons in each radial path; supplying direct current energy to the beam in directions and amount tending to increase the velocity of the electrons in the said substantially radial directions; and utilizing the high frequency energy generated by virtue of the cyclic variations in the flow of electrons in each radial path.

30. The method which consists in producing a beam of electrons; cyclically deflecting the beam at high frequency substantially in a plane over a range of directions including at least two which are 180 degrees apart while supplying direct current energy to the beam in directions of the plane and utilizing the high frequency energy radiated by the beam by virtue of its cyclic variation in direction.

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