

July 22, 1969

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3,457,450

HIGH FREQUENCY ELECTRON DISCHARGE DEVICE

Filed Aug. 31, 1966

3 Sheets-Sheet 1

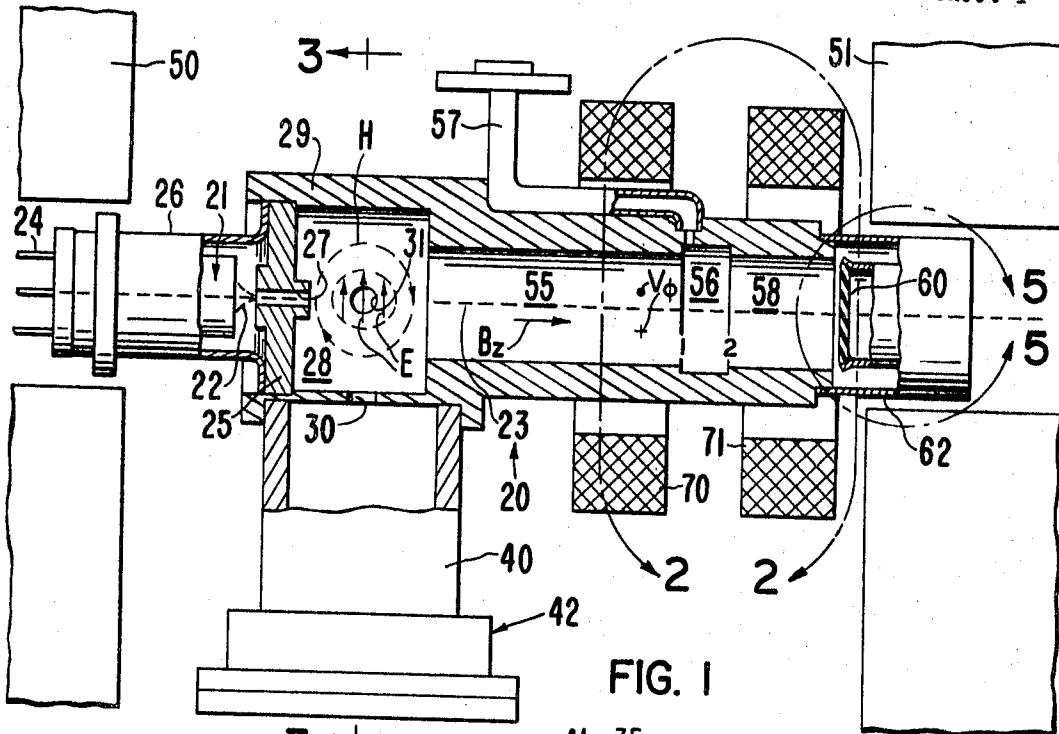


FIG. 1

FIG. 2

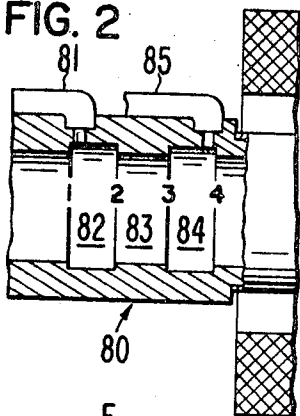
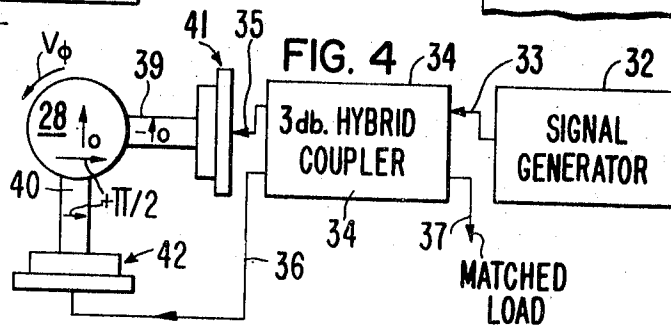


FIG. 6

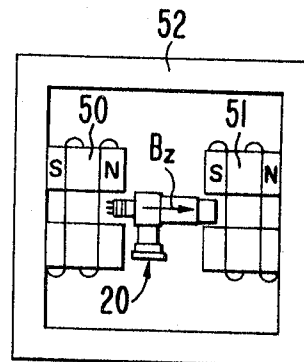
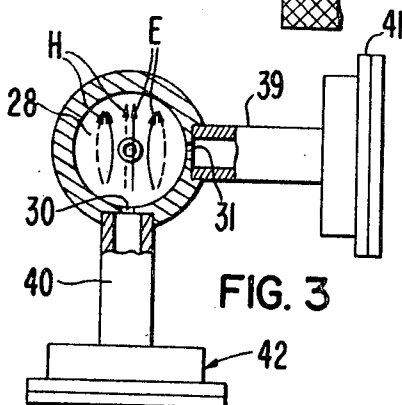


FIG. 3

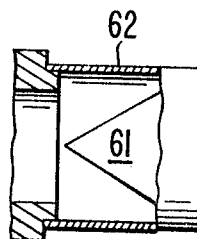


FIG. 5

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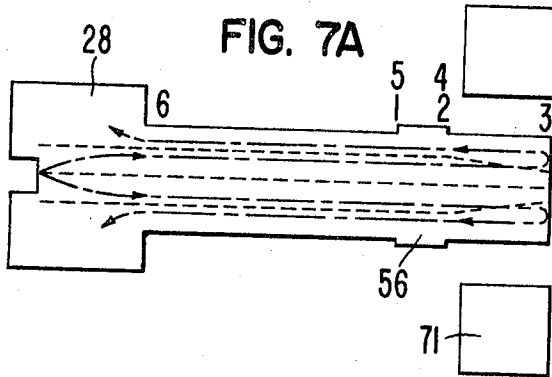
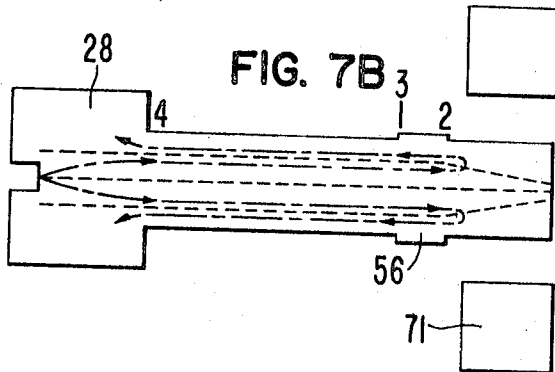
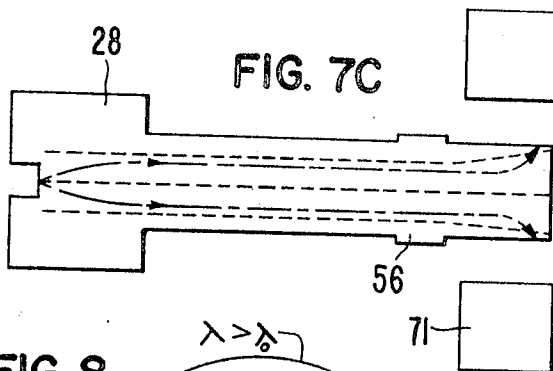
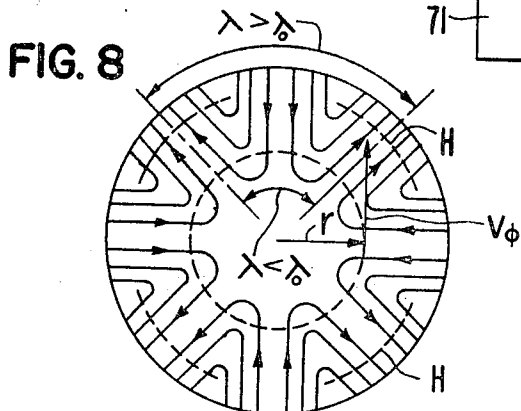
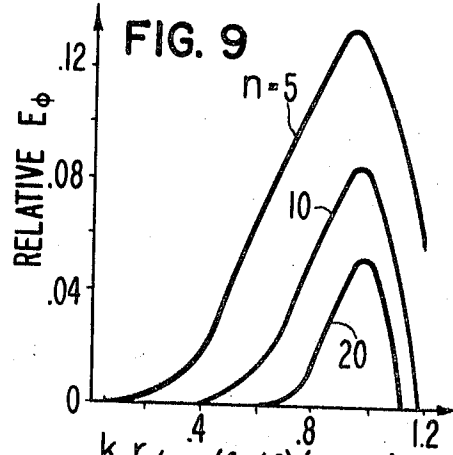
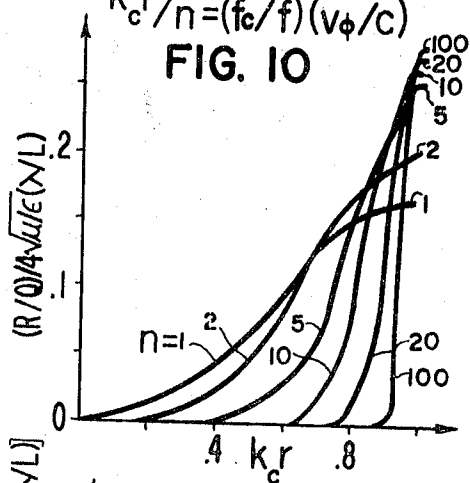
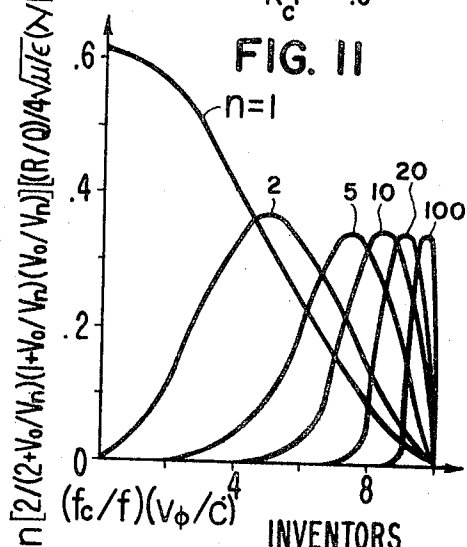
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HIGH FREQUENCY ELECTRON DISCHARGE DEVICE

Filed Aug. 31, 1966

3 Sheets-Sheet 3

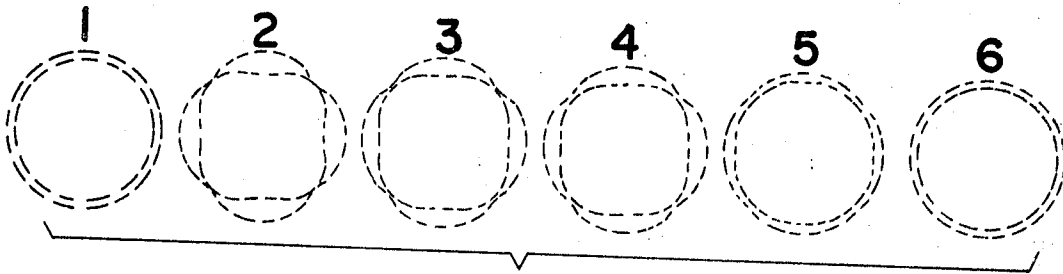


FIG. 12

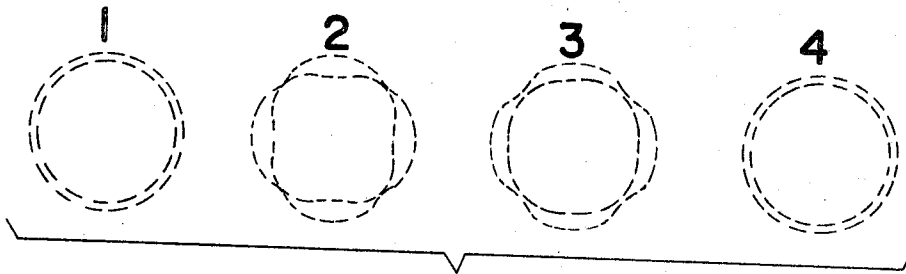


FIG. 13

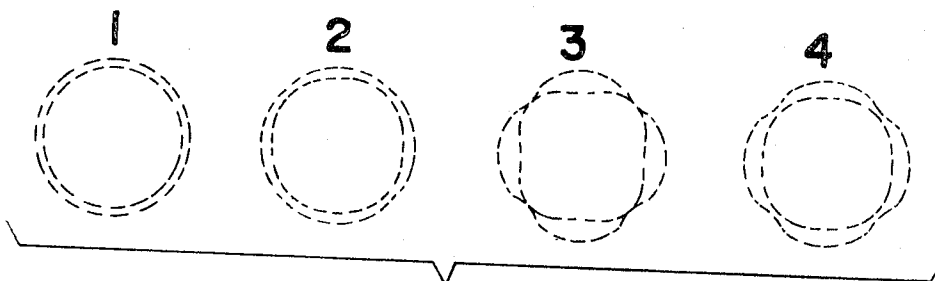


FIG. 14

FIG. 15

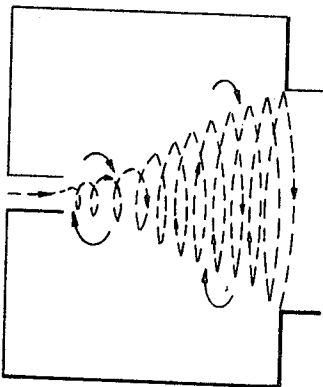
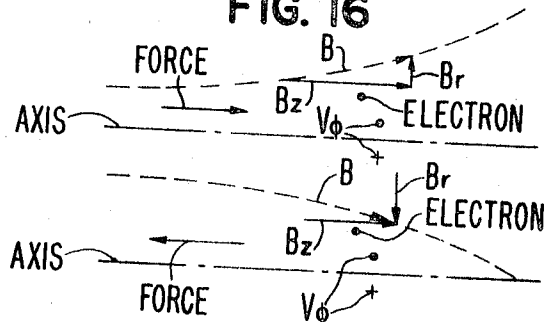


FIG. 16



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HIGH FREQUENCY ELECTRON
DISCHARGE DEVICE

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Filed Aug. 31, 1966, Ser. No. 576,407

Int. Cl. H01j 25/02, 25/50

U.S. Cl. 315—5

19 Claims

ABSTRACT OF THE DISCLOSURE

A microwave tube is disclosed. The tube includes an electron gun assembly for forming and directing a stream of electrons over an elongated beam path. Near the upstream end of the beam path a cavity resonator, excited with its electric fields transverse to the beam path and further excited to produce a circular polarization in the excited electric field converts the electron stream into a hollow rotating cylinder of electrons with the electrons executing helical orbits having greater tangential velocity components than axial velocity components. The rotating cylinder of electrons is then projected in a continuous stream through an output resonator dimensioned to be excited in one of the higher order TE_{n11} modes for converting the kinetic energy of the tangential velocity components of the electrons into microwave energy which is extracted from the output resonator and fed to a suitable load. In one embodiment an auxiliary magnet structure is disposed adjacent the output resonator for producing a transverse magnetic field component for slowing the axial velocity of the electrons to enhance conversion of the tangential kinetic energy into microwave energy.

A perusal of prior art studies of so-called "fast wave" tubes has produced many diverse types among which the following are particularly germane to an understanding of the background prior art as well as the advance in the state of the art represented by the present invention.

U.S. Patent 3,183,399 by R. H. Pantell issued May 11, 1965, and assigned to the same assignee as the present invention,

"Interaction of an Electron Beam with the High Order Modes of a Smooth Waveguide" by A. H. W. Beck and R. F. Mayo Rec. International Congress on Microwave Tubes, Munich, June 1960, Friedr. Vilweg and Sohn, Braunschweig; 1961, pages 240-241,

K. K. Chow and R. H. Pantell, "The Cyclotron Resonance Backward-Wave Oscillator," Proc. IRE, vol. 48, pp. 1865-1870, November 1960.

The interaction between TE_{n1} cylindrical waveguide fields and electrons rotating about the axis of the guide has been studied by Pantell and Chow, and by Beck and Mayo. In these cases the rotation of the electrons was controlled by a D.C. axial magnetic field. The studies have resulted in microwave amplifiers and oscillators using low order waveguide modes with n (indicating the number of angular variations) having values of one and two.

It has been pointed out that operation with large values of n would allow millimeter wave interactions to occur with moderate values of D.C. axial magnetic field, since the required magnetic field is the cyclotron field reduced by the factor, $1/n$. It has also been pointed out that high transverse beam velocities are necessary for operation with large values of n . This invention is concerned with electron-electromagnetic interactions in a klystron type arrangement in which very large values of n and high tangential beam velocities are involved and relativistic effects must therefore be included.

To evaluate the interaction, we consider a klystron

interaction mechanism using a TE_{n11} resonator. We use the usual definition of R/Q for the resonator except for the definition of R.F. voltage which is defined by an integral of the azimuthal electric field over one revolution of the beam. The stored energy in the cavity is obtained in the usual fashion. According to the definition of voltage the R/Q increases with the square of the number of beam revolutions.

Values of R/Q for the TE_{n11} resonator have been computed as a function of beam radius for n ranging from one to one-hundred. L , the axial length of the cavity, will always have a value greater than one-half λ . If, for example, $L=2\lambda$ the R/Q for one revolution of the beam is of the order of 100 to 200 ohms, which is a useful range. We show that a large beam orbit radius is necessary to realize the useful values of R/Q for large values of n .

For the interaction to be effective for large values of n the rotation of the electrons must be nearly synchronous with a rotating component of R.F. field. The synchronous condition combined with the large orbit radius leads to the requirement of a high tangential velocity. The placement of a synchronous beam at a radius of $k_{cr}=1$ requires that the electrons have a tangential or azimuthal velocity equal to the velocity of light and that the cavity radius be equal to the cut off radius. Therefore $k_{cr}=1$ represents an absolute upper limit for the beam radius.

Large values of n require larger velocities for effective interaction. With $n=10$, for example, the tangential velocity of the beam should be greater than 0.7 the velocity of light and preferably about 0.9 the velocity of light. Operation with $n=100$ requires a velocity of greater than 0.9 times the velocity of light.

In order to estimate the degree to which relativistic mass effects weaken the proposed interaction, the start oscillator current of a monotron oscillator is calculated using the definition for R/Q described above. The conventional linear beam expressions for electronic conductance and relativistic reduction in bunching are used. Although the linear beam expressions are not directly applicable in this case, they should at least give an upper bound on the starting current. The results of the calculations are given herein and show a quantity inversely proportional to the start oscillation current as a function of beam velocity (or orbit radius). It is assumed that the beam is synchronous and that the cavity is near cutoff. The most significant conclusion is that the interaction remains strong for large values of n . Apparently the relativistic reduction in bunching efficiency is compensated by the increased interaction length and increased R/Q that accompany increased n .

Another result of the relativistic mass change is an increase in the required D.C. magnetic field. This can be shown by considering the equations presented in the body of the specification wherein the rate of rotation for an electron in an axial magnetic field, B_z , is presented together with an equation which expresses the synchronism condition for strong R.F. interaction. These two equations can be combined to give a third equation which indicates that the required magnetic field is reduced from the normal rest mass cyclotron field by the factor $1/n$, but increased by the relativistic mass factor m/m_0 . For $n=10$, a relativistic mass increase of two is more than adequate for strong interaction. Therefore the reduction in magnetic field from the cyclotron value is five rather than ten. For $n=100$ the mass increase is about 4 and the field reduction is 25.

A key factor in consideration of interactions with large values of n is the generation of a beam rotating with high tangential velocity. One way that such a beam can be obtained is by accelerating a low voltage beam with

transverse R.F. electric fields in the presence of a D.C. axial magnetic field. Such acceleration might be called cyclotron wave acceleration. Calculations have been performed to determine electron motion in a TE_{111} cylindrical cavity with circularly polarized fields. R.F. magnetic forces and relativistic mass effects were included in the calculations. It was determined that although the relativistic mass increase causes injected electrons to eventually fall out of synchronism with the rotating R.F. fields, moderately high amounts of energy can be gained by the electrons with realizable R.F. electric field strengths. For example, a beam with an initial energy of 500 volts can be accelerated to have an energy of 500 kv. with X-band R.F. field strengths of the order of 10^5 volts/cm.

With the above theoretical background in mind the present invention teaches the utilization of several novel interaction devices suitable for use in microwave, especially millimeter wave, applications as generators, amplifiers, etc. The devices are extremely simplified and have large dimensions compared to a wavelength and are thus easy to manufacture and easy to cool for high power operation. A monotron type of millimeter wave generator utilizing an energy exchange process between a rotating hollow beam and the fields established in a TE_{n11} circular cylindrical resonator is presented in detail.

In another embodiment a millimeter wave amplifier is described wherein an energy exchange process between a rotating hollow beam and the fields established in a TE_{n11} cylindrical resonator is utilized for amplifying microwave energy.

A feature of the present invention is the provision of a novel millimeter wave device.

Another feature of the present invention is the provision of a microwave device which utilizes tangential electron motion of a hollow electron beam in conjunction with a circular cylindrical resonator excited in higher order TE_{n11} modes.

Another feature of the present invention is the inclusion in any of the above features of mode suppression means for enhancing higher order mode interaction in cylindrical resonators using TE_{n11} modes with n being any integer >2 .

Another feature of the present invention is the provision of means for producing bidirectional axial beam flow through devices of the type set forth in the above features for enhancing the operation of said devices.

These and other features and advantages of the present invention will become more apparent upon a perusal of the following specification taken in conjunction with the accompanying drawings wherein:

FIG. 1 is a longitudinal cut-away view partly in elevation of a millimeter wave generator of the present invention,

FIG. 2 is a fragmentary view of an amplifier version of the generator depicted in FIG. 1 which is modified in the region denoted by lines 2—2,

FIG. 3 is a view taken along the lines 3—3 of the hollow beam accelerator portion of the device depicted in FIG. 1,

FIG. 4 is a schematic representation of suitable R.F. excitation means for the accelerator cavity of the device of FIG. 1,

FIG. 5 is a fragmentary view of an alternative type of downstream termination for the device of FIG. 1 for the region denoted by lines 5—5,

FIG. 6 is a view in elevation of the device of FIG. 1 and focusing means,

FIG. 7A is a simplified schematic view of the device of FIG. 1 with bi-directional axial beam flow with a smeared beam return approach to the accelerator region,

FIG. 7B is a simplified schematic view of the device of FIG. 1 with bi-directional axial beam flow with phased return to the interaction cavity and smeared return to the accelerator region,

FIG. 7 is a simplified schematic view of the device of

FIG. 1 with simple unidirectional axial beam flow operation,

FIG. 8 is a schematic representation of the electromagnetic field pattern in a circular cylindrical waveguide or cavity for the TE_{n1} mode case with $n=4$ or the TE_{n11} (cavity case) with $n=4$,

FIG. 9 is an illustrative graphical portrayal of the radial variation of E_ϕ for a TE_{n11} mode in a cylindrical cavity for various values of n ,

FIG. 10 is an illustrative graphical portrayal of an interaction impedance parameter vs. $k_0 r$ for a TE_{n11} mode in a cylindrical cavity for various values of n ,

FIG. 11 is an illustrative graphical portrayal of a quantity which is inversely proportional to the start oscillation current as a function of beam velocity (or electron orbit radius),

FIG. 12 is a simple schematic view pictorially showing the effects on a rotating hollow cloud of electrons in the case of operation of the device of FIG. 1 with the bi-directional axial beam flow case of FIG. 7A,

FIG. 13 is a simple schematic view pictorially showing the effects on a rotating hollow cloud of electrons in the case of operation of the device of FIG. 1 with the bi-directional axial flow case of FIG. 7B,

FIG. 14 is a simple schematic view pictorially showing the effects on a rotating hollow cloud of electrons in the amplifier version of FIG. 2,

FIG. 15 is a pictorial view of electron beam motion in the accelerator section,

FIG. 16 is a schematic view of the associated $F=e(v_\phi \times B_r)$ components for expanded and contracted fields.

Turning now to FIG. 1 there is depicted an embodiment of a microwave generator 20 constructed according to the teachings of the present invention. The generator 20 includes a conventional electron gun means 21 such as for example of the confined flow type disposed at the upstream end portion of the device for generating and directing an electron beam 22 preferably solid although the beam could be hollow also, along the central axis 23 of the device. The electron gun is provided with conventional cathode-anode leads like 24 for providing the voltage requirements. The final accelerating potential is preferably applied to a copper or the like anode member 25 to which the gun housing 26 is sealed in a vacuum tight manner to provide an evacuated internal region for the device in any conventional manner such as by brazing. The anode header 25 is provided with a drift tube region 27 for permitting passage of the beam 22 while providing a cut-off mechanism for the R.F. energy in the accelerator cavity 28. The cavity 28 is a right-circular cylindrical cavity resonator which can be formed by a suitable bore in a copper or the like block 29 which forms the main vacuum envelope for the device as shown. The cavity 28 is excited in the TE_{111} mode with circular polarization via a pair of 90° space rotated R.F. input coupling ports 30, 31 which are driven 90° out of phase by an R.F. input drive system such as depicted in FIG. 4. The R.F. drive system includes a signal generator 32 such as a magnetron, klystron etc. coupled via input port 33 to any suitable 90° phase shifted energy divider means 34 such as, for example, a 3 db hybrid coupler 34 to produce equal signal energies in 90° phase relation at output ports 35, 36 with the remaining port 37 terminated in a matched load. The energy from output ports 35, 36 is coupled to a pair of 90° space rotated input waveguides 39, 40 as best seen in FIGS. 1 and 3 through any conventional pair of vacuum sealed electromagnetic wave permeable dielectric window-flange assemblies 41, 42. A pair of resonant coupling irises 30, 31 couple the 90° phase drive energy to the accelerator cavity 28 and excite a circular polarized TE_{111} mode therein which can be characterized by constant amplitude E and H fields which have an angular velocity which is given by

$$d\phi/dt = \omega/n$$

where:

$$\omega = 2\pi f, \text{ and}$$

$$n=1 \text{ for the TE}_{111} \text{ mode}$$

Of course, it is to be noted that the particular accelerator cavity drive system is only a preferred embodiment and those skilled in the art will realize that other drive systems may be employed. For example, a pair of R.F. generators such as magnetrons, klystrons, etc., may be coupled directly to the waveguides 39, 40 and their R.F. output adjusted to provide a 90° phase relationship.

Also, it is to be noted that the particular gun-accelerator mechanism which is the subject of a separate patent application Ser. No. 576,406 filed Aug. 30, 1966, by Joseph Feinstein, et al. and assigned to the same assignee as the present invention although being a preferred beam generator system because of its obvious low voltage requirements may be replaced by other drive systems which are capable of producing a hollow rotating electron beam. For example, the beam generator system described in U.S. Patent 3,183,399 is suitable.

The drift tube region 27 extends into the cavity 28 in a re-entrant manner to provide optimum beam injection as detailed more fully in co-pending application U.S. Ser. No. 576,406. A unidirectional D.C. magnetic field B_z produced by magnets 50, 51 as best seen in FIGS. 1 and 6 threads through the gun region for confined flow focusing and along the device axis 23 between the upstream and downstream end portions of the device. The magnetic field may be produced in any conventional manner such as by electromagnets 50, 51 and soft iron or the like high permeability magnetic shunt means 52 as shown in FIG. 6 or the field may be produced by a solenoid or by permanent magnets, etc.

The injected beam emanating from drift tube region 27 into the accelerator cavity 28 is subjected to a rather complex array of forces which cause the beam to traverse a helical path as shown in FIG. 15, which is characterized by a small axial velocity with a gradual expanding radius and a gradually diminishing pitch until at the accelerator cavity exit region at the entrance of the isolation region 55 the beam has been wound up into a tight pitch helix which is further characterized by rotation of the helix itself. The beam has little if any transverse velocity components prior to entrance into the cavity 28 whereupon the beam is subjected to the transverse R.F. fields which produce a radial force component which, in combination with the B_z field, initiates rotation about the axis 23. These forces continue to build up the rotational energy until the beam emerges from the accelerator cavity 28 in the form of a tightly wound rotating helix at the input to the isolator region 55 which is a cylindrical waveguide designed to be cut off for the R.F. drive frequency to prevent transmission of the R.F. from the cavity 28. The electron beam is allowed to drift down the isolation drift region 55 and is changed by auxiliary coils 70 from a tightly wound rotating helix to a simple smeared rotating hollow cylinder characterized by an average angular velocity given by

$$d\phi/dt = eB_z/m$$

where:

e =electron charge

m =relativistic electron mass

B_z =D.C. magnetic field strength

where the rotating cylinder enters the interaction cavity region 56 to induce through a monotron process R.F. energy in the millimeter wave region. The beam axial velocity can be slowed down by the use of an auxiliary magnet coil 70 via $v_e \times B_z$ forces which are achieved by an aiding D.C. field superimposed on the main field. Therefore, it is possible to slow the beam to a point where it enters the cavity 56 as a simple rotating cloud of electrons with a very small axial velocity and a relativistic tangential velocity. The cylindrical cavity 56 is dimensioned for maximum interaction in the chosen mode of operation. Theoretical analysis indicates that for given n for a TE_{n1} mode in a right-circular waveguide the maximum R/Q is obtained when

where:

$$k_c r = n$$

where:

$$k_c = 2\pi/\lambda_c$$

r =beam radius

n =number of azimuthal E-field variations

Microwave energy is extracted from the cylindrical waveguide cavity 56 via a H_ϕ coupler mechanism as shown in FIG. 1 and extracted via output waveguide 57. A simple iris coupler is satisfactory although obviously any loop or other well known coupling mechanism may be used. The output frequency will correspond to

$$f = v_\phi n / 2\pi r$$

where:

v_ϕ =tangential electron velocity

n =index number of azimuthal variations of E-field around cavity

r =beam radius

The cavity 56 is terminated at the downstream end by a lower order mode extraction filter section 58 which takes the form of a cylinder having a slightly smaller diameter than the cavity 56. The cylinder is dimensioned such as to be cut off for the chosen higher order operating mode but propagating for lower index TE_{n1} modes which have higher field strengths near the central axis than the higher order modes as the following analysis shows. The lower order TE_{n1} energy is extracted from the device via a dielectric electromagnetic wave permeable vacuum window 60 vacuum sealed across the downstream end portion of the device as shown. A uranium glass, alumina, etc. type of window is adequate.

The electron beam is then preferably handled in a manner such as depicted in FIG. 7 about which more will be said later on. An alternative means for absorbing the lower order TE_{n1} mode energy is depicted in FIG. 5 wherein a simple attenuator, V-shaped block 61 of carbon loaded ceramic or any other suitable material is disposed in the device at the downstream end in shell 62 as shown.

Before continuing the descriptive discussion of the various facets of the present invention the following theoretical analysis is presented to provide a more detailed understanding of the present invention.

Consider the circular cylindrical resonator depicted in FIG. 8.

The transverse variations of the electric fields in the circular cylindrical resonator are as follows:

$$E_\phi = A J_n'(k_c r) \begin{cases} \cos n\phi \\ \sin n\phi \end{cases}$$

$$E_r = \frac{n}{k_c r} A J_n(k_c r) \begin{cases} \sin n\phi \\ \cos n\phi \end{cases}$$

$$E_z = 0$$

These fields are sketched in FIG. 8 for the case of $n=4$. The variation of E_ϕ with radius is indicated in FIG. 9 for the cases of $n=5, 10$, and 20. It is observed that for high values of n the E_ϕ fields are concentrated in a relatively narrow region near the cylindrical wall. This results in a favorable value of R/Q .

The TE_{n1} cylindrical resonator has purely transverse electric fields having n azimuthal variations, one radial variation, and one axial variation. One possible interaction involves a beam which rotates with a high velocity along the dotted path in FIG. 8, and moves in the axial direction with minimum velocity. The transverse standing wave field pattern in FIG. 8 can be thought of as being

made up of clockwise and counter-clockwise waves, rotating with angular velocity,

$$d\phi/dt = \omega/n$$

For a synchronous interaction, the beam will rotate with the same angular velocity and will have a tangential velocity given by

$$v\phi = r\omega/n$$

For small r the tangential beam velocity can be small but the field amplitudes will also be small.

This invention is concerned with structures which are large compared with a wavelength. Therefore the index, n , will be large. For such structures, the curvature of the beam is of secondary importance because in traveling one wavelength the beam changes direction by an angle of only $2\pi/n$. Accordingly, we will evaluate the interaction by considering an equivalent linear interaction with the electric field equal in magnitude to E_ϕ . The R/Q is defined by

$$R/Q = V^2/2\omega U$$

where:

U is the total stored energy in the cavity, and
 V is the cavity voltage.

In this case, we will define V in terms of one revolution of the beam at the axial position where E_ϕ is maximum.

m.k.s. units are used in the equations.

$$V^2 = 2\pi r \int_0^{2\pi} E_\phi E_\phi^* r d\phi$$

where:

r = average beam radius, and
 E_ϕ^* is complex conjugate of E_ϕ

For the TE_{n11} cavity the azimuthal electric fields are given by

$$E_\phi = AJ_n'(k_c r) \cos(n\phi) \cos(\pi z/l)$$

$$E_r = A(n/k_c r) J_n(k_c r) \sin(n\phi) \cos(\pi z/l)$$

where:

J_n' is the derivative of J_n with respect to the argument
 K_c is the cutoff wave number $= 2\pi/\lambda_c$
 ϕ is the angular coordinate
 z is the axial coordinate
 J_n is n 'th order Bessel function of the first kind where:
 A is an amplitude factor, and
 l is cavity length.

Performing the integration for the circuit voltage, we get

$$V^2 = 2\pi r^2 A^2 [J_n'(k_c r)]^2$$

The total stored energy in the cavity is given by

$$U = \frac{1}{2} \epsilon \int_0^{2\pi} d\phi \int_{-1/2}^{1/2} dz \int_0^a r (E_\phi^2 + E_r^2) dr$$

and a is the radius of the cavity wall.

Performing the integration, we get

$$U = \frac{\pi \epsilon A^2 l}{8k_c^2} [(k_c a)^2 - n^2] J_n^2(k_c a)$$

Finally, the R/Q for one revolution of the beam can be written

$$R/Q = \frac{4\sqrt{\mu/\epsilon} [J_n'(k_c r)]^2 (k_c r)^2}{(l/\lambda) [(k_c a)^2 - n^2] J_n^2(k_c a)}$$

When the beam makes a number of revolutions, the total R/Q will increase according to the square of the number of revolutions.

The radius for maximum R/Q can be found by differentiating the expression above. The result is $k_c r = n$ for maximum R/Q . The radius of the cavity wall is given approximately by

$$k_c a = n + 0.8086n^{1/2} + 0.0725n^{-1/2} - 0.0510n^{-1} + \dots$$

Therefore, for large n the radius for maximum R/Q approaches the cavity radius.

FIG. 10 shows a quantity proportional to R/Q plotted as a function of radius for several values of n up to $n=100$. It is observed that the R/Q increases with n . This is a result of the concentration of energy near the cavity wall. For a cavity with $l=\lambda$ the R/Q will have a value of the order of 300 ohms, which offers considerable promise for electronic interaction.

As an example of TE_{n11} interaction, we will consider the case of a monotron operating with the beam and cavity fields synchronous. Then the required beam velocity is $v_\phi = r\omega/n$ and the electronic conductance is $|g_e| \approx 0.1n$. The start oscillation condition for the monotron, including relativistic effects, can be written

$$2|g_e| \frac{I_0}{V_n} \left(\frac{c}{v}\right)^2 (1 - v^2/c^2)^{3/2} \frac{L}{Q} Q_t \geq 1$$

where Q_t is the total Q of the cavity including the effects of the external load and where

$V_n = m_0 c^2 / e = 0.511 \times 10^6$ volts,
 I_0 is the D-C beam current, and
 v is the total velocity of the electrons.

It can be assumed that the axial velocity of the electrons is much less than the tangential velocity. Then we can write

$$\frac{v}{c} \approx \frac{v_\phi}{c} = \frac{1}{n} \frac{f}{f_c} k_c r$$

which is the relation between electron velocity and radius which must hold for synchronism. Assuming synchronous interaction and assuming $f \approx f_c$ we can write the start oscillation condition in the form

$$0.2n \frac{I_0}{V_n} \left(\frac{c}{v}\right)^2 (1 - v^2/c^2)^{3/2} \frac{4\sqrt{\mu/\epsilon} Q}{(l/\lambda) [(k_c a)^2 - n^2]}$$

$$\left[\frac{n \left(\frac{v}{c}\right) J_n' \left(n \frac{v}{c}\right)}{J_n \left(n \frac{v}{c}\right)} \right]^2 \geq 1$$

The portions of the left-hand side of the above relation which depend on v and n are plotted in FIG. 11. In effect, FIG. 11 shows the relative strength of the interaction as a function of electron velocity for several values of n . It is observed that the interaction remains nearly as strong for high values of n as for low values. The high values of n require a higher beam velocity for synchronism. But the resulting lower D-C beam impedance is offset by the increase of g_e with n .

There are two important conclusions to be drawn from FIG. 11. (1) The interaction is effective even for very high values of n , and (2) a certain amount of mode selection is accomplished by the choice of v/c . The first property is particularly significant for millimeter wave applications. The second property provides wide-range, step-wise electronic tuning of the device. For example, tuning from $n=5$ to $n=10$ corresponds to a 2 to 1 frequency variation, and is accomplished by varying the velocity by about 7 percent. This can be accomplished by varying the anode voltage via any suitable variable voltage power supply (not shown).

Another parameter of importance is the unloaded Q of the TE_{n11} cavity. It can be given in the following form

$$Q \frac{\delta}{\lambda} = \frac{[1 - (n/x)^2][x^2 + (\pi a/l)^2]^{3/2}}{2\pi[x^2 + (\pi a/l)^2(2a/l) + (1 - 2a/l)(\pi n a/l x)^2]}$$

where $x = k_c a$ and δ = the skin depth. For the case where cavity length equals diameter, the expression for Q simplifies considerably. For that case the Q increases as n increases. For example, with $n=10$ the Q is 1.93 times larger than for $n=1$, and for $n=100$ the cavity Q is 4.32 times larger than for $n=1$. A copper TE_{n11} cavity resonant at $\lambda=1$ millimeter, with length equal to diameter and with $n=10$, would have an ideal Q of 4500.

An area of importance to the TE_{n11} interaction is the production of the high velocity rotating beam. The most obvious method of controlling the beam is the use of an axial D-C magnetic field. If the axial velocity of the electron is small, the required magnetic field for a given radius is

$$B_z = \frac{m_e v}{er\sqrt{1-v^2/c^2}}$$

For synchronism, we require $r = nv_\phi/\omega$. Therefore, the required field is

$$B_z = \frac{m_e \omega}{en\sqrt{1-v^2/c^2}}$$

The relationship between the operating angular frequency of the device and the B_z and index number is best expressed as follows:

$$\frac{eB_z}{m\omega} \approx \frac{\omega}{n} \frac{m}{m_0}$$

Because of the factor n occurring in the denominator above, super high magnetic fields are not required for the millimeter wave region. For example, with $n=20$ the optimum value of v/c from FIG. 11 is $v/c=0.9$ and we get $\sqrt{1-(v/c)^2}=8.73$. For an output wavelength of one millimeter, a D-C field of 12000 gauss is required with $n=20$. Larger values of n would be used to produce shorter wavelength output or to allow lower values of D-C magnetic field.

The most promising method of producing the high velocity rotating beam appears to be R-F acceleration by cyclotron resonance interaction. The required beam can be obtained by this method on either a pulsed or CW basis. The main advantage of this approach is that no high voltage D-C potentials are involved and therefore no large insulators are required. The entire device can be small in size and essentially completely enclosed by metal walls. Additional description of the method of obtaining the beam is included in a following section describing experimental activities.

Although the discussion so far has been concerned with monotron oscillators, the interaction is also applicable to multi-resonator amplifiers. For amplifiers the question of efficiency is of particular interest. Achieving high efficiency requires maintaining synchronism between the wave, rotating with angular velocity, ω , and the beam rotating with angular velocity,

$$\frac{d\phi}{dt} = \frac{eB_z}{m_e(1+V/V_n)}$$

where B_z is axial D.C. magnetic field strength and V_n is $m_e c^2/e$

Since the beam angular velocity depends on the beam potential, V , the beam will in general fall out of synchronism as it loses energy. However, the loss of synchronism can be prevented by tapering the magnetic field to match the variation in beam voltage.

Assuming synchronism is maintained, a second limitation arises because of the relation between beam orbit radius and tangential velocity.

$$r = v_\phi \left| \frac{d\phi}{dt} \right|$$

Therefore, if the beam loses energy and if the magnetic field is tapered to keep $d\phi/dt$ constant, the orbit radius will decrease somewhat, putting the beam into a region of lower R-F fields. However, this is not a serious limitation. For example, with $n=10$ the beam velocity could drop from the optimum value of $0.88c$ (c is the velocity of light) to $0.81c$ with only a factor of one-half decrease in R/Q . This is equivalent to the beam voltage dropping from 560 kv. to 360 kv. which represents a conversion efficiency of 36 percent.

The following approach is used to recover the energy

from the spent beam. When the high velocity beam is obtained by cyclotron resonance acceleration, it is practical to return the spent beam to the accelerator cavity and recover over 50 percent of the energy in the spent beam as described in connection with FIG. 7. Electrons returned to the accelerator in a phase to lose energy will generally lose all but about 20 kv. of energy. Electrons returned in a phase to gain energy cannot do so because of relativistic mass effects. The mechanism employed to turn the beam around involves reducing the axial velocity to zero by forces

$$v_\phi \times B_r$$

Equation for turning around rotating beam

$$\left(\frac{v_{z2}}{v_{z1}} \right)^2 = 1 - \left(\frac{v_{\phi1}}{v_{z1}} \right)^2 \left(\frac{B_{z2}}{B_{z1}} - 1 \right)$$

where subscripts 1 and 2 refer to two axial positions

$v_z = z$ velocity

$v_\phi =$ tangential velocity (adiabatic $v_{\phi1} = v_{\phi2}$)

$B_z =$ D.C. axial magnetic field

Equation assumes adiabatic conditions i.e. magnetic field does not change by a large amount in the space of a cyclotron wavelength. Therefore, if at any upstream portion of the tube such as at the accelerator exit the conditions v_{z1} , v_ϕ , and B_{z1} are known and it is desired to reduce v_z to say zero at a downstream position for reversal purposes or to a small value, e.g. at the entrance of the interaction region a desired v_{z2} value can be inserted in the above equation to determine the B_{z2} field value. Since magnetic flux lines are continuous the required B_r values are obtained on the basis of the above determination of B_z for superimposed and tapered B fields.

The following discussion is directed to a specific device as depicted in FIG. 1 with the following design parameters.

A value of $n=10$ was selected for demonstration of the approach. Cyclotron wave acceleration was chosen as the method for obtaining the high velocity rotating beam. It was decided that a monotron oscillator was the most appropriate form for the experimental device.

To determine the required beam velocity, we refer to FIG. 11. With $n=10$, optimum interaction occurs with

$$(v_\phi/c) = 0.84(f/f_c)$$

To minimize beam velocity, we pick $f/f_c=1.05$. This choice results in a length to diameter ratio for the interaction cavity of $L/D=0.359$, which is a reasonable value. Then, the required beam velocity is $(v_\phi/c)=0.88$.

To design the cyclotron wave accelerator to produce the required beam, computer calculations can be made for relativistic electrons in cavity fields. Basically, the accelerator cavity 28 consists of a TE_{111} cylindrical cavity excited in a circularly polarized manner as discussed previously. The cavity is immersed in an axial D-C magnetic field. Electrons are injected on the axis of the cavity with a small axial velocity, e.g. 500 volts. In passing through the cavity, they gain a large transverse energy from the R-F electric fields. They leave the cavity with large transverse velocity but negligible change in axial velocity.

If relativistic effects were negligible, the beam leaving the accelerator section would have the form of a pencil beam rotating about the axis at the cyclotron frequency. Such a beam would have a large component of X-band modulation in the form of a cyclotron wave modulation. This modulation would tend to make the millimeter wave oscillator operate on a frequency harmonically related to the X-band input. However, because of relativistic mass effects, the beam actually has the form of a rotating helix of rather tight pitch. The pitch of the helical beam is sufficiently less than the length of the millimeter wave cavity that the cavity can be considered to be flooded with an unmodulated rotating cloud of elec-

trons. Therefore, the oscillator frequency will not in general be harmonically related to the accelerator frequency.

The accelerator input frequency was chosen as 9375 mc. to use power available from an existing magnetron power source indicated at 32. Required input power was 25 kw. The axial magnetic field was about 5000 gauss. A conventional laboratory magnet system as shown in FIG. 6 is used to supply the field. The beam leaves the accelerator cavity with an average orbit radius of 6 millimeters and a radial thickness of 2.5 millimeters.

The isolation section is beyond cutoff for the X-band accelerator power. Next the beam passes into a cylindrical tube of slightly larger diameter which forms the TE_{10,1} mode millimeter wave oscillator cavity.

The specification of beam velocity, orbit radius, and the index, n fixes the output frequency through the relation

$$v_0 = r\omega/n$$

Based on an orbit radius of 6 millimeters the output wavelength is about 4.5 millimeters. The oscillator cavity dimensions were picked for resonance at 4.5 millimeters, but in practice the beam velocity and orbit radius can be adjusted independently over a 20 percent range by variation of accelerator input power or D-C magnetic field.

The diameter of the drift tube isolation section was chosen as a compromise between beam transmission and R-F cutoff. It is necessary for the isolation section to be beyond cutoff for both the X-band accelerator power and the millimeter wave output power. The TE_{10,1} mode in cylindrical guide cuts off at $k_0 a = 11.75$. Then for $\lambda = 4.5$ millimeters, the cutoff radius is 8.42 millimeters. The X-band cutoff radius is 9.39 millimeters. The maximum beam radius is 7.25 millimeters. A compromise value of 7.9 millimeters was picked for the drift tube radius.

The size of the hole in the end wall of the output cavity was chosen to produce negligible loading for the TE_{10,1} resonance, but appreciable loading for resonances such as the $n=5$ and lower. For convenience, the loading hole diameter was made equal to the isolation drift tube diameter.

The 4.5 millimeter output power was brought out in WR15 guide 52. A broadband mica window was used in the output. The WR15 guide cuts off at about 7.5 millimeter wavelength. Its use permits observation of oscillations down to a value of $n=6$.

The required beam current for oscillation can be calculated using the equations in the previous section. The ideal Q of the TE_{10,1} cavity is 10,000. Based on one revolution of the beam in the cavity, I_0 is 800 ma. for the start of oscillations as a monotron. With a beam current of 50 ma., four revolutions of the beam are required. Therefore, the average drift velocity through the cavity must be about 0.1c (equivalent to 2300 volts). Calculations indicate that the axial velocity of the electrons leaving the accelerator section will be about 0.2c. The isolator and millimeter wave sections are surrounded with magnetic trimming coils 70, 71. The fields from these coils can be used to reduce the axial velocity by means of $v_0 \times B_r$ forces. The beam can be turned around and passed back through the cavity 56 thereby doubling the number of useful beam revolutions. A D-C trimming field of about 400 gauss is required for this purpose. The solenoids or trimming coils are preferably supplied by a variable current source of any conventional type (not shown) for easy control of the desired B values.

The beam velocity of 0.88c is equivalent to a voltage of 560 kv. The 50 ma. beam will load the accelerator cavity by a peak power level of about 30 kw. A 0.100-inch diameter cathode produces the required current with a current density of less than 1 amp/cm.².

A cold test model was made for the X-band accelerator cavity to check for circular polarization and to determine

the reactive effects of the large diameter drift tube. It was found that the drift tube hole lowered the cavity frequency by about 8 percent. The circularly polarized cavity mode was excited using the 3-db hybrid coupler to drive the two X-band waveguide inputs. It was found that fine tuning adjustments were advisable to insure that the cavity can be made circularly degenerate.

For the millimeter wave resonator cold tests were made to check methods of loading undesired cavity resonances. With an open ended drift tube at one end of the resonator and a flat metal plate over the drift tube at the other end of the resonator, only the desired resonances were observed. With both ends closed by metal plates, the number of observed resonances increased by at least a factor of ten, as one would expect. With one end closed by a metal plate and the other closed by a flat piece of alumina one-half inch in thickness, the desired resonances were unaffected and a few of the undesired resonances were just barely detectable. It was concluded that terminating the drift tube with a dielectric window is an effective way of damping the undesired resonances. The actual window used for the oscillator was uranium glass with a thickness of $1/16$ inch. The glass, alumina, etc. window can be aluminized to prevent charging.

A multicavity amplifier 80 modification of the monotron oscillator depicted in FIG. 1 is shown in FIG. 2. In this case, a millimeter wave R.F. input source, waveguide 81 is coupled to the first circular cylindrical cavity 82 to induce rotational velocity modulation of the cylindrical electron beam and very slight bunching in cavity 82 at the frequency to be amplified. An isolator section, cylindrical waveguide 83 is designed to be cut off for the higher order mode of operation while permitting the undesired lower order TE_{n1} modes to propagate out the device as described previously. The modulated beam is further density modulated as it passes through isolator section 83. Energy is extracted from the bunched beam in output circular cylindrical cavity 84 and is carried to a load via output guide 85.

Turning now to FIG. 7A, a novel approach is depicted for turning the beam around at the downstream end of the interaction cavity 56 by means of $v_0 \times B_r$ forces as discussed previously. Good results are obtained with additional fields of 400 to 500 gauss superimposed on the main field of around 5000 gauss. If the beam is permitted to make many revolutions before being turned around by $v_0 \times B_r$ force due to the additional B_z field set up by shim coil 71 the beam modulation will completely smear out and will not affect the R.F. in the cavity 56. The reverse beam is now simply allowed to drift back into the accelerator section where as stated previously electrons returned in proper phase will generally lose all but about 20 kv. of energy while relativistic mass effects will prevent returned electrons from gaining energy. Thus about 50% of the spent beam energy should be available to enhance the R.F. accelerator fields while due to the relativistic tangential velocities the electrons returning in improper phase will not absorb energy from the R.F. fields in the accelerator region.

The dotted lines in FIGS. 7A, 7B, 7C, are representative of the magnetic field and the sloped region at 90 resulting from the additional aiding field produced by coil 71 provides the $v_0 \times B_r$ forces.

In FIG. 7B a larger aiding auxiliary magnetic field is superimposed than in 7A and this permits a much shorter time of return of the reverse beam through the interaction cavity 56 which reduces the amount of debunching and permits return of the beam through the cavity in a phase relation to add to the R.F. fields induced in the initial passage and produce a reflex-monotron cyclotron wave action which effectively doubles the number of beam revolutions through the cavity and thus the efficiency is considerably enhanced. The reverse beam is again permitted to drift down to the accelerator cavity 28 where properly phased electrons will return about 50% of the

total remaining beam energy to the R.F. fields in the cavity.

In FIG. 7C the shim coil superimposes a bucking field on the main D.C. field and in this version the beam is simply permitted to impact on the side walls of the isolator section 58 due to the reduced field and space charge forces.

In each of the FIGS. 7A, 7B, 7C, the reverse beam is represented by the dashed lines in a merely schematic way. The actual reverse beam would have approximately the same dimensions as the forward beam and due to the extremely tenuous nature of the beam as well as the nature of electrons would not present any collision or perturbation problems in the interaction regions such as to detract from the A.C. signal level.

In FIG. 12 a pictorial diagram of a cross-section of the rotating cylindrical beam depicted for the monotron cyclotron resonance device depicted in FIG. 7A for the case where the beam is reversed and returned to the accelerator cavity for the case of index $n=4$. It is to be understood that the cases 1-6 are merely illustrative. At plane 1 the beam is a simple rotating cylinder. Between planes 1 and 2 the beam is velocity modulated and bunched and energy is extracted all within the cavity 56.

At planes 3 and 4 the beam gradually loses its modulation until it is essentially cylindrical again as it re-enters the accelerator cavity.

In FIG. 13 which depicts the phased return case depicted in FIG. 7B where the beam is reversed quickly and returned in proper phase to give up additional kinetic energy to the R.F. fields in cavity 56. The beam is unmodulated at 1 and highly modulated at 2 and 3 and again smeared back to essentially a cylinder at 4.

In the amplifier case of FIG. 2 the beam is unmodulated at plane 1, velocity modulated at 2 by the energy to be amplified, and highly bunched or density modulated at plane 3 as a result of kinematic drifting between 2 and 3. It is slightly demodulated as it leaves output cavity 84 at plane 4 after the energy extraction process as depicted in FIG. 14. In the amplifier case the axial velocity of the beam is set to be larger than for the monotron to prevent undesired oscillations.

In FIG. 15 a pictorial diagram of the accelerator cavity 28 and its conversion effects on the beam is depicted on a greatly magnified scale. It is seen that the beam enters the cavity via re-entrant drift tube 27 as a simple axial flow beam and is rapidly enlarged into a helix configuration with rapid decrease in pitch and with an additional angular rotation component which causes the entire helix to rotate as indicated by the directional arrows. For more details on this cyclotron resonance cavity accelerator see co-pending U.S. Ser. No. 576,406 by J. Feinstein et al.

It is to be noted, as discussed previously, that other known methods for producing a rotating cylindrical beam may be used in lieu of the specific case illustrated herein such as for example as described in the aforementioned U.S. Patent 3,183,399 without detracting from the scope of the present invention.

As a visual aid, the $F=e(v_\phi \times B_r)$ forces for the diverging and expanding B field regions are depicted in FIG. 16. It is seen that an aiding B field compresses the main field to produce zero v_z for the rotating beam by imposing an F component on the electrons which is directed upstream. The converse is true for an expanded B field.

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 high frequency electron discharge device operable in the microwave spectrum including, electron gun

means disposed at an upstream end portion of said device for generating and directing an electron beam along the device axis, said device including means for converting said electron beam into a hollow rotating cylinder of electrons and for causing said electrons to move substantially continuously along the axis of the device, which cylinder is characterized by being composed of electrons which have greater tangential velocity components than axial velocity components, said device further including a circular-cylindrical resonator coaxially disposed about said device axis downstream from said electron gun means and from said means for converting the beam into a rotating hollow cylinder of electrons, said resonator having a pair of axially spaced transverse end walls having aligned apertures in said respective transverse walls defining end walls for permitting the rotating hollow electron beam to pass through said resonator for electromagnetic interaction with the fields thereof to produce output microwave energy, said resonator including means for enhancing TE_{n11} mode excitations with $n>2$, said device being provided with means for producing a D.C. magnetic field B_z along the device axis.

2. The device defined in claim 1 wherein said device includes means for reversing the axial flow direction of said rotating hollow beam of electrons after said beam has passed through said resonator and directing said beam back towards said upstream end portion of said device.

3. The device defined in claim 1 wherein said means for converting said electron beam into a hollow rotating cylinder includes means for producing a unidirectional magnetic field along the device axis such that said beam has an average tangential velocity $v_\phi \approx r\omega/n$ where:

r =average beam radius

ω =angular frequency of operation of said device

n =any integer >2

4. The device defined in claim 1 wherein said device includes a plurality of circular cylindrical cavity resonators coaxially disposed about said device axis, each of said resonators having a pair of axially aligned apertures at their respective defining end walls for permitting the rotating hollow electron beam to pass therethrough along the device axis, at least one of said resonators being provided with means for velocity modulating said rotating electron beam at an angular frequency ω which is $\approx \omega_c$ where:

$\omega_c = eB_z/m$

B_z =D.C. magnetic field strength along device axis provided by said means for producing a D.C. magnetic field

e =charge of electron

m =relativistic mass of electron

5. The device defined in claim 1 wherein said means for converting said electron beam into a hollow rotating cylinder of electrons includes a circular cylindrical resonant accelerator cavity coaxially disposed about said device axis downstream from said electron gun means, said accelerator cavity including means for exciting a TE_{111} mode therein.

6. The device defined in claim 1 wherein said device includes further means for providing radial D.C. magnetic field components for reducing the axial velocity of said rotating electron beam traveling along said device axis.

7. The device defined in claim 1 wherein said means for converting said electron beam into a hollow rotating cloud of electrons includes cavity means for accelerating said electron beam with circularly polarized TE_{111} mode electromagnetic energy, said device having an operating frequency which is greater than the angular frequency of said TE_{111} mode electromagnetic energy.

8. A microwave generator for producing an output

signal in the millimeter wave region of the microwave spectrum comprising, electron gun means disposed at the upstream end portion of said device for producing a beam of electrons and directing said beam of electrons along the device axis towards the downstream end portion of said device, a circular cylindrical resonant accelerator cavity coaxially disposed about said device axis downstream from said electron gun means, means for exciting a circularly polarized TE_{111} mode in said accelerator cavity, said accelerator cavity being coupled to said electron gun means via a re-entrant drift tube means for permitting said electron beam to enter said accelerator cavity at a plane located downstream from the upstream transverse defining wall of said accelerator cavity, said drift tube being a cut-off waveguide at the operating resonant frequency of the accelerator cavity, said accelerator cavity including a pair of 90° azimuthal space rotated input coupling ports for introducing electromagnetic energy at the resonant frequency of said accelerator cavity to excite a circular polarized TE_{111} mode in said accelerator cavity, said 90° space rotated ports being coupled to hybrid directional coupler means which is fed by a signal generator means for producing an R.F. signal at the resonant frequency of said accelerator cavity, said device including an isolator section disposed downstream from said accelerator cavity, said isolator section permitting passage of said electron beam while being cut off for electromagnetic energy at the operating frequency of said accelerator cavity, said device further including another circular cylindrical cavity resonator coaxially disposed about said device axis downstream from said isolator section, said another resonator having output means for extracting electromagnetic energy coupled thereto, said another resonator having a high Q for higher order TE_{n11} modes and a relatively lower Q for lower order TE_{n11} modes, said device further including means for providing a unidirectional magnetic field along the device axis.

9. The device defined in claim 8 wherein said device is provided with at least one additional circular cylindrical resonant cavity disposed upstream from said another cavity, said additional cavity being provided with R.F. coupler means for introducing an R.F. signal to be amplified.

10. A monotron cyclotron resonance high frequency electron discharge device oscillator for generating microwave energy, said device including means for producing an electron beam having a rotating hollow cylindrical configuration and having a tangential electron velocity $>.2c$ where c =speed of light, said device including a circular cylindrical cavity resonator disposed about the device axis downstream from said means for producing said electron beam, said circular cylindrical cavity resonator being excited in a TE_{n11} mode by passage of said electron beam through said resonator along the axis of said device, said index n being an integer >2 , said beam producing means including means for causing the electrons of the hollow beam to move continuously in the axial direction from the source of the hollow beam through said cavity resonator wherein the rotational energy of the beam is converted into output microwave energy.

11. The device defined in claim 10 wherein said device includes means for producing a unidirectional magnetic field along the axis of said device, said magnetic field having an axial field strength B_z inter-related with the angular operating frequency of said device in the following manner:

$$\frac{eB_z}{m_0} \approx \frac{\omega}{n} \frac{m}{m_0}$$

where:

e =electron charge

B_z =axial D.C. magnetic field strength

m_0 =rest mass of an electron

ω =angular operating frequency of said device

n =index number for TE_{n11} mode

m =relativistic mass of electrons in device as determined at operating condition

12. A high frequency electron discharge device for operation in the microwave spectrum, said device including means for producing a rotating generally cylindrical shaped cloud of electrons having a relativistic tangential velocity of $v_\phi >.2c$ and an axial velocity of $v_z <.2c$ where c =velocity of light, and means for directing said cylindrical shaped cloud of electrons in a continuously moving stream along the device axis toward the downstream end portion thereof, said device further including means for reducing the axial velocity of said electrons, a circular cylindrical cavity resonator coaxially disposed about the device axis and said stream of electrons, said cavity being excited in a higher order TE_{n11} mode by said electron stream in its passage through said cavity to produce output microwave energy.

13. A high frequency electron discharge device for operation in the microwave spectrum, said device including means for producing a rotating generally cylindrical electron beam and directing said rotating beam down the device axis at an axial velocity which is less than the tangential velocity of said beam and continuously moving the beam through interaction means disposed along said device axis downstream from said means for producing said beam, said device further including means for reversing the axial direction of said beam downstream of said interaction means and directing said beam back through said interaction means towards the upstream end portion of said device.

14. The device defined in claim 13 wherein said beam is phased relative to the electromagnetic energy in said interaction means such that kinetic energy is extracted from said beam as it passes through said interaction means in both its forward and reversed directions.

15. The device defined in claim 13 wherein said interaction means includes a circular cylindrical cavity resonator coaxially disposed about the device axis and having a pair of axially aligned and spaced beam coupling apertures for permitting said rotating beam to pass therethrough while exciting said cavity in a higher order TE_{n11} mode with n being an integer >2 .

$$\omega \approx v_\phi n / r$$

where:

r =beam radius

v_ϕ =tangential beam velocity, and

n =index for TE_{n11} mode with n being any integer >2 .

16. A high frequency electron discharge device for generating microwave energy at a wavelength between .1 mm. and 10 mm., said device including means for producing a rotating generally cylindrical hollow beam of electrons having a tangential velocity $v_\phi >.2c$ and a smaller axial velocity, where c is the velocity of light, and means for directing said hollow cylindrical shaped rotating beam of electrons down the device axis in a continuously moving stream towards the downstream end portion thereof, interaction means disposed along said device axis downstream from said means for producing said beam, said interaction means including means for converting tangential kinetic energy of said beam into electromagnetic energy which has an angular frequency ω which is

$$\omega \approx v_\phi n / r$$

where:

r =beam radius

v_ϕ =tangential beam velocity

n =index for TE_{n11} mode with n being any integer >2 ,

and means for directing the stream of rotating electrons in a continuously moving stream through said interaction means.

17. A high frequency electron discharge device for generating microwave energy, comprising means for producing and directing an electron beam along the device disposed

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at the upstream end portion of said device, means for causing said electron beam to form a rotating generally hollow cylindrical form having a larger tangential velocity than axial velocity, cavity means disposed about said device axis for converting tangential electron beam kinetic energy into microwave energy at an angular frequency which is given by

$$\omega \approx v_{\phi} n / r$$

where:

r = beam radius

v_{ϕ} = tangential beam velocity, and

n = index for TE_{n11} mode with n being any integer > 2 , and means for directing the stream of rotating electrons in a continuously moving stream through said interaction means.

18. The device defined in claim 17 wherein said beam is velocity and density modulated in said cavity means

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along its circumference as said beam passes through said cavity.

19. The device defined in claim 17 wherein said device includes means downstream of said cavity for slowing the axial velocity of said beam to zero and reversing the axial direction of said beam.

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