

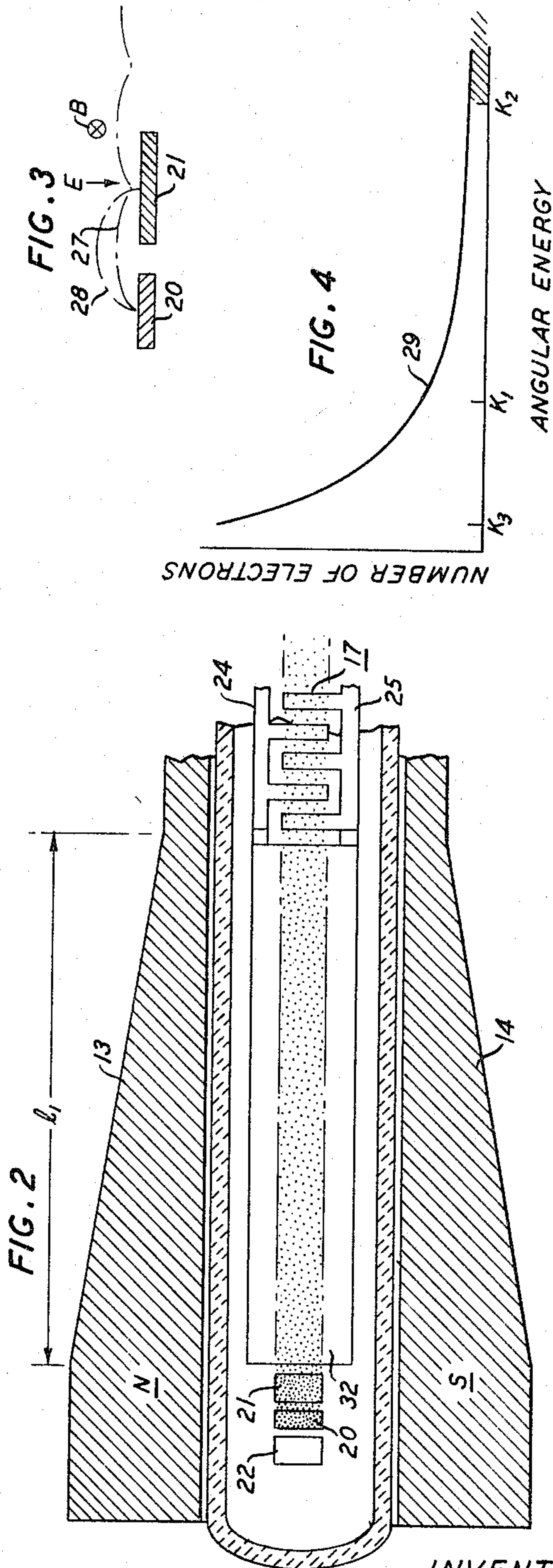
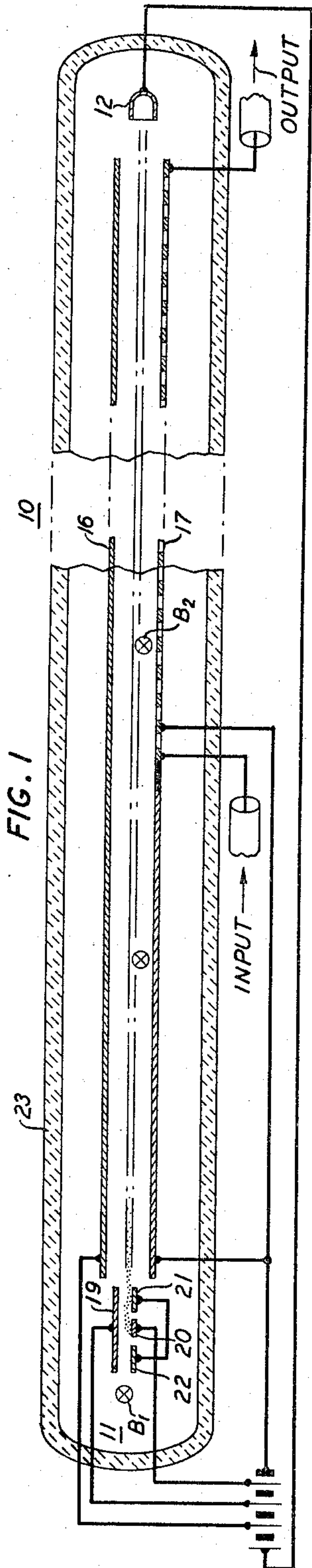
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ELECTRON BEAM DEVICE

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ELECTRON BEAM DEVICE

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This invention relates to electron beam devices and, more particularly, to electron guns for use in cyclotron-wave M-type beam devices.

The term "M-type device" refers to an electron tube which uses mutually perpendicular electric and magnetic fields (cross-field) for constraining electron flow, as distinguished from O-type devices which use longitudinal magnetic fields for this purpose. M-type devices can be used either as oscillators or as wave amplifier, their most attractive features being their inherent efficiency and capacity for high-power operation. When the device is used as an amplifier, it is usually desirable to minimize the spurious noise which invariably accompanies the generation of an electron beam, the requisite degree of noise reduction being dependent on the use to which the tube is to be put.

It is an object of this invention to reduce electron beam noise in an M-type electron beam device.

Most M-type devices amplify electromagnetic waves through synchronous wave modulation of the electron beam. These modulations are characterized by electron displacements from the mean beam path and by longitudinal velocity variations which result in electron bunching along the path. These modulations can interact with electromagnetic waves propagating on a slow-wave structure in proximity to the beam to give a net amplification of the wave. Spurious synchronous wave noise can be reduced to some extent by careful electron gun design, but experience has shown that the noise properties of conventional M-type devices are not normally competitive with O-type devices.

Any electron moving transverse to a magnetic field tends to gyrate or rotate at a frequency called the cyclotron frequency that is dependent upon the strength of the magnetic field. In an M-type device, these angular electron velocity components can be modulated by propagating an electromagnetic wave in proximity to the beam in such a manner that electric field components of the wave have additive or subtractive effects on the angular motions of the electrons. This process is referred to as cyclotron-wave modulation, and it differs fundamentally from conventional modulation. Either amplification or the generation of oscillations is effected by abstracting energy from the beam in a manner analogous to conventional beam interaction. The beam noise which may interfere with the cyclotron wave interaction process is manifested by spurious angular velocity components of the electrons as they leave the tube cathode, and is referred to as cyclotron wave noise. I have found that these angular velocity components can be removed from an M-type beam to give the beam even lower noise properties than are possible in most O-type devices.

Accordingly, it is a specific object of this invention to reduce cyclotron wave noise in an M-type electron beam device.

These and other objects of the invention are attained in an illustrative embodiment comprising an M-type electron beam device having a slow-wave structure for propagating an electromagnetic wave in interacting relationship with cyclotron wave modulations of the electron beam. Mutually perpendicular electric and magnetic fields extend along the beam path for focusing the beam in accordance with known crossed-field focusing principles.

The electron gun which forms and projects the electron

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beam comprises a cathode which is located on the tube axis and a high velocity electron collector which is located between the cathode and the slow-wave structure. The electric field in the electron gun is very weak with respect to the magnetic field so that as electrons are emitted they are constrained by the magnetic field to drift at right angles to the electric field in very close proximity to the high velocity collector before injection into the interaction region defined by the slow-wave structure. The high velocity collector is coated with a highly electron-absorptive material such as carbon and is located on the same plane as the cathode. As will be explained hereafter, electrons with high angular velocity components are caused to follow trochoidal paths from the cathode and impinge upon the high velocity collector; these high angular velocity electrons represent sources of spurious cyclotron wave noise which would otherwise degrade wave amplification in the interaction region. Electrons which do not contain such high spurious angular velocity components drift past the high velocity collector into the interaction region.

Effective separation of "noisy" electrons can be accomplished only if the electric field in the electron gun is very weak with respect to the magnetic field and the temperature of the cathode. If the electric field is high, the spurious initial angular velocity components will have little effect on electron trajectory. Only if the electric field is very weak will the electron beam "graze" the high velocity collector as is required for selectively collecting high velocity electrons. As will be explained hereafter, the threshold value of the electric field in the electron gun is given by the inequality

$$E < B \sqrt{\frac{4kT_c}{m}} \quad (1)$$

where E is the intensity of the electric field in the electron gun, B is the flux density of the magnetic field, k is Boltzmann's constant, T_c is the absolute temperature of the cathode, and m is the mass of an electron.

These and other objects and features of the invention will be more clearly understood from a consideration of the following detailed description taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a sectional view of an electron beam device employing the principles of my invention;

FIG. 2 is a top view of part of the slow-wave structure of FIG. 1;

FIG. 3 is a sectional view of part of the electron gun of the device of FIG. 1; and

FIG. 4 is a graph of the energy distribution curve of the electron beam of the device of FIG. 1.

Referring now to FIG. 1, there is shown a schematic view of an illustrative embodiment of my invention comprising an M-type cyclotron wave amplifier 10 having an electron gun 11 for forming and projecting an electron beam toward a collector 12. The electron beam is constrained to flow approximately along the tube axis by the combined action of crossed electric and magnetic fields. The magnetic focusing field is formed by pole pieces 13 and 14 which are shown schematically on FIG. 2. The electric focusing field is formed by a positively biased elongated anode 16 and a negatively biased slow-wave structure 17. In the electron gun the electric field is formed between a positively biased anode 19 and a cathode 20 and a high velocity electron collector 21. An auxiliary electrode 22 is maintained at the same potential as the cathode and the high-velocity collector and is included in the electron gun to maintain the uniformity of the electric field in the gun. The beam is maintained within a substantial vacuum by an envelope 23.

Besides establishing the electric focusing fields, slow-wave structure 17 constitutes a waveguide for transmitting

electromagnetic wave energy in interacting relationship with the electron beam. Normally, the slow-wave structure of an M-type device constitutes a positively biased anode and it is constructed so that electric fields parallel with the beam will bunch the electrons as is required for interaction. In device 10, the negatively-biased slow-wave structure is constructed so that electric field components will modulate the beam to produce a slow cyclotron wave thereon which will couple with the propagating wave to give interaction with resulting amplification. As can be best seen in FIG. 2, slow-wave structure 17 comprises an interdigital structure which defines a serpentine wave path between conductors 24 and 25. By propagating the wave along a tortuous path, slow-wave structure 17 delays the axial velocity of the wave so that it matches the inherent velocity of a slow cyclotron wave of corresponding frequency on the beam. It can be shown that the transverse electric field components of a wave propagating along slow-wave structure 17 will be in synchronism with corresponding cyclotron waves on the beam if the following equality is substantially met:

$$\frac{\omega}{v_t} = \frac{\omega + B\eta}{v_o} \quad (2)$$

where ω is the frequency of the signal wave propagating along the slow-wave structure, v_t is the effective axial phase velocity of the wave propagating along the structure, B is the magnetic flux density, η is the charge-to-mass ratio of an electron, and v_o is the velocity of the electron beam. With this condition met and with slow-wave structure 17 biased at a negative potential and in sufficient proximity to the beam to permit effective penetration of its electric fields into the beam, amplification of the propagating wave will be effected through known principles of traveling wave interaction. The phase velocity of the electromagnetic wave is determined by the construction of the slow-wave structure, while the axial beam velocity is determined by the relationship

$$v_o = E/B \quad (3)$$

where E is the electric field intensity and B is the magnetic flux density at the location under consideration.

One of the main purposes of electron gun 11 is to minimize the cyclotron wave noise that invariably accompanies the generation of an electron beam. The electron beam is generated by heating the cathode either directly or indirectly according to the principles of thermionic emission. Since cyclotron waves are defined by angular velocity components of the electrons, spurious cyclotron-wave noise results from the varying and inconsistent angular velocity components which are imparted to the electrons when they are emitted from the cathode. In accordance with the invention, electron gun 11 screens out the electrons that have high spurious angular velocity components and thereby reduces the cyclotron-wave noise of the electron beam that is injected into the interaction region.

By the "left-hand rule" the electric and magnetic fields in the electron gun force the electron beam to drift to the right at an axial velocity given by Equation 2. Superimposed on this velocity component is an angular component which results from the initial emission velocity of the electrons and the attractive force of the anode 19. The two velocity components cause the individual electrons to follow trochoidal rather than linear trajectories along the beam path. If the electric field in the electron gun is very small with respect to the magnetic field and the thermionic emission velocity from the cathode, most of the electron angular velocity component will be due to its emitted velocity.

FIG. 3 shows the path 27 of an electron having a relatively low angular velocity component and a path 28 of an electron having a larger angular velocity com-

ponent. Both electrons follow trochoidal paths having a radius of curvature r given by the equation

$$r = \frac{v_t}{B\eta} \quad (4)$$

where v_t is the tangential velocity component of the electron. Electrons having large tangential velocity components will follow paths of large radius such as path 28 and be collected by high-velocity electron collector 21. Collector 21 is coated with a highly electron-absorptive material having a very low ratio of secondary emission such as carbon. By this arrangement a significant number of the electrons which are emitted with high spurious tangential velocity components are collected by collector 21, thus reducing the cyclotron wave noise on the beam that is injected into the interaction region.

It is apparent that if the electric field E were very high by comparison with the magnetic field B or the temperature of the cathode, velocity sorting of the type described above could not take place because the tangential velocity components due to differences in emission velocity would be very small with respect to the tangential components due to the electric field E . An understanding of the intensity of the electric field required for optimum noise reduction under different circumstances can be gained from a consideration of FIG. 4 which illustrates the Maxwellian distribution of electrons having different tangential energy levels. It can be shown that the mean tangential energy of the electrons K_1 is directly proportional to the temperature at the cathode:

$$K_1 = kT_c \quad (5)$$

where k is Boltzmann's constant and T_c is the absolute temperature of the cathode in degrees Kelvin. The cathode temperature can be measured in a known manner by a pyrometer probe, or any other suitable temperature measuring device. I have found that a detectable cyclotron wave noise reduction will occur if all electrons having an energy level of twice the mean energy level are sorted out by high velocity collector 21. This energy level is denoted on the graph by K_2 where

$$K_2 = 2kT_c \quad (6)$$

It can be shown that all electrons at energy level K_2 and above, designated on the graph by the shaded portion, will be collected by collector 21 if

$$E_1 = B\sqrt{\frac{4kT_c}{m}} \quad (7)$$

where E_1 is the electric field intensity in the electron gun and m is the mass of an electron. Since energy level K_2 is the threshold level at which perceptible noise reduction occurs, the electric field required for detectable noise reduction is defined by

$$E_1 < B\sqrt{\frac{4kT_c}{m}} \quad (8)$$

The electric field defined by inequality (8) is much lower than that used in any conventional M-type electron tube; as a result the beam drifts at a very low velocity toward the interaction region. Another result is a substantial reduction in beam current by the low electric field. Beam current I depends on the electric field according to the relationship

$$I = 2\epsilon_o w \frac{E_1^2}{B} \quad (9)$$

where ϵ_o is the dielectric constant of a vacuum and w is the width of the beam. The beam current should be high enough to give usable gain because amplification energy is derived from the beam. This consideration should be balanced against the consideration that as the electric field E_1 in the gun is reduced, a larger proportion of high tangential velocity electrons will be collected on collector 21. With reference to FIG. 4, as the field

E_1 is reduced, a greater proportion of the curve is "cut off" by the electron interception. Energy level K_3 represents the approximate minimum electric field E_1 that can be used to give a beam current that is high enough for practical amplification purposes. All of the electrons represented by the curve as lying to the right of level K_3 will be intercepted by collector 21 if

$$E_1 = \sqrt{\frac{4k0.001T_c}{m}} \quad (10)$$

Since Equations 7 and 10 define the upper and lower limits for field E_1 , the field E_1 , for noise reduction in accordance with the invention, can be defined as

$$B\sqrt{\frac{4k0.001T_c}{m}} < E_1 < B\sqrt{\frac{4kT_c}{m}} \quad (11)$$

As a typical example, the magnetic field in the electron gun may be 1000 gauss, the separation between the cathode 20 and anode 19 one millimeter, the beam width one centimeter and the cathode temperature 1000 degrees Kelvin. In accordance with inequality (11), the electric field E_1 should be less than 23 volts for detectable noise reduction; this results from the relationship

$$E_1 = \frac{V_1}{d} \quad (12)$$

where V_1 is the voltage between the cathode and anode 19 and d is the separation between cathode and anode 19. Anode 19 may be biased, for example, at 2.3 volts with respect to the cathode, which gives an electric field that is well within the range of inequality (11) to give high noise reduction and which produces a current of 500 microamperes which is sufficient for most low-noise microwave frequency preamplification.

The beam drift velocity resulting from the field E_1 and the flux density B_1 is normally too low for interaction purposes and so the beam must be accelerated to a more suitable velocity in the interaction region. If, however, the acceleration is abrupt the beam cyclotron waves will mix with beam synchronous noise waves with a resulting transfer of synchronous wave noise to the beam cyclotron mode. To avoid such noise transference, the change in electric or magnetic field for giving acceleration must be adiabatic, or so gradual that the cyclotron wave and synchronous wave noise quantities remain invariant. It can be shown that a magnetic field transition will be sufficiently gradual, or adiabatic, if the following relationship is met:

$$2.4n > \frac{B_1}{B_2} - 1 \quad (13)$$

where n is the number of cyclotron wavelengths in the transition region, B_1 is the magnetic flux density before acceleration, and B_2 is the flux density after acceleration. The cyclotron wavelength λ is the axial distance traveled by an electron during one trochoidal rotation and, for a given electric field intensity E and magnetic flux density B , is given by

$$\lambda = \frac{2\pi E}{eB^2} \quad (14)$$

where e is the charge on an electron.

In order to comply with Equation 13, and in order to accelerate the beam according to Equation 3, the magnet pole pieces 13 and 14 are tapered along a transition region of length l_1 as shown in FIG. 2. The length l_1 may typically be four centimeters, the magnetic flux density B_1 in the gun 1000 gauss and the flux density B_2 in the interaction region 80 gauss. The voltage between elongated anode 16 and slow-wave structure 17 may be 6.9 volts with a separation of three millimeters. A transition electrode 32 is maintained at the same voltage as the slow-wave structure, but is insulated therefrom to avoid backward propagation of electromagnetic wave energy. Under these conditions, the change in magnetic

field will be sufficiently gradual to satisfy inequality (13); the beam will be accelerated to a sufficiently high velocity to permit interaction with a wave transmitted by a slow-wave structure of convenient size. With a tube of this type, the slow-wave structure may typically be 15 centimeters long for amplifying waves of approximately 1500 megacycles.

Rather than reducing the magnetic field, the beam may also be accelerated by increasing the electric field in the interaction region. An adiabatic electric field transition usually involves additional complexities, however, because a uniform transition can only be approximated by a succession of electrode plates each producing a successively higher electric field. Neglecting fringing field effects, an adiabatic electric field change can be approximately defined by a condition analogous to that of the magnetic field transition defined above; this is:

$$2.4n > \frac{E_2}{E_1} - 1 \quad (15)$$

where E_1 is the low electric field before acceleration and E_2 is the high electric field after acceleration. For example, with a constant flux density of 1000 gauss, the electric field may be increased from 2.3 volts in the electron gun to 900 volts in the interaction region with the same separation of three millimeters between the slow-wave structure and the elongated anode 16. A satisfactory transition may be made by a plurality of electrodes of successively increasing potential between the electron gun and the interaction region. Alternatively, the beam may be accelerated by gradually adjusting both the electric and magnetic fields. In such a case, both inequalities (13) and (15) should be met, and the electric and magnetic fields for adiabatic invariance would be defined by

$$2.4n > \frac{E_2 B_1}{E_1 B_2} - 1 \quad (16)$$

In summary, it can be appreciated that by using cyclotron wave interaction in an M-type device, those electrons that contribute most of the spurious noise energy to an electron beam can be selectively removed from the beam before interaction. The specific disclosed embodiments have been presented merely as illustrative examples. Numerous other modifications and embodiments may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron beam device comprising:
 - an electron gun for forming and projecting an electron beam along a central axis;
 - a pair of elongated conductive members located on opposite sides of the axis;
 - means for producing a first direct-current electric field between said conductive members;
 - means for producing a magnetic field transverse to both the first electric field and the central axis;
 - said electron gun comprising a cathode, an anode, and an electron collector;
 - the emitting surface of the cathode and the collecting surface of the collector lying on the same plane;
 - the anode being located on a plane parallel with the cathode and collector;
 - and means for producing a second direct-current electric field between the anode and the cathode which is substantially transverse to the magnetic field;
 - the second electric field being defined by the inequality

$$E < B\sqrt{\frac{4kT_c}{m}}$$

where E is the intensity of the second electric field, B is the flux density of the magnetic field, k is Boltzmann's constant, T_c is the absolute temperature of the cathode, and m is the mass of an electron.

2. An electron beam device comprising:

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an electron gun for forming and projecting an electron beam along a predetermined path;
 means for providing an electric field transverse to the electron beam along said path;
 means for providing a magnetic field transverse to the electron stream along the path and transverse to the first electric field, thereby establishing a cyclotron mode of wave propagation within the beam;
 means for propagating electromagnetic wave energy in interacting relationship with cyclotron waves on the beam;
 said electron gun comprising a cathode and a high velocity electron collector located between the cathode and the propagating means;
 and means for providing a second electric field through the cathode and collector which is transverse to the magnetic field;
 the second electric field being defined by the inequality

$$E < B \sqrt{\frac{4kT_c}{m}} \quad 20$$

where E is the intensity of the second electric field, B is the flux density of the magnetic field, k is Boltzmann's constant, T_c is the absolute temperature of the cathode, and m is the mass of an electron. 25

3. In an M-type electron beam device of the type employing cyclotron wave interaction between an electron beam and electromagnetic wave energy, an electron gun for injecting a low noise electron beam into the interaction region of the device comprising: 30

a cathode and auxiliary electrode, and a high velocity electron collector located within a first plane;
 a planar anode located within a second plane parallel to the first plane;
 means for biasing the cathode auxiliary electrode and high velocity electron collector at a single predetermined direct-current potential which is negative with respect to the anode, whereby a substantially uniform electric field is established between the first and second plane; 35

means for establishing a magnetic field which is transverse to the electric field;
 the electric and magnetic fields comprising means for directing electrons emitted from the cathode past the high velocity electron collector toward the interaction region; 40
 the intensity of the electric field being defined by the relationship

$$B \sqrt{\frac{4k0.001T_c}{m}} < E < B \sqrt{\frac{4kT_c}{m}} \quad 50$$

where B is the flux density of the magnetic field, k is Boltzmann's constant, T_c is the absolute temperature of the cathode, m is the mass of an electron, and E is the intensity of the electric field.

4. A cyclotron wave M-type electron beam device comprising:

an electron gun for forming and projecting an electron beam along a predetermined path;

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means for providing a first electric field transverse to the electron beam along a first path portion;
 means for providing a first magnetic field transverse to the electron beam along a first path portion and transverse to the first electric field;
 means for propagating electromagnetic wave energy in interacting relation with cyclotron waves of the beam substantially in accordance with the relationship

$$\frac{\omega}{v_f} = \frac{\omega + B\eta}{v_o}$$

where ω is the frequency of the electromagnetic wave, v_f is the phase velocity of a magnetic wave in the direction of the path portion, B is the flux density of the first magnetic field, η is the charge-to-mass ratio of an electron, and v_o is the axial velocity of the electron beam along the first path portion;

said electron gun defining a second path portion and comprising a cathode and a high velocity electron collector located between the cathode and the propagating means;

means for providing a second magnetic field transverse to the electron stream along the second path portion;
 means for providing a second electric field through the second path portion which is transverse to the second magnetic field;

the second electric field being defined by the inequality

$$E_2 < B_2 \sqrt{\frac{4kT_c}{m}}$$

where E_2 is the intensity of the second electric field, B_2 is the flux density of the second magnetic field, k is Boltzmann's constant, T_c is the absolute temperature of the cathode and m is the mass of the electron;

and a transition region interconnecting the first path portion with the second path portion;
 the transition region being sufficiently long to conform to the relationship

$$2.4n > \frac{E_1 B_2}{E_2 B_1} - 1$$

where n is the number of cyclotron wave lengths in the transfusion region.

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