

June 17, 1969

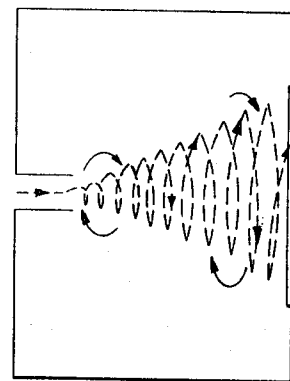
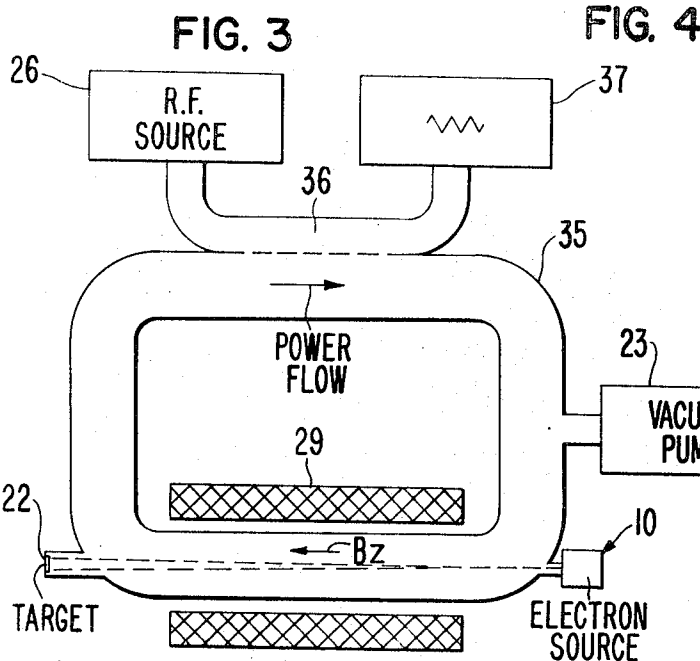
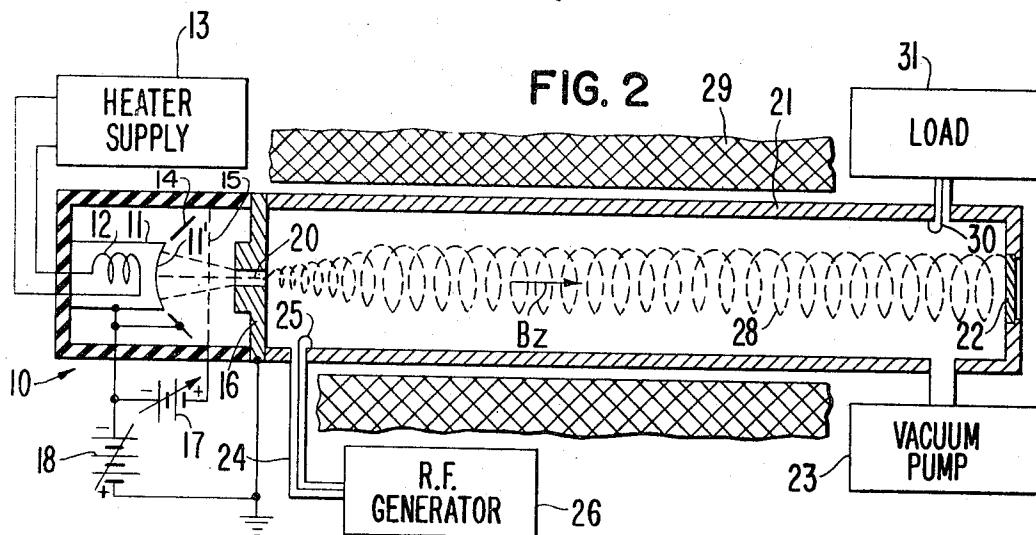
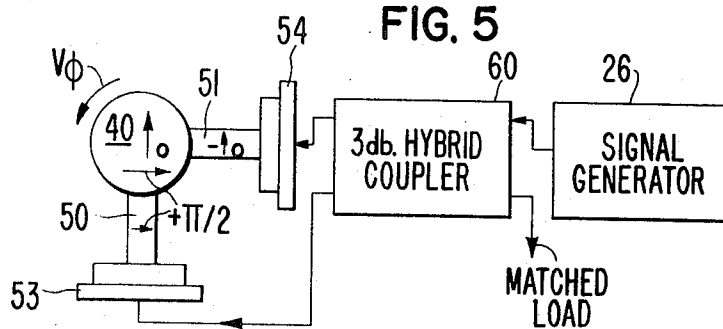
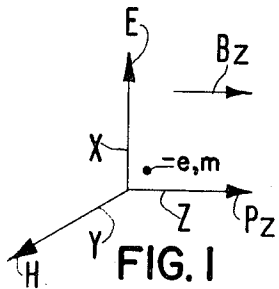
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3,450,931

CYCLOTRON MOTION LINEAR ACCELERATOR

Filed Aug. 30, 1966

Sheet 1 of 2



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Sheet 2 of 2

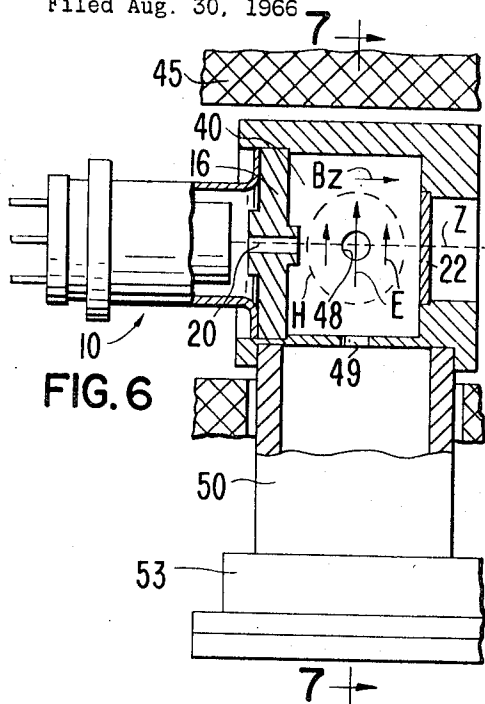


FIG. 6

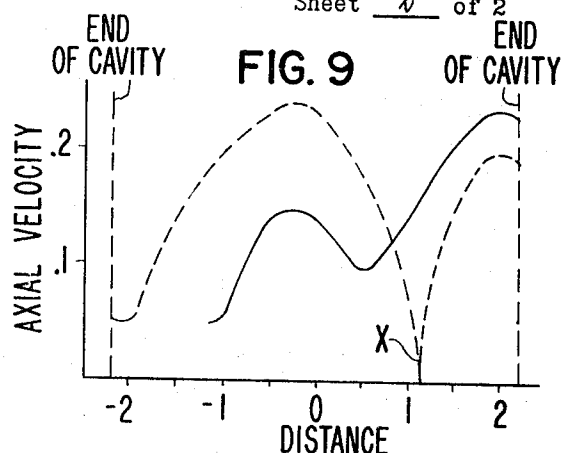


FIG. 9

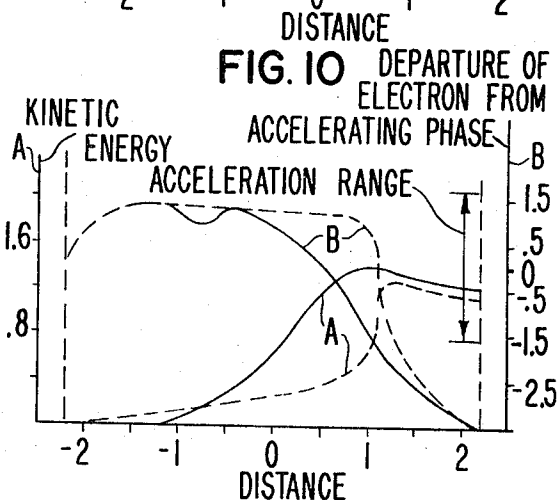


FIG. 10

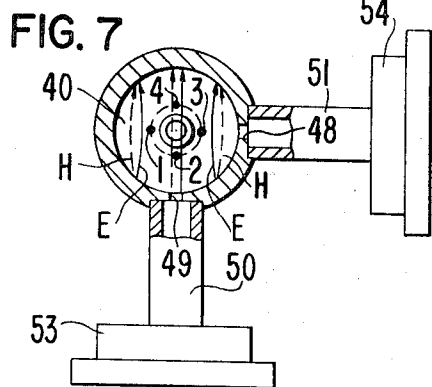


FIG. 7

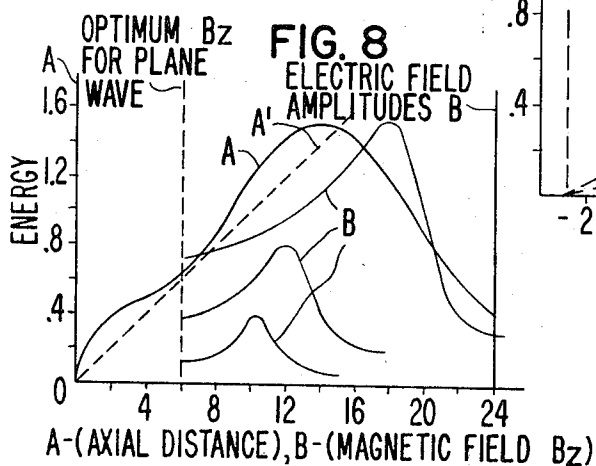


FIG. 8

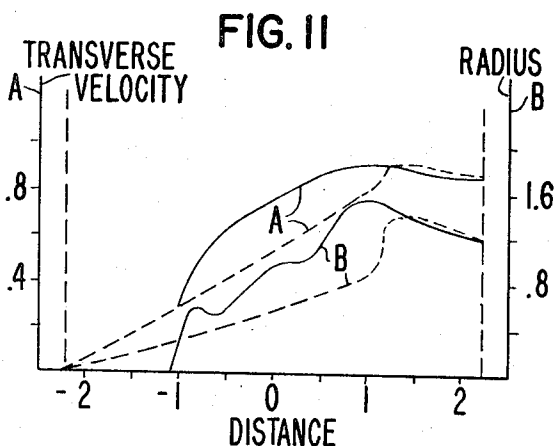


FIG. 11

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CYCLOTRON MOTION LINEAR ACCELERATOR
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U.S. Cl. 315—5

12 Claims

ABSTRACT OF THE DISCLOSURE

Charged particle accelerators, preferably using electrons are advantageously constructed using a cyclotron-electromagnetic wave drive mechanism in which the R.F. Lorentz force causes the particle to move in the direction of power flow. The particle will accelerate in the direction of power flow in such a way that it takes an amount of wave momentum such that

$$\frac{1}{2} \Delta m_{\perp}^2 = c \Delta m v_{\parallel}$$

By maintaining $\omega_{co} > \omega$ optimum conversion efficiency is realized. The accelerator can take the form of travelling or cavity types and the cyclotron field can be either magnetostatic or electrostatic.

This invention relates in general to the field of charged particle accelerators and more particularly to the field of electron accelerators which produce high energy electron beams by a cyclotron resonance mechanism induced by a combination of an axial DC magnetic field in conjunction with an electromagnetic wave.

The prior art is replete with descriptions of various types of electron accelerator devices such as for example the linear accelerator, cyclotron, etc. The field of usage for such machines is widespread and well known and need not be repeated herein. The present invention is directed to a novel form of electron accelerator which can best be termed a cyclotron resonance linear accelerator. The basic acceleration mechanism relies on the utilization of a combination of a DC static axial magnetic field and transverse time varying electromagnetic fields confined in waveguide and resonator structures together with means for compensating for relativistic mass changes at high energies to produce a novel form of accelerator device which does not require complex slow wave circuits which are used in conventional linear accelerators. The particular embodiments depicted herein take several forms which include waveguide, cavity resonator, and ring resonator, each of which is structurally simple and economical to manufacture. In addition means are disclosed whereby the axial magnetic field may be replaced with a positive ion cloud which is produced by high RF powers in a ring resonator configuration. The ring resonator configuration being chosen as a means of achieving high RF field strengths with a minimal amount of drive power. In essence then, the present invention teaches several novel approaches of obtaining large electron energy levels in the relativistic regions where v^{ϕ} (electron tangential velocity) approaches the speed of light c by means of a cyclotron resonance accelerator process utilizing a combination of RF electromagnetic energy and a DC B_z field.

An object of the present invention is the provision of a novel cyclotron resonance type of linear accelerator.

A feature of the present invention is the provision of a cyclotron resonance type of linear accelerator utilizing a resonant cavity excited by either a linearly or a circularly polarized TE_{111} mode.

Another feature of the present invention is the provision of a cyclotron resonance type of linear accelerator which utilizes a combination of circularly polarized traveling waves and an axial DC magnetic field to achieve relativistic electron energies in an axial direction.

Another feature of the present invention is the provision of a cyclotron resonance type of linear accelerator incorporating a rectangular waveguide or a rectangular guide ring resonator for providing a TE_{10} linearly polarized traveling wave and interacting with a circularly polarized component.

Another feature of the present invention is the provision of utilizing a positive ion cloud confined in a waveguide to provide the equivalent focusing effect of a DC axial magnetic field in a cyclotron resonance type of linear accelerator utilizing either a linearly or circularly polarized TE_{11} traveling wave for driving the electrons along the Z-axis of the waveguide.

Another feature of the present invention is the utilization of axial DC magnetic field strength variations to improve synchronization between the traveling RF wave and the rotating hollow electron beam.

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 depicts the relationship between a plane wave, electron and DC magnetic field B_z which is useful in arriving at an understanding of the accelerating mechanism of the present invention.

FIG. 2 is a cutaway longitudinal view of a cyclotron resonance type of linear accelerator incorporating the teachings of the present invention.

FIG. 3 is a cutaway view of a ring resonator cyclotron resonance type of linear accelerator.

FIG. 4 is an illustrative view of the electron motion in a cavity accelerator using a circular polarized TE_{111} drive mode.

FIG. 5 is a schematic of a typical drive system of exciting the cavity or waveguide accelerators in a circular polarized TE_{11} mode.

FIG. 6 is a cutaway view of a cavity cyclotron resonance linear accelerator incorporating the teachings of the present invention.

FIG. 7 is a sectional view of the cavity accelerator depicted in FIG. 6 taken along the lines 7—7 in the direction of the arrows.

FIG. 8 is a theoretical plot of energy vs. axial length for a cyclotron resonance type of linear accelerator and a conventional linear accelerator.

FIGS. 9, 10 and 11 are theoretical plots of various electron parameters for the cyclotron resonance cavity accelerator comparing the advantages to be gained from on-axis electron injection at the cavity upstream end wall and at a point removed from the upstream end wall.

Turning now to FIG. 1 there is depicted a plane electromagnetic wave composed of the conventional E-H vectors and traveling in the +z-direction as indicated by the power flow vector P_z . If a DC magnetic field of B_z is directed along z as indicated, it can be shown that an electron e starting from rest will gain energy from the wave indefinitely if

$\omega = \omega_{co}$ where $\omega_{co} = eB_z/m_0$,
 e = electron charge,
 m_0 = rest mass of an electron,
 B_z = DC magnetic field strength,
 ω_{co} = cyclotron angular frequency of electrons based on rest mass,
 ω = angular frequency of electromagnetic wave if radiation damping is ignored.

This acceleration of the electron is along a helical path with components both parallel and perpendicular to the direction of power flow. The acceleration perpendicular to the power flow results from the transverse electric field of the wave driving the particle in cyclotron resonance. If this were the only effect, the particle would gain energy until the change in mass shifted the resonant rotational frequency of the particle away from the frequency of the driving field and the particle would lose energy. The rotational frequency of the particle is the relativistic cyclotron frequency ω_c defined by $\omega_c = eB_z/m$ where m is the relativistic mass. In circular orbit machines this change in mass is compensated for by changing the magnetic field to keep the cyclotron frequency equal to the driving frequency (synchrocyclotron), or by changing the driving frequency to compensate for the changing cyclotron frequency of the particle (FM-cyclotron).

In the device disclosed here, the particle is also accelerated in the direction of power flow of the wave so that the frequency of the wave as seen by the particle is Doppler shifted to a lower value. It turns out that the decrease in frequency as seen by the particle is exactly the amount necessary to compensate for the lower cyclotron frequency that results from the relativistic increase in particle mass.

This acceleration in the direction of power flow is a result of the interaction of the particle with the RF magnetic field of the wave. Roughly speaking, the particle is accelerated by the electric field of the wave as shown in FIG. 1. The RF Lorentz force $(\mathbf{v} \times \mathbf{B})_z$ causes the particle to move in the direction of power flow. To conserve energy and momentum in its interaction with the wave, the particle must accelerate in the direction of power flow in such a way that it takes an amount of wave momentum such that

$$\frac{1}{2} \Delta m v_{\perp}^2 = c \Delta m v_{\parallel}$$

where $v_{\perp}$ is the velocity perpendicular to the DC magnetic field B_z and $v_{\parallel}$ is the parallel component of velocity. This says that if the particle gains approximately a rest mass of energy in the direction of the electric field that it must also have a velocity in the direction of power flow of the wave that is approximately the same fraction of the velocity of light.

It is this forward velocity that Doppler shifts the frequency as seen by the particle to a lower frequency at precisely the same rate as the cyclotron frequency of the particle is lowered as a result of the relativistic increase in mass from the energy gain. This permits the particle to remain at cyclotron resonance indefinitely until other effects such as radiation reaction forces or space charge forces introduce effects not included in this simple model.

For this cyclotron resonance acceleration, it can be shown that the energy gain W_c normalized to the rest mass energy ($W_0 = m_0 c^2/e$) is

$$\frac{W_c}{W_0} = \left(\frac{3}{\sqrt{2}} AZ \right)^{2/3}$$

where

$$A = \left(E \lambda / 2 \pi \frac{m_0 c^2}{e} \right)$$

[E is the RF electric field in volts/meter, λ is wavelength in meters] and $Z = 2\pi z/\lambda$ is the length in wavelengths. In the same units the energy gain W_L in a conventional slow-wave linear accelerator is

$$W_L/W_0 = AZ$$

This illustrates that the cyclotron resonance accelerator has a two-thirds power energy gain with distance while the linear accelerator has a linear energy gain with distance.

A prime advantage in the wave driven linear accelerators of the present invention is the fact that the electrons are accelerated in all conductive environments without the

necessity of utilizing high voltage DC accelerating fields and accompanying insulators. Although the injected electrons are preferably on axis at the point of injection it is seen that off-axis injection will produce acceleration also. With regard to the beam size (diameter) it is seen that the thickness of the rotating helix will be the injection beam diameter neglecting space charge forces.

In FIG. 2 a practical cyclotron resonance type of linear accelerator utilizing the aforementioned theoretical discussion as a generic design basis is depicted.

The accelerator includes electron gun means 10 disposed at the upstream end portion thereof for producing and directing an electron beam along the central beam axis of the device. A suitable gun means 10 includes a thermionic cathode 11 having any suitable filament 12 disposed therein and supplied by any conventional heater supply 13. A focusing anode 14 and grid 15 together with main anode 16 is fed by suitable power supplies 17, 18 as shown. A cutoff waveguide section 20 in the anode 16 prevents RF energy from flowing into the gun region while permitting the electron beam emanating from cathode emission surface 11' to enter the cyclotron resonance waveguide region. The cyclotron resonance accelerating region includes a circular cylindrical waveguide 21 coaxially disposed about the central beam axis and terminated at the downstream end portion thereof by any suitable load means 22 such as a thin aluminum foil which will maintain vacuum integrity while permitting the accelerated electrons to pass therethrough or a tungsten target for x-ray generation or any other load means depending upon the desired usage of the accelerator. The cylindrical waveguide 21 is evacuated to a suitable low pressure, e.g., 10^{-6} torr by means of a suitable vacuum pump means 23. Electromagnetic wave energy is introduced into the cylindrical waveguide 21 at the upstream end portion via any suitable dominant mode excitation mechanism such as coaxial line 24 and coupling loop 25 fed by a suitable RF generator 26 such as a klystron, magnetron, etc. for launching a linearly polarized TE_{11} traveling wave. In this case the electron will synchronize (depending on the direction of the DC magnetic field) with one or the other of a pair of equal and oppositely rotating circularly polarized waves into which the linearly polarized TE_{11} wave can be resolved. This excitation system is not as efficient as exciting a circularly polarized TE_{11} wave via any conventional mechanism since effectively only half the field strength in the wave is being used but is considerably simplified in construction. The electron beam emanating from gun means 10 will assume a helical trajectory of expanding radius as represented by 28 which is a general representation of the motion. By an appropriate selection of B_z values produced by a suitable DC magnetic field generating means such as, e.g., solenoid 29 it is possible to achieve a somewhat stable orbit radius with v_{ϕ} (electron tangential velocities) approaching the speed of light c together with a v_z motion toward the target 22 at the downstream end. The upper limit of v_{ϕ} is a compromise between a desired orbit radius and positive v_z as will be discussed more fully hereinafter.

At the downstream end of the accelerator any suitable electromagnetic wave energy extraction means such as loop coupler 30 and terminating load 31 are used to remove any residual energy which has not been converted into electron kinetic energy.

The following general expression provides the equations of electron motion for electrons in both the traveling wave and cavity types of cyclotron resonance linear accelerator versions.

Equations of motion:

$$\frac{dv}{dt} = \frac{-e}{m_0 \gamma} \left[\frac{E}{c} \times \underline{v} \times \underline{B} - \frac{v}{c^2} (\underline{v} \cdot \underline{E}) \right]$$

$\underline{v}$ =electron velocity (a vector quantity)

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$$

c =velocity of light

$\underline{E}$ =RF electric field (vector)

$\underline{B}$ =magnetic field (RF and DC) (vector)

For circularly polarized TE₁₁ wave in cylindrical waveguide the electron cannot remain in synchronism indefinitely at the rest mass cyclotron magnetic field because the guide phase velocity is greater than the velocity of light. However, the value of the magnetic field can be adjusted to result in useful energy gains. The following are calculated results for a guide operated at $f/f_c = \sqrt{2}$, with the elections starting from rest: where f =RF drive frequency and f_c =guide cutoff frequency for TE₁₁ mode,

$$eE\lambda/2\pi m_0 c^2 \text{ (electric field amplitude)} = 0.1 \ 0.1 \ 0.1 \ 0.1$$

$$(eB_z/m_0\omega) \text{ (DC magnetic field)} = 1.0 \ 1.2 \ 1.3 \ 1.4$$

$$(eV/m_0 c^2) \text{ (output energy)} = 0.611 \ 1.198 \ 1.521 \ 0.142$$

For larger electric field amplitudes the optimum value of $eB_z/m_0\omega$ will also be larger.

It is seen from the above that in contradistinction to the case of a plane wave having a power flow directed along B_z that relative parameters of B_z , E and ω are considerably different to obtain good energy gains.

For a plane wave

$$\omega = \omega_c = eB_z/m_0$$

where

ω is the angular frequency of the wave

ω_c =cyclotron angular frequency of electrons based on the rest mass

e =charge on electron

m_0 =rest mass of electrons

B_z =DC axial magnetic field strength

whereas for the guided wave case of the present invention

$$\frac{eB_z}{m_0} > \omega$$

and

$$\frac{eB_z}{m_0\omega} > 1$$

Similarly, the electric field amplitudes must be different for the guided wave case as compared to the plane wave case as more clearly described in connection with FIG. 8 curves labeled B which are plots of output energy E vs. B_z values for the circular cylindrical waveguide propagating the TE₁₁ mode and the plane wave case. It is seen that as the desired output energy levels increase the optimum E and B_z values for the guided wave case will increasingly deviate from the plane wave E and B_z values for cyclotron resonance operation. These relative values are determined on the basis of the rest mass value of electron mass and will as stated previously result in practical upper limit for cyclotron resonance linear accelerators. This is determined by the upper limit of orbit radius values possible in a given accelerator configuration.

By increasing B_z along the axis of the accelerator from the gun end to the target end, e.g., by adding turns to solenoid 29 or adding auxiliary shim coils or by any other conventional field strengthening means it is possible to keep the electrons in synchronism over longer axial distances and thus obtain increased energy gain. However, a fundamental limitation exists in the rate at which it is permissible to increase B_z . Namely, that as B_z is increased B_r components are introduced which produce $v_\phi \times B_r$ axial forces which decrease the axial electron velocity. If B_r components are permitted to attain large enough values the beam will eventually slow down to zero v_z and turn around.

In FIG. 8 plots of output energy vs. Z (axial distance) for the cyclotron resonance linear accelerator of the trav-

eling wave type curve labeled A and conventional axial bunching linear accelerator curve labeled A¹ are plotted for purposes of showing the most useful energy-distance (axial length of accelerator) ranges for the cyclotron resonance traveling wave type of linear accelerator. Since as stated previously the cyclotron resonance linear accelerator has a two-thirds power energy gain vs. distance while the conventional linear accelerator has a linear power energy gain vs. distance there is a range of energies and accelerator length where the cyclotron resonance linear accelerator is clearly superior from an energy-length standpoint alone.

In FIG. 3 a cyclotron resonance linear accelerator incorporating a ring resonator waveguide is depicted. The advantages of using a ring resonator such as 35 in lieu of a simple waveguide are the elimination of the necessity of extracting unused RF drive energy and the ability to achieve extremely high RF power levels with a single RF source. Since the electron gun means 10, focusing means 29 and target or load means 32 can be of the same type as depicted in the embodiment of FIG. 2 similar reference numerals are used. The ring resonator 35 is fed by a suitable RF source 26 which as in FIG. 2 can be a high power klystron, magnetron, etc., which is coupled to a directional coupler 36 of any conventional type, e.g., such as a magic tee or ratrace junction which couples the desired electromagnetic energy from source 26 into the ring resonator 35 in a unidirectional manner as indicated by power flow arrow. The residual uncoupled energy from source 26 is absorbed in matched load 37. The ring resonator 35 is designed to be $2\pi N$ wavelengths long where N is any positive integer at the desired drive frequency of source 26. The solenoid 29 is designed to provide a B_z component along the accelerator axis such that B_z is greater than the B_z value for $\omega = \omega_c$ which is the optimum value for synchronization in the case of a plane wave. Again B_z may be increased along the device axis to produce improved synchronization with the upper limit being determined by the desired v_z electron velocity at the output or target area.

Experimental results on a ring resonator in the absence of a magnetic DC field component such as provided by solenoid 29 indicate that at guide pressures, e.g., 10^{-6} torrs in an S-band resonant ring it is possible to generate the equivalent conditions of cyclotron resonance orbiting electrons which are focused by a charged positive cloud which is produced by RF acceleration of background free electrons. The electrons are accelerated by the RF drive field and undergo ionizing collisions with the residual gas atoms in the guide to produce positive ions which help focus the electrons which in turn result in inducing more ionizing collisions between the electrons and gas atoms. The ions build up steadily thus increasing the positive ion cloud which produces a steadily increasing radial E-field which serves to produce inwardly directed radial force components on the electrons which are driven by the RF wave.

The process continues to build up the charge cloud and hence increases the focusing path length if a source of electrons such as gun 10 directs an electron beam along the ring resonator axis toward the target 22. Without an electron source an experimental S-band ring resonator using rectangular waveguide produced X-ray energies in excess of 4 mev. for 100 megawatts of circulating RF power. Similar results at other frequencies will occur whenever the quantity $eE\lambda/2\pi m_0 c^2$ is of order unity. When an electron gun means is provided such as depicted in the embodiment of FIG. 3 and the guide evacuated by pump 23 to around 10^{-6} torrs the mean free path of the electrons should be greater than the circumference of an electron orbit which means that the background electrons will produce enough ionizing collisions to produce a positive ion focusing cloud while still permitting the injected electrons to traverse a substantial distance down the waveguide toward the target under the RF drive power while

undergoing helical motion. Thus, a novel mechanism is provided for focusing the orbiting electrons via a positive ion cloud which is relatively unaffected by the RF drive power due to the relatively much greater mass of the ionized atoms. A suitable lower limit for ion focusing would be to make the guide transverse dimensions less than a mean free path of an electron in the guide at the pressure level involved. In lieu of utilizing residual gas atoms to supply the ions the utilization of a suitable low ionizing potential gas such as argon is within the purview of the present invention. In any of the embodiments depicted herein the force vector which constrains the electrons to undergo helical electron motion whether due to B_z or ion focusing will be of an intensity such that the electrons undergo helical orbits with a period substantially equal to the period of the RF drive frequency.

Turning now to FIG. 6 a cyclotron resonance cavity accelerator is depicted which includes an electron gun means 10 such as depicted in FIG. 2 for generating and directing an electron beam through apertured anode 16 which has a drift tube region 20 dimensioned to be a cutoff waveguide for the RF drive power frequency. The drift tube 20 protrudes into cavity 40 in a re-entrant manner about 20% of the axial cavity length in a preferred embodiment for reasons which will be given in more detail hereinafter.

It is of course to be noted that cavity 40 is to be evacuated below atmospheric pressure by any suitable vacuum pump means such as 23 shown in connection with FIG. 2. Of course, the cavity as well as waveguide accelerators although preferably continuously evacuated, may be evacuated and permanently sealed by any suitable pinch off tubulation or the like if desired and if vacuum maintenance problems are not encountered. The cavity can be terminated by a target 22 such as discussed previously in connection with FIG. 2 for the production of X-rays if desired or to simply permit the electrons to pass through a thin vacuum wall to any desired utilization device. A solenoid such as 45 or any other suitable means is provided to supply a DC axial magnetic field B_z having a value greater than the rest mass cyclotron resonance field as given by

$$B_z = \omega_{co} m_0 / e$$

where

$\omega = \omega_{co}$ = angular frequency of the RF drive energy

m_0 = rest mass of an electron

e = electron charge

The cavity can be excited by either linearly polarized TE_{111} mode or circularly polarized TE_{111} mode RF energy at $\omega = \omega_{co}$. In the case of linear polarization, as discussed previously, the electrons injected into cavity 40 will interact with either one or the other of two equal amplitude oppositely rotating circularly polarized waves which means only $\frac{1}{2}$ the RF drive power is being effectively used. Since the injected electrons will have a preferred direction of rotation in the magnetic field B_z they will couple strongly to one of the circularly polarized oppositely rotating RF field components of the linearly polarized TE_{111} wave energy and weakly to the counterrotating wave. Theoretical calculations indicate that for a given power input to the cavity the circularly polarized TE_{111} field will produce an accelerated beam with about 30% more energy than a linearly polarized field. Also theoretical calculations indicate that the output energy of the electrons will vary over a few percent in the linearly polarized case depending on the phase of the linearly polarized fields at the instant of electron injection into the accelerator cavity. In the case of the circularly polarized fields the output energy is constant with time. Thus, if a simple RF drive feed is desired the coupling scheme depicted in FIG. 2 which is a simple RF generator 26 coupled to a loop coupler 25 via coaxial line 24 can be used to excite accelerator cavity 40 in a linearly polarized manner in the TE_{111} mode.

However, since theoretical analysis indicates that certain advantages are to be gained by exciting accelerator cavity 40 in a circularly polarized manner a discussion of such a scheme is given hereinafter.

Cavity 40 can be excited with circularly polarized TE_{111} waves by providing a pair of 90° azimuthal space rotated coupling apertures 48, 49 in the side walls of the circular-cylindrical $\frac{1}{2}\lambda$ cavity 40. The coupling apertures are fed via waveguides 50, 51 by the RF drive system depicted in FIG. 5.

An RF signal generator 26 feeds a 3 db hybrid coupler 60 which has one port terminated in a matched load as indicated and which splits the input RF energy from generator 26 into two 90° time phased equal amplitude waves which are coupled via any conventional coupling means 61, 62, e.g., coax line, waveguide, into the input waveguide ports 50, 51 via conventional vacuum window flange assemblies 53, 54 as shown in FIG. 5 to excite a TE_{111} circularly polarized drive wave in accelerator cavity 40. The drive angular frequency ω is set at

$$\omega_{co} = eB_z / m_0$$

where B_z is the DC field value associated with conventional rest mass cyclotron resonance. The actual B_z used is then set up such that

$$\frac{eB_z}{m_0} > \omega$$

The exact value selected for optimizing a given parameter. The RF field pattern associated with the TE_{111} circularly polarized fields is depicted in FIGS. 6 and 7.

The following analysis using the force equation given previously, namely,

$$\frac{d\mathbf{v}}{dt} = \frac{-e}{m_0\gamma} \left[\mathbf{E} + \mathbf{v} \times \mathbf{B} - \frac{\mathbf{v}}{c^2} (\mathbf{v} \cdot \mathbf{E}) \right]$$

is presented to provide a better understanding of the motions undergone by the injected electrons.

If rotation is clockwise, see FIG. 7, an electron at 1 is in position of maximum deceleration. If rotation is counterclockwise, this is position of maximum acceleration.

Note field pattern rotates with time with constant amplitude.

Note that E_t and H_t (transverse field components relative to z axis) are parallel (or antiparallel depending on axial position) to each other (except for slight curvature). This is different from traveling wave case where $E_t \perp H_t$. At the center of the cavity H_t is zero and E_t is maximum. At the ends of the cavity E_t is zero and H_t is maximum with opposite polarity at opposite ends.

In traveling through the cavity the electron experiences axial velocity changes of the type shown in FIG. 9. The axial velocity changes are complicated in their origin. The first term in the axial equation of motion is zero, since there is no axial electric field. The second term contributes by means of $\mathbf{v}_t \times \mathbf{B}_\phi$ and $\mathbf{v}_\phi \times \mathbf{B}_t$, and the third term has a value which depends on $\mathbf{v}_z$. The dominant contribution to the $\mathbf{v} \cdot \mathbf{E}$ product for electrons in an accelerating phase is from $\mathbf{v}_\phi$ and $\mathbf{E}_\phi$ which have opposite signs. If $\mathbf{v}_z$ is positive, then the third term is equivalent to a positive $\mathbf{E}_z$ field which results in a reduction of the axial velocity of an electron. The effect of this term is observed at $z=0$, the center of the cavity where $\mathbf{B}_t$ and $\mathbf{B}_\phi$ are zero, but the axial velocity is observed to be decreasing.

The major changes to the axial velocity are produced by the $\mathbf{v}_\phi \times \mathbf{B}_t$ term. While the electron is in the left half of the cavity, it is ahead in phase with respect to the optimum acceleration phase (between positions ① and ② for counterclockwise rotation). The resulting axial acceleration is positive. At the center of the cavity $\mathbf{B}_t$ goes through zero and changes sign resulting in decreasing axial velocity immediately to the right of the center of the cavity. The shift of the maximum axial velocity point

slightly into the left half of the cavity is caused by the third term of the force equation, as discussed above. The minimum in axial velocity in the right half of the cavity occurs at the point where the electron has slipped back in phase slightly to the point of optimum acceleration (point ① for counterclockwise rotation). At this point B_r again goes through zero and changes sign thereby producing a minimum in the axial velocity.

During its transit through the remainder of the cavity the electron continues to slip back in phase until near the right end of the cavity it passes through the maximum decelerating phase (point ③ for counterclockwise rotation). At this point B_r again changes sign producing the final maximum in axial velocity.

The effect of the $v_r \times B_\phi$ force is not significant except at the point of electron injection where v_ϕ is small. Near injection, the electron moves ahead of the optimum accelerating phase resulting in a $v_r \times B_\phi$ force which opposes the $v_\phi \times B_r$ force. As soon as v_ϕ becomes large compared to v_r , the $v_\phi \times B_r$ force dominates. v_r , V_z and v_ϕ are the radial, axial and azimuthal velocity components of the electrons velocity v and the E and B symbols refer to the RF drive components, E and $B = \mu h$.

A cylindrical TE_{11} cavity was constructed with a diameter to length ratio of 1.3 and a resonant frequency of 920 mc. A 500 volt 1.0 ma. beam was injected into the cavity on the axis through a metal tube projecting into the cavity for about 20% of the cavity length. Calculations were made for a field strength in the cavity corresponding to 14 kw. RF input. The calculations predict that electrons should strike the end wall of the cavity with 650 kv. voltage when the DC magnetic field has a value of 1.45 times the cyclotron field. This experiment corresponds to the configuration depicted schematically in FIG. 4.

During the experiments, the cavity input power ranged from 10 to 12 kw. The voltage of the accelerated electrons was determined by measuring the X-ray spectrum emitted from the cavity. Electron voltages in the range of 500 kev. to 1 mev. were observed with various configurations of DC magnetic field.

As discussed previously, analysis has shown that electron injection at a point downstream from the accelerator cavity 40 end wall 16 provides certain advantages over injection at the end wall itself. The calculated plots of electron motion, energy and velocity parameters depicted in FIGS. 9-11 bear this out. In each instance, the solid curves labeled A or B or unlabeled represent a parameter for electron injection at a point downstream from the upstream cavity end wall while the dashed curves represent equivalent parameters for electron injection at the upstream end wall. The curves were plotted for a 20% re-entrant condition which appears to be optimal for zero or small injection voltages which are simulated by 500 volt equivalent v_z electron velocities at the point of injection. All parameters are normalized to simplify the results. FIG. 9 shows that an extreme dip in axial velocity as indicated at X can be effectively removed by re-entrant injection. FIG. 10 indicates that a gain in overall kinetic energy is experienced by re-entrant injection in comparison to end wall injection (curves A) and that not much, if any, advantage is gained with respect to useful acceleration range by re-entrant injection (curves B). FIG. 11 indicates that re-entrant injection provides quicker gain in v_ϕ (curves A) and orbital radius (curves B) than end wall injection.

The particular motion undergone by electrons entering accelerating cavity 40 under TE_{11} circularly polarized RF drive and axial B_z DC magnetic fields is then seen to be quite complex and ultimately takes the form of a rotating helix with axial velocity which can be resolved into a beam spot rotating with

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

where ω =angular frequency of RF drive and a given electron in the helix moving with

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

where B_z =axial DC field, e =electron charge, and

$$m = \text{relativistic electron mass} = m_0 \left(1 + \frac{W}{W_0} \right)$$

where W is the kinetic energy of the electron and where $W_0 = m_0 c^2/e$ is the rest mass energy.

Using either the cavity or accelerator cyclotron resonance types of linear accelerators as taught herein, it is possible to achieve relativistic electron energy levels with

$$v_\phi > .9c$$

where

v_ϕ =tangential electron velocity

c =velocity of light

The precise optimized conditions for maximum acceleration can be arrived at by simple variation of the B_z field strength and injection parameters for a given RF drive level.

It is within the teachings of the present invention to utilize square rather than circular cylindrical waveguide for operation in the TE_{11} mode. The excitation of linear polarized TE_{11} waves in square and circular guide is conventional. To excite circular polarized TE_{11} travelling wave modes in square or circular cylindrical guides the techniques shown on page 342 of "Microwave Theory and Techniques" by Reich et al., D. Van Nostrand Co., Inc., 1953, may be used or any other well known approach is within the teachings of the present invention. The dominant TE_{10} mode in rectangular guide is a preferred embodiment in both the rectangular linear axis case, e.g., using rectangular waveguide in lieu of circular cylindrical guide in the FIG. 2 embodiment and in the ring resonator configuration rectangular guide in the TE_{10} dominant mode is preferred due to mode conversion problems associated with a circular configuration. The positive ion focusing scheme may obviously be used in the FIG. 2 embodiment in either square, rectangular, or circular cross-sections as well as in the ring resonator embodiment.

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 drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. In a cyclotron resonance type of accelerator for accelerating electrons to high velocity, a hollow microwave resonator having a portion disposed about a central beam axis, means for generating and injecting an electron beam into said portion of said resonator, means for producing within said resonator a force vector on said electrons which constrain said electrons to undergo a helical type of orbit about the axis of said portion of said resonator when said electrons are driven by an electromagnetic wave with an angular phase which is related to the phase of the helical orbits, means for exciting said resonator with electromagnetic wave energy at an angular frequency such that said electrons are induced to move into helical orbits along the axis of said portion of said resonator while producing a net cumulative transfer of energy from said electromagnetic field to the electrons, thereby causing a substantial number of the electrons to be accelerated to a velocity in excess of 0.5 times the velocity of light.

2. The apparatus according to claim 1 wherein said resonator comprises a ring resonator.

3. The apparatus according to claim 1 including means for exciting said resonator with microwave energy in a transverse electric mode wherein the E fields are oriented

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transverse to a central cavity axis which is generally parallel to the direction the electron beam is accelerated.

4. The apparatus of claim 3 including means for injecting the electron beam in a re-entrant manner within said cavity at a point downstream from the upstream end wall of said cavity.

5. A cyclotron resonance type of linear accelerator for accelerating electrons to tangential velocities in excess of $.5c$ where c is the velocity of light, while undergoing a helical type of motion, comprising a ring resonator waveguide having means for injecting electrons along an axis of said ring resonator, means for reducing the pressure in said ring resonator to below atmospheric pressure, means for introducing electromagnetic energy into said ring resonator at a power level in excess of 1 megawatt at a frequency f , said ring resonator being $2\pi N\lambda g$ wavelengths long as determined at f where N is any positive integer, said ring resonator being evacuated to a level such that the mean free path of an electron is greater than the transverse dimensions of said waveguide.

6. In a method for accelerating electrons to a high velocity along a linear path the steps of, cumulatively interacting a stream of electrons with microwave energy in a microwave structure to cause the electrons in the stream to execute helical orbits around a linear path along which the electrons are to be accelerated, causing the period of the microwave energy within the interaction region to be related to the period of the helical orbits of the electrons such that there is a cumulative and net conversion of microwave energy into increased velocity of the electrons along the helical orbit, and maintaining the interaction until a substantial percentage of the electrons are accelerated in the process to a velocity in excess of 0.5 times the velocity of light.

7. The method of claim 6 including the step of, circularly polarizing the microwave energy in the interaction region for enhancing the cumulative interaction between the microwave energy and the electrons being accelerated.

8. The method of claim 6 including the step of, producing a force vector on the electrons which constrains the electrons to undergo a helical type of orbit.

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9. The method of claim 8 wherein the step of producing the force vector on the electrons includes the step of, producing an axially directed D.C. magnetic field throughout the interaction region, such DC magnetic field being directed generally along the linear path of acceleration.

10. The method according to claim 8 wherein the step of producing a force vector includes the step of producing a cloud of positive ions along the linear path of acceleration within the interaction region.

11. The method according to claim 9 where the angular frequency ω of the interacted microwave energy and the intensity of the axially directed magnetic field are inter-related as follows:

$$\omega_{co} = \frac{e}{m_0} B_z > \omega$$

where,

e is the electron charge,

m_0 = rest mass of an electron,

ω_{co} = conventional cyclotron resonance angular frequency based on rest mass, and

B_z is the intensity of the axial component of the DC magnetic field along the linear path of particle acceleration.

12. The method according to claim 9 including the step of increasing the DC magnetic field B_z in the direction of acceleration of the electrons in the axial direction.

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