Feb. 7, 1967 D. L. BOBROFF 3,303,379

ELECTRON DISCHARGE DEVICES WITH MAGNETIC FIELD AND MAGNETIC FIELD GRADIENT, CROSSED, FOR COMPELLING ELECTRONS TO FOLLOW A CYCLOIDAL PATH

Filed June 11, 1963 2 Sheets-Sheet 1

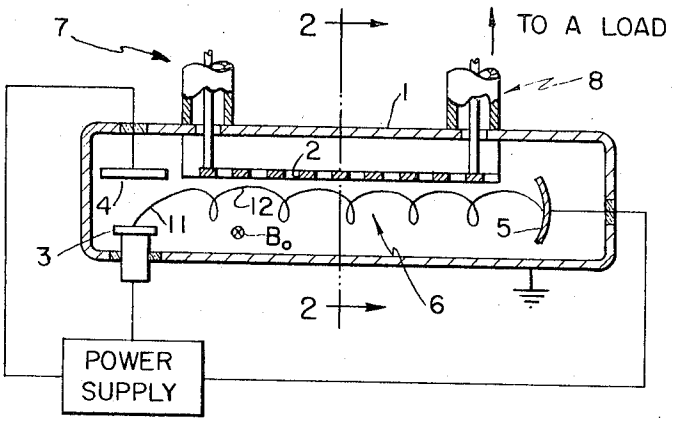


FIG. 1

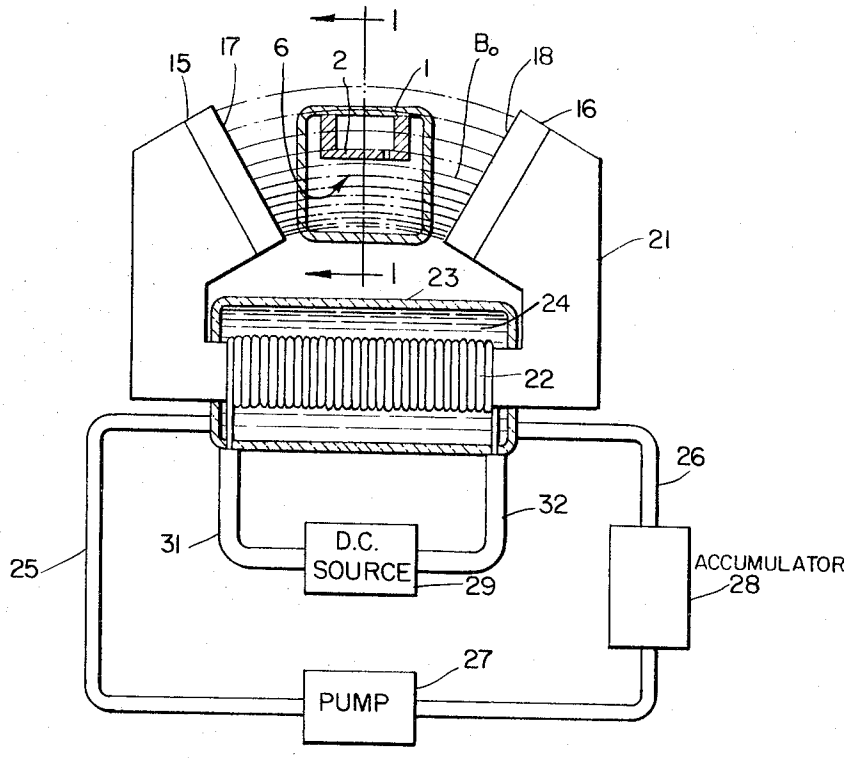


FIG. 2

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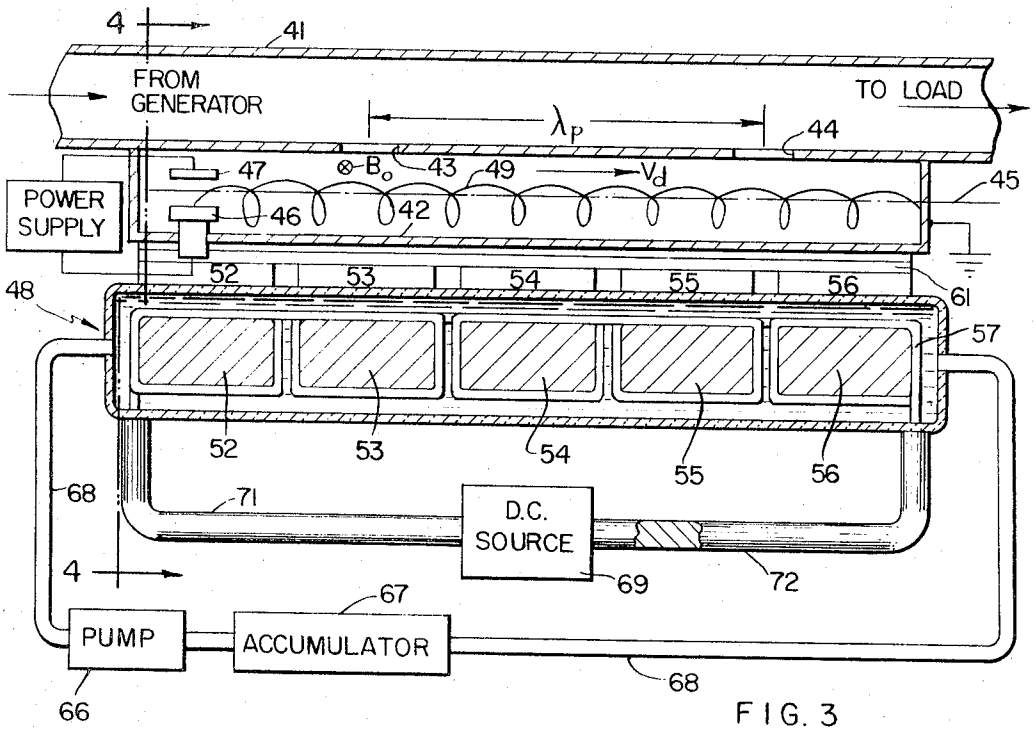


FIG. 3

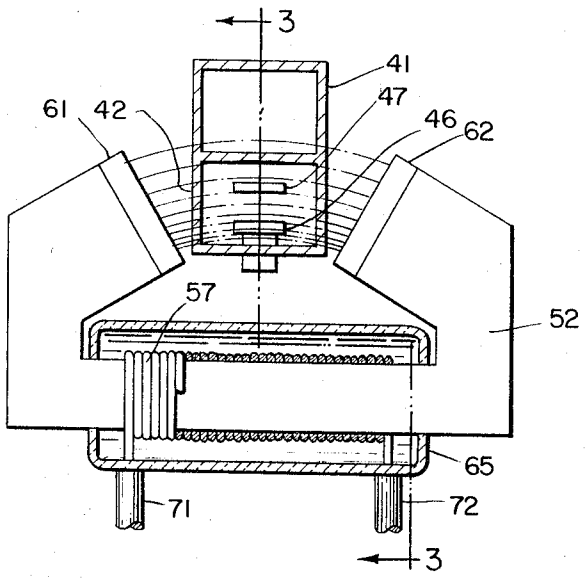


FIG. 4

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ELECTRON DISCHARGE DEVICES WITH MAGNETIC FIELD AND MAGNETIC FIELD GRADIENT, CROSSED, FOR COMPELLING ELECTRONS TO FOLLOW A CYCLOIDAL PATH

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This invention relates to electron discharge devices wherein electrons are compelled to move in synchronism with the fields of electromagnetic waves exchanging energy with the waves, and more particularly, to such a device in which the motion of the electrons is compelled by a transverse magnetic field.

Heretofore, electron discharge devices in which the fields of electromagnetic waves interact with electrons exchanging energy therewith have employed what is commonly called a slow wave structure for conducting the wave. Examples of slow wave structures are the helix and the interdigital delay line, and the purpose of these structures is to slow down the wave so that the phase velocity of the wave is synchronized with the moving electrons. As the frequency of operation of such devices increases into the millimeter wave region, the slow wave structure becomes very small and difficult to fabricate, and the electrons must move very close to the structure in order to achieve sufficient interaction and exchange of energy. Both these factors contribute to difficulties which make fabrication expensive and limit the power of operation of the device. However, both problems are avoided in a fast wave device wherein the wave is conducted by a transmission line such as a waveguide and the phase velocity of the wave is often greater than the speed of light. Here the structure is simple to fabricate, and the power than can be conducted by the structure is not particularly limited. Fast wave traveling wave devices are disclosed in United States Patent 2,591,350 which issued April 1, 1952, to E. J. Gorn and in an article by Beck and Mayo entitled, "Interaction of an Electron Beam with the Higher-Order Modes of a Smooth Wave Guide," published in June 1960 in "Microwave Tubes" which is part of the record of the International Congress on microwave tubes.

The fast wave traveling wave tube, however, raises new problems. The fundamental problem in the fast wave traveling wave tube is to impose on the beam a periodic motion which contains a space harmonic with wavelength close to that of the wavelength of the millimeter wave to be generated. Some success has been achieved by imparting a cyclotron motion to the electrons. Such a tube is described in an article by Chow and Pantell entitled, "The Cyclotron Resonance Backward Wave Oscillator," published in 1960 in the "Proceedings of the I.R.E.," vol. 48, page 1865.

It has also been proposed to employ the cycloidal motion obtained by movement of electrons in crossed D.C. electric and magnetic fields. Very high D.C. electric fields would be required at millimeter wavelengths. Since the waveguides are very small at millimeter wavelengths, this would lead to serious voltage breakdown problems.

It is one object of the present invention to provide a means for compelling cycloidal motion of the electrons without the requirement of the high intensity transverse electric field.

It is a feature of the present invention to compel electrons issuing from a cathode to move along substantially cycloidal type paths by injecting said electrons into a transverse magnetic field, the strength of the magnetic field being graded in a direction transverse to the field and to the direction of drift of the electrons.

In one specific embodiment of the invention, the gradation in the strength of the magnetic field is produced by contouring the pole pieces which define the magnetic field gap so that some corresponding areas of the faces of the pole pieces are closer together than others.

The average strength of the magnetic field in the gap is relatively high, and for this reason, the embodiment described includes an electromagnet attached to the pole pieces and energized by D.C. current flowing in the coil which is super-cooled so that the conductivity of the coil is very high, and the coil can carry very large currents without overheating.

Other features and objects of the invention will be apparent from the following specific description taken in conjunction with the figures in which:

FIG. 1 is a sectional view taken through the axis of an electron discharge device including features of the invention and wherein electrons are compelled to move along substantially cycloidal paths adjacent a waveguiding structure exchanging energy with waves conducted therein;

FIG. 2 is a sectional view of the tube in FIG. 1 transverse to the axis showing a magnet structure for producing the graded magnetic field;

FIG. 3 is a longitudinal sectional view of an embodiment of the invention including two side wall coupled waveguides, one for conducting fast waves in energy-exchanging relationship with electrons compelled to move along substantially cycloidal paths exchanging energy with the waves by a graded magnetic field, and the other coupling the waves to the first; and

FIG. 4 is a sectional view of the structure shown in FIG. 3 taken transverse to the longitudinal axis of the guides.

Turning first to FIGS. 1 and 2 there is shown an embodiment of the invention as applied to a somewhat conventional traveling wave tube structure. This includes an envelope **1** enclosing a slow wave propagating structure **2** which is, for example, an interdigital type of delay line and also enclosing a cathode **3**, an accelerating electrode **4** and a collecting electrode **5**. The interaction space **6** into which the electrons are injected and through which the electrons flow exchanging energy with waves conducted by the structure **2** is an elongated space coextensive with the structure. In operation a wave conducted by, for example, a coaxial transmission line **7** which is coupled to one end of the structure **2** is conducted through the structure **2** and coupled from the other end of this structure to a second coaxial transmission line **8** which is, inturn, coupled to a load. Fringing fields of the wave extend from the structure **2** into the interaction space **6**, and electrons **11** issuing from the cathode interact with these fields exchanging energy therewith to amplify the wave.

The electrons are compelled to drift through the interaction space **6** along substantially cycloidal paths illustrated by path **12**. Initially, as the electrons leave the cathode surface **3**, they are accelerated toward the accelerating electrode **4**, and thus the velocity of the electrons increases. These accelerated electrons are immediately acted upon by a transverse graded magnetic field of average strength B_0 which causes the electrons to follow an arcuate path which leads to the cycloidal path **12**. The electrons move along a cycloidal path **12** through the interaction space **6** by the influence of the transverse graded magnetic field in the interaction space. This field is produced in the gap between the pole pieces **15** and **16**. The faces **17** and **18** of these pole pieces are each coextensive with the interaction space **6** and are non-

parallel as shown in FIG. 2. That is, one pair of corresponding ends of the pole pieces is closer together than the other pair, and so the magnetic field strength between the first-mentioned pair of ends is greater than between the other ends and, thus, the magnetic field in the gap is of nonuniform strength or is graded in a direction transverse to the direction of the field and also transverse to the general direction or drift of the electrons through the interaction space **6**. The cyclotron frequency ω_c is related to the field B_0 by the relation

$$\omega_c = \frac{e}{m} B_0$$

where e and m are the charge and mass, respectively of an electron.

The cycloidal motion is a composite of a circular motion at the cyclotron frequency ω_c and a drift velocity V_d. The cycloidal motion is highly nonsinusoidal, and, consequently, operation of the tube at harmonics of the cyclotron frequency is possible.

It can be shown that the drift velocity V_d of the electrons through the interaction space is a function of the cross product of the transverse magnetic field gradient $\Delta\overline{B}_0$, and the average strength $\overline{B}_0$ of the magnetic field in the interaction space. This relationship is expressed as follows:

$$\overline{V}_d \cong -\frac{(\overline{B}_0 \times \overline{\Delta B}_0)}{\omega_c B_0^2}\left(\frac{1}{2}V_0^2\right)$$

In the above equation ω_c is the cyclotron frequency or the undulating frequency of the electron beam caused by the cycloidal motion of the electrons, and V_0 is the total velocity of the electrons or the velocity imparted to the electrons by the accelerating field between the accelerating electrode **4** and the cathode **3**. The equation is a vector equation and shows that the drift velocity V_d is at right angles to both the direction of the magnetic field and the direction of the gradient of the magnetic field.

If the magnetic field is substantially uniform in the direction of the drift velocity, but varies linearly in a direction transverse to the drift and transverse to the direction of the magnetic field, the electrons will rotate at the cyclotron frequency in circular orbits of radius R_0, where $R_0 = V_0/\omega_c$, and the center of this circular orbit will drift through the interaction space at the drift velocity V_d. Thus, the magnitude of the drift velocity V_d can be expressed as follows:

$$V_d = R_0 \frac{|\Delta B_0|}{B_0} \cdot \frac{V_0}{2}$$

Suitable values for the above parameters, of course, depend upon the desired frequency of operation and the means available for producing the magnetic field B_0. Generally, it is preferred that the parameter R_0 be small so that the trajectory of the electrons through the interaction space **6** is reasonably flat. If it is not flat, and if R_0 is relatively large, then the electrons will swing close to the delay line for efficient exchange of energy with waves conducted by the line only during a portion of the cycloidal path followed by the electrons, and this will result in generally poor coupling and low efficiency.

For operation at high frequencies, large magnetic fields are required. By operating at harmonics of the cyclotron frequency the magnetic field strength B_0 can be reduced to one-half or less than the field strength required for operation at the fundamental cyclotron frequency. This requires values of V_0 on the order of half the velocity of light and values of V_d on the order of a few hundredths the velocity of light. Typical values would be $V_0 = 0.4c$ and $V_d = 0.02c$, where c is the velocity of light. In this case, we find that

$$R_0 \frac{|\Delta B_0|}{B_0} = 0.1$$

This is an entirely practical value which can be achieved,

for example, by tilting the pole pieces as illustrated in FIGS. 2 and 4.

Operation at a fundamental of the cyclotron frequency of 300 kmc. (1 mm. wavelength) requires a magnetic field of about 100,000 gauss. Operation at the second harmonic requires only 50,000 gauss.

Conventional electromagnets could be constructed to produce magnetic fields of the above strength; however, a magnet energized by currents conducted by a super-cooled conductor offers a more practical structure. Such an energizing scheme is illustrated schematically in FIG. 2 and includes a substantially U-shaped magnetically permeable body **21** having ends which abut the pole pieces **15** and **16**. A portion of the body **21** is encircled by a coil contained within a nonconductive casing **23** through which a low temperature fluid **24**, such as liquid helium, is circulated by a system including conduits **25** and **26** for conducting the fluid from a pump **27** and accumulator **28** through the casing **23**.

Opposite ends of the coil **22** connect electrically to a source of D.C. current **29**. Electrical connections **31** and **32** between the coil and the D.C. source are not supercooled and so they must be of much heavier gauge than the coil to match the conductivity of the coil.

The U-shaped body **21** preferably tapers from a relatively narrow cross section around which the coil is placed to a relatively broad cross section which abuts the pole plates so that the magnetic field between the faces **17** and **18** of the pole plates is substantially uniform in directions parallel to the axis of the tube or parallel to the drift velocity V_d of electrons through the interaction space **6**.

Turning next to FIGS. 3 and 4, there are shown sectional views of a fast wave electron discharge device in which electrons exchange energy with high frequency waves conducted in a waveguide transmission line and in which the phase velocity of the waves V_p is equal to or greater than the free space speed of light. As shown in FIG. 3, two waveguides **41** and **42** are joined by a side wall coupling arrangement which includes, for example, two openings **43** and **44** spaced a wavelength apart and common to the broad walls of both of the waveguides. Thus, waves launched into guide **41** from a high frequency wave generator are coupled from waveguide **41** into guide **42** and are conducted therethrough in, for example, a TE_{10} mode. These waves are amplified by an exchange of energy from electrons injected along the axis **45** of waveguide **42**, and the amplified waves are coupled back into waveguide **41** from which they are applied to a load. The electrons issue from a cathode **46** at one end of the waveguide **42**. As the electrons issue from the cathode and drift off the surface of the cathode, they are accelerated by a field between the cathode and accelerating electrode **47**, and thus, the total velocity V_0 is imparted to the electrons. The accelerated electrons are compelled by a graded transverse magnetic field of average strength B_0 to flow along arcuate paths. This field is generated by a magnetic structure **48** and has a very high gradient in a direction transverse to the axis **45** and also transverse to the direction of the magnetic field which is into the page. Thus, by the physical phenomenon described above, the electrons are caused to follow substantially cycloidal paths as illustrated by path **49**, and in doing so, the electrons drift down the length of waveguide **42** and exchange energy with the waves conducted by the guide.

A structure for producing the graded magnetic field includes a plurality of U-shaped magnetically permeable bodies **52–56** disposed alongside the waveguide **42** as shown in FIGS. 3 and 4. A section of each of these bodies is encircled by a coil such as **57**, and the coils are connected in series for convenience. It is preferred that the magnetization produced when the current flows through the coils be progressively greater in the bodies **52–56** in the direction of the drift velocity V_d. Con-

sequently, in the embodiments shown in FIGS. 3 and 4, the number of turns of the coil around the U-shaped bodies **52–56** are progressively increased, and so there are more turns about body **56** than body **52**.

Each of the U-shaped bodies abuts the pole pieces **61** and **62** which are disposed adjacent and coextensive with the waveguide **42** and which define a magnetic field gap coextensive with the waveguide **42**. The faces of the pole pieces **61** and **62** are substantially nonparallel with respect to each other, and so one set of corresponding ends of these pole pieces is closer to each other than the other ends producing magnetic fields graded in a direction transverse to the drift velocity of the electrons and also transverse to the direction of the field. In addition, since the magnetization of bodies **52–56** is progressively greater, the magnetic field is also graded in a direction parallel to the drift velocity, the magnitude increasing in the direction of the drift velocity.

The average magnitude B_0 of the transverse magnetic field in the embodiment of the invention shown in FIGS. 3 and 4 is relatively large. For this reason, means are provided to super-cool the coils to increase the conductivity of the coils permitting them to conduct very high currents as required to produce the high average magtic field B_0. A structure for accomplishing this includes, for example, insulating means **65** enclosing portions of the bodies **52–56** about which the coils are wound and means for conducting a low temperature fluid such as liquid helium through the enclosure. This means includes a pump **66**, an accumulator **67** and conduits **68**. A D.C. current is applied to the coils from a source **69** which couples to the coils by very heavy conductors **71** and **72** of substantially the same resistance as the super-cooled coils.

This completes the descriptions of two embodiments of the present invention wherein electrons are compelled to move along cycloidal paths by a graded transverse magnetic field and whereby the drift velocity of the electrons moving along these paths is determined by the magnitude of the gradient and the magnitude of the magnetic field. More specifically, the embodiments include a structure whereby the drifting electrons exchange energy with electromagnetic waves and wherein the motion of the electrons or a harmonic of the motion is synchronized with the phase velocity of the waves. The description of these embodiments is made only by way of example. however, and does not limit the spirit and scope of the invention as set forth in the accompanying claims.

What is claimed is:

1. An electron discharge device comprising:
means emitting electrons in a substantially cycloidal trajectory;
and means compelling said electrons to drift through an elongated interaction space free of tranverse steady electric fields including means producing a magnetic field directed transverse to said electron drift, said magnetic field varying linearly in a direction transverse to said electron drift and transverse to the direction of said magnetic field whereby the drift velocity of electrons through said space is a function of the cross product of the transverse magnetic field gradient and the average strength of the magnetic field.

2. An electron discharge device comprising:

means conducting electromagnetic waves;
means emitting an electron beam in a substantially cycloidal trajectory path adjacent to said wave conducting means;
and means compelling said electrons to drift through said path free of transverse steady electric fields in energy-exchanging relationship with said waves including means producing a magnetic field directed transverse to the general direction of said drift, said magnetic field varying linearly in a direction transverse to said electron drift and transverse to the direction of said magnetic field whereby the cyclotron frequency of said electron beam is established at substantially the fundamental frequency of said electromagnetic waves.

3. An electron discharge device comprising:
an elongated wave conducting structure;
means coupling electromagnetic waves to one end of said structure;
means emitting an electron beam in a substantially cycloidal trajectory path adjacent to said wave conducting structure;
and means for compelling said electrons to drift adjacent said structure free of transverse steady electric fields exchanging energy with the fields of waves conducted by said structure, said last-mentioned means including a magnetic field directed transverse to the direction of said drift and varying linearly in a direction transverse to said drift and transverse to the direction of said magnetic field whereby the cyclotron frequency of said electron beam is established at substantially a harmonic frequency of said electromagnetic waves.

4. An electron discharge device comprising:
a wave conducting structure;
a cathode at one end of said structure;
means for accelerating electrons issuing from said cathode;
and means for compelling said accelerated electrons to drift in a substantially cycloidal trajectory path adjacent to said structure in an interaction space free of transverse steady electric fields exchanging energy with waves conducted by said structure, comprising magnetic members coextensive with said space and having opposing faces tilted in a direction transverse to said beam path to produce a magnetic field in said space varying linearly in a direction transverse to said electron drift and transverse to said magnetic field.

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