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Budker et al.

[11] **3,885,193**
[45] **May 20, 1975**

[54] **MICROWAVE ELECTRON DISCHARGE DEVICE**

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[21] Appl. No.: **391,314**

[52] **U.S. Cl.** **315/5.25;** 315/5; 315/5.24
[51] **Int. Cl.** **H01j 25/22**
[58] **Field of Search** 315/4, 5, 5.24, 5.25, 5.26, 315/3

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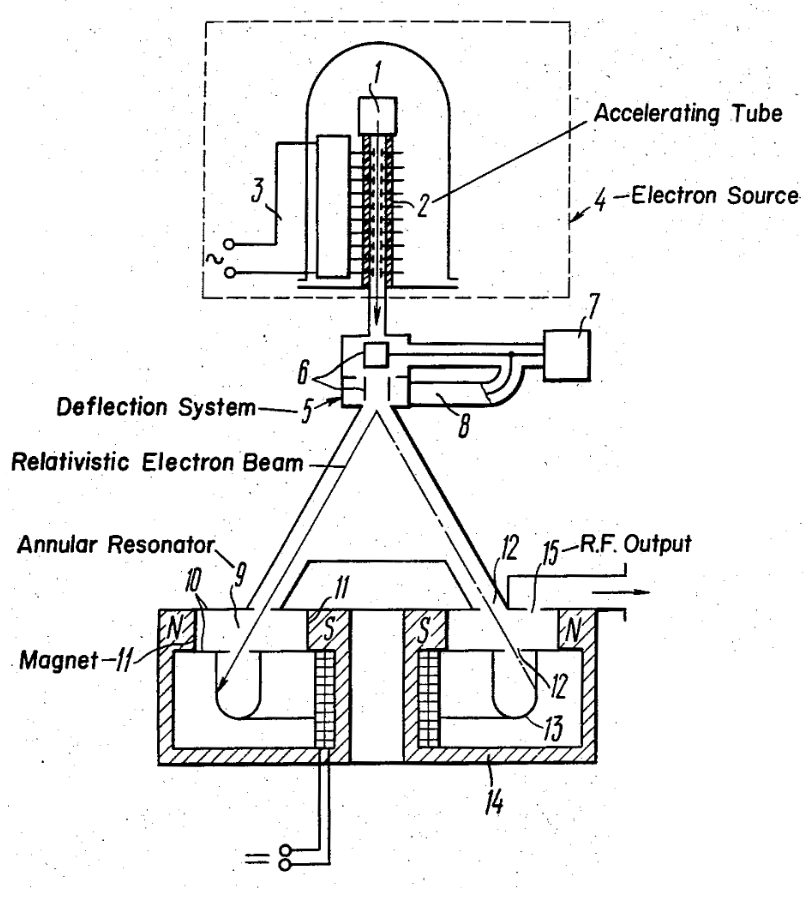
Primary Examiner—James W. Lawrence
Assistant Examiner—Saxfield Chatmon, Jr.

[57] **ABSTRACT**

A microwave electron discharge device comprising a means for forming a charged particle beam and having an accelerating tube for imparting relativistic energies to the charged particle beam. Besides, the device contains a deflection system for circular sweep of the beam disposed subsequent to the beam-producing means along the same axis, and a travelling-wave annular resonator positioned subsequent to the deflection system and also coaxial with this system and having circular slots at its and surfaces to permit the ingress of the scanned beam and its egress into the collector. The annular resonator is provided with a means for extracting electromagnetic microwave power which takes the form of two or more identical nondirectional power terminals distributed over the circumference of the resonator.

4 Claims, 11 Drawing Figures



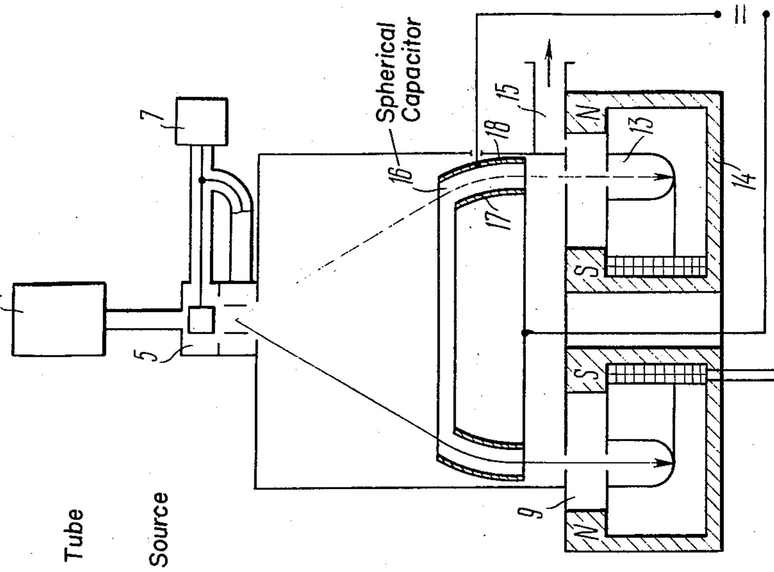

Spherical Capacitor
4
5
7
9
13
14
15
16
17
18
N
S
N

FIG. 2

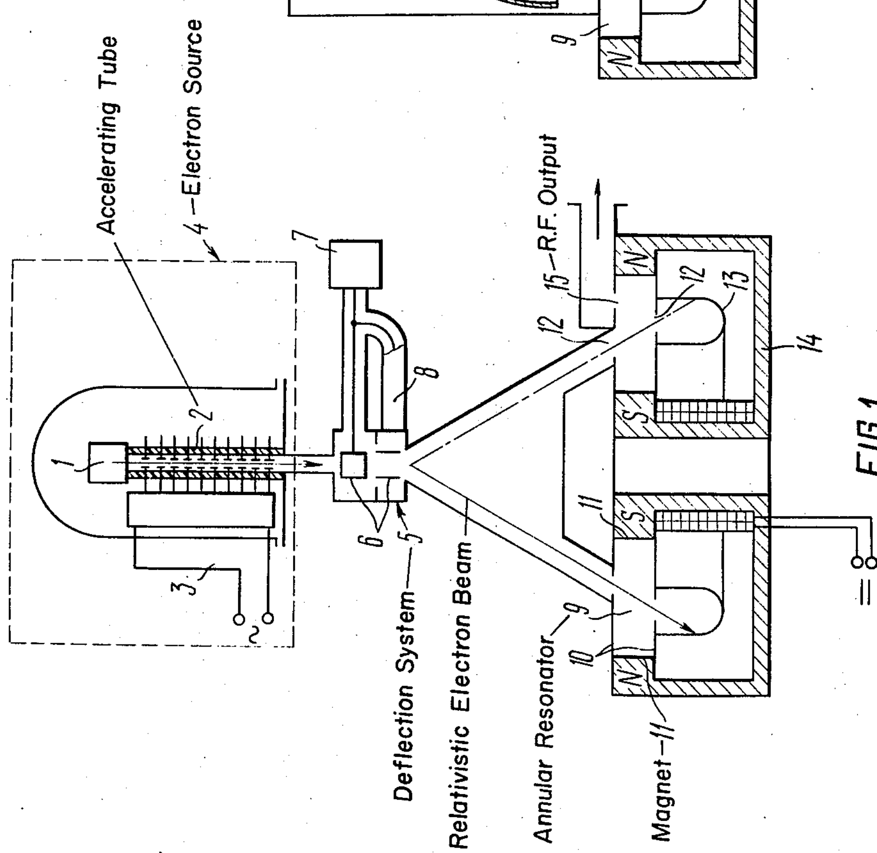

Accelerating Tube
4 —Electron Source
1
2
3
5
6
7
8
15—R.F. Output
12
13
14
Deflection System
Relativistic Electron Beam
Annular Resonator
9
10
Magnet —11
11
N
S
S
N

FIG. 1

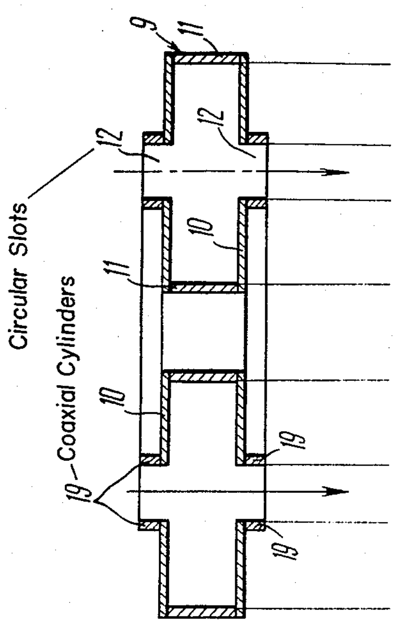


FIG. 4a

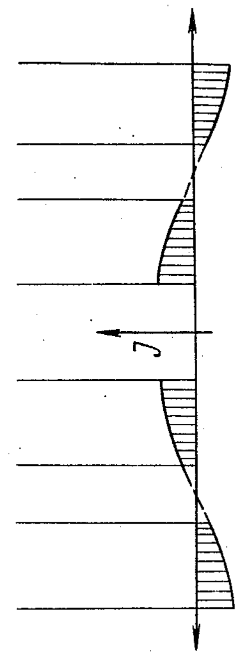


FIG. 4b

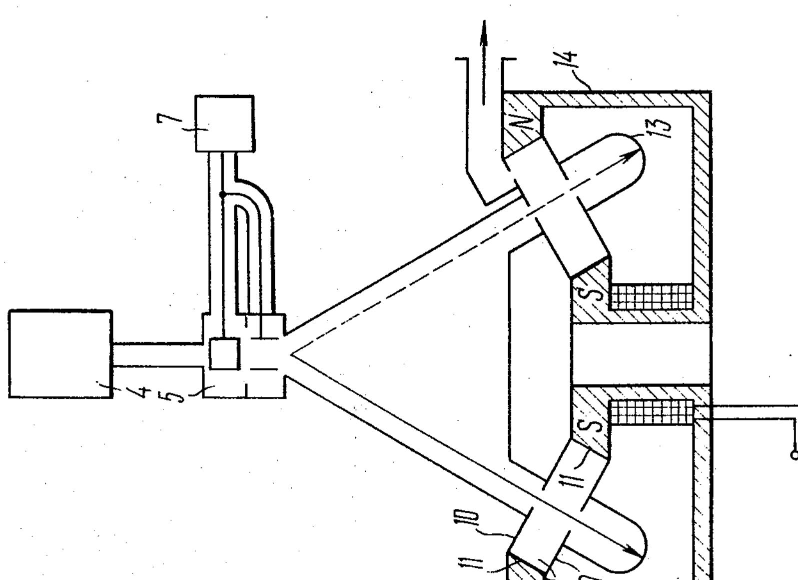


FIG. 3

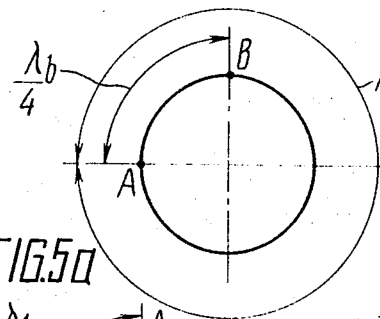


FIG.5a

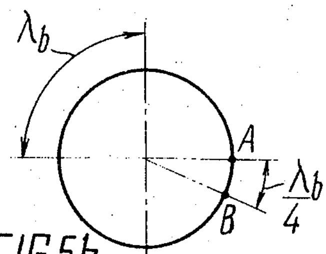


FIG.5b

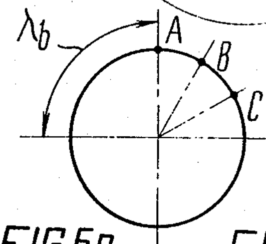


FIG.5c

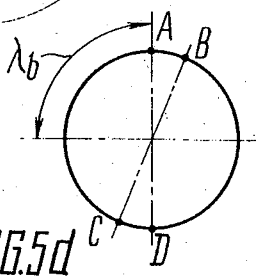


FIG.5d

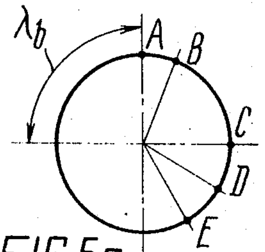


FIG.5e

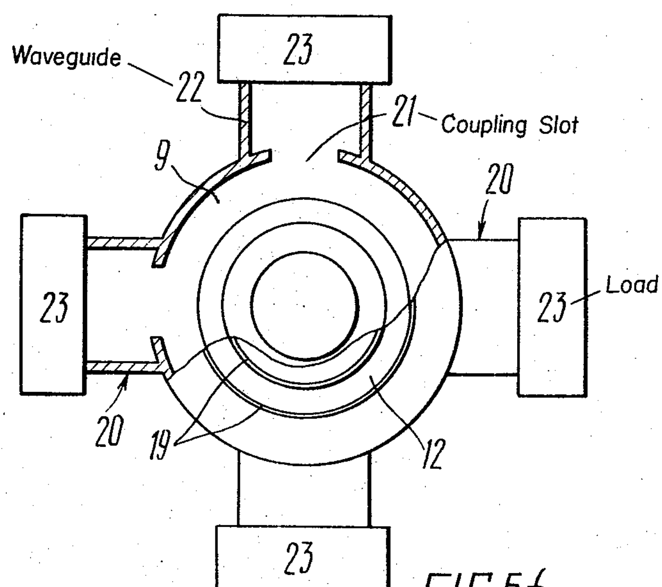


FIG.5f

MICROWAVE ELECTRON DISCHARGE DEVICE

The present invention relates to electron discharge devices and more particularly to microwave electron discharge devices used for power amplification and multiplication of high- and super-high frequency signals in various radio systems, for example, in charged particle accelerators.

The microwave electron discharge device of the prior art (see U.S. Pat. No. 321.987.3, Class 315-5.25, issued in 1965) comprises a means for forming an axially symmetric electron beam, a deflection system disposed coaxially after the beam-producing means and intended for circular sweep of the electron beam under the effect of the input signal, and a beam-excited traveling-wave annular resonator also disposed coaxially after the beam-producing means and having circular slots at its front and rear surfaces to permit the ingress and egress of a circularly deflected electron beam. The annular resonator is also provided with a means for extracting microwave power made as a directional coupler. For transmitting the beam from the deflection system to the resonator there is provided a means for post-deflection acceleration of particles interposed between the deflection system and the annular resonator.

This prior art device suffers from the disadvantage that is it unfeasible to obtain high power due to the fact that its construction does not permit the use of relativistic beams. When relativistic energies are imparted to the beam after its deflection, oscillations that arise in the particle-accelerating means cause coherent instability of the excited beam which is a phenomenon indentical with that occurring in linear accelerators for charged particles.

Besides, an increase of power usually requires a higher efficiency on account of necessary heat sinking from the structural elements.

In the prior art device, an efficiency close to 100 percent is not possible to obtain, because the magnetic component of the radio-frequency field set up by the beam in the traveling-wave resonator becomes so large that it distrorts the paths of the particles in the resonator and prevents exit of the particles to a collector at low energies.

A high efficiency is unattainable in the prior art device also due to the fact that apart from the longitudinal velocity component parallel to the lines of force of the electric field at the entry to the annular resonator, the particles possess a perpendicular velocity component which arises following beam deflection in the circular sweep system. Therefore, the electrons are not completely decelerated and the electronic efficiency will be limited by:

$$\eta = 1 - \frac{E_o}{T_k}\left(\frac{1}{\sqrt{1-\left(\frac{V_1}{C}\right)^2}}-1\right)$$

where:

η = maximum electronic efficiency;

T_k = kinetic energy of an electron at the entry point to the traveling-wave resonator;

E_0 = energy of an electron at rest;

C = light velocity;

V_1 = electron velocity component normal to the line of force of the electric field in the resonator.

The efficiency of the device is also restricted by strong electromagnetic power loss through the circular slots for beam traversal. At the same time, extraction of power from the resonator through one directional coupler limits the power output to the user.

It is on object of the present invention to provide a microwave electron discharge device with an unbunched relativistic beam for efficiently producing high frequency and very-high frequency power.

It is another object of the present invention to provide a microwave electron discharge device with a high electronic efficiency.

The foregoing objects are accomplished by using a microwave electron discharge device comprising a means for forming a beam of charged particles, a deflection system for circular deflection of this beam at the input signal fequency positioned along the beam axis immediately subsequent to the beam-forming means, and a traveling-wave annular resonator which is positioned also along the beam axis subsequent to the deflection system and has circular slots at its front and back surfaces to permit the ingress of the deflected beam of charged particles and egress of this beam to a collector and which also has a means for extracting electromagnetic microwave power; wherein, according to the invention, there is provided an eccelerating tube interposed between the beam-forming means and the deflection system and intended for imparting relativistic energies to the beam of charged particles.

Preferably, the annular resonator is provided with a source of constant magnetic field which would compensate the radio-frequency magnetic field induced by the traveling wave at a point where the beam traverses the resonator.

Also preferably, interposed between the deflection system and the annular resonator is an additional deflection system coaxial with the deflection system and the annular resonator which projects the charged particle beam perpendicular to the resonator end walls.

The additional deflection system may be made in the form of a magnetic lens.

The additional deflection system may also be electrostatic and take the form of a spherical capacitor.

Instead of mounting an additional deflection system, the annular resonator may be constructed and arranged so that its front and back walls are normal to the path of charged particles in a circularly deflected beam, and its side walls have a configuration at which the lines of force of the electric field induced by the resonator traveling wave are parallel to the direction of movement of the charged particles beam at the place of its travel through the resonator.

In order to minimize electromagnetic radiation through the circular slots, they are preferably disposed so that their center lines coincide with the line characterized by the absence of transverse radio-frequency currents flowing along the inner surface of the resonator.

For the same purpose it is desirable that cylinders of conducting material electrically coupled with the resonator surface be provided along the slot edges.

Preferably, the means for extracting electromagnetic microwave power takes the form of two identical non-directional output power terminals mounted on the resonator surface and having an azimuth shift equal to one quarter wavelength of the traveling wave in the annular resonator.

The means for extracting electromagnetic microwave power can also be made in the form of more than two identical non-directional output power terminals mounted on the resonator surface and having such an azimuth shift relative to one another as would ensure uniform distribution of these terminals along the angular wavelength of the wave traveling within the annular resonator.

The microwave electron discharge device of the present invention provides high microwave power output and has high electronic efficiency (about 100 percent).

The present invention may be best understood by reference to the following description taken in accordance with the accompanying drawings wherein:

FIG. 1 is a schematic illustration of a microwave electron discharge device;

FIG. 2 is a schematic illustration of the same device with an additional deflection system;

FIG. 3 is a schematic illustration of the same device with an annular resonator the front and back walls of which are arranged perpendicular to the path of the particles;

FIG. 4*a* diagrammatically illustrates an annular resonator with coaxial cylinders at the slot edges;

FIG. 4*b* is a diagram of approximate current distribution in the front and back walls of the resonator;

FIG. 5*a* shows the arrangement of two directional power terminals in a device of the present invention used for amplification of microwave signals;

FIGS. 5*b*, 5*c*, 5*d*, 5*e* are versions of the arrangement of power terminals in a device of the present invention used for frequency multiplication (quadrupling) of microwave signals;

FIG. 5*f* illustrates a traveling-wave resonator with four power terminals (used for power amplification).

In FIG. 1 of the accompanying drawings, there is shown diagrammatically a microwave electron discharge device which comprises a means for forming a charged particle beam in the form of an electron gun **1** which produces an axially symmetric pencil beam of charged particles, and a sectionalized accelerating tube **2** for imparting relativistic energies to the particles disposed at the output of the electron gun **1** and supplied from a high-voltage rectifier **3.**

The device may use any charged particles, but it can be most easily accomplished using electrons. The description below considers an embodiment of the device intended for work with electrons.

The electron gun **1**, accelerating tube **2** and rectifier **3** form a relativistic electron source **4.** Apart from these elements, the microwave device contains also a deflection system **5** for circular sweep of the electron beam which is disposed along the axis of the acclerating tube **2** and subsequent to the latter in the beam travel direction. The deflection system **5** consists of two capacitors **6** with a mutual 90° spatial shift which are connected to an input signal source **7** through coaxial transmission lines **8.**

Diposed subsequent to the deflection system **5** and coaxial with the latter is a traveling-wave annular resonator **9** designed for converting the kinetic energy of the particles into the energy of an electromagnetic field. The resonator **9** has end walls **10** and side walls **11,** the end walls **10** being, provided with axially symmetric circular slots **12** for passing the electron beam into the resonator **9** and exiting the beam out of the resonator **9** into a collector **13.** The traveling-wave resonator **9** has a circular D.C. electromagnet **14** used to compensate for the radio-frequency magnetic field induced by the wave at a place of beam traversal through the resonator **9,** and a directional coupler **15** for extracting microwave power (a means for microwave power extraction).

Unlike the device of FIG. **1,** another embodiment of the device illustrated in FIG. **2** comprises an additional deflection system **16** interposed between the deflection system **5** and the traveling-wave resonator **9** along the same axis. The additional deflection system **16** takes the form of a spherical capacitor having an inner electrode **17** and an outer electrode **18.**

The additional deflection system **16** may be not only electrostatic, but also magnetic, for instance, take the form of a thin magnetic lens embracing the scanned beam (not shown in the figures).

Another embodiment of the device shown in FIG. **3** differs from the device of FIG. **1** in that an annular resonator **9′** has its front and back walls **10** oriented perpendicularly to the path of particles in a circularly deflected beam, while the side walls **11** are so shaped that the lines of force of the electric field induced by the traveling-wave inside the resonator **9′** are perpendicular to the end walls **10** at places traversed by the beam particles traveling through the resonator **9′.**

FIG. 4*a* illustrates a sectional view of the traveling-wave annular resonator **9** wherein in order to minimize a loss of the electromagnetic power, the circular slots **12** are arranged so that their center lines coincide with the line along which there are no transverse radio-frequency electric currents passing over the inner surface of the resonator **9** (or so that they are coincident with the nodal lines of the radio-frequency current flowing transverse to the slots **12**). Along the edges of the slots **12** are disposed coaxial cylinders **19** made of some conducting material which are electrically connected to the surface of the resonator **9** and serve as cut-off waveguides.

FIG. 4*b* illustrates a diagram of transverse current I flowing in the end walls **10** of the resonator **9.**

FIG. 5*a* is a diagrammatic arrangement of two identical non-rectional power terminals (A and B) mounted on the surface of the resonator **9** with an azimuth shift equal to one quarter wavelength (λb/4). The device illustrated in this figure acts as a power amplifier.

FIGS. 5*b*, 5*c*, 5*d*, 5*e* show various versions of the arrangement of identical non-directional power terminals (A, B, C, D, E) in a device operating as a frequency multiplier (quadrupoler). In FIG. 5*b*, two terminals A and B have a mutual azimuth shift of λb/4, in FIG. 5*c*, three terminals, A, B and C have a shift equal to λb/3. In FIG. 5*d*, the resonator has four terminals A, B, C and D arranged in two pairs in the opposite quarters of the resonator and having a λb/4 shift in each pair. FIG. 5*e* shows a resonator with five terminals A, B, C, D and E arranged as follows: two terminals A and B in one quarter of the resonator **9** with a shift of λb/4, and three terminals C, D and E in the adjacent quarter of the resonator **9** with a shift of λb/3.

FIG. 5*f* is a top view of the traveling-wave resonator **9** (in a device used as a power amplifier) having four identical non-directional terminals **20** distributed through equal intervals along the circumference of the resonator **9.** Each terminal **20** consists of a coupling slot **21** and a waveguide **22** connected to a termination **23** (power consumer).

The device operates as follows.

The electron gun 1 (FIG. 1) producing an electron beam carries a voltage of 1–3 MV with respect to the last electrode of the sectionalized accelerating tube 2 which receives voltage from the rectifier 3. The electron beam derived from the electron gun and accelerated to relativistic energies enters the deflection system 5 which is excited from the input signal source 7. The input signal is divided in two parts and enters the deflection system 5 through two coaxial transmission lines 8, the lengths of the lines being so selected that signals coming to the capacitors 6 and 90° out of phase. Such a deflection system sets up a radio-frequency deflecting electric field with circular polarization and causes the electron beam to circularly scan the resonator.

After acceleration and scanning, the beam enters the travelling-wave annular resonator 9 through the axially symmetric slot 12 and builds up direct current passing through this resonator 9. Continuously varying its entry point into the resonator 9, the current excites a wave traveling, or rotating, in a circle. The dimensions of the resonator 9 are selected such that the natural frequency of the oscillations built up in the resonator is close to, or is a multiple of, the beam rotation frequency, and that the electric field associated with the traveling wave is perpendicular to the end walls 10 of the resonator 9. Voltage at the resonator 9 rises so that, if the Q-factor of the resonator is sufficiently high and coupling with the termination is properly adjusted, the voltage becomes close to the beam accelerating voltage. To avoid the deleterious effects from generation of secondary electrons, the particles that have given their energy to the electromagnetic field exit from the resonator through the other circular slot 12 into the collector 13. Useful power is extracted into the matched termination through the directional coupler 15.

Apart from the radio-frequency electric field, a magnetic field is also built up in the traveling-wave resonator 9. This field turns the particles in a direction opposite to that of wave progatation. The magnetic field is sufficiently large to turn the particles having a kinetic energy of 20–40 percent of the initial energy through an angle of 90° which limits the efficiency of the device to 60–80 percent. For compensation of the radio-frequency magnetic field, the resonator 9 has the D.C. electromagnet 14 which sets up a constant magnetic field offsetting the radio-frequency field at a place where the beam traverses the resonator 9.

Since high power of the device necessitates abstraction of heat from its elements, a further increase of the efficiency is attainable by making the paths of the charged particles parallel to the lines of force of the electric field set up by the traveling wave within the resonator 9. FIG. 2 illustrates an embodiment of the device which successfully solves this problem.

The relativistic electron beam derived from the source 4 enters the deflection system 5 where the electrons are deflected at a present angle from the longitudinal axis. The velocity component perpendicular to the axis is proportional to the tangent of the deflection angle. Passing further between the electrodes 17 and 18 of the spherical capacitor, the electron beam is deflected by the electric field of this capacitor at the same angle but in the opposite direction and enters the traveling-wave resonator 9 parallel to the electric lines of force of the radio-frequency field associated with the traveling wave. With properly selected operating characteristics of the resonator 9, the electrons are decelerated practically down to zero, and the electronic efficiency of the device will then be restricted by the second-oder effects, for example, by the particle energy scatter, space charge, etc.

The same desirable effect is accomplished if a magnetic lens is used as the additional deflection system 16.

Another way of raising the efficiency of the device is the use of a device shown in FIG. 3 in which the resonator 9′ has its end walls 10 oriented perpendicularly to the travel of the scanned electron beam. The side walls 11 of this resonator are so inclined as to make the lines of force of the electric field of the resonator 9′ in the beam traversal area normal to the end walls 10. A required shape of the walls is determined easily either by computation on an electronic computer or by a simulation.

In this case, the circular electron beam entres the resonator 9′ also parallel to the electric lines of force of the radio-frequency field set up by the traveling wave. Here, too, the efficiency of the device is determined by the second-order effects.

When the microwave electron discharge device employs the resonator 9 (FIGS. 4*a*, 4*b*) with the circular slots 12 thereof arranged so that their center lines coincide with the line along which there are no transverse electric currents, and with the coaxial conducting cylinders 19 mounted at the edges of the slots 12, electromagnetic radiation from the resonator 9 is reduced reducing thereby a power loss and decreasing the distortion of the particle paths.

Since the line along which there are no transverse currents passes through the centre of the circular slot 12, practically no H_{11} waves are excited in the cylinders 19 which would be free to propagate along the coaxial line formed by the cylinders 19. On the other hand, E_{11} waves are attenuated sufficiently quickly. To prevent the Q-factor of the resonator 9 from going down by than 5 percent on account of radiation, (as shown by calculations for slots of the width equal to 5–10 percent of the wavelength) a shift of the centre line of the circular slot 12 with respect to the line with no transverse electric currents must not exceed 7–10 percent of the width of the slot 12, while the height of the coaxial cylinders 19 must be comparable with the width of the slot 12.

Extraction of the radio-frequency power from the traveling-wave resonator 9 is effected through several identical non-directional terminals which are arranged along the azimuth of the resonator 9 so as to compensate for the reflected waves arising at the terminals in the traveling-wave resonator 9.

This is achieved as follows:

If the device is used for power amplification of the input signals, one wavelength is accommodated along the azimuth of the resonator and power is extracted through two or more terminals shifted 90° along the azimuth of the resonator 9 if two such terminals are employed, or arranged equally along the resonator azimuth if more than two terminals are provided. FIG. 5*a* illustrates schematically the arrangement of two power terminals (A and B) for extracting power from the resonator.

If the device is used for frequency multiplication, *n* wavelengths are accommodated along the resonator azimuth (where *n* is a frequency multiplication factor).

In this case the minimum number of terminals is two and these terminals are arranged at any wavelength (accommodated in a circle) in the same way as in a device used for power amplification.

FIGS. 5*b*, *c*, *d*, *e* illustrate different arrangements of the terminals in a device acting as a frequency quadrupler ($n = 4$), the number of terminals (A, B, C, D, E) being determined by the amount of extracted power and consumer's requirements.

In an embodiment of the resonator **9** shown in FIG. 5*f* power is extracted through the four identical coupling slots **21** and then transmitted through the waveguides **22** to the termination **23.** Thus, each coupler **20** extracts one quarter of the total power taken out of the resonator **9** into the termination **23.**

It should be pointed out that apart from increasing power output and facilitating the operating conditions of the terminals, use of several identical non-directional terminals has the following additional advantages:

— first, use of several power terminals makes it easier to distribute power for supply of several consumers, for example, when feeding multi-resonator accelerating systems of charged particle accelerators;

— second, power extraction does not depend on the direction of wave propagation in the annular resonator;

— third, when identical reflected waves arise in the terminations, no standing wave is built up in the resonator, whereas if power is extracted through a non-directional terminal power reflected from the termination causes a standing wave to appear in the annular resonator which leads to a non-uniform heat load on the collector.

What is claimed is:

1. A microwave electron discharge device, comprising beam-producing means for forming a charged particle beam; an accelerating tube positioned at the output of said beam-producing means for imparting to particles of said beam a velocity close to the velocity of light; a deflection system for circular scanning of said beam at a predetermined input signal frequency, said deflection system being mounted subsequent to said accelerating tube in the direction of beam travel along the axis of said accelerating means; a hollow annular resonator disposed subsequent to said deflection system in the direction of beam travel along the axis of the deflection system, said resonator having circular slots in its walls to permit the ingress of a circularly scanned beam and egress of the beam out of the resonator, said resonator being internally dimensioned and shaped to support the traveling along an annulus of an electromagnetic wave at a frequency comprising a multiple of the frequency of said beam scanning, said electromagnetic wave having its electric field substantially parallel to the direction of the motion of said beam particles; a collector mounted after said annular resonator in the direction of beam travel for receiving the charged particle beam upon exiting the resonator.

2. A microwave electron discharge device, comprising: beam-producing means for forming a charged particle beam; an accelerating tube positioned at the output of said beam-producing means for imparting to particles of said beam a velocity close to the velocity of light; a deflection system for circular scanning of said beam at a predetermined input signal frequency, said deflection system being mounted subsequent to said accelerating tube in the direction of beam travel along the axis of said accelerating means; a hollow annular resonator disposed subsequent to said deflection system in the direction of beam travel along the axis of the deflection system, said resonator having circular slots in its walls to permit the ingress of a circularly scanned beam and egress of the beam out of the resonator, said resonator being internally dimensioned and shaped to support the traveling along an annulus of an electromagnetic wave at a frequency comprising a multiple of the frequency of said beam scanning, said electromagnetic wave having its electric field substantially parallel to the direction of the motion of said beam particles; a collector mounted after said annular resonator in the direction of beam travel for receiving the charged particle beam upon exiting the resonator; and means for creating a continuous magnetic field substantially inside said resonator at the paths of the particles of said beam, the direction and magnitude of said continuous magnetic field compensating for the effect of the magnetic field of said electromagnetic wave travelling along the annulus, said electromagnetic wave being excited by said beam.

3. A microwave electron discharge device, comprising beam-producing means for forming a charged particle beam; an accelerating tube positioned at the output of said-beam-producing means for imparting to particles of said beam a velocity close to the velocity of light; a deflection system for circular scanning of said beam at a predetermined input signal frequency, said deflection system being mounted subsequent to said accelerating tube in the direction of beam travel along the axis of said accelerating means; hollow annular resonator disposed subsequent to said deflection system in the direction of beam travel along the axis of the deflection system, said resonator having circular slots in its walls to permit the ingress of a circularly scanned beam and egress of the beam out of the resonator, said resonator being internally dimensioned and shaped to support travelling along an annulus of an electromagnetic wave at a frequency comprising a multiple of the frequency of said beam scanning, said electromagnetic wave having its electric field substantially parallel to the direction of the motion of said beam particles; a collector mounted after said annular resonator in the direction of beam travel for receiving the charged particle beam upon exiting the resonator; and means for electromagnetic microwave power extraction in form of two identical coupling devices mounted on the surface of said resonator with an azimuthal shift equal to one quarter of the angular wavelength of said electromagnetic wave travelling in said resonator.

4. A microwave electron discharge device, comprising beam-producing means for forming a charged particle beam; an accelerating tube positioned at the output of said beam-producing means for imparting to particles of said beam a velocity close to the velocity of light; a deflection system for circular scanning of said beam at a predetermined input signal frequency, said deflection system being mounted subsequent to said accelerating tube in the direction of beam travel along the axis of said accelerating means; a hollow annular resonator disposed subsequent to said deflection system in the direction of beam travel along the axis of the deflection system, said resonator having circular slots in its walls to permit the ingress of a circularly scanned beam and egress of the beam out of the resonator, said resonator being internally dimensioned and shaped to support travelling along an annulus of an electromagnetic wave at a frequency comprising a multiple of the frequency of said beam scanning, said electromagnetic wave having its electric field substantially parallel to the direction of the motion of said beam particles; a collector mounted after said annular resonator in the direction of beam travel for receiving the charged particle beam upon exiting the resonator; and means for electromagnetic wave power extraction in form of more than two identical coupling devices disposed on the surface of said resonator with an azimuthal shift relative to one another and providing uniform distribution of said devices along the angular wavelength of said electromagnetic wave travelling in said resonator.

* * * * *