April 12, 1949. A. E. HARRISON 2,466,704

FREQUENCY MULTIPLIER APPARATUS

Filed Aug. 30, 1945

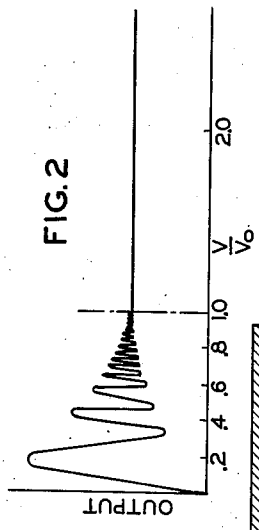


FIG. 2

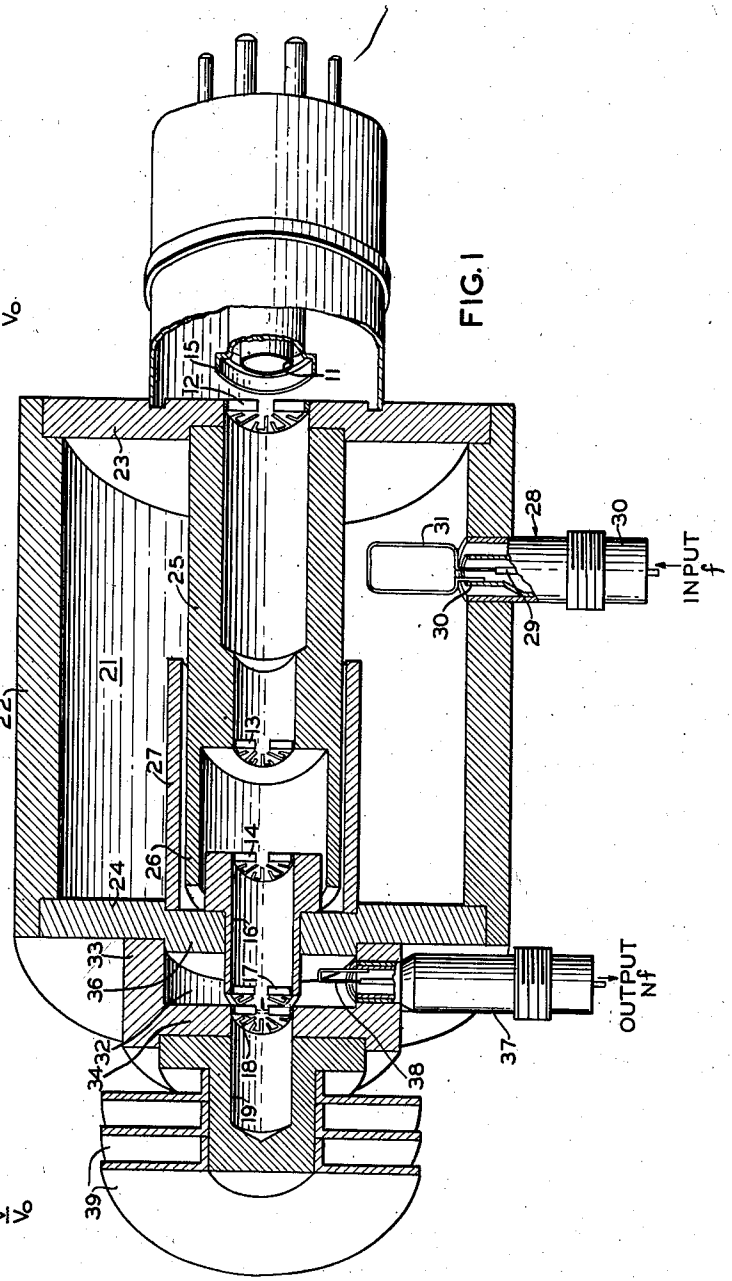


FIG. 1

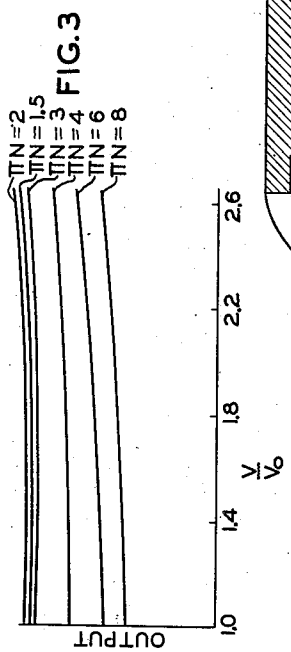


FIG. 3

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FREQUENCY MULTIPLIER APPARATUS

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12 Claims. (Cl. 315—6)

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The present invention is related to the art including electron discharge devices and their associated circuits, and especially to such devices operable in the ultra-high-frequency region above approximately three hundred megacycles per second, for the purpose of producing frequency multiplication; that is, for converting a given fundamental frequency into a much higher frequency harmonically related to the fundamental frequency.

The present invention uses the velocity-modulation principle for producing such frequency multiplication. An electron stream of uniform velocity and constant intensity is subjected to an oscillating electric field extending in the direction of the electron flow and of the fundamental frequency to be multiplied. This field alternately accelerates and decelerates the electrons of the stream, which is known as the process of velocity-modulation. The stream velocity-modulated in this manner is passed into a field-free drift space in which the faster electrons overtake the slower electrons, thereby converting the constant intensity stream into a variable intensity stream. This process has been termed "velocity grouping."

The velocity-grouped electron stream is essentially an electron current having a constant unidirectional component upon which are superposed alternating components of the fundamental frequency and harmonics thereof. By passing this variable electron current through a pair of grids or other electron-permeable electrodes to which is coupled a resonant circuit, usually a cavity resonator, tuned to one of the harmonic frequencies, energy of this harmonic frequency is extracted from the stream and is available for use as desired. Such devices are discussed, for example in the Klystron Technical Manual, published in 1944 by the Sperry Gyroscope Company, Inc., pages 27 to 30 thereof.

The present invention is directed toward devices of this type with improvements to overcome certain of the defects inherent in the devices of the prior art. One such defect was the fact that the output of such a device was an extremely sensitive function of the amplitude of the input and of the initial electron-accelerating voltage which produced the electron stream. As discussed in the above-mentioned Klystron Technical Manual, it was formerly believed that optimum operation was produced for values of the bunching parameter x equal to the first maximum of the function $J_m(mx)$, where m is the frequency-multiplication ratio, and this bunching parameter x is defined by the equation

$$x=\pi N V_1/V_0=\sqrt{\frac{M}{8e}}\frac{\omega_1 S}{\sqrt{V_0}}\frac{V_1}{V_0}$$

where N is the transit time of electrons of average velocity between the velocity-modulation point and the energy-extraction point (that is, is the

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length of the drift space) measured in cycles of the fundamental frequency; M is the mass of electron; e is the charge of the electron; π_1 is the radian frequency $2\pi f$ of the velocity-modulating voltage; s is the length of the drift space; V_1 is the peak value of the alternating voltage producing the bunching or velocity-modulating electric field; and V_0 is the electron-accelerating voltage producing the initial constant-velocity electron stream. This condition meant that x should be between 1.84 for low values of m and 1.0 for higher values of m.

As conventionally used, V_1 was kept substantially less than V_0; for example, less than 20 per cent of V_0. This, of course, required N to be fairly large, such as of the order of three to ten, to provide the required value of x between 1.0 and 1.84. Under these customary operating conditions, it was found that a very slight change in x, such as produced by a change in V_1 or in V_0, would produce a fairly large change in output of the device. This was a distinct disadvantage and handicap in the operation of these devices, since for system stability it is necessary that the output of such frequency-multiplier devices remain substantially constant, or at least fluctuate but slightly with changes in operating conditions. The marked sensitivity of output in response to change of input voltage, being highly undesirable, required special precautions to provide stability for the output of the driver supplying the input to the frequency-multiplier. At the usual input frequencies in the neighborhood of three hundred megacycles per second, great difficulty is experienced in stabilizing the output of such driver devices. Such stabilization can be effected only at the expense of greatly increased complexity and increase in cost of construction of the apparatus. Automatic volume control circuits could be used. However, such circuits are well-developed only at low frequencies and are not yet practical at the frequencies of these driver devices in the neighborhood of three hundred megacycles per second. Therefore, temperature-compensated tank circuits and highly accurate voltage regulators are necessary to stabilize such driver outputs. Also, accurate voltage regulators were necessary for the beam voltage supply for the frequency multiplier itself.

All of these special devices are rendered unnecessary by the present invention, in which the output of the frequency multiplier device is very stable and is substantially independent of variation of input over a relatively wide range. The frequency multiplier device of the present invention has inherent in it what is effectively an automatic volume control providing uniform output despite variation in input.

In addition, the fairly long transit time of the electrons in the drift space customary in the prior art devices permitted substantial electron de-

bunching to occur due to the repulsive forces between the individual electrons. This action reduced efficiency and output. Also, the fairly large values of N required long drift tubes and made such devices physically large.

According to the present invention, each of these disadvantages of the prior art is overcome by specifically disregarding what were formerly considered to be essential criteria of operation. In the present invention, values of V_1 are utilized which are larger than V_0, so that, in fact, some electrons fail to pass the input field, but are rather reflected thereby, since the input voltage is larger than the beam voltage. It has been found that this condition of operation produces an entirely different type of dependence of output upon input voltage. A critical point appears to exist at the point where electrons are initially turned back at the input gap ($V_1=V_0$). For input voltages greater than this value, it has been found that the dependence of output upon input is greatly minimized, and, with proper design, substantially constant outputs can be obtained for inputs ranging from

$$\frac{V_1}{V_0}=1$$

to much larger values; in fact, such stabilized output is obtained even for zero accelerating voltages when the electron stream is blocked every half-cycle. In this way, an extremely difficult problem has been solved, and a distinct disadvantage of the prior art has been overcome.

In addition, values of buncher parameter x greater than two are utilized, and are found to have more desirable results than the values between 1.0 and 1.84, which were formerly considered necessary. At the same time, the device of the present invention utilizes a drift space transit time of less than one cycle, thereby inhibiting electron debunching and improving efficiency.

Accordingly, it is an object of the present invention to provide improved velocity-modulation frequency-multiplier devices, such as are useful at ultra high frequencies, having improved efficiencies.

It is another object of the present invention to to provide velocity-modulation frequency-multiplier devices using relatively short electron transit times, having less electron debunching and permitting decreased over-all length with respect to prior practice.

It is a still further object of the present invention to provide improved velocity-modulation frequency-multiplier devices which are relatively insensitive to changes in input voltage.

The invention in another of its aspects relates to novel features of the instrumentalities described herein for achieving the principal objects of the invention and to novel principles employed in those instrumentalities, whether or not these features and principles are used for the said principal objects or in said field.

A further object of the invention is to provide improved apparatus and instrumentalities embodying novel features and principles, adapted for use in realizing the above objects and also adapted for use in other fields.

According to one feature of the present invention, velocity-modulation electron discharge frequency-multiplier devices are operated with the fundamental frequency voltage larger than the beam voltage.

According to another feature of the present invention, velocity-modulation frequency-multiplier devices are operated with drift-space transit times less than one cycle of the fundamental frequency.

According to a further feature of the present invention, velocity-modulation frequency-multiplier devices are operated with bunching parameters of value greater than two.

Other features and advantages will become apparent from the specification, taken in connection with the accompanying drawings wherein the invention is embodied in concrete form.

In the drawings,

Fig. 1 shows a longitudinal perspective view partly in cross-section of a preferred form of the present invention.

Figs. 2 and 3 are graphs useful in explaining the principles and conditions of operation of the present invention.

Referring to Fig. 1, there is shown a velocity-modulation electron-discharge device incorporating the principles of the present invention. In this device a cathode **11** serves as a source of electrons and cooperates with an accelerating or smoother grid **12** and a suitable source of beam or accelerating voltage connected therebetween, but not shown in the drawing, to provide a linear stream of electrons of substantially uniform velocity and constant intensity. A control electrode **15** serves to control the magnitude of this electron stream. This stream of electrons flows successively through the buncher or input velocity-modulating grids **13, 14**, through the drift tube **16** and through the catcher or output energy-extracting grids **17, 18**, until it is finally collected by the electron-collector electrode **19**. Coupled between the input grids **13, 14** is an input or buncher cavity resonator **21** having an outer cylindrical wall **22** and a pair of end walls **23** and **24**. End wall **23** carries the accelerating grid **12** and also carries a tubular member **25** which surrounds the path of the electron stream between grids **12** and **13**. Member **24** also supports grid **13**.

The drift tube **16** is fixed within the end wall **24** and carries the input grid **14** at one end and the output grid **17** at the other end. Tubular member **25** has an extension **26** concentrically disposed around the end of drift tube **16** carrying input grid **14**. Extension **26** and drift tube **16** define a fixed capacity-loading for the resonator **21** so as to reduce the physical size of this resonator for the desired fundamental frequency to which resonator **21** is tuned. Also carried by the end wall **24** is a concentric tubular member **27** which cooperates with member **24** to provide additional lumped capacitance for capacity-loading the resonator **21** to a greater extent.

Resonator **21** may be a fixed frequency resonator tuned to the desired input fundamental frequency or may be provided with any conventional type of tuning means (not shown) by which its resonant frequency may be adjusted to equal that of the input fundamental frequency. Resonator **21** is provided with an input terminal **28** comprising a short coaxial line section having an inner conductor **29** and an outer conductor **30**. A vacuum seal (not shown) between conductors **29** and **30** completes the vacuum envelope of which the outer walls of resonator **21** form a part. The conductors **29** and **30** are joined by a coupling loop **31** within the resonator **21** so that a high frequency voltage applied to the input terminal **28** will excite oscillations within the resonator **21** and thereby produce an alternating electric field of this input frequency between grids

13 and 14 and extending along the direction of travel of the electrons of the beam. Grids 13 and 14 may be omitted, if desired, without materially affecting operation.

By means of this action, as discussed above, the electrons of the stream are velocity-modulated, and their subsequent travel through the drift tube 16 causes them to become bunched, or, from another viewpoint, causes the uniform intensity electron stream from cathode 11 to become pulsating with a component of the desired harmonic of the fundamental frequency.

Coupled between the output grids 17 and 18 is an output or energy-extracting resonator 32 having a cylindrical outer wall 33, an end wall 34 carrying grid 18, and an end wall 36 which may be integral with end wall 24 of resonator 21. The end of drift tube 16 carrying grid 17 opposite grid 18 forms a reentrant pole for resonator 32. An output terminal 37 is provided similar to input terminal 28, and having a coupling loop 38 extending within resonator 32. Resonator 32 is designed or adjusted to be resonant at the desired output harmonic frequency, and energy of this frequency is supplied to any desired load or utilization device by way of the terminal 37. After passing through grids 17 and 18, the electron stream impinges upon and is captured by the recessed electron-collector electrode 19, which may have heat-radiating fins 39 for dissipating the heat generated by impact of the electrons thereupon.

According to the present invention, the peak value of the alternating voltage impressed between grids 13 and 14 is made larger than the beam voltage applied between cathode 11 and grid 12. Then, during those parts of the fundamental frequency cycle in which the alternating electric field between grids 13 and 14 opposes the electron flow, some of the electrons will be completely decelerated and reversed in flight and will never proceed through grid 14. Other electrons, of course, will be slightly decelerated, but will proceed to the catcher or output resonator 32, and still others will be accelerated.

The length of the drift tube 16 is so designed in relation to the beam voltage that the distance between the centers of the respective gaps between grids 13, 14 and between grids 17, 18 is relatively small. A theoretical optimum value for this distance is substantially

$$\frac{2}{\pi}$$

or .64 times the distance travelled by an electron of average velocity in one cycle of the fundamental frequency, although in practice, where conditions may depart from the theoretical, some variation from this value may be expected. Under these conditions the above-enumerated advantages of the present invention are derived.

The conditions of operation of the present invention may be better understood by reference to Figs. 2 and 3. In Fig. 2 there is plotted a curve of computed output amplitude derived from resonator 32 versus the ratio V_1/V_0 (that is, the ratio of the peak high frequency voltage V_1 between grids 13 and 14 to the beam voltage V_0 between cathode 11 and grid 12) for representative values of multiplication ratio and drift tube length. As shown in this figure, for values of V_1/V_0 of 0.2 or less, generally considered previously to be an essential condition of operation, the output curve generally follows that shown in the above-mentioned Klystron Technical Manual. It will be clear that any slight voltage instability either in V_1 or V_0 will materially alter the output. This, of course, is an undesirable characteristic. I have found, however, that as the input voltage is increased relative to the beam voltage, the output continually oscillates between limits which approach one another as V_1/V_0 increases.

These limits become substantially equal when $V_1=V_0$. For V_1 greater than V_0, the previous marked fluctuations in output with changes in input completely vanish, and the output changes only slightly with input, if at all. It has further been found that for any particular tube, a certain value of beam current can be found, as by adjusting the voltage on the control grid 15, such that the output is substantially perfectly constant despite variation in input voltage. For current values differing slightly from this optimum condition, the output may rise slowly and gradually with increase in voltage V_1 or may decline gradually, but even such gradual rise or decline represents a marked improvement in operating characteristics over that inherent in the prior art operation, where V_1/V_0 was less than two-tenths, since the change in output is still very slight even for material changes in V_1/V_0.

The point at which $V_1=V_0$ appears to be a very critical one at which the operating characteristics of the device completely alter their character. For V_1 less than V_0, the output rapidly oscillates as the input changes. This variation in output is so marked that prior practice generally limited operation to values of V_1/V_0 less than 0.2. Values of V_1/V_0 greater than unity were never contemplated, because it was realized that for such values, not all electrons would pass the buncher gap, some necessarily being reflected. This is not true for V_1/V_0 less than unity, where the entire stream passes the buncher. It was formerly believed that the reflection of electrons at the buncher gap would impair operation both by interfering with the effectiveness of velocity modulation by virtue of the space charge between the buncher grids, and by reducing output by reducing the electron current intensity. Also, the effect upon the grouping or bunching phenomenon, of periodically removing some electron from the stream was not understood, and was believed to represent a further source of disadvantage.

I have found, however, that at the point where $V_1=V_0$, a complete change in mode of operation occurs abruptly. This is believed to be caused by the very effect previously considered undesirable, namely, that at this point certain of the electrons are turned back by grid 14 and never reach the output grids 16, 17. The beam current is then essentially a rectangular wave, passing the input gap for only a portion of each cycle, the duration of the portion depending on V_1/V_0. This completely changes the operating characteristics of the device in an unexpected manner, and, as shown by the portion of the curve of Fig. 2 to the right of point

$$\frac{V_1}{V_0}=1$$

instead of producing disadvantageous operation, highly stable operation is obtained. Such stable operation is equivalent to incorporating an automatic volume control system in the device. However, at these ultra-high frequencies, such automatic volume control is presently very difficult of attainment, so that the present invention produces a result almost impossible to attain other-

wise, and simultaneously greatly simplifies the apparatus by omitting special voltage regulators or driver-stabilizing devices.

Fig. 3 demonstates the effect of differing drift tube lengths upon the computed output in the useful range where V_1/V_0 is greater than unity. As shown in this figure, for any particular value of πN, the output is substantially uniform and constant despite variation in input. However, for πN greater than three, the output falls off markedly. The computed optimum value of πN is in the neighborhood of $\pi N=2$ corresponding to a value of $N=.64$, although values of πN from 1.5 of 3.0 are useful. In practice, some departures from these values are experienced.

Accordingly, by applying the principles of the present invention in operating the velocity-modulation frequency-multiplier apparatus under conditions inconsistent with those previously thought to be necessary, namely, by using an input voltage greater than the beam voltage and by using a drift tube length producing a transit time shorter than one cycle, I have been able to provide an extremely stable output substantially independent of input voltage. At the same time this condition permits the use of extremely short drift tubes relative to those previously used, whereby the physical size of the device is substantially reduced so as to provide more compact apparatus, and the decrease in efficiency and output formerly attributed to the phenomenon of electron debunching inherent in the use of long drift tubes is markedly reduced.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. High frequency electron discharge apparatus comprising means, including a cathode, an accelerating electrode and a source of unidirectional voltage of predetermined magnitude coupled therebetween, for producing a uniform-velocity electron stream; a pair of electron-permeable electrodes positioned adjacent one another along the path of said stream, means defining a field-free drift-space surrounding said stream path beyond said pair of electrodes, a second pair of electron-permeable electrodes positioned adjacent one another along said stream path beyond said drift-space, a source of fundamental-frequency voltage of peak value greater than said predetermined magnitude means coupling said source to said first pair of electrodes for impressing said voltage therebetween for velocity-modulating said uniform-velocity stream, and a tuned circuit tuned substantially to a harmonic of said fundamental frequency and coupled to said second pair of electrodes for extracting high frequency energy of said harmonic frequency therefrom, whereby the amplitude of said extracted energy is substantially stabilized with respect to variation of said fundamental-frequency voltage.

2. Apparatus as in claim 1, wherein said pairs of electrodes are separated by a distance smaller than that traversed by an electron of average velocity in one cycle of said fundamental frequency.

3. Apparatus as in claim 1, wherein said predetermined magnitude of unidirectional voltage, said peak value of fundamental-frequency voltage and the spacing between said pairs of electrodes provide a bunching parameter greater than two.

4. High frequency electron discharge apparatus comprising means for producing a uniform-velocity electron stream, a first pair of electron-permeable electrodes positioned in the path of said stream, means coupled to said electrodes for providing an alternating fundamental-frequency voltage therebetween for velocity-modulating said uniform-velocity stream, means defining a field-free drift space surrounding said stream path beyond said electrodes, a second pair of electron-permeable electrodes positioned along said stream path in energy-exchanging relation thereto, tuned circuit means coupled to said second pair of electrodes and tuned to a harmonic of said fundamental frequency for extracting high frequency energy of said harmonic frequency from said stream, the spacing of said two pairs of electrodes being less than the distance traversed by an average velocity electron in one cycle of said fundamental frequency.

5. High frequency electron discharge apparatus comprising means for producing a uniform-velocity electron stream, a pair of electron-permeable electrodes positioned along said stream path in controlling relation thereto, a source of fundamental-frequency voltage of a magnitude sufficient to reverse some of the electrons of said stream during a part of each cycle of said fundamental frequency, means coupling said source to said electrodes for velocity-modulating said stream, and energy-extracting means positioned along said stream path in energy-extracting relation thereto for extracting high frequency energy from said stream at a frequency harmonically related to said fundamental frequency.

6. Apparatus as in claim 5, wherein said energy-extracting means is spaced from said pair of electrodes by a distance correlated to said voltage magnitude and to the average velocity of said stream electrons to provide a bunching parameter greater than two.

7. High frequency electron discharge apparatus comprising means for producing a uniform-velocity electron stream, a first cavity resonator tuned substantially to a fundamental frequency and having a pair of electron-permeable walls positioned along the path of said stream, a drift tube surrounding said stream path beyond said walls, a second cavity resonator tuned substantially to a harmonic of said fundamental frequency and having a pair of electron-permeable walls positioned along said stream path beyond said drift tube, a source of alternating fundamental-frequency voltage of sufficient amplitude to reverse some of the electrons of said stream during a portion of each cycle of said fundamental-frequency voltage when applied between said first pair of walls and means coupling said source to said fundamental-frequency resonator for exciting said resonator and for maintaining said voltage between said pair of walls, whereby the amplitude of excitation of said second resonator is substantially stabilized with respect to variation in amplitude of said voltage.

8. Apparatus as in claim 7, wherein said drift tube has a length shorter than the distance traversed by an average-velocity electron in one cycle of said fundamental-frequency voltage.

9. Apparatus as in claim 7, wherein said drift tube has a length providing a bunching parameter greater than two.

10. High frequency electron discharge appa-

ratus comprising means including a source of accelerating voltage of magnitude V_0 for producing an electron stream of predetermined uniform velocity, velocity-modulating means including a pair of electrodes positioned along the path of said stream for maintaining in part an alternating fundamental-frequency voltage of magnitude V_1 and radian frequency ω between said electrodes and extending along the direction of flow of said stream, energy-extracting means positioned along said stream path and spaced from said velocity-modulating means by a distance S for extracting high frequency harmonic energy from said stream, said distance S having a value yielding a bunching parameter

$$x=\sqrt{\frac{M}{8e}}\frac{\omega . S}{\sqrt{V_0}}\frac{V_1}{V_0}$$

of a value greater than two, where M is the mass of electron and e is charge of the electron, whereby the amplitude of said extracted energy remains substantially stabilized despite variations in said alternating voltage magnitude.

11. High frequency electron discharge apparatus comprising means for producing a uniform-velocity electron stream, including a cathode, an accelerating electrode and a source of unidirectional voltage coupled therebetween, a cavity resonator having a pair of electron-permeable walls along the path of said stream, a source of alternating voltage of a peak value greater than said unidirectional voltage, and means coupling said source to said resonator for exciting said

resonator to oscillation and for maintaining said alternating voltage between said walls, whereby some electrons of said stream are turned back during a portion of each cycle of said alternating voltage.

12. High frequency electron discharge apparatus comprising means including a source of direct potential for producing an electron stream, a pair of electron-permeable electrodes positioned along the path of said stream, a source of alternating voltage of a magnitude relative to said direct potential sufficient to turn back some electrons of said stream during a portion of each cycle of said alternating voltage when coupled to said electrodes, and means coupling said source to said electrodes for applying said voltage therebetween.

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