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W. C. HAHN
HIGH-FREQUENCY APPARATUS

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2,463,267

Fig. 2.

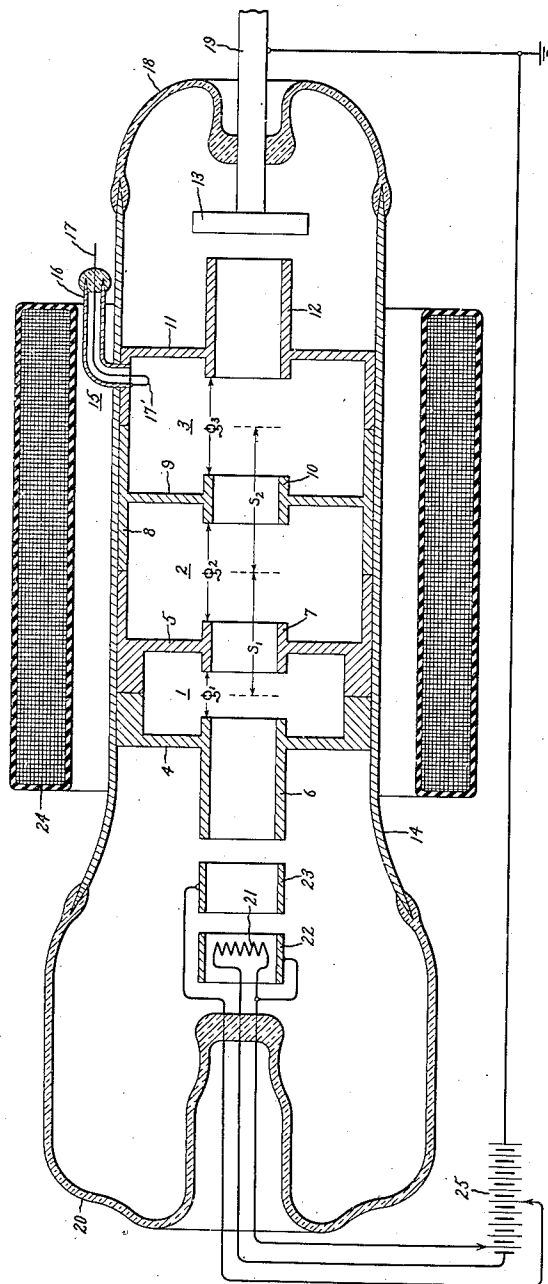
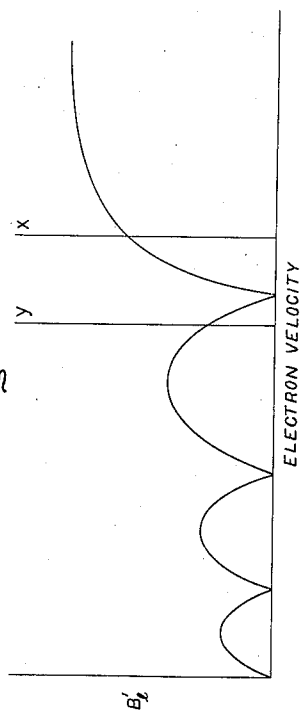


Fig. 1.



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UNITED STATES PATENT OFFICE

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HIGH-FREQUENCY APPARATUS

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Application May 31, 1943, Serial No. 489,129

3 Claims. (Cl. 250—27.5)

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My invention relates to ultra high frequency apparatus and more particularly to ultra high frequency apparatus employing the principles of velocity modulation.

The present invention relates to improvements in ultra high frequency apparatus using the principles of velocity modulation described in United States Letters Patent No. 2,220,839 granted November 5, 1940 upon my application filed July 14, 1937, and of which a reissue application Serial No. 456,380 was filed August 27, 1942, both of which are assigned to the assignee of the present application.

Heretofore, by investigators in the velocity modulation field it has been somewhat generally considered that the maximum theoretical efficiency obtainable was approximately 58%. In accordance with the teachings of my invention described hereinafter, I provide new and improved electronic apparatus of the velocity modulation type applicable to ultra high frequency amplifiers, oscillators, converters and the like, either of the space resonant type or otherwise, whereby efficiencies are obtainable substantially in excess of those previously considered possible.

It is an object of my invention to provide new and improved ultra high frequency apparatus and methods of operation.

It is another object of my invention to provide new and improved ultra high frequency discharge apparatus of the velocity modulation type.

It is a further object of my invention to provide a new and improved ultra high frequency oscillator of the velocity modulation type.

It is a still further object of my invention to provide a new and improved ultra high frequency oscillator of the space resonant type employing the principles of velocity modulation.

Prior to a detailed consideration of my invention, it is believed appropriate to review certain fundamental aspects of velocity modulation systems. As a general matter, it may be considered that in velocity modulation systems a beam of charged electric particles, such as electrons, produced by means of a pair of principal electrodes, such as an anode and a cathode, is established and the electrons constituting the beam are subjected to a signal voltage such as a high frequency signal voltage to velocity modulate the electrons. This velocity modulation may be accomplished cyclically or periodically, causing electrons in contiguous parts of the electron beam to be alternately accelerated and decelerated. Velocity modulation of the electrons consequently causes a grouping of the electrons due to the tendency of the higher velocity electrons to overtake the

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lower velocity electrons, effecting a decided spatial charge density distribution of the beam. For example, if a uniform beam of electrons is caused to traverse a region which is subjected to cyclically variable potential gradients, the electrons which traverse the region when the gradient in it is positive will be accelerated while the electrons which enter the region during the period of negative potential gradient will be decelerated.

In systems of this nature energy may be extracted from the electron beam by electrode means such as capacitive or inductive coupling means. One example of such electrode means is a structure forming a gap having an appreciable capacitive characteristic with which the electron beam cooperates to produce across the gap variations in potential in accordance with the charge density distribution of the beam. These gaps may be defined by a conductive enclosing shell for the electron beam and the entire structure may be designed to have the characteristics of a space resonant system wherein energy is supplied to the space resonant structure by the interaction of the modulated electron beam and the structure. As a further matter, a plurality of such space resonant structures may be employed and arranged axially the electron beam so that the electron beam successively traverses the space resonant electrodes or cavities, and wherein the net effect of the elements is accumulative making it possible to effect successive operations upon the beam. Such a system is disclosed and claimed in United States Letters Patent No. 2,222,902 granted November 26, 1940 upon my application, and which is assigned to the assignee of the present application.

Considering now more particularly the phenomenon by virtue of which energy may be extracted from an electron beam through or by means of an associated electrode or gap, it may be generally stated that for an infinitesimal gap the dimensionless ratio B_1 of induced velocity modulation in volts along the electron beam axis to the gap radio frequency peak potential in volts, may be expressed as follows:

$$B_1 = \frac{v_z}{v_0} \frac{V_0}{V_g} \quad (1)$$

where

v_z is the electron velocity at the gap

v_0 is the average electron beam velocity

V_0 is the potential corresponding to the velocity v_0 , and

V_g is the radio frequency gap potential.

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If a gap is considered as having a length z_g centimeters long, it may be assumed that an effective gradient

$$\frac{dV}{dZ} = E_0 e^{i\omega t}$$

volts per centimeter appears therealong. The wave produced at z_g (origin at incoming side of gap) by an infinitesimal gap displaced from the origin by a distance Z is:

$$B_1 E_0 (dZ) e^{-i\omega \frac{z_g - Z}{v_0}} \quad (2)$$

and the total amplitude of wave produced at z_g by the entire gap is then:

$$\int_0^{z_g} B_1 E_0 e^{-i\omega \frac{z_g - Z}{v_0}} dZ = B_1 E_0 \frac{v_0}{\omega} \left\{ \sin \left(\frac{\omega z_g}{v_0} \right) + i \left[\cos \left(\frac{\omega z_g}{v_0} \right) - 1 \right] \right\} \quad (3)$$

E_0 represents the maximum value of the time-varying voltage gradient observed at the spacial region under consideration. Where the quantity

$$\frac{\omega z_g}{v_0}$$

is simply the transit angle in the distance z_g at beam velocity, it may be termed θ_g . Accordingly, expression (3) reduces to:

$$B_1 v_g \frac{\sin \theta_g + i(\cos \theta_g - 1)}{\theta_g} \quad (4)$$

It will be noted that this gives a multiplying factor for the effect of the gap length which is independent of B_1 and this multiplying factor may be denoted by the quantity L which takes into consideration the geometry of the particular gap employed.

Where the gap is formed by a space resonant structure associated with an electron beam, the factor L may be determined to represent accurately the voltage distribution across the gap commensurate with a desired resonant condition of the structure. For example, the quantity L may be expressed as follows:

$$L = \frac{\sin \left(\frac{a\theta_b}{4\pi} 360 \right)}{\left(\frac{a\theta_b}{4\pi} \right) 2\pi} \left[1 - \sum_{n=1}^{\infty} \frac{(-1)^n \frac{A_n}{A_0}}{4 \left(\frac{a\theta_b}{4\pi} \right)^2 - 1} \right] \quad (5)$$

in which

a =per unit gap width referred to distance between center-lines of adjacent gaps.

θ_b =transit time at beam velocity in radians between center lines of adjacent gaps.

A_n and A_0 are coefficients of a Fourier series.

The coefficients A_n and A_0 may be determined in accordance with the procedure set forth in my paper entitled "A new method for the calculation of cavity resonators" appearing in the January 1941 issue of Journal of Applied Physics on pages 62-68.

To facilitate the subsequent discussion, the dimensionless ratio B'_1 representing the induced velocity modulation effect or coefficient for a gap of finite length may then be defined as follows:

$$B'_1 = LB_1 \quad (6)$$

In accordance with my present invention, I have found that substantial improvements may be obtained in the efficiency of velocity modulation systems by the proper correlation of the induced velocity modulation effect and the electron

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beam average velocity. It is to be understood that after an electron beam has been velocity modulated, the electrons tend to group themselves at predetermined places in the beam and that in order to derive energy from the beam the net or aggregate effect of any energy extraction means must be such as to produce a net deceleration of the electrons constituting the beam. While some of the electrons of the beam may undergo an acceleration, that is, derive energy from the field within the region of the energy extraction means or gap, the net effect within the region of the gap must be that of deceleration; that is, a majority of the electrons must undergo a deceleration by moving in opposition to an electric component of an associated field.

Referring now to Fig. 1 of the accompanying drawing, there is shown a curve comprising a series of sinusoidal loops representing the relationship between the quantity B'_1 and the electron velocity. Although the lobes of the characteristics shown in Fig. 1 are shown as lying above the horizontal axis, it is to be appreciated that there is a phase shift between adjacent points on the curve so that successive or adjacent regions generate induced velocity modulation effects of opposite sign. If, as heretofore, the velocity modulation system is operated within the region of one of these loops, such as point x , an accelerated electron causes an increased B'_1 , and decelerated electron causes a decreased B'_1 . Therefore, the overall tendency is to keep the average electron velocity at a relatively high value.

In accordance with my invention, the system is arranged so that the average velocity of the electron beam is within a region of a B'_1 loop such as at point y , wherein the B'_1 -electron velocity curve has a negative slope; that is, the system is operated with respect to the electron beam velocity at a point where the ratio of velocity modulation of the electrons to the gap voltage decreases with increasing electron velocity. In accordance with this feature, the whole or resultant tendency is to decelerate and slow down the electron beam, the action confining the velocity spread of the electrons preferably between the first and second null points of the B'_1 curve. In this manner, the amount of power which may be derived from the electron beam is increased, resulting in an increased efficiency.

One way in which the above described improvement in efficiency may be obtained is by designing a velocity modulation system to have a relatively large ratio of gap length to electrode or grid length. Referring to Equations 5 and 6 above, particularly the former, it will be observed that B'_1 approaches zero near

$$\frac{a\theta_b}{4\pi} 360 = 180$$

or

$$\frac{a\theta_b}{2\pi} = 1$$

Since from the definition of θ_b in column 3, lines 47 and 50, $\theta_g = a\theta_b$ it is seen that θ_g approaches zero at 2π and at values of θ_g in excess of 2π energy may be derived from the beam on that part of the characteristic shown in Fig. 1 where B'_1 increases with decreasing electron velocity. Of course, θ_g may be made to exceed 2π by an integral number of half-cycles of potential variation at operating frequency of the apparatus provided proper consideration is given to the phase relationships.

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By reference to column 3, line 25, it is noted that

$$\frac{\omega z_g}{v_o}$$

is equal to θ_g . If θ_g is to exceed 2π as set out above, then z_g must exceed

$$\frac{v_o}{f}$$

or in other words, the gap length must exceed the average beam velocity divided by the operating frequency.

By utilizing the above described principles correlating the gap length to the electron beam velocity, it will be appreciated that I provide an arrangement where there is obtained a selective controlling effect on the electrons of the beam with respect to the accelerating and decelerating phenomena, so that any electrons within the gap region which are accelerated, necessarily by virtue of the B'1 characteristic reduce the power output by progressively smaller amount. Accordingly, the effect of the higher speed electrons or the accelerated electrons is reduced by choosing the gap length to produce an operating point on the B'1-velocity curve which minimizes the energy supplied to the beam and maximizes the energy extracted therefrom at the gap. In calculations and studies made by prior investigators in this field, the operation of the velocity modulation systems has been based on the condition that the induced velocity modulation effect remains constant. For example, in order to obtain a relatively large value of the induced velocity modulation effect, the prior art systems were operated on one of the loops of the induced velocity modulation-electron velocity characteristic where the induced velocity modulation effect was maintained at a relatively large substantially constant value, such as at points at or beyond point x shown in Fig. 1. While in the utilization of my invention wherein a negative slope region of the characteristic is employed the velocity modulation effect is of a lower numerical value than with operation upon a loop or lobe of greater maximum amplitude, the net or resultant power derived by utilization of the selective influence of the induced velocity modulation effect more than compensates for the decrease in the numerical or absolute maximum value of B'1.

The above outlined features and principles of operation are applicable to velocity modulation systems generally, whether of the type employing associated space resonant structures or of the type employing electrodes, resonant or otherwise, for the extraction of energy from a velocity modulated electron beam.

In those instances where it is desired to employ a plurality of structures successively traversed by the velocity modulated electron beam for extracting energy from the beam, it is important to take into consideration the relationship of the distance between electrodes or gaps of adjacent structures in order to obtain successive accumulative effects due to the passage of the electron beam through the various contiguous structures. As an example, consider a space resonant system of the nature shown in Fig. 2 which will be discussed more particularly hereinafter. In such a system, which may be of the self-excited type, it is important in order to obtain the accumulative effect due to the passage of the beam successively through the various space resonant cavities or regions that a proper correlation be obtained between center

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lines of adjacent gaps. As set forth in my above mentioned Patent No. 2,222,902, the distances between the gaps which cooperate with the electron beam must be correlated to the dimensional and electrical characteristics of the various parts employed. This aspect of a multi-electrode or multi-gap velocity modulation system is of particular importance where it is desired to obtain a certain degree of mechanical symmetry among the various individual structures or elements.

Upon determination of the optimum distance between center lines of an adjacent pair of gaps, the distances between center lines of the other gaps of the system may be determined by the electron beam velocity at the particular gap and by the physical and electrical dimensions of the other associated gap structures. In following such a procedure, it may be necessary in the proportioning or designing of one of the gaps, as for example the first gap which is traversed by the electron beam, to foreshorten it, thereby causing a reversal in the sign of the B'1 quantity while still obtaining the desired cumulative velocity modulation effect.

Referring now to Fig. 2 of the accompanying drawing, I have there illustrated one embodiment of my invention as applied to a velocity modulation oscillator which is of the space resonant type comprising a plurality of adjoining space resonant regions or cavities 1, 2 and 3. These cavities may be formed by a plurality of adjoining conductive members and are respectively dimensioned to be resonant to the operating frequency of the system. For example, cavity 1 may be defined by a pair of annular metallic members 4 and 5 in abutment, the former of which is provided with a tubular electron beam entrant-part 6 which constitutes an electrode or grid. The annular part 5 may include a similar tubular member 7 which, in turn, constitutes an electrode or grid element cooperatively associated with both cavities 1 and 2. The intermediate boundary between cavities 2 and 3 may be formed by an annular metallic part 8 having a transverse wall part 9 which is provided with a longitudinally extending tubular member 10 through which the electron beam passes. The right-hand end of cavity 3 may be defined by a metallic end member 11 comprising a longitudinally extending tubular member 12 through which the electron beam passes to be collected by an anode 13.

The above described structure, particularly members or parts 6, 7, 10 and 12, defines gaps g_1 , g_2 and g_3 . The first gap g_1 traversed by the electron beam serves to velocity modulate the electrons, the cavity 1 being energized by the coupling existing between it and cavity 2. Cavities 2 and 3 are maintained in electrical oscillation by virtue of the energy supplied thereto by the electron beam upon traversing gaps g_2 and g_3 . When the cavities 2 and 3 are resonant, the fields thereof may be resolved into standing potential and current waves which vary cyclically. The extraction of energy from the electron beam after assuming the spatial charge density distribution may be viewed from an elementary viewpoint as comprising the movement of grouped electrons in opposition to the electric components of the fields appearing along the gaps.

The entire above described space resonant system may be supported in the position illustrated by means of a flared metallic cylinder 14 provided with an aperture through which there extends a concentric transmission line 15 includ-

ing an outer tubular conductor 16 and an inner conductor 17 which extends into one of the cavities, such as cavity 3, to form a loop 17' which may be employed to extract ultra high frequency energy from the system. The entire system may be maintained at a predetermined low pressure and is provided with appropriate sealing structure for maintaining the desired degree of vacuum. Cylinder 14 may be provided at its right-hand extremity with a reentrant vitreous seal and insulator 18 which supports an anode connecting rod 19. In like manner, the left-hand end of cylinder 14 may be provided with a reentrant vitreous insulator and seal 20 which supports a suitable thermionic cathode 21 and focusing electrodes 22 and 23.

Although not required in carrying out my invention, the electron beam transmitted between the cathode and the anode may be electromagnetically focused by means of a coil 24 surrounding the space resonant system and which is energized to produce a longitudinal magnetic field.

Suitable potentials for energizing the anode-cathode circuit and for impressing a biasing potential upon electrodes 22 and 23 may be obtained from a source of potential such as a battery 25, the potential on electrode 23 being adjusted to obtain the desired narrowing or focusing effect on the electron beam. It will be noted that the distance s_1 between center lines of the first and second gaps is shown as being less than the distance s_2 between the second and third gaps. This design was based on keeping the velocity modulation of the first gap as small as possible so as to facilitate the starting of the oscillation. The distance s_1 is chosen relative to assumed velocity modulation of the first gap to produce maximum charge density modulation in the region of the second gap.

In the incorporation of the above outlined principles of operation in a velocity modulation system built in accordance with my invention, the distance s_2 , as one example, may be considered as being equal to 540 electrical degrees referred to the operating frequency of the oscillator corresponding to a wave length of 9.75 cm. Upon establishment of the physical dimensions of the cavities 2 and 3, the distance s_1 would then be approximately 450 electrical degrees referred to the same operating wave length. Proceeding a step further, the first gap g_1 may then be chosen to impart the desired velocity modulation to the beam as it traverses this gap, the energy for the excitation of cavity 1 being derived from cavity 2 or cavities 2 and 3 by virtue of the coupling therebetween.

The choice of the physical dimensions of the space resonant structures is in a measure determined by the voltage requirements of the apparatus and the electrical lengths of the gaps and the distance between center lines of the gaps is, of course, determined with these considerations in mind. Upon determination of one gap length, such as the length of gap g_3 , to meet the above stated requirement relative to the quantity ϕ_b for the gap, in the design of the remaining resonant cavities defining the other gaps it is necessary, in order to obtain the accumulative velocity modulation effect whereby energy is extracted from the beam, to choose dimensions for the distances between center lines of gaps and, hence, the gaps lengths so that the signs of the respective quantities B_1 are proper.

Furthermore, when the system is of the self-excited type, the axial dimensions of the struc-

ture must be such that the voltage fed back from cavity 2 to cavity 1 is of the proper phase to maintain oscillation of the system.

It is to be appreciated that the above specifically recited electrical lengths of the various gaps are given merely by way of illustration, and it will be further appreciated that the principle of employing a large ratio of gap length to structure or electrode length may be incorporated in numerous other velocity modulation systems, whether of the space resonant type or otherwise.

As stated above, the operation of a velocity modulation system upon a negative slope region of the induced velocity modulation characteristic may be effectively obtained by the utilization of large ratios of gap length to electrode or grid length. This feature is incorporated in the system shown in Fig. 2 where the ratio of gap g_1 to the length of member 7 is 1.41/1.34, and where the ratio of gap g_2 to the axial dimension of member 10 is 2.98/1.26. The length of gap g_3 is correspondingly large with respect to the electrode or grid axial length. It is to be appreciated that the above stated ratios are not critical, and that the feature of obtaining an improved and greater efficiency by operating on the negative slope portion of the induced velocity modulation characteristic may be obtained by using a wide variety of dimensions and ratios, the values of which are determined by several factors, including the electron beam velocity, the physical and electrical dimensions of the structure and the operating frequency of the system.

Although in the arrangement shown in Fig. 2 the electrode or grid structures comprise tubular members extending into the various adjacent cavities, the electrode structure need not be so accentuated. As a matter of fact, the electrode structure, depending upon the nature of the physical and electrical requirements, may be no more than the periphery of an aperture located in transverse partitions corresponding to members 5, 9 and 11.

In the above described embodiment of my invention, the electron discharge device has been illustrated as comprising one in which the beam moves longitudinally. It is to be appreciated that my invention may also be applied to discharge devices or systems in which the beam moves transversely or radially in a sheet-like configuration and in which the gaps are positioned radially therealong, the high frequency voltages being effective radially.

While my invention has been illustrated as applied to an oscillator of the space resonant type and employing various elements, it will be appreciated that my invention has been applied to velocity modulation systems generally, and I, therefore, aim in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent to the United States is:

1. A velocity modulation system for operation at a predetermined frequency comprising a conductive structure providing a cavity resonator resonant at said predetermined frequency and including aligned openings defining a gap, a cathode positioned on one side of said resonator, electrode means in alignment with the openings in said resonator and cooperating with said cathode to direct a beam of electrons through said openings, said gap having a length greater than the average velocity of electrons traversing the gap divided by said frequency.

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2. A velocity modulation system for operation at a predetermined frequency comprising a conductive structure providing a cavity resonator resonant at said predetermined frequency and including aligned openings defining a gap, a cathode positioned on one side of said resonator, electrode means in alignment with the openings in said resonator and cooperating with said cathode to direct a beam of electrons through said openings, the length of said gap being greater than the gap length corresponding to a transit angle of 2π radians at said frequency.

3. A velocity modulation system for operation at a predetermined frequency comprising a conductive structure providing a cavity resonator resonant at said predetermined frequency and including aligned openings defining a gap, a cathode positioned on one side of said resonator, electrode means in alignment with the openings in said resonator, means impressing a unidirectional component of voltage on said cathode and

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electrode means to direct a beam of electrons through said openings at a predetermined average velocity, the length of said gap being greater than the gap length corresponding to a transit angle of 2π radians at said frequency.

WILLIAM C. HAHN.

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