

Oct. 1, 1946.

J. W. McRAE

2,408,437

HARMONIC GENERATING SYSTEM

Filed Oct. 11, 1941

2 Sheets-Sheet 1

FIG. 1

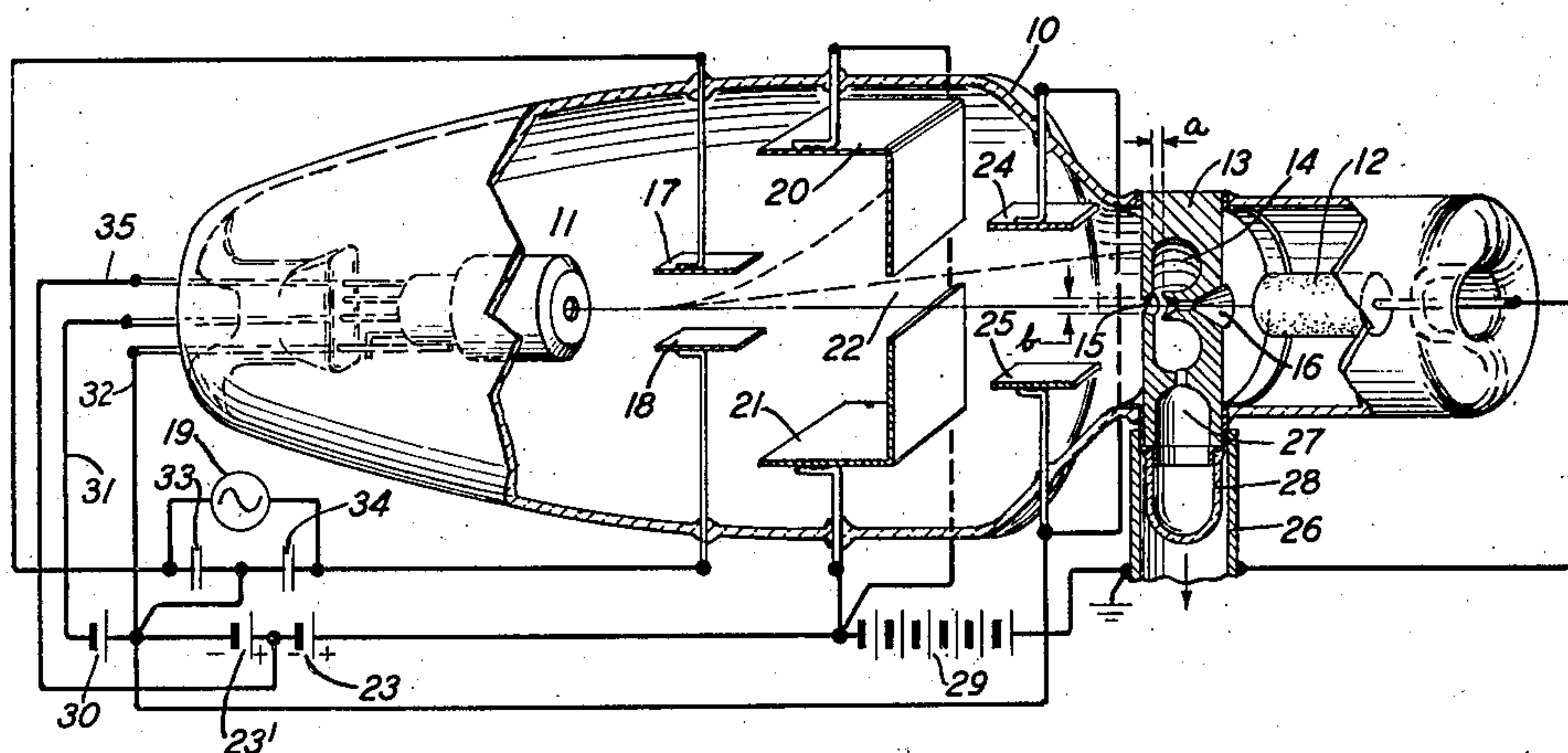


FIG. 2

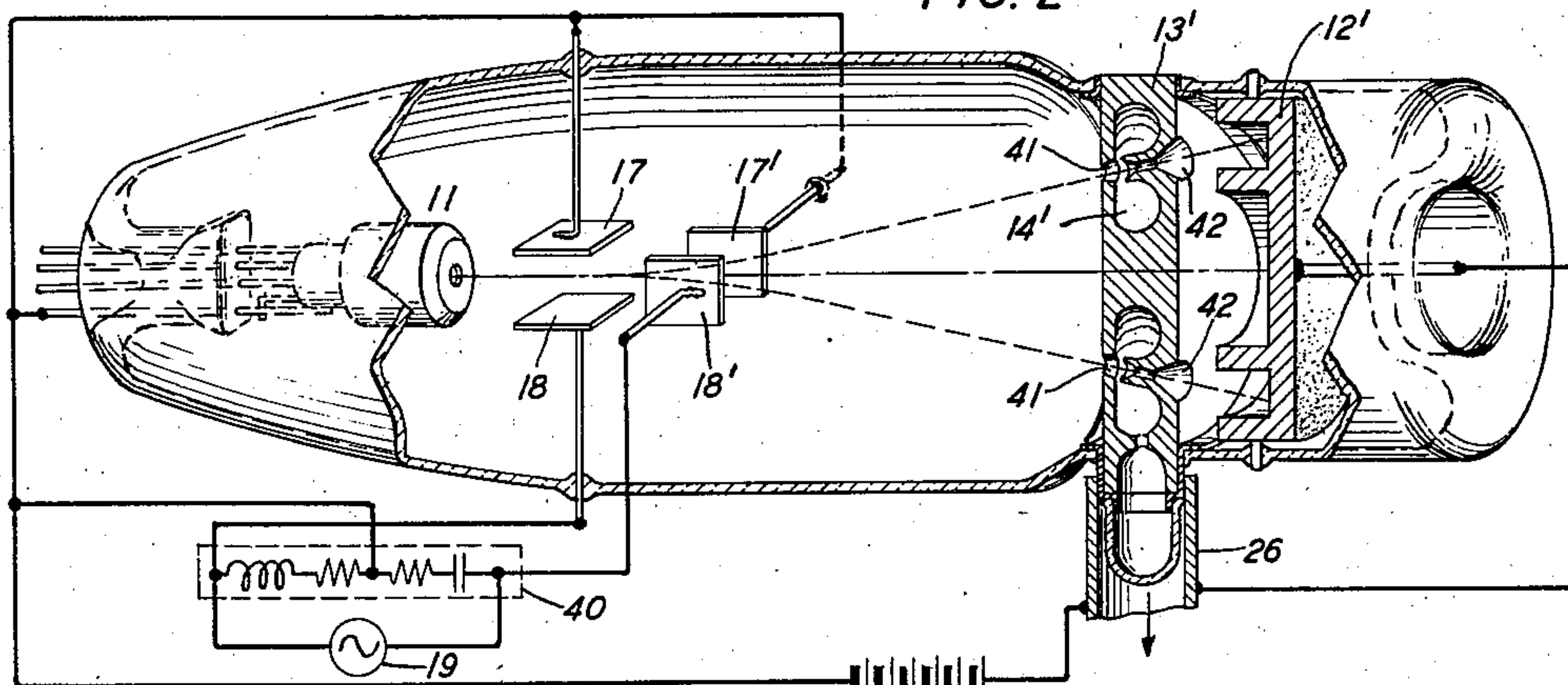


FIG. 2A

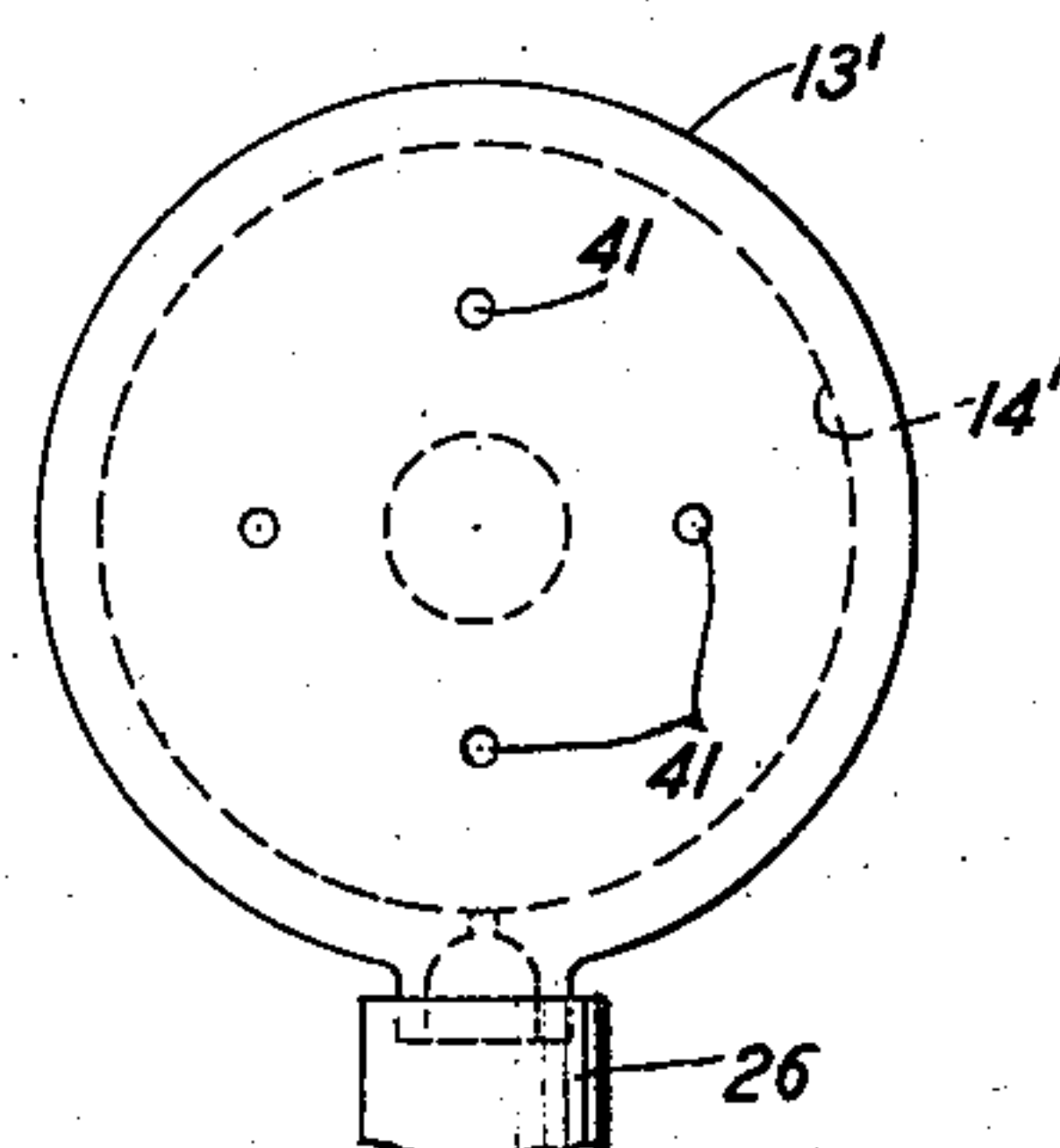
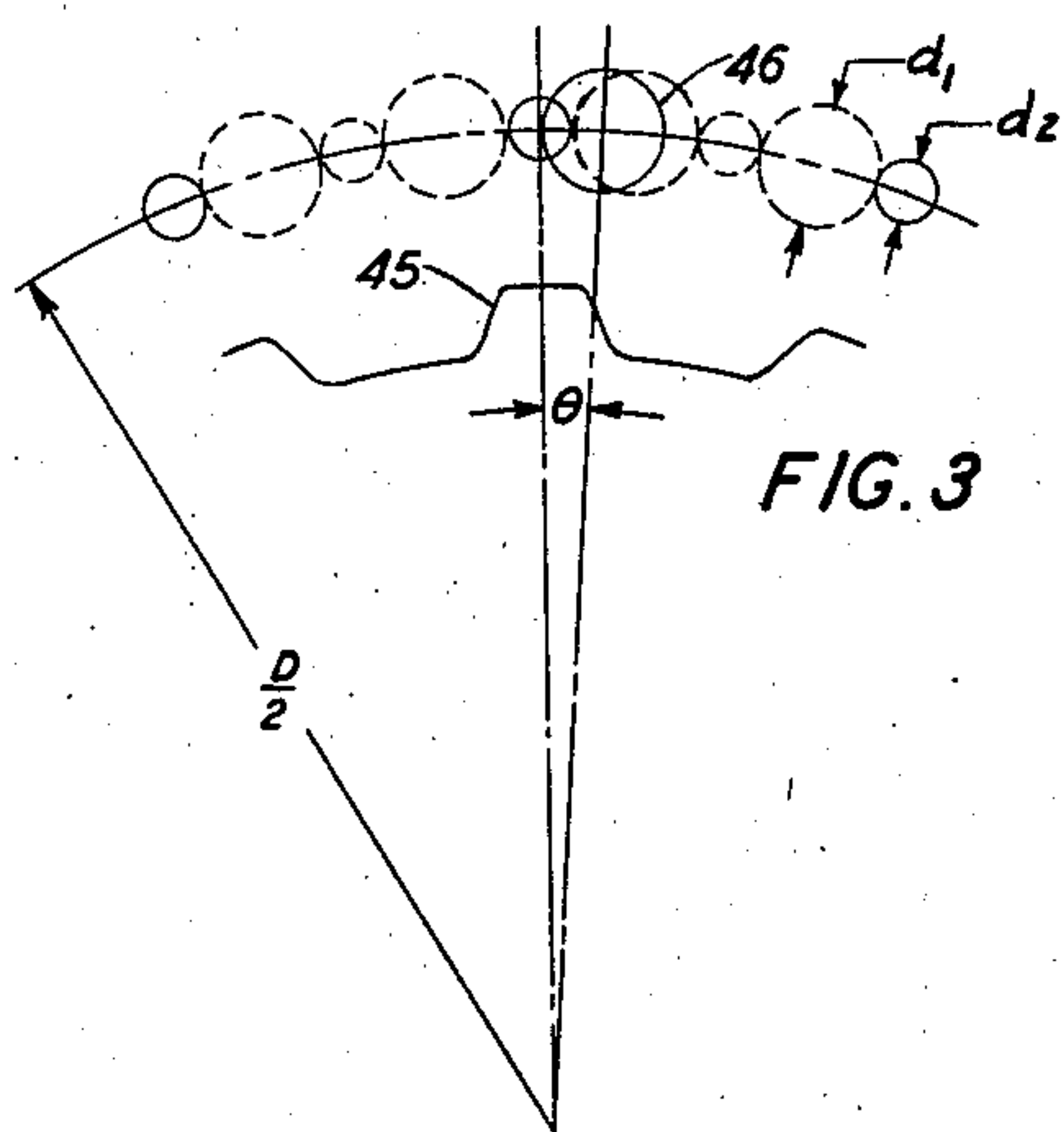


FIG. 3



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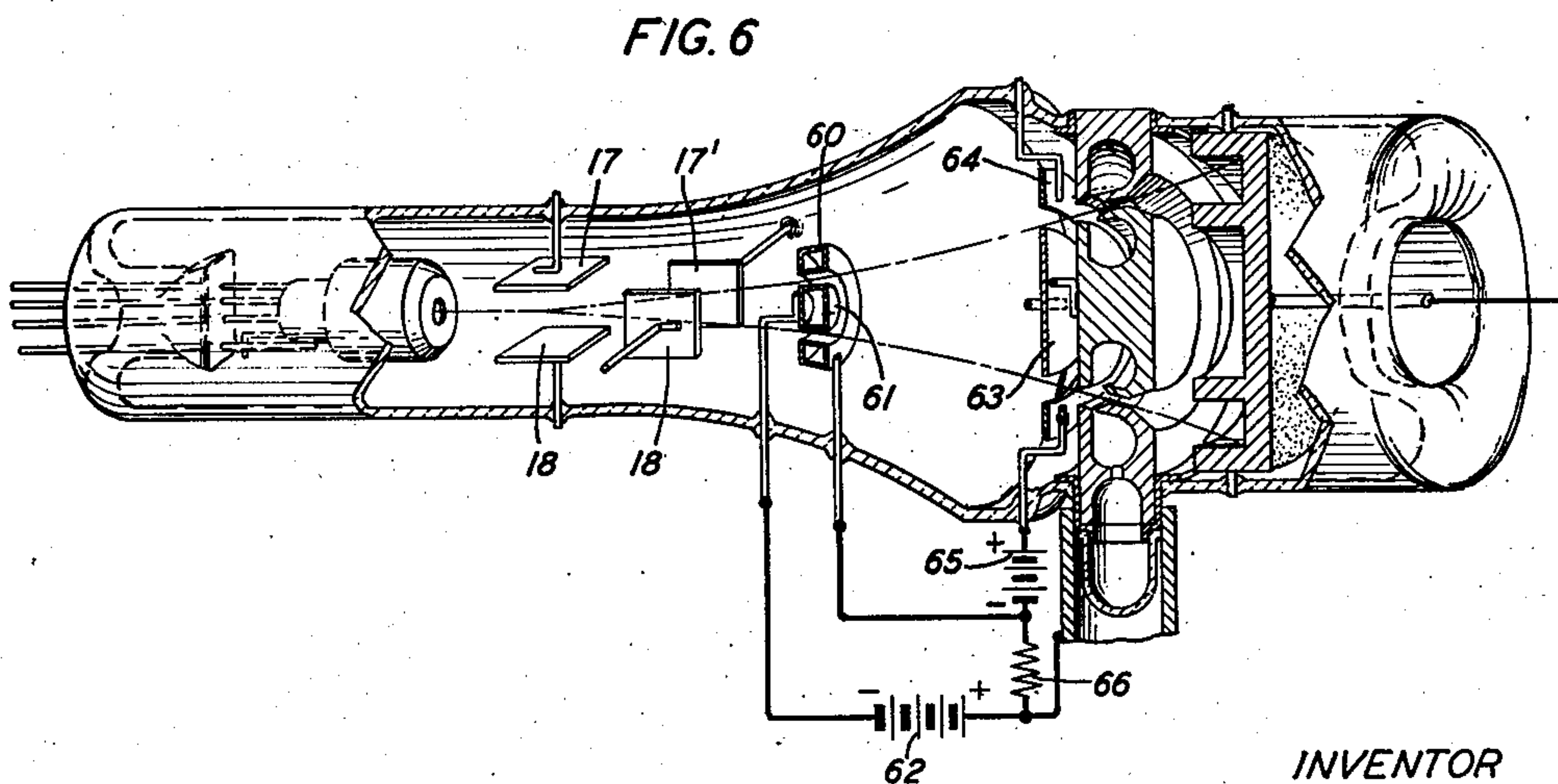
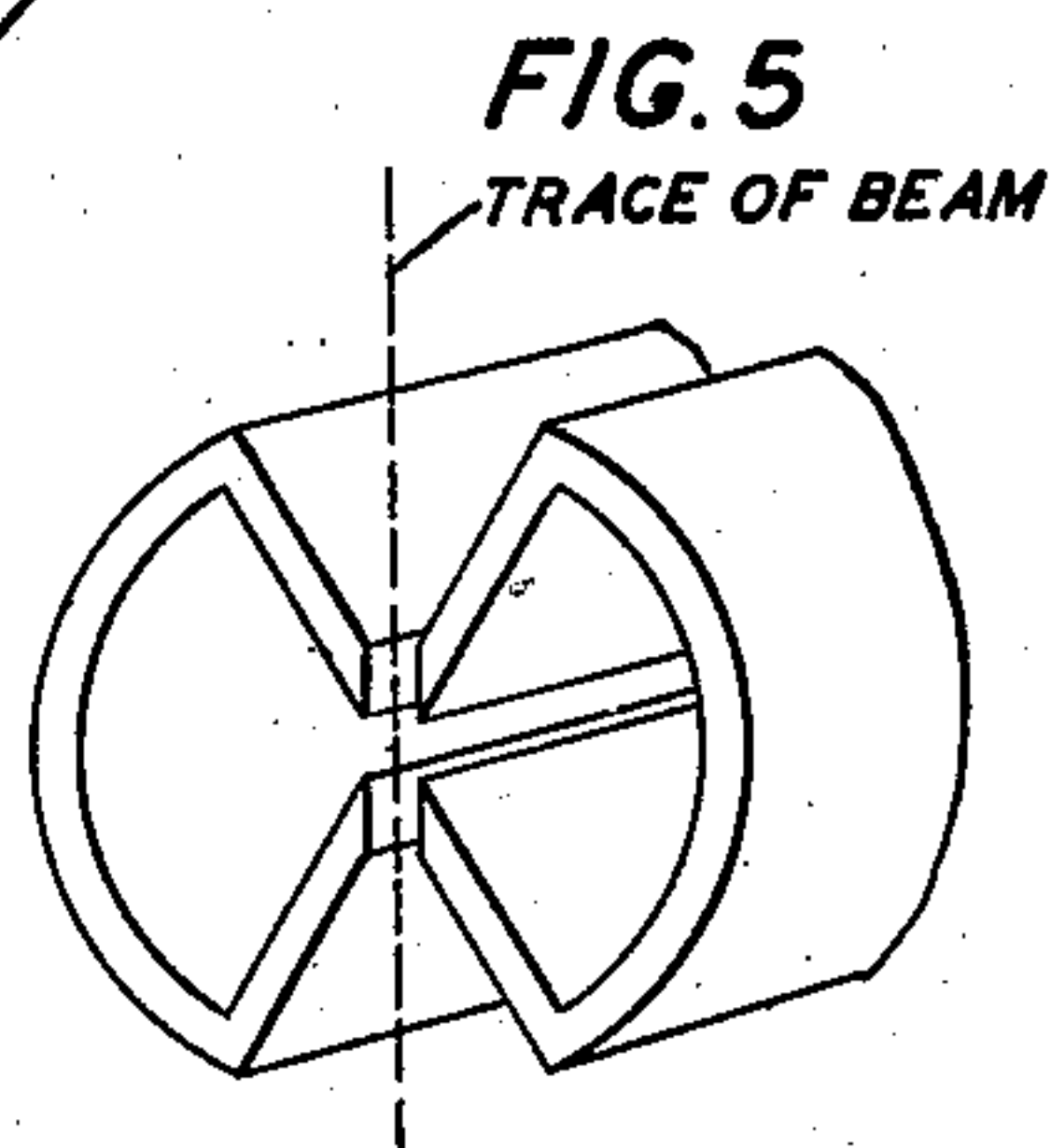
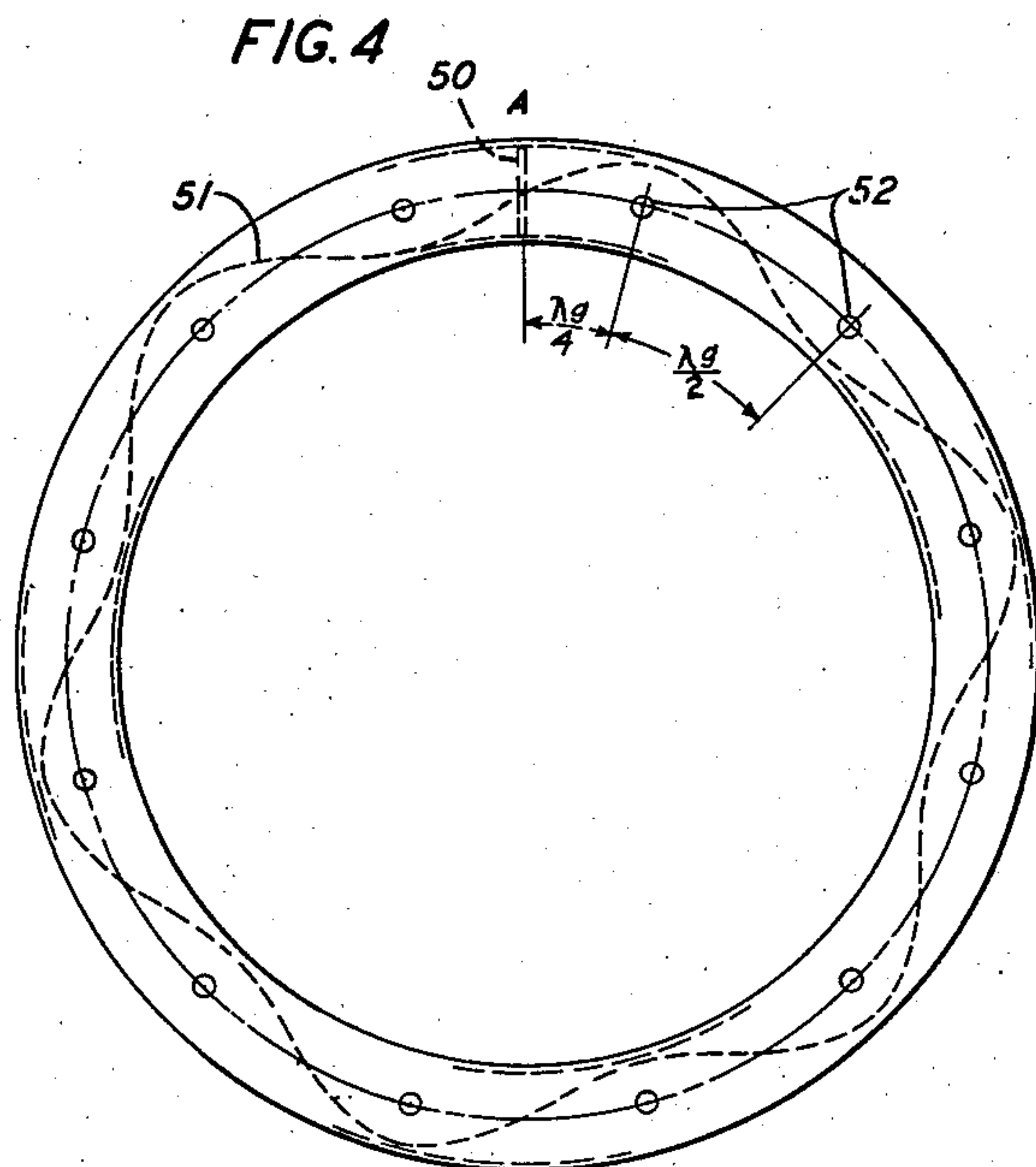
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2 Sheets-Sheet 2



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2,408,437

HARMONIC GENERATING SYSTEM

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Application October 11, 1941, Serial No. 414,695

8 Claims. (Cl. 315-5)

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This invention relates to harmonic generating or frequency multiplying systems and more particularly to those employing streams of charged particles, e. g., electrons, together with hollow resonators or wave guides especially at ultra-high frequencies.

An object of the invention is to provide increased outputs of ultra-high frequency power, at frequencies above the practical operating limits of oscillators and amplifiers already available in the art.

A related object is the efficient transfer of power from a beam of electrically charged particles, e. g., electrons, to an ultra-high frequency wave or current in a transmission line, wave guide or the like.

Another object is to effectively excite electromagnetic oscillations within a resonating chamber of very small dimensions, such as may be designed to resonate at a wave-length of a few centimeters or less, by means of an electron beam or cathode ray deflected or rotated periodically at a frequency relatively low compared with the resonant frequency of the chamber.

In addition to other uses the invention may be employed to multiply the frequency of an electromagnetic wave after it has been subjected to frequency modulation or frequency stabilization or other process at a relatively low frequency where the necessary techniques of the latter operations are more readily available than at the desired final frequency.

The invention is more fully described herein-after with reference to the accompanying drawings illustrating a number of embodiments, while the scope of the invention is defined in the appended claims.

In the drawings:

Fig. 1 shows an arrangement in which an electron beam swinging in a plane passes through a resonating chamber during a small portion of each cycle of the oscillation;

Fig. 2 shows an arrangement in which an electron beam is swung around continuously to describe a conical surface and a reaction between the beam and an associated resonator occurs several times during each revolution of the beam;

Fig. 2A is an elevational view of the resonator in the system of Fig. 2;

Fig. 3 is a diagram useful in developing design formulae for the system disclosed in Fig. 2;

Fig. 4 is an elevational and somewhat diagrammatical view of a resonator in the form of a wave guide, suitable to be employed with a system embodying the invention;

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Fig. 5 is an enlarged cross sectional fragmental view of a wave guide such as that shown in Fig. 4; and

Fig. 6 shows an embodiment that is in some respects a modification of the system illustrated in Fig. 2.

Referring to Fig. 1, there is shown a vacuum tube with an insulating air-tight envelope 10 containing an electron gun, indicated generally at 11, and an electron intercepting electrode or collector 12. A block 13 of conductive material such as copper is shown fused into the envelope 10. The block 13 is hollowed out to form an internal resonating chamber 14 with smooth, highly conductive inner walls, the space within the chamber communicating with the interior of the envelope 10 through an entrance aperture 15 and an exit aperture 16. The axis of the electron gun 11 of the collector 12 and of the apertures 15 and 16 are arranged colinearly so that an electron beam emitted by the gun may be passed through the chamber 14 by way of the apertures 15 and 16 to the collector 12. A pair of deflecting plates 17 and 18, supported in any suitable manner as by rods extending through the envelope 10, are mounted on either side of the common axis and connected respectively to the two terminals of a source 19 of high frequency waves. A pair of shielding plates 20 and 21 with their edges separated to form a slot 22 are mounted on either side of the axis and both are conductively coupled to a relatively low voltage source 23 of substantially constant positive biasing potential. A pair of beam focusing plates 24 and 25 are mounted one on either side of the axis at a position along the course of the beam beyond the shielding plates 20 and 21. The plates 24 and 25 are conductively coupled to the negative terminal of a source 23'. The block 13 is conductively connected with a hollow conductive pipe or wave guide 26, the interior of which communicates with the chamber 14 through a passageway 27 hollowed out of the block. A suitable air-tight or vacuum seal is provided by a small bulb 28 or bead of insulating material fused to the block 13. A source 29 of relatively high positive biasing potential is connected between the plates 20, 21 and the conductive mass comprising the block 13 and the wave guide 26, the positive terminal of the source 29 being connected to the latter system, and grounded if desired. The collector 12 may also be connected to the system comprising the block 13 and guide 26. The heating element within the electron gun 11 may be energized in any suitable manner, as for example, by a

source 30 of electromotive force connected by leads 31 and 32 to the appropriate terminals of the gun. By-pass condensers 33 and 34 may be shunted across the source 19 and the common terminal of the condensers may be connected to the lead 32 to fix the average potential of the plates 17 and 18. An electron beam controlling electrode within the gun 11 may be connected by means of a lead 35 to the positive terminal of the source 23' to determine the current strength of the electron beam.

In the operation of the system of Fig. 1, the electron beam is swung up and down in a vertical plane by the action of a high frequency wave impressed upon the plates 17 and 18 from the source 19. Twice during each cycle of the oscillations the beam lies in the axis and a pulse or group of electrons is projected through the resonating chamber 14 by way of the apertures 15 and 16. The electron pulses or groups, if properly timed, serve to sustain electromagnetic oscillations within the chamber 14. Evidently the timing will be correct if the pulses are made to arrive at intervals of an integral number of cycles of the oscillations in the chamber 14. For example, the frequency of the source 19 may be 500 megacycles per second and the beam may be made to sustain oscillations in a suitably adjusted resonating chamber at a frequency of 10,000 megacycles per second, in which case one electron pulse traverses the chamber for every 10 complete oscillations of the field within the chamber.

The physical dimensions of a resonating chamber or cavity designed to oscillate in the fundamental mode at 10,000 megacycles per second or more, corresponding to 3 centimeters or less in wave-length, are necessarily very small. Furthermore, the length of the gap, designated by a as shown in Fig. 1, traversed by the electrons, must be very minute. This is because the electron transit time in the gap should be short and preferably not more than a half cycle at the resonant frequency of the chamber, or in other words a transit angle of not over 180 degrees. If it is desired, for example, that the electrons traverse the gap in a transit angle of only 75 degrees, and if the speed of the electrons corresponds to 2400 electron volts, then for a 3 centimeter wave-length resonator, the dimension a of the gap should not exceed about 0.025 inch. The hole through which the beam passes, the diameter of which is designated b in Fig. 1, should also be small in proportion to the principal dimensions of the cavity 14. In the case of a 3 centimeter wave-length resonator b should not much exceed 0.05 inch. If then, a beam of 0.05 inch diameter is focused to pass through the cavity with zero deflection voltage on the plates 17 and 18, the application of a sinusoidal deflecting voltage to the plates will result in a short pulse of current entering the cavity at every instant of zero deflecting voltage. The duration of this pulse should evidently be less than half a cycle of the resonant frequency of the chamber in order that the field in the resonator may not return energy to the electrons during part of the cycle. In the example, under consideration, the time of a half cycle is $\frac{1}{20,000}$ microsecond. In order for the beam to cross the aperture within the period of a half cycle, the linear velocity, v , of the beam in the vertical direction must be given by

$$v = 2 \times 0.05 \times 20,000 \times 10^6 = 2 \times 10^9 \quad (1)$$

inches per second. This value of v is equal to

about 0.5×10^{10} centimeters per second or approximately one-sixth of the velocity of light.

At first sight such a velocity seems much too high for practical realization. However, it must be remembered that there is no physical mass moving with this high velocity. The velocity v is merely an apparent velocity resulting from the slightly different angles made with the axis of the tube by successive electrons. This is the velocity with which the beam appears to sweep across the aperture 15 and will be referred to hereinafter as the "writing velocity" of the beam, from the tracing or writing motion executed by the beam.

The required value of the velocity v together with the frequency of the deflecting source 19 serves to determine the maximum amplitude of deflection which must be imparted to the beam. For the purpose of making this calculation, the deflection of the beam in the vertical direction at the position of the aperture 15 may be represented by

$$y = A \sin \omega t \quad (2)$$

where A is the maximum amplitude to be calculated and ω is 2π times the deflecting frequency. The instantaneous velocity of the beam is determined by

$$\frac{dy}{dt} = A\omega \cos \omega t \quad (3)$$

from which it appears that the maximum writing velocity is $A\omega$. In the numerical example under consideration

$$A = \frac{2 \times 10^9}{2\pi \times 500 \times 10^6} = 0.64 \text{ inch} \quad (4)$$

It is also simple to calculate the approximate voltage required upon the plates 17 and 18 to effect an amplitude of deflection of 0.64 inch. If, for example, the distance along the axis of the tube from the deflecting plates 17, 18 to the aperture 15 is taken as $6A$, or 3.82 inches, the lateral velocity which must be imparted to the electrons at maximum deflection is one-sixth that of the longitudinal velocity. In the assumed case of a 2400 volt beam, the deflection may be effected by $\frac{1}{36}$ of 2400 volts or approximately 67 volts. If desired, the amount of deflecting voltage required may be reduced by increasing the length of the tube, and conversely, a shorter tube will require a greater deflecting voltage.

If the high energy beam were allowed to strike the block 13 during all the time except when it was passing through the aperture 15, only a small fraction of the total energy of the beam would be imparted to the cavity. An improvement in the efficiency of the device is secured by the use of the shielding plates 20, 21 and the focusing plates 24 and 25. The plates 20 and 21 being at a relatively low potential with respect to the cathode and serving to shield the beam from the high potential of the source 29 impressed upon the block 13, the electron beam is in effect a low voltage beam except during a small interval when the beam is passing through the slot 22 between the plates 20 and 21. Thus during most of the time that the beam is not passing through the aperture 15, it is composed of low voltage electrons which strike one or the other of the shielding plates 20 and 21 at low velocity and with correspondingly low dissipation of energy. During the small fraction of the time when the beam passes through the slot 22, the electrons are accelerated longitudinally by the high voltage upon

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the block 13. The plates 24 and 25 serve to focus the beam during the interval when it is passing through the slot 22. The spent electrons which emerge from the aperture 16 are collected by the collector 12. The ultra-high frequency wave maintained within the chamber 14 gives rise to a traveling wave in the wave guide 26 by way of the coupling afforded by the passage 27 and may be led away to any desired point for utilization.

In the arrangement of Fig. 2, two pairs of deflecting plates at right angles to each other are provided at 17, 18 and 17', 18' respectively. The source 19 is connected to the deflecting plates through a phase shifting network 40 of any known suitable design which provides two substantially equal voltages in time quadrature. Plates 17 and 17' are connected together and also connected to the cathode and to the center terminal of the network 40. The plates 18 and 18' are connected respectively to the remaining terminals of the network 40. The block 13 is replaced by a somewhat similar conductive block 13' having a hollow cavity 14' of annular form with a cross sectional shape substantially the same as that of the cavity 14 in Fig. 1. The cavity 14' is a figure of revolution about the central axis, which lies outside the cavity. A series of equally spaced entrance apertures 41 and corresponding exit apertures 42 are provided, the arrangement of the apertures 41 being shown more clearly in Fig. 2A. A collector electrode 12' is provided beyond the exit apertures 42.

In the operation of the arrangement of Fig. 2, the electron beam is given a rotating motion by means of the crossed electric fields maintained between the pairs of deflecting plates. The electron beam generates a conical surface, sweeping out a circular trace on the surface of the block 13'. The radius of this circle is adjusted so that the trace passes approximately through the centers of the entrance apertures 41. In the course of rotation the beam sends successive electron pulses through the chamber 14' by way of the apertures 41 in rotation. Provided the resonant frequency of the chamber 14' is equal to an integer times the frequency of the source 19 times the number of apertures, a high frequency electromagnetic wave may be maintained inside the cavity 14' and ultra-high frequency power delivered to the associated wave guide 26. Each exit aperture 42 is aligned with an entrance aperture 41 and an element of the conical surface generated by the beam.

The minimum diameter of the circle upon which the apertures 41 lie, may be determined by calculation in a given case. Referring to Fig. 3, let the diameter of the electron beam d_1 and the diameter of each of the holes in the cavity be d_2 . Then, if the ratio of the input frequency to the output frequency is to be n , and a pulse is to be delivered to the resonator for each cycle of the harmonic wave, there must be n holes equally spaced around the circumference of a circle of diameter D , where

$$D = 2n \frac{d_1 + d_2}{\pi} \quad (5)$$

For the case of $d_1 = d_2 = 0.05$ inch, and $n = 20$, the diameter $D = 1.24$ inches. It is evident from (5) that a larger beam diameter would require an increased value of D and would result in reduced output for the same hole diameter because of the larger fraction of electrons striking the outer surface of the resonator without en-

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tering it. It would be desirable to have the beam diameter much less than that of the holes, but the use of a smaller beam diameter requires a higher beam current density in order to deliver the same amount of power by way of the beam. The curve 45 in Fig. 3 indicates the fluctuations of the current entering the cavity as a function of the angular position of the beam as represented by the angle θ . The instantaneous position of the beam indicated by a solid circle 46 corresponds to the value of θ shown between the dot-dash radial lines.

The embodiments of the invention hereinabove described may generally be so designed as not to require the use of maximum writing velocities equal to or greater than the velocity of light. However, as the writing velocity of the beam is not the velocity of any material body and is not inherently limited to values less than the velocity of light, illustrative arrangements are described hereinafter which require writing velocities greater than the velocity of light.

One such arrangement will be described by use of a somewhat diagrammatic representation in Fig. 4. The figure represents a length of hollow, conductive-walled wave guide bent into circular form with a conductive radial partition 50 across the interior. If preferred, the length of wave guide may first be closed at both ends and then bent into the form of a circle with the closed ends in contact, this being the equivalent for present purposes of a circular guide with a radial partition. The wave guide is assumed to be capable of accommodating oscillations comprising a standing wave, the wave form of which is represented by the dotted curve 51. Equally spaced holes 52 similar to the holes 41 in the system of Fig. 2 are provided at the antinodal points of the standing wave configuration, there being of necessity a node at the partition. The wave guide of Fig. 4 may be used in place of the block 13' in the system of Fig. 2, for example.

In the operation of a system employing a wave guide as illustrated in Fig. 4, the standing wave may be sustained in the wave guide by means of a rotating electron beam entering the guide periodically through the successive holes 52. The writing velocity of the beam must be equal to the velocity of propagation of the wave motion causing the standing wave 51. Or, considering the standing wave to be composed of two traveling waves traversing the guide in opposite directions with equal velocity, the writing velocity of the beam must equal the phase velocity of the traveling waves.

A numerical example at this point will aid in the explanation as well as indicate how a system based on Fig. 4 may be designed for given input and output frequencies. Suppose that a wave guide with a particular shape and size of cross section has been selected, for example, the form shown in Fig. 5. The input and output frequencies will be assumed, as before, to be 500 megacycles and 10,000 megacycles per second, respectively. The frequency ratio being thus determined, the circumference of the circle upon which the apertures 52 lie is accordingly fixed at 20 wave-lengths, measured in the guide. To find the actual length of the circumference, a knowledge of the wave-length in the guide is required, or of the phase velocity in the guide, from which the wave-length is readily calculated. It is known from the theory of guided wave transmission that the phase velocity in a hollow guide with conductive walls is always greater than the velocity

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of light for all finite frequencies which the guide will freely transmit, and that the phase velocity approaches the velocity of light asymptotically as the frequency is increased. The phase velocity in a particular wave guide will depend upon the shape and size of cross section as well as upon the desired output frequency. The value of the phase velocity may be obtained most readily in many cases from measurements, by known methods, of the wave-length of standing waves in a length of the actual guide. The sample upon which the measurements are made may be straight and the results will apply with sufficient approximation to the same guide bent in the form of a circle. If formulae are available for the type of guide employed it is also possible to calculate the wave-length and phase velocity.

For the purposes of the present example it will be assumed that the phase velocity in the guide is known to be 1.25 times the velocity of light. Twenty wave-lengths of a wave propagated at 1.25 times the velocity of light evidently make a length equal to four-fifths of 20, or 16 wave-lengths of a wave propagated with the velocity of light. The circumference of the wave guide is, accordingly, 48 centimeters and the diameter is approximately 15.3 centimeters, or 6 inches. The number of apertures provided will be 40, that is, one for each antinodal voltage point. In practice, the wave guide may be brought into precise resonance at a harmonic of the input frequency by tuning, as for example, by adjusting the volume of the resonant cavity by any suitable known means.

In order to avoid loss of efficiency arising from the fact that the electrons during so large a proportion of the time strike the outside surface of the wave guide between the holes, a continuous slot extending around the entire means circumference may be employed instead of the holes. Such a slot is illustrated in the wave guide shown in Fig. 5. Since the electron beam moves along this slot with a writing velocity equal to the phase velocity in the guide, the beam will continuously enter the guide against an opposing electric field. That this is so may be visualized by considering again the equivalence of the standing wave and a pair of traveling waves going in opposite directions. The beam keeps in a constant phase relationship with the traveling wave going in the same direction, thus continually transferring energy to that wave. At the partition, the traveling wave is reflected and merges with the wave traveling in the opposite direction, thereby transferring some of its energy to the other traveling wave.

A wave guide of the cross section illustrated in Fig. 5, approximately comprising two circular sectors, is adapted to permit the electrons to pass through the guide in a time comparable with the periodic time of the output frequency. For example, a gap of about $\frac{1}{20}$ inch may be advantageously employed with an output frequency of 10,000 megacycles.

In the arrangement of Fig. 4 it is feasible to omit the partition 50 and allow the rotating beam to enter the guide through a continuous slot. Without the partition, the guide can sustain a traveling wave which progresses continuously around the circumference. The traveling wave may be maintained by continuous abstraction of energy from the electrons, which come into the guide at a point of maximum opposing electric field. Thus the transfer of energy from the beam to the electromagnetic wave in the guide is sub-

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stantially continuous. This method of sustaining a traveling wave in an endless wave guide by means of a rotating electron beam is disclosed in a copending application of R. V. L. Hartley, Serial No. 385,629, filed March 28, 1941, and assigned to the assignee of the present application.

Fig. 6 shows an embodiment of the general arrangement described in connection with Fig. 4 with certain modifications, the system in some respects resembling that illustrated in Fig. 2. The wave guide shown in Fig. 6 has substantially the same cross section as the resonator in block 13' of Fig. 2. Instead of holes for the electron beam to enter, a continuous slot is shown, the central portion of the block being supported in any suitable manner as, for example, by radial rods which cross the path of the electron beam but intercept relatively few electrons. Advantage may be taken of an arrangement disclosed in the above-cited Hartley application for increasing the circumference swept out by the electron beam while using relatively low energizing potentials. Electrodes 60 and 61, respectively, provide between them a conical slot through which the electron beam passes. A steady electric field impressed between the electrodes 60 and 61 by a battery 62 or other suitable source of electromotive force, causes an outward bending of the electron beam, thereby increasing the divergence of the beam from the axis. Reversal of the polarity of the source 62 would, of course, result in a decrease in the diameter of the circle swept out by the electron beam. A pair of electrodes 63 and 64 separated by a circular slot may be placed near the resonator and polarized somewhat positive with respect to the conductive surface of the wave guide by a battery 65 or other suitable source of electromotive force, in order that any secondary electrons which may be emitted due to the electron beam striking any portion of the surface of the wave guide may be attracted to and collected by the electrodes 63 and 64. The circular slots in the electrode systems 60, 61 and 63, 64 are arranged to register with the slot in the wave guide so that the electron beam may readily pass through all three slots.

One or both of the electrodes 63 and 64 may also be employed to effect an automatic control of the deflection of the electron beam. For example, a resistor 66 may be inserted in series with the source 65 and the potential drop across the resistor 66 may be arranged to subtract from the potential difference between the electrodes 60 and 61, the potential across the resistor partially offsetting the electromotive force of the source 62. When the input or deflection amplitude changes, tending to throw the beam out of register with the slot in the wave guide and thereby tending to reduce the current through the cavity, the current intercepted by one or the other of the electrodes 63, 64 is changed, for example, in this case the current to electrode 64. Supposing that the current to the electrode 64 is increased, then the potential difference across the resistor 66 will also be increased and, accordingly, there will be a decrease in the potential difference between the electrodes 60 and 61. The latter will tend to draw the beam closer to the axis and away from the electrode 64, thereby decreasing the current to that electrode and tending to minimize the resultant change in the deflection of the beam. The control potential of the resistor 66 may be employed, if desired, to control the amplitude of the high frequency, input to the

plates 17, 18, 17' and 18' with similar effect upon the deflection of the beam. Likewise, it is feasible to employ electron current intercepted by the electrodes 60 and 61 to secure correcting potentials which may then be applied to the electrodes 17, 18, 17' and 18' as before.

What is claimed is:

1. A harmonic generating system comprising a source of waves of given frequency, means to provide a beam of moving charged particles, a resonating chamber resonant to a harmonic of said given frequency and having an aperture in its wall permitting access of said beam into the interior of the chamber, means energized by said source of waves of given frequency to direct said beam into said aperture to react with an electromagnetic wave within said resonating chamber, and means to control said beam directing means to limit the phase of said reaction substantially to transfer energy only from said beam to said wave.

2. A harmonic generating system comprising a source of waves of a given frequency, means to provide a beam of moving charged particles, a resonating chamber resonant to a harmonic of said given frequency, said chamber having an aperture in its wall permitting access of said beam into the interior of the chamber, and means energized by said source of waves to deflect said beam about a substantially fixed point of deflection and cause said beam to sweep once per cycle of the given frequency over said aperture and through an arc relatively great compared with and including the arc subtended by said aperture at the said point of deflection.

3. A harmonic generating system comprising a source of waves of a given frequency, a resonating chamber tuned to a harmonic of said given frequency and having an aperture in its wall, means to provide a beam of moving charged particles, and means energized by said source of waves to deflect said beam to and fro across said aperture and substantially about a fixed point of deflection once per cycle of the given frequency through an arc relatively greater compared with and including the arc subtended by said aperture at said point of deflection.

4. A harmonic generating system comprising a source of waves of a given frequency, means to provide an electron beam, a hollow resonator coaxial with said electron beam and having conductive walls and an axial aperture, said resonator being tuned to a harmonic of said given frequency, and means energized by said source of waves of given frequency to deflect said beam to and fro across said aperture and substantially about a fixed point in the axis once per cycle of the given frequency through an arc relatively large compared with and including the arc subtended by said aperture at the said point of deflection.

5. An electron beam system comprising a cathode, means to form an electron beam from elec-

trons emitted by said cathode, a target containing an aperture, means to deflect said beam about a substantially fixed point of deflection through an arc relatively greater than and including the arc subtended by said aperture at said point of deflection, means to impress a relatively large potential difference between said cathode and said target to accelerate electrons toward said target, means to shield said electron beam from said target throughout the major portion of the arc of deflection, said shielding means having an axial opening permitting access of the beam to the aperture in the target, and means to impress a relatively small potential difference between said cathode and said shielding means to collect electrons with low energy dissipation on said shielding means.

6. A harmonic generating system comprising a source of waves of a given frequency, a toroidal-shaped resonating chamber tuned to the harmonic of said given frequency, said resonating chamber having a plurality of apertures uniformly spaced about its periphery, means to provide a beam of moving charged particles, and means energized by said source of waves of given frequency to sweep said beam over said apertures in rotation once per cycle of said given frequency, the ratio of the number of the harmonic to the number of apertures having an integral value.

7. A harmonic generating system comprising a source of waves of a given frequency, a hollow resonator with conductive walls, the cavity of which resonator is a figure of revolution about an axis outside the cavity, said resonator having a resonant frequency that is a multiple of the given frequency, and said resonator having a plurality of apertures communicating with the cavity of the resonator and uniformly spaced about a circle concentric with said resonator, a source of a beam of electrons, and means energized by said source of waves of given frequency for sweeping said beam of electrons over said apertures in succession at a uniform rate correlated with the resonant frequency of said resonator to sustain an electromagnetic wave within the cavity of said resonator at said multiple frequency.

8. A harmonic generating system comprising a source of waves of a given frequency, a hollow conductive wave guide closed at both ends of a length to support a plurality of cycles of a standing electromagnetic wave of a frequency which is a multiple of said given frequency, said wave guide being bent into circular form and provided with a plurality of apertures lying upon a circle and coinciding substantially with the antinodal points of said standing wave, means to provide a beam of electrons and means synchronized with said source of waves of given frequency to sweep said electron beam over said apertures in succession with a writing velocity equal to the phase velocity of the electromagnetic wave in said wave guide.

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