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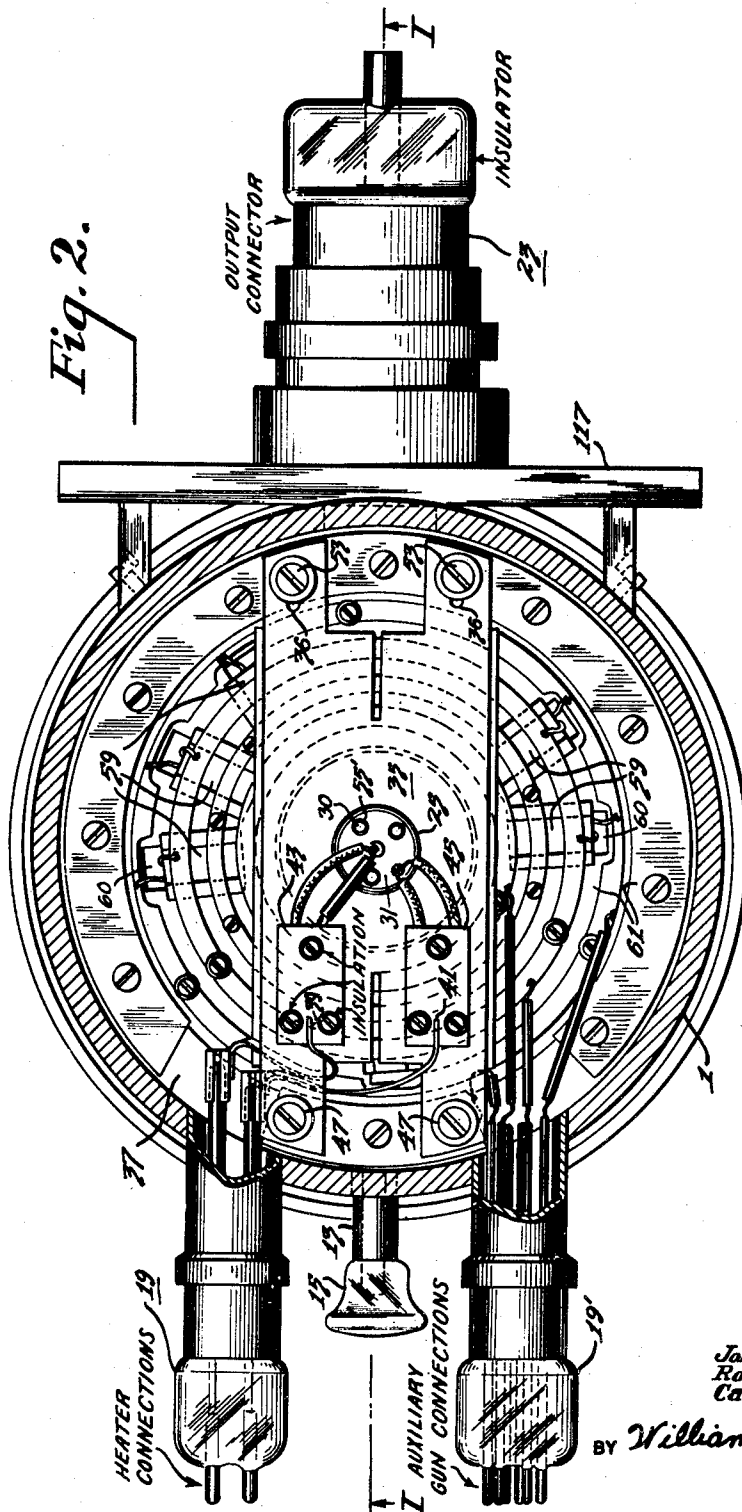
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2,534,503

FREQUENCY-MODULATED MAGNETRON MICROWAVE GENERATOR

Filed June 28, 1947

5 Sheets-Sheet 2



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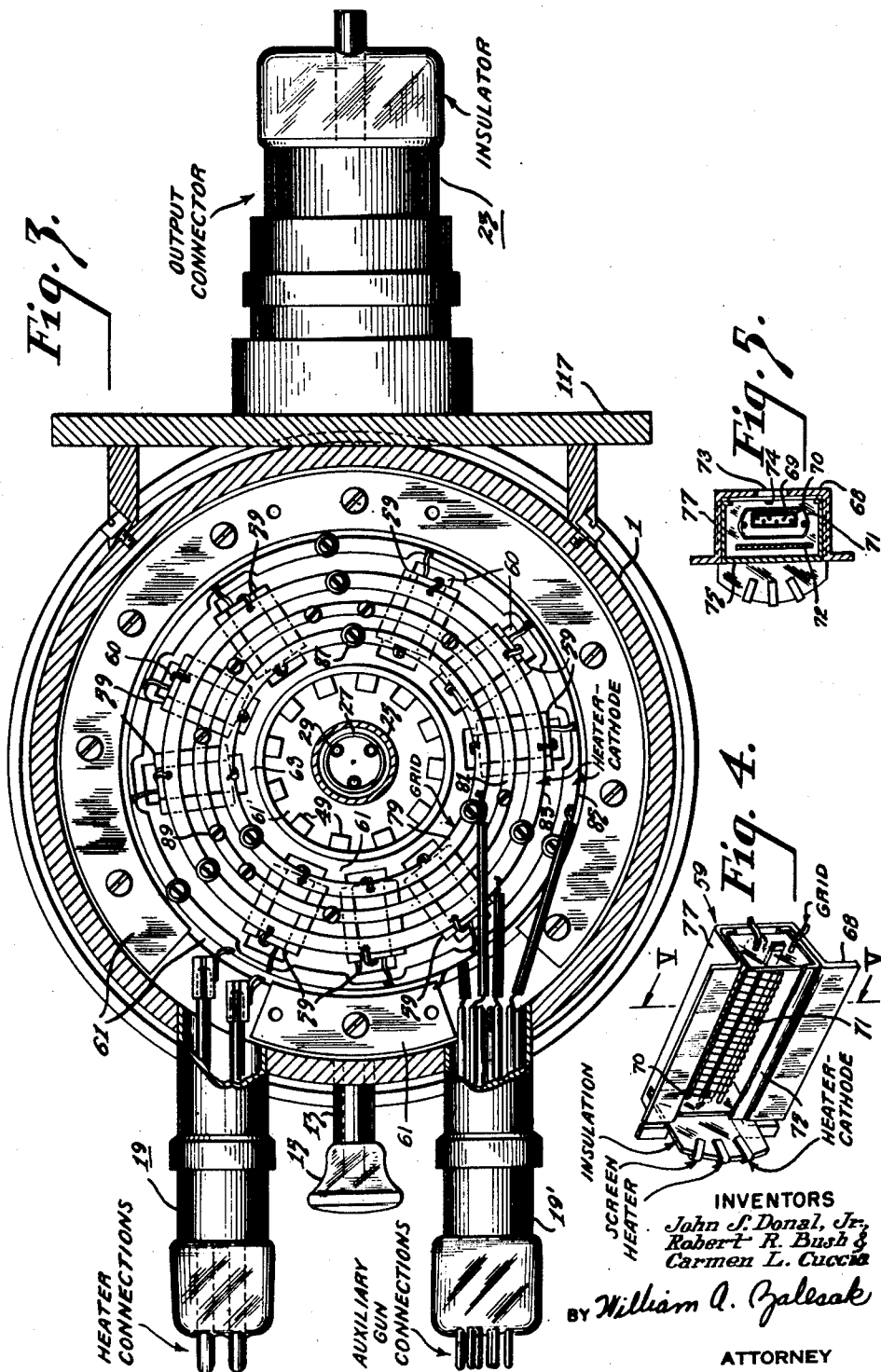
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FREQUENCY-MODULATED MAGNETRON MICROWAVE GENERATOR

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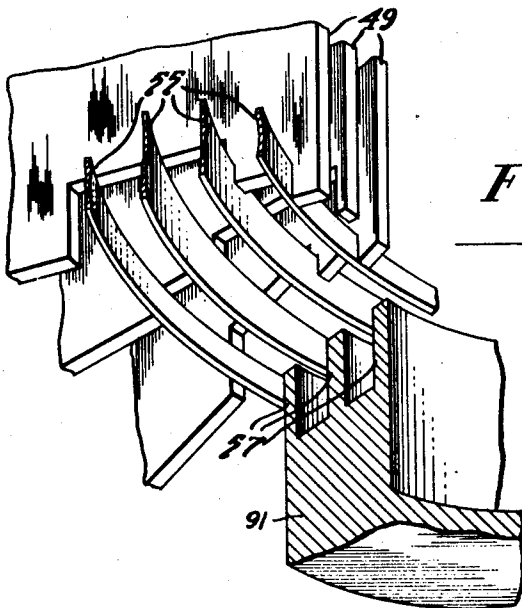
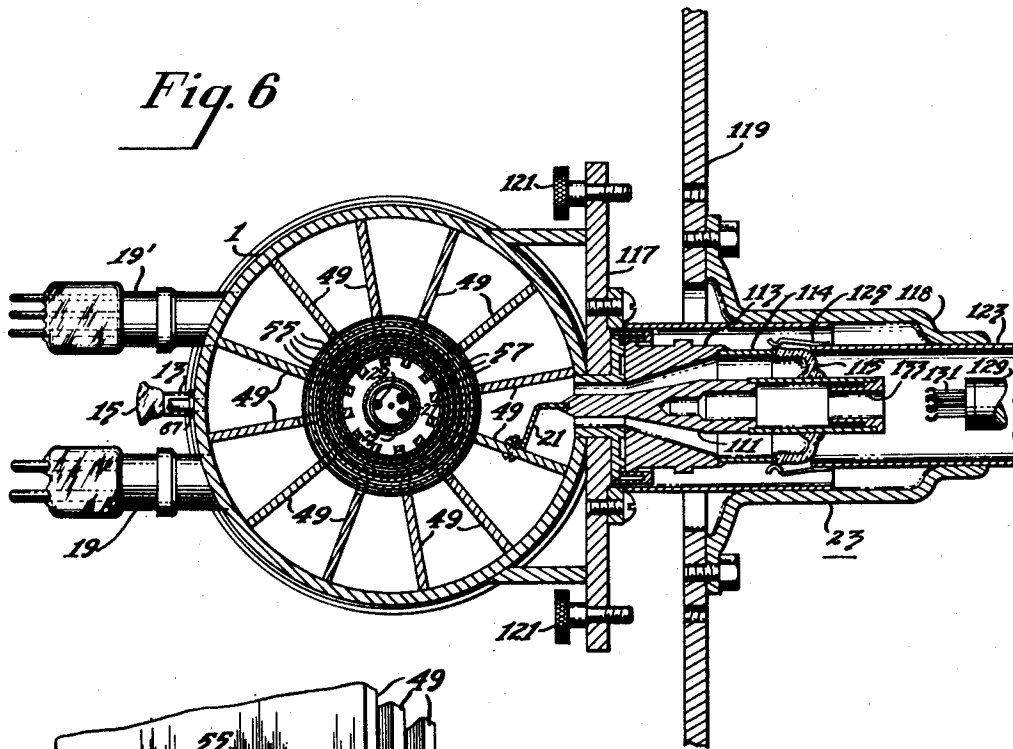
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FREQUENCY-MODULATED MAGNETRON MICROWAVE GENERATOR

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5 Sheets-Sheet 4



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FREQUENCY-MODULATED MAGNETRON MICROWAVE GENERATOR

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5 Sheets-Sheet 5

Fig. 8

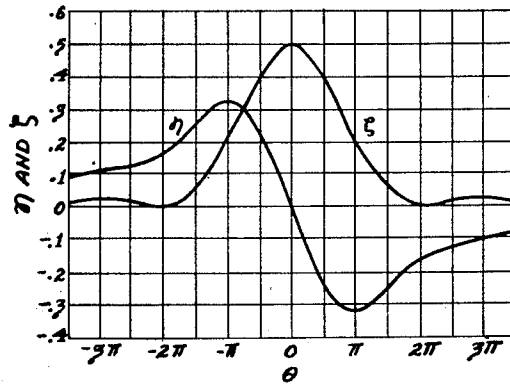


Fig. 9

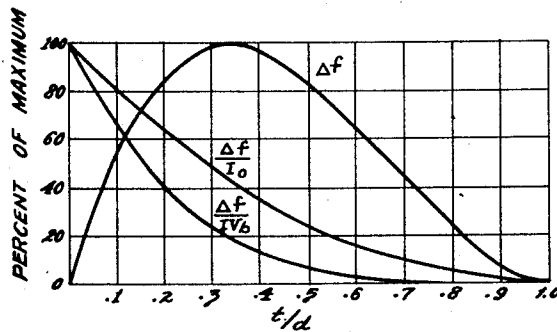
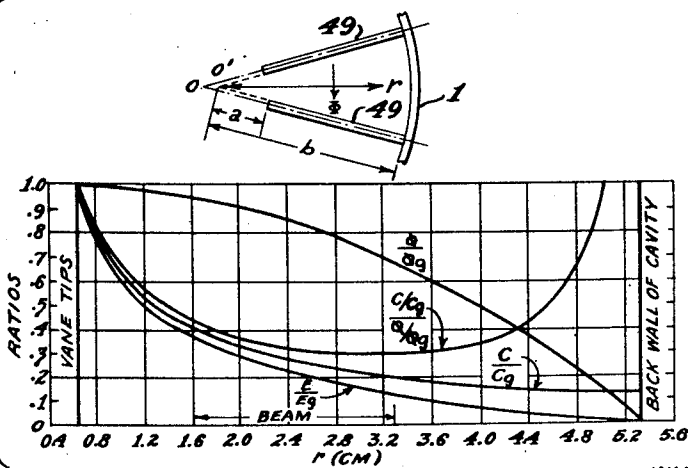


Fig. 10



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2,534,503

FREQUENCY-MODULATED MAGNETRON
MICROWAVE GENERATOR

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Application June 28, 1947, Serial No. 757,756

14 Claims. (Cl. 332-5)

1

This invention relates generally to frequency-modulated magnetron microwave generators of the type employing auxiliary electron guns for directing modulating electron beams through the resonators of a multicavity magnetron generator and more particularly to novel modulating electron beam structures and to methods of and means for supporting and connecting to said modulating beam structures.

The copending U. S. application of Lloyd P. Smith Serial No. 563,732, filed November 16, 1944, discloses and claims a novel frequency-modulated magnetron microwave generator wherein the reactive effects of one or more coaxial modulating electron beams upon the microwave fields within the resonators of a multicavity magnetron are employed for shifting the frequency of the magnetron generator as a function of the energy of the modulating electron beams. The energy of the modulating electron beams is controlled preferably by applying modulation signals to a control electrode of the modulating electron beam source. For selected operating parameters, the output frequency of the device is a function of the magnetron operating potentials, the axial constant intensity magnetic field, the energy of the modulating electron beams and the relative positioning of said modulating beams in the microwave fields within the magnetron generator resonator structures. In general, the most efficient frequency modulation is provided by locating the modulating electron beams on axes parallel to and surrounding the central magnetron cathode closely adjacent to, and equidistantly spaced from, the apices or inner ends of the radial anode vanes forming the magnetron anode resonators.

Heretofore, such frequency-modulating electron beam devices have employed simple grid-controlled electron beam guns for directing electron beams through the several cavity resonators to electron collector electrodes. One of the novel features of the instant invention is the use of additional positively-biased screen or shielding electrodes in each of the frequency modulating electron gun structures for improving the efficiency of the modulating electron guns, for reducing secondary emission instabilities in the system, for reducing electron gun cathode bombardment by returning secondary electrons from the collector and resonator structures, and for reducing undesired loading effects on the closely adjacent resonator structure. Another novel feature of the instant invention is the arrangement of a plurality of modulating electron beam devices concentrically with the central magnetron cathode

2

and closely adjacent to the apices of the magnetron anode vanes, said arrangement being provided and facilitated by a plurality of concentric connecting and supporting rings providing electrical connections to the several electrodes of the equally angularly spaced electron guns.

Among the objects of the invention are to provide improved methods of and means for frequency-modulating magnetron microwave generators of the type employing cavity resonator type anode structures. Another object is to provide improved frequency-modulated magnetron microwave generators employing screen grid type modulating electron beam devices for directing modulating electron beams through the cavity resonators of the magnetron generator. A further object of the invention is to provide an improved supporting and electrical connection structure for a plurality of frequency-modulating electron beam reactive devices supported in operative relation to a plurality of cavity resonator anodes of a frequency-modulated multicavity magnetron. An additional object is to provide an improved method of and means for extending the frequency-modulation range of a multicavity magnetron generator. Another object is to provide improved methods of and means for reducing secondary-emission instabilities and reducing cathode bombardment by returning secondary electrons in modulated magnetron microwave generators. A still further object of the invention is to provide improved methods of and means for improving the operating characteristics and efficiency of magnetron microwave generators. Another object of the invention is to provide an improved frequency-modulated magnetron microwave generator which is tunable over a relatively wide frequency range.

The invention will be described in greater detail by reference to the accompanying drawings of which Figure 1 is a cross-sectional, elevational view, taken along the section line I—I of Figure 2, of a preferred embodiment of a magnetron including the novel features of the invention, Figure 2 is a plan cross-sectional view taken along the section line II—II of Figure 1 of said preferred embodiment of the invention, Figure 3 is a cross-sectional plan view of said preferred embodiment of the invention taken along the section line III—III of Figure 1, Figure 4 is a perspective view partially cut away of a frequency modulating electron gun structure comprising a portion of said preferred embodiment of the invention, Figure 5 is a cross-sectional view taken along the section line V—V

3

of Figure 4, Figure 6 is a cross-sectional bottom view taken along the section line VI—VI of Figure 1, Figure 7 is an enlarged fragmentary perspective view of the magnetron vane strapping means and tuning means in the region of the section line VI—VI of Figure 1, and Figures 8, 9 and 10 are graphs explanatory of the operating characteristics of the invention. Similar reference characters are applied to similar elements throughout the drawings.

Referring to Figures 1 to 7, inclusive, of the drawings, a preferred embodiment of the invention comprises a cylindrical conductive envelope 1 having a flat top portion 3 welded to the upper end 5 thereof and having an annular supporting ring 7 welded to the lower end thereof. A tuning mechanism 9, to be described in detail hereinafter, is supported by the annular ring 7 and includes a corrugated Sylphon diaphragm 11. The envelope 1 is evacuated through an exhaust tube 13 and seal 15. An axial magnetic field indicated by the arrows 17 is applied to the device from an external, substantially constant intensity, magnetic field generating structure, not shown.

All of the operating circuit connections for the tube are brought through the upper end of the envelope through second and third seals 19, 19' for supplying operating potentials to the magnetron cathode and anode vanes and to the modulating electron beam generating devices. Output microwave energy is derived from an output coupling loop 21 coupled through an output coaxial line connector 23 which is sealed into the side of the cylindrical envelope 1, as shown in detail in Fig. 6.

The magnetron generator portion of the tube includes a central cylindrical silicon steel cathode 25 coated with any suitable electron-emissive material, applied to a weight of 5.5 grams per cm.². The cathode is heated by an internal heating coil 27 comprising approximately 50 turns of tungsten wire of about .025 inch diameter. The heater winding 27 is supported upon three ceramic supporting rods 29 the ends of which are fitted into Nichrome cups 30. Metal cups 31 at the upper and lower ends of the cathode structure support the Nichrome mounting cups 30 and space the supporting ceramic rods 29 and heater winding from the internal face of the cylindrical cathode 25. Since the heater is separated from the cathode cylinder, the usual stray 60 cycle field interaction effects are minimized, and heater vibration effects producing spurious frequency-modulation are obviated. A lower cathode shield 33 shields the cathode electron emission from the tuning element located at the lower end of the tube. The cathode is supported at its upper end by a flat cathode mounting bracket 35 which also serves as an upper cathode shield, and which also provides good heat conduction to the tube envelope. The bracket 35 is supported rigidly at one end to an internal supporting ring 37 welded to the internal surface of the envelope 1. The opposite end of the bracket 35 includes slots 36 to permit transverse motion of the cathode with respect to the supporting ring 37 to prevent buckling of the cathode support due to transverse thermal expansion. The heater and cathode terminals 39, 41 are supported on metallic blocks 43, 45 respectively, mounted upon the cathode supporting bracket 35. One of the terminal blocks is connected to the cathode bracket and the other is insulated therefrom.

When the tube is assembled, the cathode bracket

4

is fastened by the screws 47 through the left side thereof as shown in Fig. 1 in a position whereby the cathode is off center approximately .013 inch from the center axis of the tube and the axis of the radially-disposed anode vanes 49. When the cathode reaches operating temperature, the resultant transverse thermal expansion moves the entire cathode assembly transversely until the cathode axis coincides with the center axis of the tube and anode vanes. The cathode bracket 35 is insulated from the tube envelope by insulating bushings 51 surrounding the mounting screws 47 and 53.

The center magnetron cathode 25 is surrounded by a plurality of radially-disposed anode vanes 49 which are welded to the internal surface of the evacuated envelope 1. The lower ends of alternate ones of the anode vanes 49 adjacent to the cathode are connected together by a plurality of concentric vane strapping rings 55. The tube is tuned by a capacitive element comprising three coaxial cylindrical rings 57 which telescope with the strapping rings 55 on the radial anode vanes 49. An actuating mechanism for longitudinal positioning of the capacitive tuning elements 57 is coupled through the Sylphon diaphragm 11 to a gear-operated, screw-feed mechanism to be described in detail hereinafter.

Cooling of the evacuated envelope 1 is accomplished by circulating water through a pair of circular water jackets 58, 58 milled into the envelope wall and connected together by a diagonal water duct 62. Cover plates 66, 67 for the water ducts are welded or silver soldered to the surface of the envelope.

Anode vane straps are omitted from the upper edges of the anode vanes in order to permit the frequency modulating electron beam guns to be mounted as closely as possible to the vane tips to provide more efficient modulation of the microwave oscillations generated by the magnetron. The auxiliary, or modulating, electron guns 59 are mounted above one or more of the anode cavities or cavity resonators formed between adjacent radial anode vanes. The modulating electron guns are supported by an annular aperture plate 61 supported by the supporting ring 37 which also supports the magnetron cathode assembly. The aperture plate 61 includes a large center aperture 61' surrounded by a flange 63 which shields the center magnetron cathode from the modulating electron guns. The aperture plate supports the auxiliary or modulating electron guns 59 in close proximity to the edge of the corresponding anode cavities. A modulating beam collector electrode, comprising a heavy annular conductive element 64 located adjacent to the lower end of the anode cavities, provides a common collector for all of the auxiliary electron beams. The collector electrode 64 is conductively secured to a third mounting ring 65 welded or soldered to the internal surface of the evacuated envelope 1. Both the aperture plate 61 and the collector 64, as well as the anode vanes 49, are maintained at the potential of the tube envelope which is positively biased with respect to the magnetron cathode. The direct connections between the envelope support rings 37 and 65 and the aperture plate 61 and collector 64 provide good heat conduction paths from these elements.

The modulating electron guns 59 are mounted upon the aperture plate 61 in apertures 60 therein and comprise unitary screen grid gun structures each including an aperture cup 68 contain-

ing a heater 60 surrounded by a cathode 70 and a control grid 71. A plane reflector electrode 72, disposed on the rear side of the control grid 71 and cathode 70, directs the electrons through an aperture 73 in the aperture plate cup 68 and projects the electrons through the corresponding cavity between the adjacent anode vanes 49. The aperture cup 68, the anode vanes and the collector 64 are positively biased with respect to the modulating gun cathodes so that the aperture cup, anode vanes and collector will serve as an effective accelerating electrode for the modulating electron guns. Such a simple triode arrangement has been found to be unsatisfactory since a relatively large proportion of the electron modulating electron beams is attracted to the aperture cup 68 providing unnecessary heating thereof and poor modulation efficiency. Also a large proportion of the secondary electrons emitted by the collector and the anode vanes is returned to the modulating gun cathodes. In order to obviate this condition a screen grid 74 is attached across the open side of an inner electron gun cup 75 which fits into and is welded to the complementary channel 77 in each of the aperture cups 68. The screen grid 74 is operated at the same positive potential as the magnetron anode vanes and the collector electrode. The screen grid wires are aligned with the control grid wires to provide beam tube operation characteristics.

A modulating electron gun structure similar to that shown in Fig. 5, but not including the electron electrode 72 or the screen grid wires 74, is disclosed and claimed in a copending application of C. I. Shulman, Serial No. 720,546, filed January 7, 1947, now Patent No. 2,490,008, dated November 29, 1949, and assigned to the same assignee as the instant application.

The aperture cup and the collector electrode both may be insulated from the tube envelope in order to determine the effect of different operating voltages thereon. However, it usually is preferable to operate the aperture cup, and hence the screen grid, as well as the collector electrode at envelope potential in order that these elements may have good heat conduction paths to the envelope to insure proper operating temperatures. Otherwise some type of internal cooling system is essential to prevent over-heating of the aperture cup and collector electrode. The maximum distance between the aperture cup and the adjacent radial anode vanes is determined from the space charge relation

$$(I)_{\max} = \frac{1}{9\pi} \sqrt{\frac{2e}{m}} \frac{(\sqrt{V_b} + \sqrt{V_a})^3}{s^2} A$$

where s is the effective distance between the aperture cup and the anode vanes, V_b is the voltage on the anode vanes, V_a is the voltage on the aperture cup, A is the effective modulating electron beam area, and $(I)_{\max}$ is the maximum beam current. For $V_b = V_a = 500$ volts, for a current of 143 ma., the maximum value for s is .83 cm. For 300 volts operation, the maximum value of s is .57 cm. Since it has been found from cold resonance measurements that electrodes placed appreciably closer than this to the anode vanes have very little effect on mode separation and frequency, the aperture cup may be located approximately $\frac{1}{8}$ inch (.32 cm.) from the ends of the vanes.

The several modulating electron guns described hereinafter are supported in the appropriately located apertures 60 in the aperture plate 61 so that the guns are supported directly over the corresponding magnetron anode cavities

and as close to the anode vane tips as practicable. Four coaxial rings 79, 81, 83 and 85, disposed above the modulating electron gun structures, support the guns in the corresponding apertures 60 in the aperture plate and provide parallel connections for the heater, cathode, and control grid electrodes of the several guns. The inner ring 79 is insulated from the aperture plate by insulating spacers 87 and is connected to the control grids of each of the modulating guns. The next ring 81 is directly connected to the aperture plate by a plurality of screws 89 and abuts upon the back surface of the inner gun cups 75. The two outer rings 83, 85 also are insulated from the aperture plate 61 and provide parallel connections for the heaters and cathodes of the several modulating electron guns. Connections to external power circuits are made through the tube seal 19' to the grid and heater-cathode connecting rings.

The screen grid type of frequency modulating electron guns are much to be preferred over triode guns of the type utilized heretofore since the screen or shield grid aligned with the control grid reduces the electron current diverted to the aperture cup which would result in heating thereof and low modulation efficiency. Furthermore, by reducing the electric field across the aperture in the aperture cup, the modulating gun static characteristic will be straightened since the aperture current drain is much more linear. It is also possible to extend the frequency modulation range for a predetermined modulating electron current by obtaining a greater percentage of electron current through the anode cavities for the same current drain on the modulating electron beam cathodes. The permissible modulating beam cathode current thus is the principal limitation on the modulation characteristics. Utilizing a screen or shield electrode at the potential of the anode resonators also reduces secondary emission instability previously encountered, and reduces the back-bombardment of the modulating electron beam cathodes by returning primary or secondary electrons which have traversed the anode cavity resonators or which are reflected or generated by the collector electrode. Such returning electrons are collected by the positively charged screen grid. Utilization of a screen or shield grid in the modulating electron guns also provides much improved electron current cutoff characteristics. If desired, the magnetic field applied to the device may be of different intensity for the magnetron generating and modulating portions of the device to provide optimum operating characteristics.

The operational characteristics of the modulating electron beams in controlling the frequency modulation of microwave oscillations generated by the magnetron generating elements is described hereinafter by reference to a general example of such modulating devices and more particularly by reference to the improved characteristics obtainable with the screen or shield grid type of modulating system comprising the instant invention.

It has been known that if an electron beam is projected between two parallel plane electrodes which are part of a resonant circuit or cavity resonator, the frequency shift caused by the beam is

$$\Delta f = \frac{e}{m} \frac{I_0 r^2}{8\pi C_0 d^2} \eta(\theta) \quad (1)$$

the parameter, θ , is defined by

$$\theta = (\omega_0 - \omega) \tau$$

and the function $\eta(\theta)$ by

$$\eta(\theta) \cong \frac{\sin \theta - \theta}{\theta^2}$$

wherein the symbols are defined as follows:

- I_0 = total beam current
 τ = electron transit-time
 C_0 = effective circuit capacitance
 d = separation of the electrodes
 e/m = charge-to-mass ratio of electrons
 ω = angular frequency of the cavity resonator
 $\omega_0 = H \frac{e}{m}$, where H is the magnetic field intensity.

Of course, the transit time, τ , is given by

$$\tau = \frac{l}{\sqrt{2 \frac{e}{m} V_b}}$$

where

l = length of the electrodes in the direction of the magnetic field H

V_b = beam voltage

The electronic loading provided by the beam is expressed by a conductance between plates:

$$G = \frac{e}{m} \frac{I_0 \tau^2}{2 d^2} \zeta(\theta)$$

in which

$$\zeta(\theta) \cong \frac{1 - \cos(\theta)}{\theta^2}$$

The functions, η and ζ , proportional to Δf and G , respectively, are shown as functions of θ in Figure 8.

The maximum electron current which can be passed between the plates is

$$(I_0)_{\max} = \frac{4}{9\pi} \sqrt{2 \frac{e}{m} V_b} \frac{w}{d} F_{\max}$$

where w is the beam length and $F_{\max}$ is a function of t/d (where t is the beam width). $F_{\max}$ varies from 2, for $t/d=1$, to 0.866 for $t/d=0$. Introducing Equations 7 and 4 in Equation 1,

$$\Delta f = \frac{\sqrt{2 \frac{e}{m} V_b} \sqrt{V_b}}{36 \pi^2} \frac{F_{\max} \eta(\theta)}{C_0 d^3}$$

The capacitance between the electrodes is

$$C = \frac{wl}{4 \pi d}$$

which when substituted in Equation 8 gives

$$\Delta f = \frac{\sqrt{2 \frac{e}{m} V_b}}{9 \pi} \frac{l \sqrt{V_b}}{d^2} \left(\frac{C}{C_0} \right) F_{\max} \eta(\theta)$$

If the electrons are to pass through the cavity resonator and be collected at the opposite end, the maximum deflection of the electrons must be less than $\frac{1}{2}(d-t)$. It has been shown that the maximum electron deflection is

$$|y_0|_{\max} = \frac{E_0 \tau}{H |\theta|}$$

where E_0 is the magnitude of the R.-F. electric field between the plates. The R.-F. voltage between the plates is simply

$$\phi_0 = E_0 d$$

Equation 11 then provides the condition that for electrons just "grazing" the plates,

$$\frac{\phi_0 \tau}{H |\theta|} = \frac{1}{2} d^2 (1 - t/d)$$

When Equation 13 is solved for d (which is its minimum value) and the result is used in Equation 10, the maximum frequency shift is

$$|\Delta f|_{\max} = \frac{e/m}{9\pi} \left(\frac{C}{C_0} \right) \frac{H V_b}{\phi_0} \theta \eta(\theta) F_{\max} (1 - t/d)$$

Although Equation 14 was derived for the parallel plane electrode case, and neglecting the effects of the R.-F. field on space charge, experience has shown that it is a very useful design formula, particularly for "scaling" results already obtained to a device for operation at a different frequency.

An important design consideration is not apparent from Equation 14, however. V_b is limited by the maximum current density from the cathode as determined by cathode operating life considerations. This current density is

$$J_0 = \frac{I_0}{wt}$$

which from Equation 7 is

$$(J_0)_{\max} = \frac{4}{9\pi} \sqrt{2 \frac{e}{m} V_b} \frac{1}{d^2} \frac{F_{\max}}{t/d}$$

It is informative to rewrite Equation 1 using Equations 15 and 9, thus giving

$$\Delta f = \frac{e}{m} \frac{J_0}{2l} \left(\frac{C}{C_0} \right) \left(\frac{t}{d} \right) \tau^2 \eta(\theta)$$

in which it is to be understood that the conditions of Equation 16 are to be fulfilled. From Equation 11 it is seen that the maximum τ is determined by the maximum spiral deflection and so if Equation 13 is introduced into Equation 17,

$$|\Delta f| = \frac{e}{m} \frac{J_0 H^2 |\theta|^2}{8 \phi_0^2 l} \left(\frac{C}{C_0} \right) \eta(\theta) d^4 [(1 - t/d)^2 t/d]$$

When the quantity $[(1 - t/d)^2 t/d]$ is maximized with respect to t/d it has a maximum value of 0.148 for $t/d=1/3$. It is seen from Equation 2 that H is a function of τ and therefore of t/d , but as will be shown, H is a slowly varying function of τ and is determined chiefly by the frequency. Therefore, it will be assumed that Δf is maximum for $t/d=1/3$.

By the same procedure the frequency shift per unit current and per unit beam power may be determined. The expressions obtained are

$$\frac{\Delta f}{I_0} = \frac{e}{m} \frac{H^2 \theta^2 d^3}{8 w l \phi_0^2} \left(\frac{C}{C_0} \right) \eta(\theta) (1 - t/d)^2$$

$$\frac{\Delta f}{I_0 V_b} = \left(\frac{e}{m} \right)^2 \frac{H^4 \theta^4 d^7}{16 w^2 \phi_0^4} \left(\frac{C}{C_0} \right) \eta(\theta) (1 - t/d)^4$$

It is readily seen that both these expressions are a maximum for $t/d=0$. In Figure 9, the functions in Equations 18, 19 and 20 are plotted as a function of t/d .

Thus far, for the sake of simplicity, it has been implicitly assumed that the electrons would make a single transit through the cavity resonator and be collected at the opposite end. However, it has been demonstrated that multiple transit operation is possible, by reflecting the electrons at the end of the resonator remote from the cathode electron source. The space charge considerations expressed by Equation 7 are independent of the direction of current flow and the number of transits, and so the effective beam current can be no greater than $(I_0)_{\max}$. However, the cathode current would be reduced by a factor, n , where n is the effective number of transits, and since cathode current density is a limitation, multiple transit operation would be ad-

vantageous. In spite of this advantage, difficulties with instabilities and secondary emission phenomena, which have not been completely investigated, have made multiple transit operation impracticable.

Use of magnetron cavity

The previous discussion applies to the design of external reactance tubes of the spiral beam type as well as to the use of the modulating electron beams within the magnetron. However, each method has further special considerations; those which follow will apply only to the use of one or more of the magnetron cavities.

Although the explanation provided heretofore was derived for parallel plane electrodes, it is applicable to other types of cavity resonators if the variation of the several parameters is considered.

In a cavity resonator of a magnetron of the conventional radial vane type, the electric field amplitude, E_0 , decreases from a maximum at the vane tips to zero at the back of the cavity. This field distribution may be determined readily by neglecting the effects of the vane straps and other end effects and assuming infinitely conducting walls. The variation of R.-F. voltage ϕ_0 , is also shown in Figure 10. The capacitance per unit length varies as $1/d$ and is also shown.

If it is assumed that V_b is chosen so that the cathode current density is within the safe operating limits, given by Equation 16, and if it is assumed that the vane length l , is chosen such that Equation 13 is fulfilled, then Equation 14 is applicable. In this equation, all quantities will be constant except the ratio C/ϕ_0 which varies as shown in Figure 10. Since this ratio rises rapidly at the back of the cavity (actually to a finite value, since E_0 is not quite zero as a result of losses in the walls), one might be tempted to place the beam at the extreme back of the cavity. However, this would not only require a high V_b , in order to satisfy Equations 7 and 14, but would also require a very large cathode in order to satisfy Equation 13. Moreover, it is really the area between certain points under the curve of C/ϕ which is significant, since the beam will have appreciable length in the radial direction. The results of using a cathode placed in the front of the cavity, which is long in the radial direction but narrow, may be compared to the results of using a cathode of the same area which is short but very wide, placed in the back of the cavity. In all cases of practical interest, the area under the curve corresponding to the cathode in the front will actually be larger. This deduction, along with the beam voltage consideration mentioned above, leads to the perhaps obvious conclusion that the modulating electron beams should be placed as near the vane tips as is mechanically practicable.

The condition that electrons leaving the edge of the cathode are just "grazing," expressed by Equation 13 cannot be fulfilled at all positions along the beam, if l and V_b and thus τ are constant, unless t/d increases as d becomes larger and ϕ_0 decreases. Since this would require a tapered cathode, it would be more practicable to use a rectangular cathode and permit some of the electrons from the front of the cathode to be captured by the vanes. These electrons would not be entirely wasted from the standpoint of frequency shift, although they would result in electronic loading when $\theta=2\pi$ for the electrons not captured.

Considerable attention has been given to the possibility of using cavity resonators with shapes other than the sectoral cavities in conventional vane-type magnetrons. It is desirable to build up the cavity capacitance in the region of the beam and to make optimum operating conditions possible at all positions of the beam. If carried to the extreme of using a slot type magnetron, or a "rising-sun" type, it was estimated that perhaps a factor of two in improvement of performance could be obtained from a single cavity. However, the total tube capacitance, C_0 , which appears in the denominator of all the expressions for Δf , is greater perhaps by a factor of 1.5 for such types than for the vane type magnetron. In addition, the disadvantage, at lower frequencies, of all types other than the vane type, is appreciably greater size. Since size and weight usually are important considerations, the radial vane type of construction is preferable.

Determination of beam position and size

In view of the foregoing discussion it usually is preferable to locate the modulating beam cathodes just outside of the vane strapping system which is located as near the center of the tube as possible. In the device described, the "leading edge" of the cathode is 2.6 cm. from the center of the tube, and a somewhat arbitrary rectangular cathode length of 1.5 cm. was chosen.

The value of d varies from 0.86 cm. to 1.66 cm. along the cathode. Since the optimum value of t/d is $1/3$; this leads to values of t from 0.28 cm. to 0.55 cm. A value of t of 0.318 cm. (0.125 inch) was then chosen, since this is a standard size of cathode tubing.

Determination of beam voltage and current

In receiving tube practice, a value of J_0 of 300 ma. per cm.² is considered a safe current density from oxide-coated cathodes. Since it was decided to use single transit operation because of the multiple transit difficulties mentioned heretofore, this value of J_0 was then taken as the maximum current density of the beam. Equation 16 permits a determination of V_b . t/d varies from 0.37 to 0.19, and $F_{\max}$ from 1.14 to 1.000. Therefore, V_b should vary from 392 volts to 657 volts. A beam voltage of 500 volts is suitable.

For a total cathode area of 0.48 cm.², the total current to be expected is 143 ma. per beam.

Determination of vane length

Determination of the vane length, l , involves determination of the transit time, τ , since the beam voltage has already been determined. The transit time is determined by the spiral deflection condition expressed by Equation 13, but before it can be calculated it is necessary to determine the values of θ and ϕ_0 .

Calculation of the electronic loading, for $\theta=\pi$, at which point the function $\eta(\theta)$ is a maximum, shows that excessive amplitude modulation would result from use of this value of θ . Therefore, the value 2π should be selected, since at this point the electronic loading is zero.

The value of the R.-F. voltage ϕ_0 is considerably more difficult to determine accurately since it depends on the power output and loaded Q of the tube as well as unknown geometrical factors. An estimate of ϕ_0 provides a value of ϕ_0 of 1,100 volts for a power output of 1,000 watts and a loaded Q of 100.

Since the magnetic field intensity, H , is a

function of the operating frequency, ω , the angle θ , and the transit time, as given by Equation 2, all the quantities in Equation 13 are known except τ . If Equation 2 is inserted in Equation 13, a quadratic in τ results; the positive root is

$$\tau = \theta \frac{\omega d^2 (1 - t/d) + \sqrt{\omega^2 d^4 (1 - t/d)^2 + 8 \phi_0 \frac{e}{m} d^2 (1 - t/d)}}{4 \phi_0 \frac{e}{m}} \quad (21)$$

For the value of d of 0.86 cm., at the "leading edge" of the cathode, Equation 21 provides a value of τ of 5.15×10^{-9} sec. Equation 4 then provides a value of l of 6.85 cm. for V_b of 500 volts. Actually, the potential distribution caused by space charge increases the transit time beyond the value given by Equation 4; thus permitting using a value of l smaller than the calculated value. For this reason, and because of size and weight limitations, the value of l of 5.08 cm. (2.00 inches), may be considered satisfactory.

Determination of magnetic field

Since the transit time has been determined by the selection of vane length, l , and beam voltage, V_b , it is possible to determine the magnetic field intensity. A very accurate determination would require an accurate knowledge of the transit time, as determined by the potential distribution referred to heretofore. Because of this distribution, all electrons, leaving the same radial position along the cathode, would not be similarly affected, and so would have slightly different transit times. To accurately calculate the transit time of a single electron would require a detailed knowledge of its trajectory which is influenced by space charge.

However, electrons leaving the back of the cathode, where t/d is smaller and where the deflection is smaller, will have a somewhat lower accelerating potential and therefore a slightly longer transit time than electrons leaving the front of the cathode. This latter effect, from Equation 2, means that in order to maintain the same value of θ along the beam, the magnetic field should decrease slightly at increasing radii. This is fortunate since most magnets do have such a distribution in the radial direction.

Insofar as detailed calculations of all these effects are very difficult to carry out, it is assumed that the transit time is given by Equation 4. For 5 cm. vane length and 500 volts beam voltage, the transit time is about 3.8×10^{-9} sec. For 300 volts it is about 4.9×10^{-9} sec. Thus for $\theta = 2\pi$ and for a frequency of 900 mc., H has values of 416 gauss and 395 gauss for a V_b of 500 and 300 volts, respectively. This was consistent with the assumed value of H of 400 gauss.

Since the tube is made tunable over a wide range of frequencies, the value of H should be calculated as a function of frequency.

Summarizing all the previous calculations we have, for a particular tube, the following parameters:

$w = 1.5$ cm.
 $d = 0.86$ cm. to 1.66 cm.
 $t = 0.32$ cm.
 $V_b = 500$ volts
 $I_0 = 143$ ma. per beam
 $l = 5$ cm.
 $\theta = 2\pi$, $\eta = \frac{1}{2}\pi$
 $\phi_0 = 1,100$ volts

$\tau = 3.8 \times 10^{-9}$ sec.
 $H = 400$ gauss
 $f = 900$ mc.

It is necessary to estimate the ratio C/C_0 , which appears in the several expressions for Δf . As discussed heretofore, the capacitance of a single cavity is one-twelfth of the capacitance of twelve cavities which is about one-half of the total tube capacitance, C_0 . However, not more than two-thirds of the cavity capacitance appears in the region of the beam, and so C/C_0 is about one-thirty-sixth per beam.

The expected frequency shift is calculated from the equations. Using the foregoing data and a value of d of 1 cm., Equations 1, 10, and 17 provide a conservative value of Δf of about 1.0 mc. per beam.

Modulating electron gun design

The modulating electron guns are considered to be triodes with the accelerating electrode (the aperture cup 68), the cavity, and the collector considered as an effective anode at potential, V_a , and distance, b , from the control grids. If a is the grid-cathode spacing, V_g the grid voltage, and μ the amplification factor, the current density reaching the anode is

$$J = \frac{1}{9\pi} \sqrt{\frac{2e}{m}} \frac{1}{a^2} \left[\frac{V_a + V_g}{1 + \frac{1}{\mu} + \frac{4}{3} \frac{b}{\mu a}} \right]^{3/2} \quad (22)$$

For reasons discussed later, it was decided to operate the accelerating electrode at beam potential, and for simplicity of construction, an aperture of width equal to the cathode width, t , is used. The effective grid-anode spacing, b , for an aperture, cannot be less than the aperture width, as may be readily seen from field plots. Using $b = t$, and requiring that $J = J_0$ for $V_g = 0$, a numerical relation between μ and a was determined.

For a small grid bias to produce cut-off, a high μ is required, but this demands that a be small. In addition to constructional difficulties, if a is much smaller than the distance between grid wires, Equation 22 does not obtain in the cut-off region, and a remote cut-off is obtained. In view of these considerations, a value of a of 0.005 inch was chosen, giving μ a value of about 32.

The method of Vogdes and Elder, described in Physical Review, volume 24, December 1924, page 683, was used to determine the grid pitch. The grid wire diameter was made as small as practicable (0.002 inch) since a larger diameter requires a smaller number of turns per inch for the same μ . A value of 50 turns per inch may be selected. Since the distance between grid wires is 0.018 inch, compared to a grid-cathode spacing of 0.005 inch, a remote cut-off is to be expected.

However, if a were made larger, requiring a smaller μ , the number of turns per inch would be still smaller. For example, 0.010 inch cathode grid spacing would require a μ of 8.4 and a distance between grid wires of 0.044 inch. This is even a larger ratio of grid wire separation to grid-cathode spacing. Therefore, except for practical considerations, it would be desirable to use a still smaller grid-cathode spacing. The only way of overcoming the difficulty is to reduce the effective grid-anode spacing. Reduction of the aperture width would of course accomplish this but it would cut off part of the beam. The use of the screen grid 74, however, placed 0.025 inch from the control grid 71 provides a satisfactory solution. The two grids, which are aligned

in beam-power fashion, have 65 turns per inch, a wire diameter of 0.004 inch (increased to permit adequate cooling of the screen wires) giving a μ of 25 and a grid-cathode spacing of 0.006 inch, compared to a distance between grid wires of 0.013 inch. As a result, an appreciably less remote cut-off is provided.

Mechanical tuning mechanism

The anode vane straps 55 comprise two pairs of coaxial split straps in which each pair is connected to alternate ones of the anode vanes 49. The anode vane straps, as described heretofore, are located only on the lower inner edges of the anode vanes, and are considerably wider in the longitudinal dimension of the tube than is customary in order to provide increased anode cavity capacitance, thus providing improved mode separation. The tuning element comprises three coaxial cylindrical elements 57, carried by a common support 91, and telescoped between the four coaxial anode strapping rings 55. A clearance aperture 93 is provided in the center of the collector 93 for the tuner support 91. The tuner support 91 is connected through a rigid arm 95 to the center of the Sylphon diaphragm 11 and the arm 95 is rigidly connected to the end of an externally threaded actuating rod 97. The Sylphon diaphragm 11 provides a vacuum seal for the lower end of the evacuated envelope 1.

The ring of the envelope 1 externally of the Sylphon diaphragm 11 supports the fixed portion 98 of a ball bearing race 99. The movable portion of the ball bearing race comprises an annular element 101 having a central aperture which is complementarily threaded to the actuating rod 97. A cover plate 103 for the ball bearing race is fastened to the inner side of movable element 101. In order to provide for vernier actuation of the tuning mechanism, a large gear 105 is fastened to the outer surface of the movable element 101 and may be actuated by a vernier gear 107 and control knob 109. Thus rotation of the control knob 109 provides vernier rotation of the movable element 101 which, in turn, provides longitudinal motion of the threaded rod 97, the Sylphon diaphragm 11, and the tuning mechanism 57, 91. Since most efficient tuning of the system is provided with minimum capacitance across the magnetron anode cavities, the tuning of the device should be adjusted so that the tuning mechanism 57 is substantially withdrawn from between the anode vane straps 55 at the highest operating frequency. When the tuning element 57 is completely telescoped between the spaces between the anode straps 55, the lowest operating frequency is obtained. If the tuning actuating mechanism is carefully designed and assembled, a spacing of the order of .020 inch between the movable and fixed elements of the tuning mechanism may be employed advantageously.

Output coupling and load line seal

A coaxial output coupling and load line seal is required which will satisfactorily handle a constant power output of at least one kilowatt coupled into a 52 ohm transmission line having a maximum standing wave ratio of 1.5. It is desirable that the output seal and coupling assembly shall introduce negligible electrical discontinuity between the output coupling loop 21 and the output transmission line. For reasons of convenience and economy it also is desirable that the device be self-cooled. For ease in as-

sembly, the use of a prefabricated output seal, coupling loop and transmission line termination is to be desired.

The coupling loop 21 is preformed and welded to the end of the tapered inner conductor 111 of the output transmission line connector 23. The outer end of the connector inner conductor is provided with an aperture 133 to receive the inner conductor 129 of the output transmission line. The outer conductor 113 of the connector also is tapered to minimize electrical discontinuity and supports the inner conductor 111 by a sleeve 114 and a tapered glass seal 115 which provides a vacuum seal for the output circuit. The tapered glass seal 115 should be designed, in accordance with known technique, to introduce minimum electrical discontinuity in the line. The outer conductor 113 of the connector 23 is fastened by a bracket 117 to the outer surface of the evacuated envelope 1. A sleeve 118 and second bracket 119 which may be secured to the first bracket 117 by locking screws 121 provides a support for the outer conductor 123 of the output transmission line. The output transmission line outer conductor 123 includes spring contacts 125 which engage the sleeve 114 of the output conductor of the connector when the output line is connected thereto. The inner conductor 129 of the output transmission line includes a spring connector 131 which telescopes within the aperture 133 in the outer end of the inner conductor of the connector.

Thus the invention described comprises an improved multi-cavity frequency modulated magnetron generator, utilizing a plurality of electron beams derived from screen grid electron generating sources and including novel support and connection means for said modulating electron sources providing a convenient and compact assembly insuring uniform operation of all of the modulating electron sources. The novel frequency-modulated magnetron described includes a novel output termination and a novel frequency control mechanism for adjusting the mean operating frequency of the device.

We claim as our invention:

1. A microwave generator comprising a cathode, an anode cavity resonator adjacent to said cathode, and frequency modulating means including means for projecting an electron beam along a predetermined path through said resonator to vary the reactance of said resonator as a function of the energy of said electron beam and means comprising screen grid wires extending across said path for collecting secondary-electrons generated by said beam.
2. A magnetron microwave generator comprising a centrally located cathode, a plurality of anode cavity resonators surrounding said cathode, and frequency modulating means including means for projecting an electron beam along a predetermined path through one of said resonators to vary the reactance of said resonator as a function of the energy of said electron beam and means comprising screen grid wires extending across said path for collecting secondary-electrons generated by said beam.
3. A magnetron microwave generator comprising a centrally located cathode, a plurality of radial conductive vanes forming a plurality of anode cavity resonators surrounding said cathode, and frequency modulating means for projecting a separate electron beam along a predetermined path through each of said resonators to vary the reactance of said resonators as

15

a function of the energy of said electron beams and means comprising screen grid wires extending across each of said paths for collecting secondary-electrons generated by said beams.

4. A magnetron microwave generator comprising a centrally located cathode, a plurality of sectoral anode cavity resonators surrounding said cathode, and frequency modulating means including a plurality of electron guns arranged to project a separate electron beam along a predetermined path through each of said resonators to vary the reactance of said resonators as a function of the energy of said electron beams and means comprising screen grid wires extending across each of said paths for collecting secondary-electrons generated by said beams.

5. A magnetron microwave generator comprising a centrally located cathode, a plurality of radial conductive vanes forming a plurality of anode cavity resonators surrounding said cathode, and frequency modulating means including a plurality of electron guns each including a thermionic cathode, a control electrode and an accelerating and screen grid electrode arranged to project a separate electron beam through each of said resonators to vary the reactance of said resonators as a function of the energy of said electron beams, each of said accelerating and screen grid electrodes comprising screen grid wires extending across the path of the beam.

6. A magnetron microwave generator comprising a centrally located cathode, a plurality of radial conductive vanes forming a plurality of anode cavity resonators surrounding said cathode, and frequency modulating means including a plurality of electron guns each including a thermionic cathode, a control electrode and an accelerating and screen grid electrode arranged to project a separate electron beam through each of said resonators to vary the reactance of said resonators as a function of the energy of said electron beams, each of said accelerating and screen grid electrodes comprising screen grid wires extending across the path of the beam, and means for collecting said electron beams after projection through said resonators.

7. A magnetron microwave generator comprising a centrally located cathode, a plurality of radial conductive vanes forming a plurality of anode cavity resonators surrounding said cathode, and frequency modulating means including a plurality of electron guns each including a thermionic cathode, a control electrode and an accelerating and screen grid electrode arranged to project a separate electron beam through each of said resonators to vary the reactance of said resonators as a function of the energy of said electron beams, each of said accelerating and screen grid electrodes comprising screen grid wires extending across the path of the beam, and a common collector electrode for collecting said electron beams after traversal of said resonators.

8. A magnetron microwave generator comprising a centrally located cathode, a plurality of radial vanes forming a plurality of juxtaposed anode cavity resonators surrounding said cathode, frequency modulating means including means for projecting a separate electron beam along a predetermined path through each of said resonators in regions adjacent to the apices of said resonators to vary the reactance of said resonators as a function of the energy of said electron beams, and means interposed in said paths to collect secondary-electrons generated by

16

said beams, a pair of concentric conductive means connecting together alternate ones of said radial vanes, and adjustable conductive means concentric with and telescoped between said connecting means for adjusting concurrently the tuning of all of said resonators.

9. A magnetron microwave generator including a centrally disposed cathode, a plurality of radial conductive vanes forming a plurality of anode cavity resonators surrounding and opening toward said cathode, a plurality of frequency-modulating electron beam devices each operative to project an electron beam through one of said resonators to vary the reactance thereof as a function of the energy of each of said beams, said devices each comprising a cathode, a control grid and a screen grid mounted adjacent one side of one of said cavity resonators, each of said screen grids comprising screen grid wires extending across the path of the beam, and an electron collector electrode on the other side of said resonators remote from said devices.

10. Apparatus according to claim 9 including means for supporting and connecting to each of said electron beam devices comprising a plurality of concentric annular conductors insulated from and supported adjacent to one end of said resonators, one of said conductors supporting all of said devices in spaced angular relation adjacent different ones of said resonators, and others of said conductors providing bus connections to similar electrodes of said devices.

11. A magnetron microwave generator including a centrally disposed cathode, a plurality of radially disposed anode cavity resonators surrounding and opening toward said cathode, a plurality of frequency-modulating electron beam devices each operative to project an electron beam through one of said resonators to vary the reactance thereof as a function of the energy of each of said beams, said devices each comprising a cathode, a control grid, an electron reflector electrode adjacent one side of said cathode and an electrode substantially surrounding said cathode, grid and reflector electrodes and having an aperture therein adjacent the side of said cathode remote from said reflector electrode, an electron collector electrode on the side of said resonators remote from said devices.

12. Apparatus according to claim 11 including means for supporting and connecting to each of said electron beam devices comprising a plurality of concentric annular conductors insulated from and supported adjacent to one end of said resonators, one of said conductors supporting all of said devices in spaced angular relation adjacent different ones of said resonators, and others of said conductors providing bus connections to similar electrodes of said devices.

13. A magnetron microwave generator including a centrally disposed cathode, a plurality of radially disposed vanes forming a plurality of anode cavity resonators surrounding and opening toward said cathode, a plurality of frequency-modulating electron beam devices each operative to project an electron beam through one of said resonators in regions adjacent to the apices of said resonators to vary the reactance thereof as a function of the energy of each of said beams, said devices each comprising a cathode, a control grid, an electron reflector electrode adjacent one side of said cathode and an electrode substantially surrounding said cathode, grid and reflector electrodes and having an aperture therein adjacent the side of said cathode remote from

17

said reflector electrode, an electron collector electrode on the side of said resonators remote from said devices, a plurality of concentric conductive means connecting together alternate ones of said radial vanes, and adjustable conductive means concentric with and telescoped between said connecting means and providing an adjustable capacitance for tuning concurrently all of said resonators.

14. Apparatus according to claim 13 including means supporting and connecting said electron beam devices comprising a plurality of concentric annular conductors insulated from and supported adjacent to one end of said resonators, one of said conductors supporting all of said devices in spaced angular relation adjacent different ones

18

of said resonators, and others of said conductors providing bus connections to similar electrodes of said devices.

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