Sept. 20, 1966 I. EL-HEFNI 3,274,430

BIASED-GAP KLYSTRON

Filed Aug. 1, 1963 2 Sheets-Sheet 1

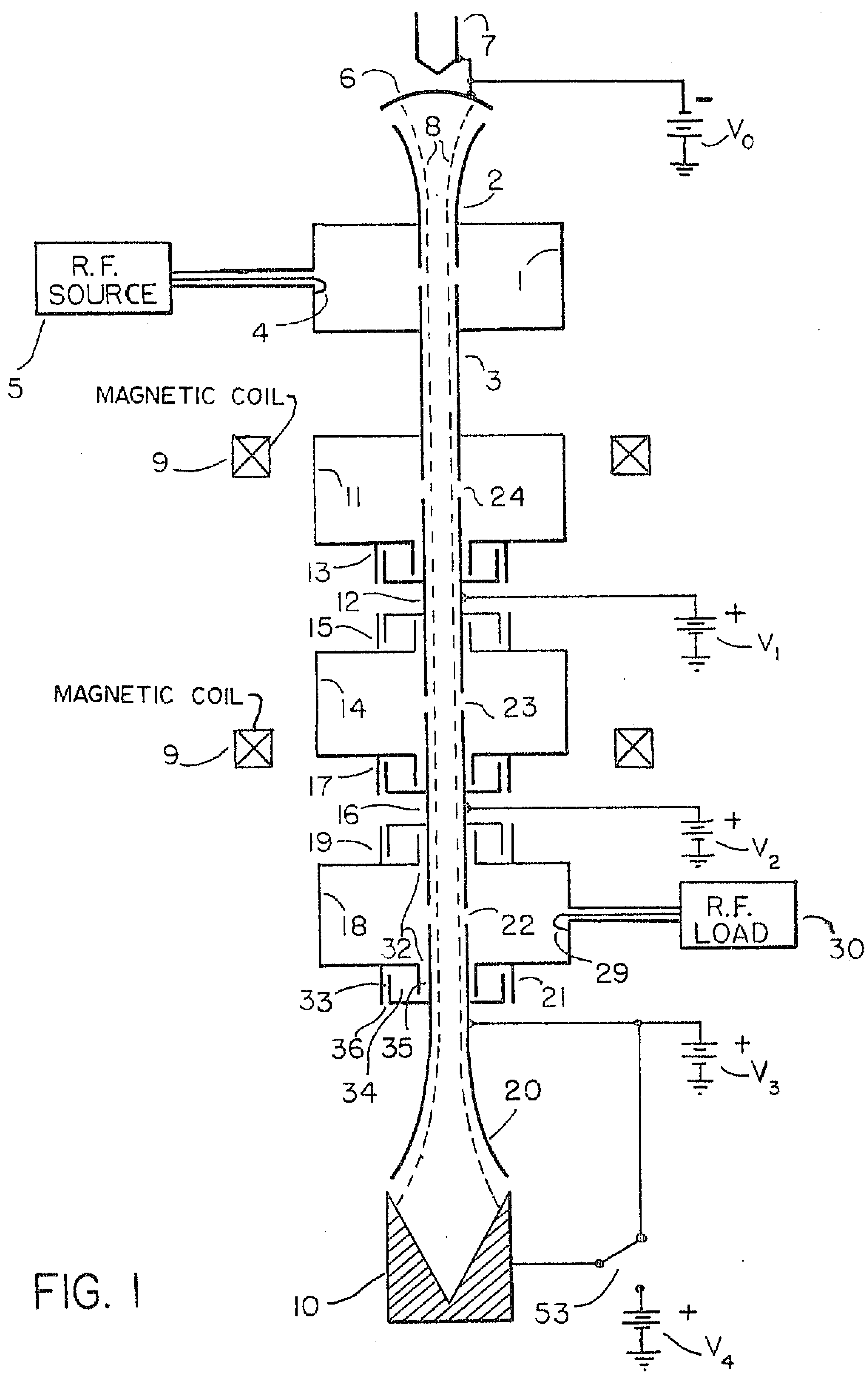

FIG. 1

INVENTOR.
IBRAHIM EL-HEFNI

BY Martin M. Santa
ATTORNEY

BIASED-GAP KLYSTRON

Filed Aug. 1, 1963 2 Sheets-Sheet 2

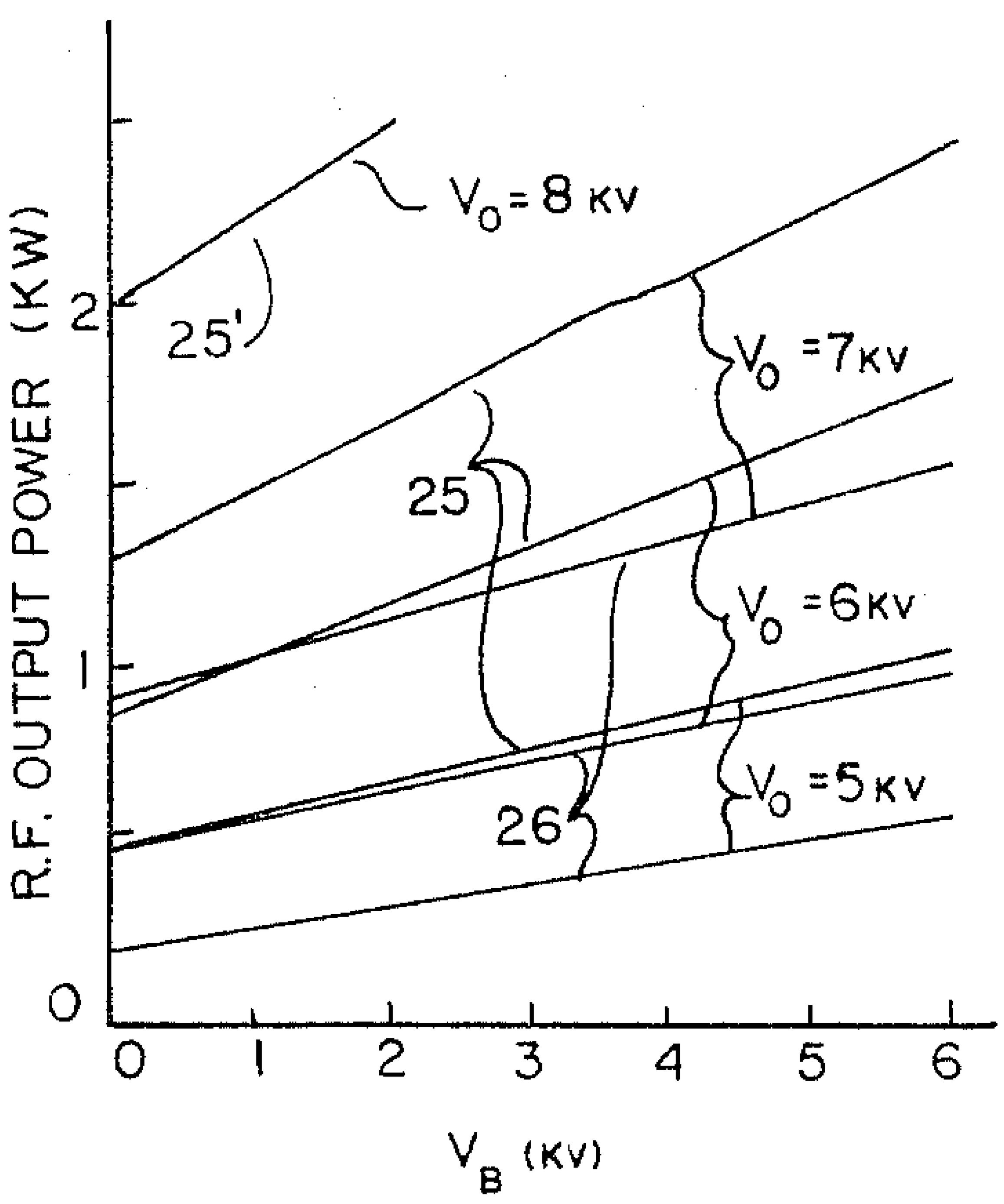

FIG. 2

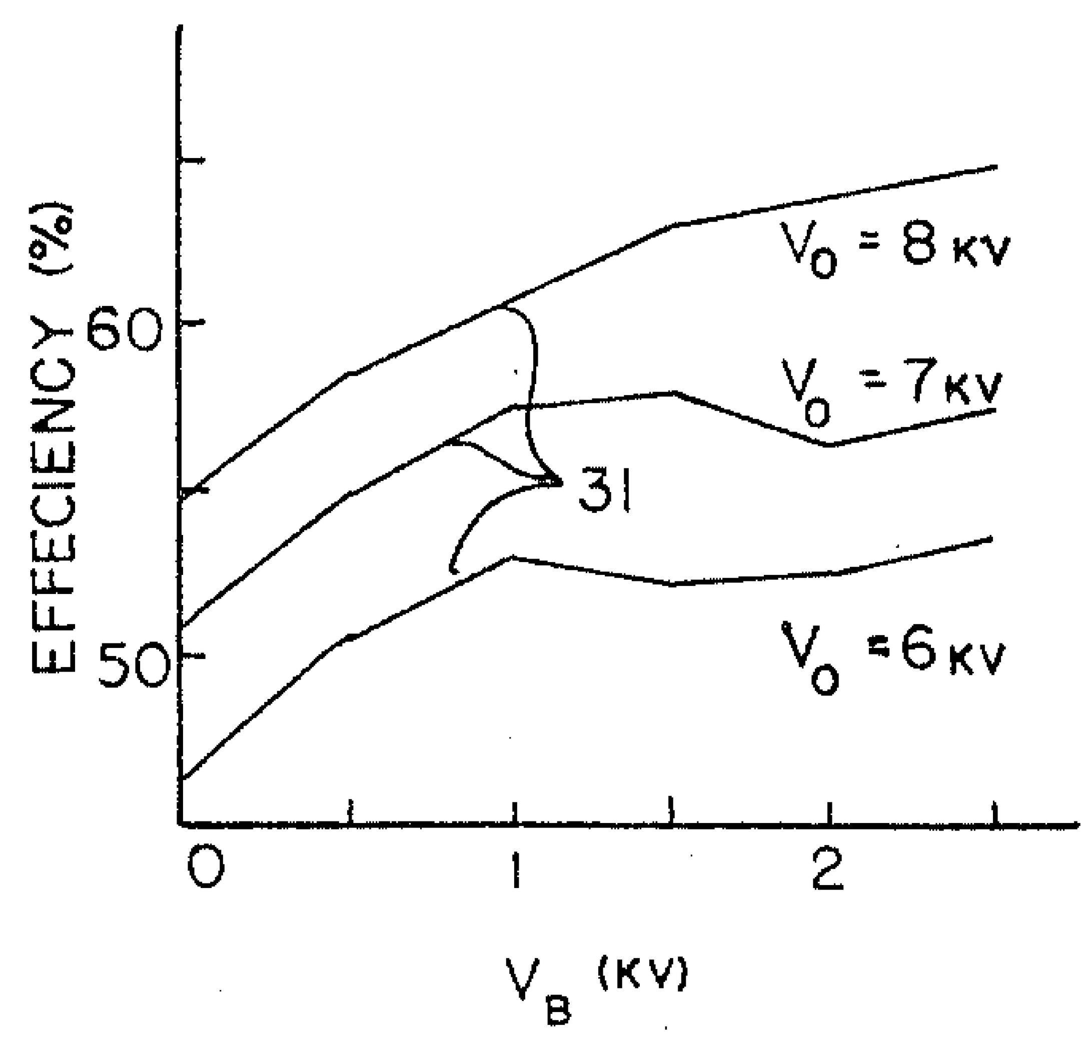

FIG. 3

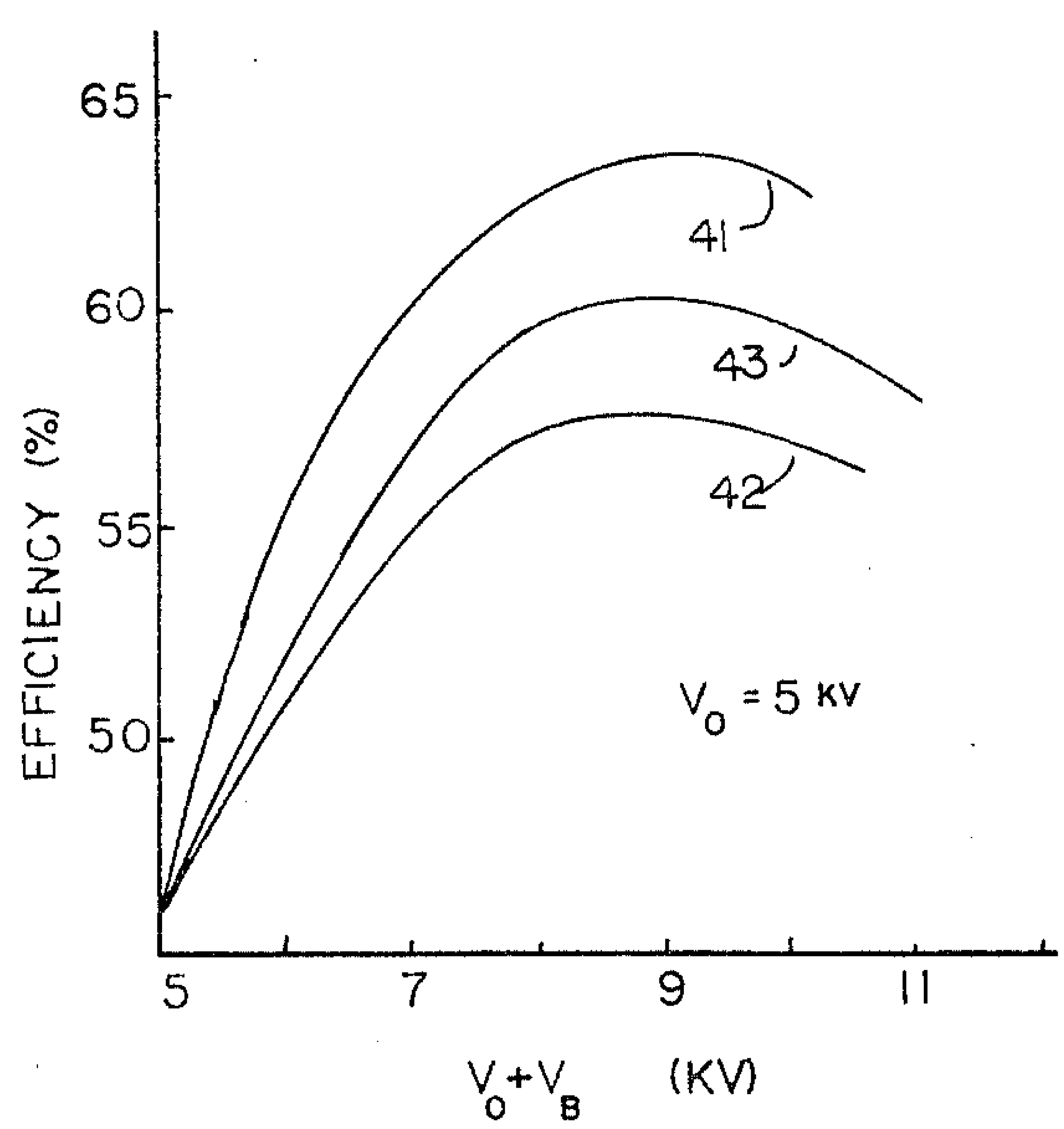

FIG. 4

INVENTOR.
IBRAHIM EL-HEFNI
BY Martin M. Santa
ATTORNEY

United States Patent Office

3,274,430

Patented Sept. 20, 1966

3,274,430

BIASED-GAP KLYSTRON

Ibrahim El-Hefni, North Andover, Mass., assignor to Massachusetts Institute of Technology, Cambridge, Mass., a corporation of Massachusetts

Filed Aug. 1, 1963, Ser. No. 299,350

7 Claims. (Cl. 315—5.41)

This invention relates to an electron beam microwave tube and in particular to a multi-cavity klystron wherein an accelerating D.C. voltage is applied along the R.F. interaction region and more specifically across the interaction gaps of the cavities.

In general, klystron tubes designed for high-power operation operate at relatively low efficiencies compared to other types of high frequency tubes, but are much more stable at high gains (30 db), and for this reason continue to be preferred in certain applications despite lower efficiency. However, even a slight increase in efficiency of the high-power klystron is highly desirable and much effort to provide this increase has been expended without great success. Moreover, the high-power klystron has other operating characteristics which limit its power capability. Among these are the problems of beam interception and multipactor. It is to obtain improvement in all these operating characteristics but especially efficiency that the apparatus of this invention is directed.

In the conventional multi-cavity klystron the electron beam is accelerated to its full potential in the gun region before it is injected into the R.F. structure of the tube. In the klystron according to this invention, the beam is only partially accelerated in the gun region and as it is being bunched by the radio frequency gap fields further D.C. acceleration is applied by one or more of these gaps. It has been found that the application of an accelerating D.C. potential across the gap of a cavity of a klystron produces an increase of efficiency, an increase in power output, an increase in stability and an improvement in beam transmission. One would expect, therefore, that the multipactor problem would be reduced. The extent of the influence upon any one of these items being dependent upon the particular cavity in the multi-cavity klystron to which the potential is applied. It has also been found that additional improvement is obtained when the collector is at a lower potential than the accelerating D.C. potential.

It is, therefore, an object of this invention to provide an improved tube of the type employing R.F. cavities to provide velocity modulation of an electron beam.

It is another object to provide an improved klystron in which one or more of its R.F. cavity gaps has a direct voltage accelerating field.

It is a further object to provide a klystron in which the collector is at a lower potential than the accelerating potential.

The novel features which are believed to be characteristic of the invention together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example.

FIGURE 1 is a diagrammatic sectional view of an embodiment of the invention together with associated circuitry.

FIGURE 2 is an illustrative diagram of the power output for a biased output gap.

FIGURE 3 and FIGURE 4 are illustrative diagrams of efficiency versus bias voltage on various cavity gaps.

Referring now to the drawings, FIGURE 1 illustrates an embodiment of the present invention comprising a four-cavity klystron tube with three of the cavities direct

voltage insulated from their associated drift-tubes by means of R.F. chokes. For clarity of illustration, in order to more effectively present the novel features of this invention, the mechanical details by which adjacent drift-tube sections are connected to provide rigidity and a vacuum tight enclosure are not shown. Also, the supporting housing for the cathode **6** and the collector **10** are omitted for a like reason.

Input cavity **1** is in direct electrical contact with the internal drift-tube sections **2** and **3** to form an R.F. resonant chamber as in a conventional klystron. This cavity is at direct ground potential. When the klystron is operated as an amplifier, R.F. energy is induced in cavity **1** by excitation of coupling loop **4** from a low-power R.F. source **5**. The cathode **6** heated by filament **7** are both electrically connected to a negative high voltage source V_0. The potential V_0 which exists between cathode **6** and drift-tube section **2** causes the electrons emitted from the surface of cathde **6** to be accelerated down through drift-tube sections **2** and **3** in the form of a beam **8**. The beam proceeds down the length of the klystron through drift tubes **12**, **16**, and **20** under the influence of the focussing magnetic field of magnetic coils **9** until the beam **8** strikes the collector **10**.

The experimental evaluation of this invention was performed chiefly on a commercially available tube, the Eimac 4KM–3000–LR, rated at 2 kw. as a C.W. amplifier at 8 kv. cathode voltage, having an electrically isolated collector, a narrow gap (0.8 radian), and designed for operation with four external cavities. The efficiency of this tube is relatively high (40 to 55% depending upon the accelerating voltage V_0) when operated in the conventional manner with all the cavities directly connected to the drift-tube sections without gap bias. Some data was taken on a wide-gap tube (2 radians) for comparison purposes. As a general rule, the data given in this application which shows the superiority of biased-gap operation on the narrow-gap klystron applies equally well and more so to the wide-gap klystron.

Drift-tube **3** is shared by cavity **1** and the next buncher cavity **11** seen by the beam **8** as it progresses down the length of the klystron. The cavity **11** is electrically connected to drift-tube **12** through R.F. choke **13**. Drift-tube **12** is also electrically connected to the adjacent buncher cavity **14** through choke **15**. Therefore, a D.C. potential V_1 may be directly applied to drift-tube **12** while allowing cavities **11** and **14** to be at ground potential which is usually desired for safety and convenience. Cavity **14** is also electrically connected to drift-tube **16** through choke **17**. Drift-tube **16** is also connected through R.F. choke **19** to the output cavity **18** which is in turn connected to the final drift-tube **20** through choke **21**. D.C. potentials V_2 and V_3 may then be applied to the isolated drift-tubes **16** and **20**, respectively. It is to be noted that two drift-tubes choke coupled to their associated cavity form a reentrant resonant cavity or resonator which when energized with radio frequency signals produces an R.F. voltage gradient in cavity gap. In addition, a D.C. voltage gradient is produced across the gap by the difference in voltage on adjacent drift-tubes. Therefore, gaps **22**, **23**, and **24** have R.F. and D.C. voltage gradients if $V_3>V_2>V_1>0$. It should be noted that although FIGURE 1 shows drift-tubes **12**, **16** and **20** at potentials V_1, V_2 and V_3, it is possible to operate this klystron with drift-tube **12** grounded, or alternatively drift-tubes **12** and **16** both grounded. For example, if both drift-tubes **12** and **16** are grounded, cavities **14** and **18** may be directed connected to these drift-tube sections as in a conventional klystron without the necessity of the R.F. chokes **13**, **15**, **17** and **19**. It is also to be noted that since the potentials across gaps **22**, 23 and 24 are desired to be accelerating potentials relative to the motion electron beam 8, it follows that the potentials $V_3 \geqslant V_2 \geqslant V_1 \geqslant 0$ be maintained at all times.

For biased output gap operation with undepressed collector, only the output cavity gap 22 is to be biased with an accelerating potential. The voltage sources V_1 and V_2 are set to zero or ground potential, and the collector 10 is connected through switch 53 to the voltage source V_3. Drift-tube electrode 20 and collector 10 are, therefore, directly connected in undepressed collector operation. Biasted-output gap 22, operation for the narrow-gap klystron for various values of cathode voltage V_0 is shown as curves 25 of FIGURE 2. It is seen that the available R.F. output power to the load 30 increases as the bias voltage $V_b=V_3$ across the output gap 22 increases. It was found that the available output power is related to the bias voltage V_b by the simple equation $P_{av}=I_1(V_0+kV_b)$ when P_{av} is the available output power I_1 is a constant representing the fundamental component of the R.F. beam current at the output gap 22, V_0 is the cathode 6 voltage, and k is a constant equal to unity for the narrow-gap klyston and greater than unity for the wide-gap klystron (curves 26 of FIGURE 2). In both narrow- and wide-gap tube operation, for biased-output gap 22 operation (non-depressed collector 10) the D.C. beam current I_0, 8, is determined by the magnitude of the cathode voltage V_0, and the power V_0I_0 is supplied by source V_0. The beam 8 is intercepted at the other end of the klystron either on electrode 20 or collector 10 both of which are connected to potential source $V_3=V_b$ which must, therefore, supply a power V_bI_0. Thus, the D.C. input power is given by $P_{D.C.}=I_0(V_0+V_b)$.

For the narrow-gap klystron where $k=1$, the R.F. output power P_{av} increases at the same rate as the D.C. input power $P_{D.C.}$ and hence biased output gap (non-depressed collector) operation does not increase efficiency. However, there is some advantage to biased output gap operation even in this case. Reference to curve 25' of FIGURE 2 shows that the 2 kw. rated output of this tube is obtained at $V_0=8$ kv. If it is assumed as is the case in many high power klystrons, that the cathode voltage V_0 is the limiting factor on the maximum output power and that in this case the 8 kv. cathode voltage is the limiting factor on output power, it is seen that greater power than 2 kw. is obtained with $V_0=8$ kv. and output gap D.C. voltage $V_3=V_b>0$ even though the efficiency is not changed.

For the wide-gap klystron where $k>1$, reference to FIGURE 2, curves 26 shows that the R.F. power is seen to increase at a greater rate than the increase in D.C. input power from the biased gap 22 source and, therefore, the efficiency increases with bias voltage $V_3=V_b$, even for non-depressed collector.

Increased efficiency can be obtained with biased output gap 22 operation if collector 10 is connected through switch 53 to a potential $V_4<V_3$. This type of operation is termed depressed collector operation. FIGURE 3 illustrates the efficiency improvement where the collector 10 is connected to $V_4=$ground potential and different values of voltage V_3 are applied to the electrode 20 for certain fixed values of cathode potential V_0. Curves 31 show that a significant increase in efficiency is obtained with depressed collector operation. Operation with $V_4<V_3$, where $V_3=V_b$ is a larger fraction of V_0 than the values of FIGURE 3, has been found to result in significant increases in efficiency also. The increase in efficiency for depressed collector operation is attributed to the fact that the R.F. power output into load 30 remains the same whether or not the collector 10 is depressed; however, the D.C. power input from source V_3 and V_4 is reduced. The beam current I_0 divides between electrode 20 and collector 10; the D.C. power input $[V_3(\alpha I_0)+V_4(1-\alpha)I_0]$ where α is the ratio of the current on electrode 20 to the current on collector 10, for depressed collector operation is less than the D.C. power input V_3I_0 for undepressed collector operation. Optimum efficiency occurs for that combination of collector voltage V_4 and electrode 20 voltage V_3 which results in minimum D.C. power input. It should be noted that although the collector 10 of the experimental tube was not designed for depressed operation, significant increase in efficiency was obtained. The highest efficiency achieved was approximately 65%. However, the results shown are by no means optimum and higher efficiencies are expected for the situation where the collector is designed for depressed operation.

It should be noted that in other techniques to increase efficiency by depressed collector operation, the kinetic energy of the spent team is recovered as D.C. energy, and is often dissipated in a resistor and assumed to be recoverable as D.C. energy at the cathode input supply V_0. This is not the case with the depressed collector biased-gap klystron operation in accordance with this invention. Here the energy of the electron beam 8 is converted directly as R.F. energy, and the efficiency calculated is the overall electronic efficiency of the klystron with no attempt to recover D.C. energy at the collector for subsequent utilization as D.C. input energy.

A biasing potential across the penultimate cavity gap 23 or across the preceding buncher cavity gap 24 is also effective in increasing klystron efficiency and hence power output. Bias potential $V_b=V_2$ is applied across gap 23 for the condition $V_1=0$ and $V_4=V_3=V_2$. The curve 41 of FIGURE 4 shows the efficiency for this condition of operation for $V_0=5$ kv. and $5 \geqslant V_b \geqslant 0$. A comparison of curve 41 with curve 42, which is the efficiency curve of the experimental tube conventionally operated with no accelerating bias potential, shows that the biased penultimate gap 23 produces a significant increase in efficiency. For instance, for a total beam voltage $V_0+V_b=8$ kilovolts, the efficiency of the klystron with the biased penultimate cavity 14 is approximately 63% as compared to an efficiency of approximately 56% for the conventionally operated tube at a beam voltage V_0 of 8 kv. The increase in the efficiency obtained by biasing the penultimate cavity 14 is attributed to the effective change in electrical length of the drift-tube 16 between the penultimate cavity 14 and output cavity 18, and secondarily to the increase in the fundamental component of the R.F. current at the output gap 22. The change in electrical length of the drift tube 16, caused by the change in velocity of the electrons under the influence of the D.C. accelerating potential at gap 23 is thought to result in improved performance because of shifting of the bunched R.F. current maximum with respect to the output gap to a more optimum position. Inspection of curve 41 of FIGURE 4 shows that there is a limited region of bias voltage V_b where a peak in efficiency occurs. It is also believed that the bunching of the electron beam is increased by the biased gap whereby the fundamental component of R.F. in the beam current is increased.

The maximum efficiency for undepressed collector 10 operation with the biased penultimate cavity gap 23 is seen by inspection of curve 41 of FIGURE 4 to be 63%. However, efficiency of greater than 70% was achieved with depressed collector operation when collector 10 was grounded through switch 53. The increased efficiency of the biased penultimate gap 23 with depressed collector is believed attributable to the same cause advanced for biased output gap 22 depressed collector operation. It was found that the cathode 6 voltage V_0 did not appreciably affect the maximum efficiency of biased penultimate gap 23 operation although curve 41 for $V_0=5$ kv. was slightly different for higher values of cathode voltage V_0.

An accelerating potential $V_b=V_1$ across the gap of the buncher cavity 11 preceding the penultimate cavity 14 resulted in an efficiency curve 43 of FIGURE 4 which was intermediate the unbiased klystron efficiency curve

42 and the biased penultimate cavity efficiency curve 41. Depressed collector operation with $V_4=0$ and

$$V_1=V_2=V_3$$

resulted in a maximum efficiency of about 60%.

It is to be concluded that depressed collector 10- biased penultimate gap 23 operation results in the optimum efficiency and power output. However, it is possible to apply accelerating potentials across other gaps, particularly the output gap 22, at the same time although the experimental tube did not indicate that this was a superior mode of operation over the depressed collector-biased penultimate cavity gap alone.

The chokes 13, 15, 17, 19 and 21 are designed to provide an effective R.F. short circuit to electrical energy within their respective cavities at the input slot 32 of each choke. The location of the choke input slot 32 is of primary importance and should be located at a region of its associated cavity where the R.F. current is a minimum. The location of the current minimum depends on the particular cavity configuration and for most cavities used in practice must be determined experimentally. In a practical situation, mechanical considerations may require that the choke be placed other than this current minimum location. For example, in the applicant's tube which uses external cavities, it was found mechanically convenient and electrically satisfactory to place the chokes at the junction where the external cavities make electrical contact with contact rings of the drift tubes.

The choke itself is a conventional three transmission line design such as that described in "Principles of Microwave Circuits," Montgomery, Dicke and Purcell, McGraw-Hill, 1948, page 198, where the length and impedance of lines 33, 34, and 35 are selected by the use of transmission line formulas to produce a short circuit impedance at the input slot 32 for a free space termination at output slot 36 over a wide frequency band. A three section choke properly designed and located in the cavity was found to have very low level of R.F. energy radiation from the output slot 36.

Biased gap operation of a klystron provides other desirable features other than increased efficiency and R.F. power output. It is found that there is an increase in beam transmission and better high-gain stability. It is also expected that possibility of multipactor is reduced.

Multipactor is defined as the electronic gap admittance resulting from a sustained secondary-emission discharge produced in a gap by the motion of the secondary electrons in synchronism with the electric field in the gap. Attempts by others to eliminate multipacting by coating one edge of the output gap 22 with a low secondary emission material results in a lossy cavity and hence is undesirable. Also indenting the edges of the gap 22 to destroy the symmetry which is helpful to synchronism has been moderately successful. The biased output gap should minimize the multipactor problem since the D.C. potential across the gap destroys the symmetry in the electric field in the gap since the field in one direction is greater than in the other during one cycle of the R.F. voltage in the gap.

Interception of even a small fraction, less than 5%, of the D.C. beam current I_0 by an element of the klystron other than the collector 10 or the portion of the tube electrode 20 facing collector 10, is highly undesirable in a high power klystron. In general, interception is found to take place primarily at the edge of the output gap 22 where the localized region of impact of the intercepted electrons causes severe heating where interception of only 2% of the beam 8 of a 1 megawatt klystron resulting in 20 kilowatts of power to be dissipated. Biased gap operation of the experimental klystron caused the beam 8 transmission from cathode 6 to collector 10 to increase from 97% to over 99%. Therefore, it is seen that biased output gap or penultimate gap operation will reduce the localized heating problem due to beam interception.

High gain stability of klystrons is also seen to be improved by biased gap operation. In conventional klystrons, any electron which has been decelerated to a point where its velocity direction has reversed will return to the gap of input cavity 1 without difficulty. Instability is the likely result of the presence of such electrons. The presence of the D.C. biased gap provides an electric field which opposes the return of these reversed electrons to the input cavity 1 resulting in greater isolation of the R.F. output and input and hence greater stability.

It was mentioned earlier that the application of an accelerating voltage to the cavity gaps 24 and 23 causes a change in the electrical length of drift tube sections 12 and 16 respectively. This change in electrical length may be used to phase control the output R.F. energy relative to the input R.F. energy. This may be accomplished by tapping a small portion of the R.F. output energy of load 30 into a phase detector whose other input is the R.F. input energy source 5. The D.C. output from this phase detector is D.C. amplified to control the voltage applied to drift tube sections 16 or 12 instead of using fixed potential sources V_2 and V_1. It is also seen that since the accelerator voltage V_1, V_2, and V_3 affect the output power, the output power amplitude can be controlled by an amplitude detector sampling the output power and then being connected to a controllable source of D.C. voltage which is used in place of any of the fixed potential sources V_1, V_2, or V_3.

Although the tube described was operated as an amplifier, it is not to be construed that this invention could be so restrictive. It is believed that improved operation of a klystron functioning as an oscillator would also be obtained using bias gap construction. Although a klystron has been used as the preferred embodiment of this invention, the principle of bias gap acceleration of an electron beam would be applicable to other tubes in which velocity modulation of an electron beam is used in conjunction with drift tube sections.

What is claimed is:

1. An electron beam modulation device comprising, an electron beam source for providing a beam having a defined axis, a plurality of cavities of the reentrant type, said cavities having drift tube sections as their reentrant portions through which the beam passes, said drift tube sections of each cavity being in axial alignment and in spaced apart relation to form a gap, said gap being a part of said cavity, whereby an R.F. electric field within said cavity provides an R.F. electric potential across said gap to act on said beam, means for applying a D.C. potential across at least one of said gaps to provide a D.C. electric field across the gap acting upon the beam to increase its velocity, and a collector for termination of said beam.

2. The apparatus as defined in claim 1 comprising in addition a plurality of R.F. chokes, at least one choke of said plurality being placed between the drift tube forming one side of the gap to which a D.C. potential is applied and the cavity connected to the drift tube forming the other side of the gap, said choke providing an electrical short circuit at the resonant frequency of the cavity while providing an open circuit for the D.C. potential applied across the gap.

3. The apparatus as in claim 1 comprising in addition said collector being connected to a source of D.C. potential to provide a decelerating D.C. electric field acting on said beam to reduce its velocity before terminating on said collector.

4. The apparatus as defined in claim 1 comprising in addition at least one R.F. choke placed between each drift tube forming one side of the gap to which a D.C. potential is applied and the said cavity, said choke providing an electrical short circuit at the resonant frequency of the cavity while providing an open circuit for the D.C. potential difference between said drift tube and the remainder of said cavity.

5. The apparatus as defined in claim 2 wherein said

cavity has a region of low R.F. current density at its resonant frequency, said choke being located in the region of low current density in the cavity.

6. An electron beam modulation device comprising, an electron beam source for providing a beam having a defined axis, a plurality of cavities each resonant at an R.F. frequency, each cavity having a gap to allow said beam to pass through the cavity whereby said beam is acted upon by the R.F. field at each cavity gap to change its velocity and space charge distribution, said plurality of cavities including an input cavity, an output cavity and intermediate cavities, means for applying a D.C. potential across the gap of the one of said intermediate cavities adjacent said output cavity, whereby said potential produces a D.C. electric field in said cavity gap to cause said beam to increase in velocity, and a collector for terminating said beam.

7. The apparatus as in claim 6 comprising in addition, means for providing a D.C. decelerating electric field acting on said beam to reduce the velocity of the beam in the region between the output cavity and the collector.

References Cited by the Examiner

UNITED STATES PATENTS

2,547,061	4/1951	Touraton et al.	315—5.41
2,918,599	12/1959	Beck et al.	315—5.41
3,020,439	2/1962	Eichenbaum	315—5.41 X
3,172,008	3/1965	Schmidt et al.	315—5.41 X

HERMAN KARL SAALBACH, *Primary Examiner.*

P. L. GENSLER, *Assistant Examiner.*