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Lien

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[54] **VELOCITY MODULATION MICROWAVE TUBE EMPLOYING A HARMONIC PREBUNCHER FOR IMPROVED EFFICIENCY**

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[21] Appl. No.: **332,447**

Related U.S. Application Data

[63] Continuation of Ser. No. 767,774, Oct. 15, 1968, abandoned.

[52] **U.S. Cl.** **315/5.43,** 315/5.51, 315/5.52, 315/5.39

[51] **Int. Cl.** **H01j 25/10**

[58] **Field of Search** 315/5.39, 5.43, 5.51, 5.52

[56] **References Cited**

UNITED STATES PATENTS

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[57] **ABSTRACT**

The velocity modulation microwave tube includes an electron gun for projecting a stream of electrons over an elongated beam path to a collector structure. An input circuit and an output circuit are disposed at the upstream and downstream ends, respectively, of the beam for applying microwave energy to be amplified to the tube and for extracting the amplified microwave energy from the beam. A penultimate resonator circuit, tuned for a mode of resonance at a frequency near the passband of the tube, is provided just upstream of the output circuit for bunching the current density of the beam passing into the output circuit. A harmonic floating resonator structure is disclosed along the beam path intermediate the input circuit and the penultimate resonator. The harmonic resonator is tuned for a mode of resonance approximately at a frequency corresponding to a harmonic higher than the first of the center frequency of the passband of the tube. The harmonic resonator serves as a prebuncher to bunching the electrons of the beam prior to their entering the final stage of bunching performed by the penultimate floating resonator. The combined action of the harmonic prebuncher resonator and the penultimate final buncher resonator is to substantially increase the radio frequency conversion efficiency of the tube.

10 Claims, 6 Drawing Figures

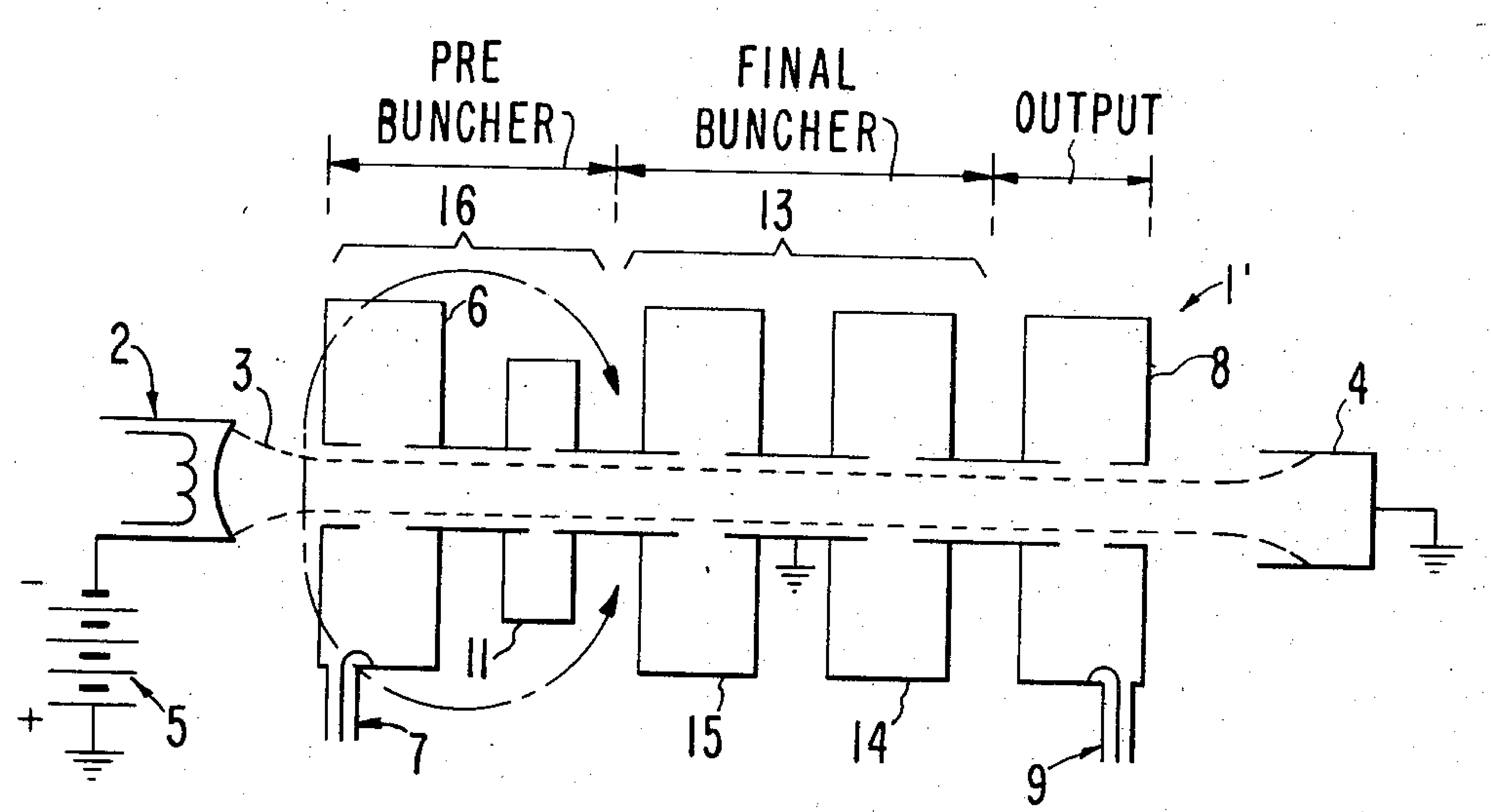


FIG. 1
PRIOR ART

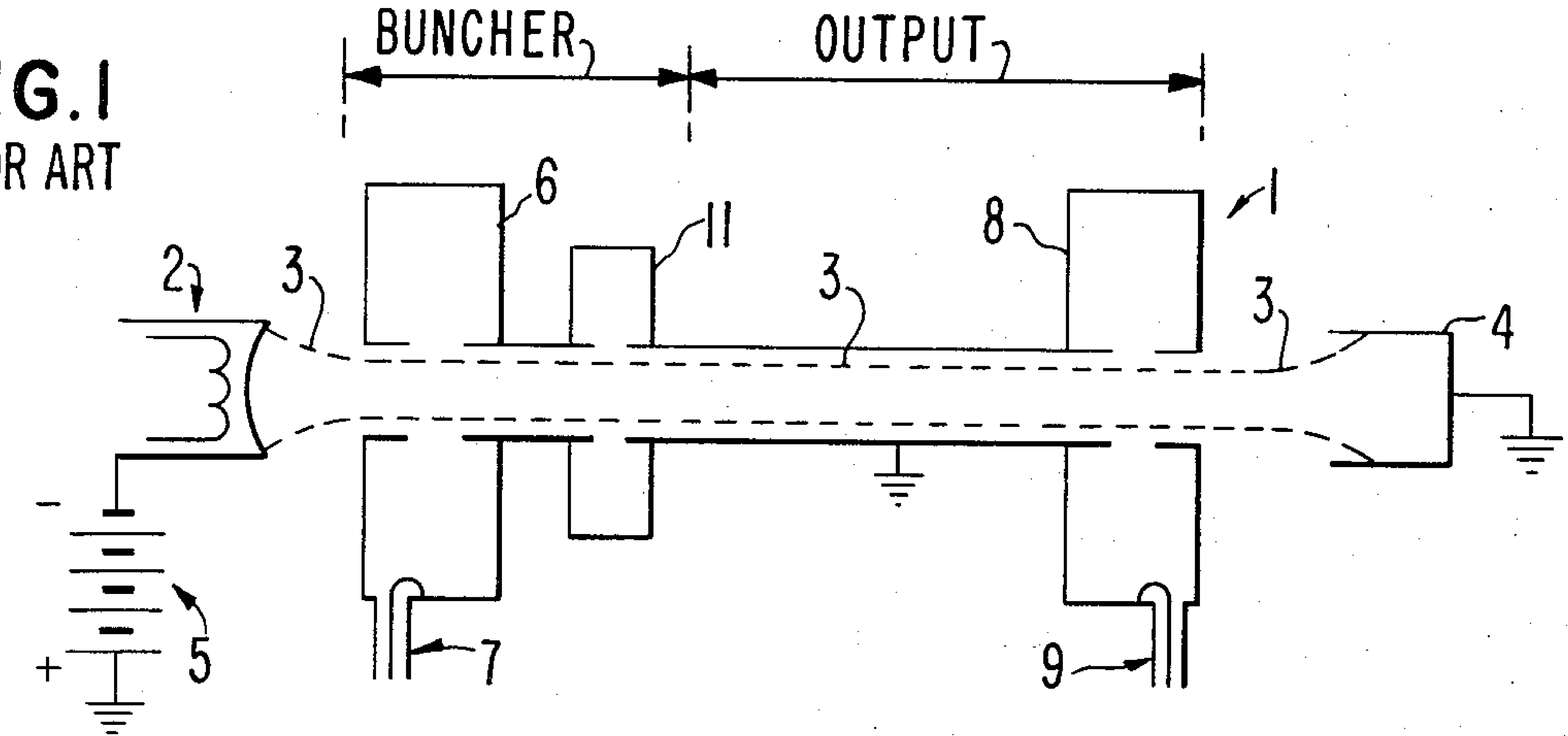
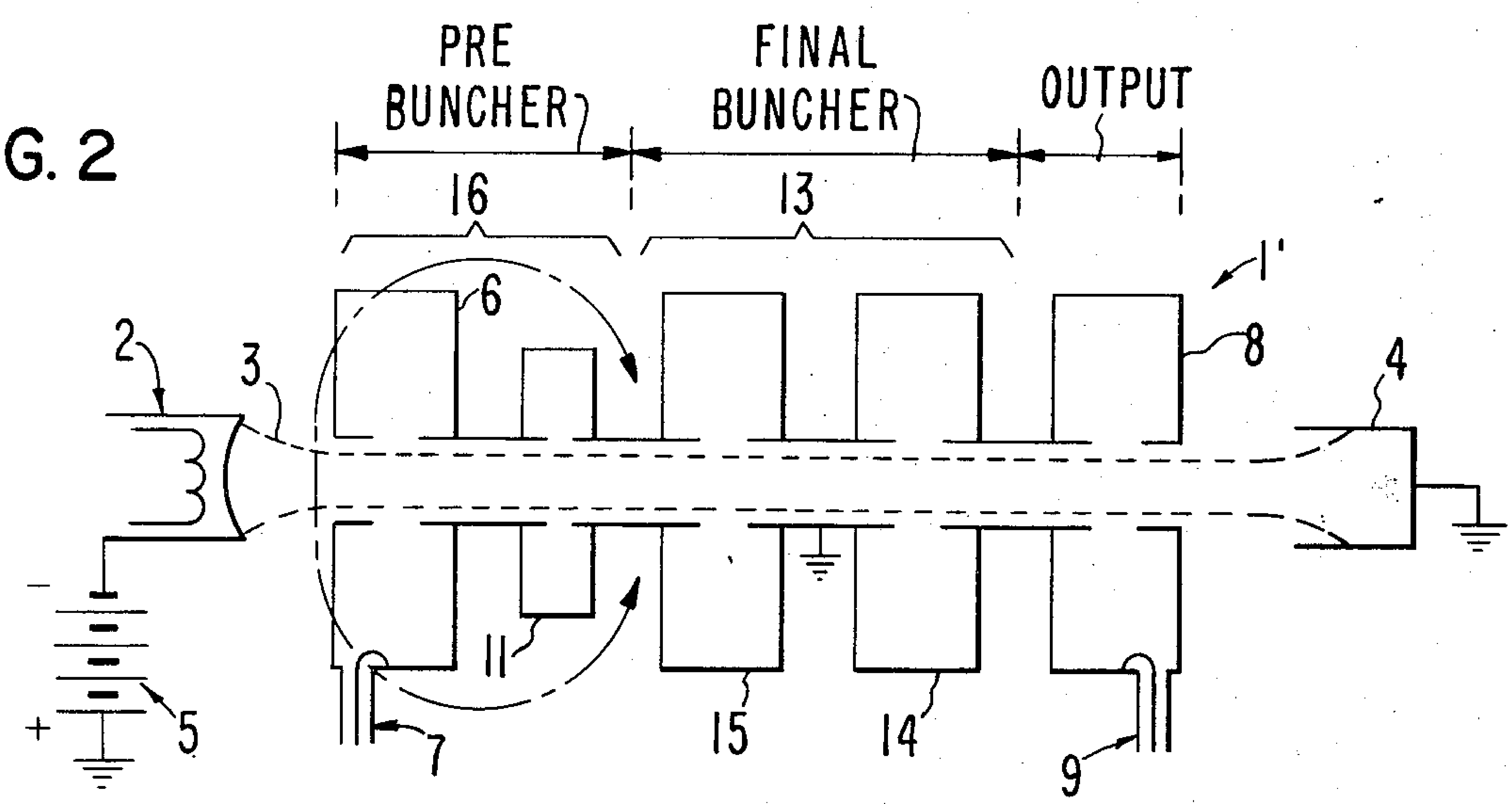


FIG. 2



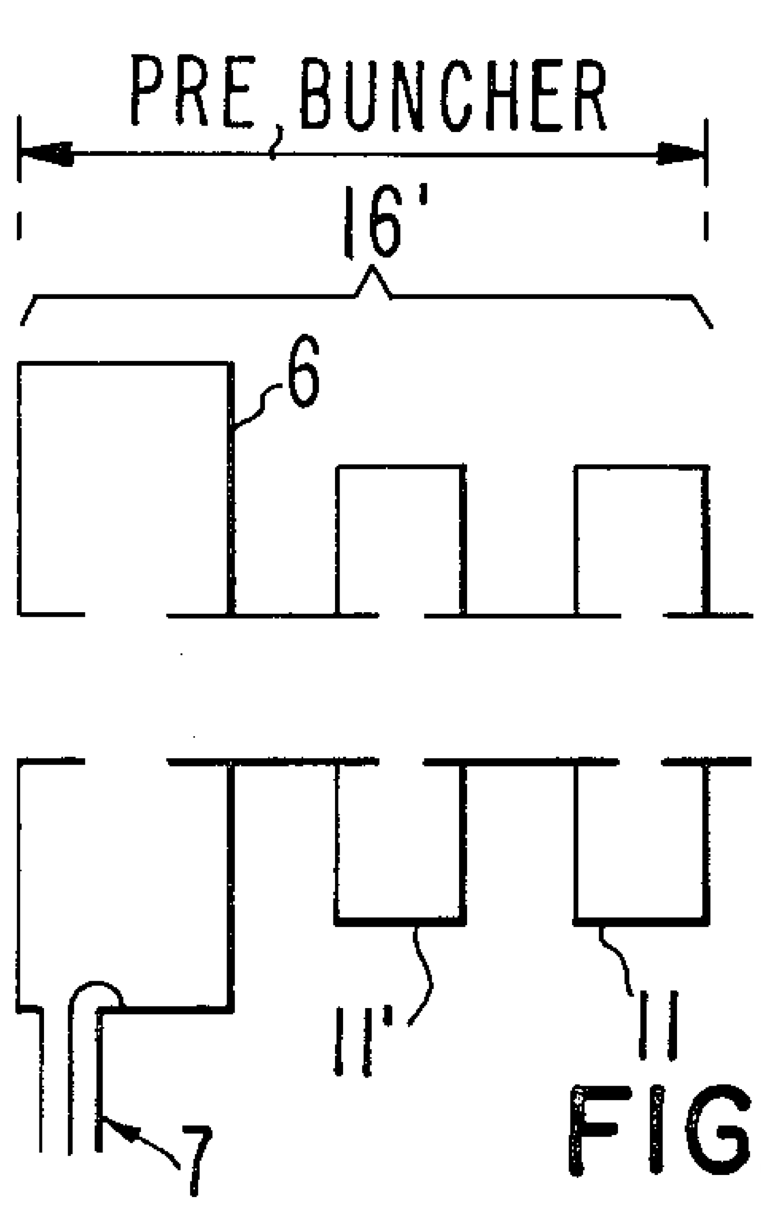


FIG. 3

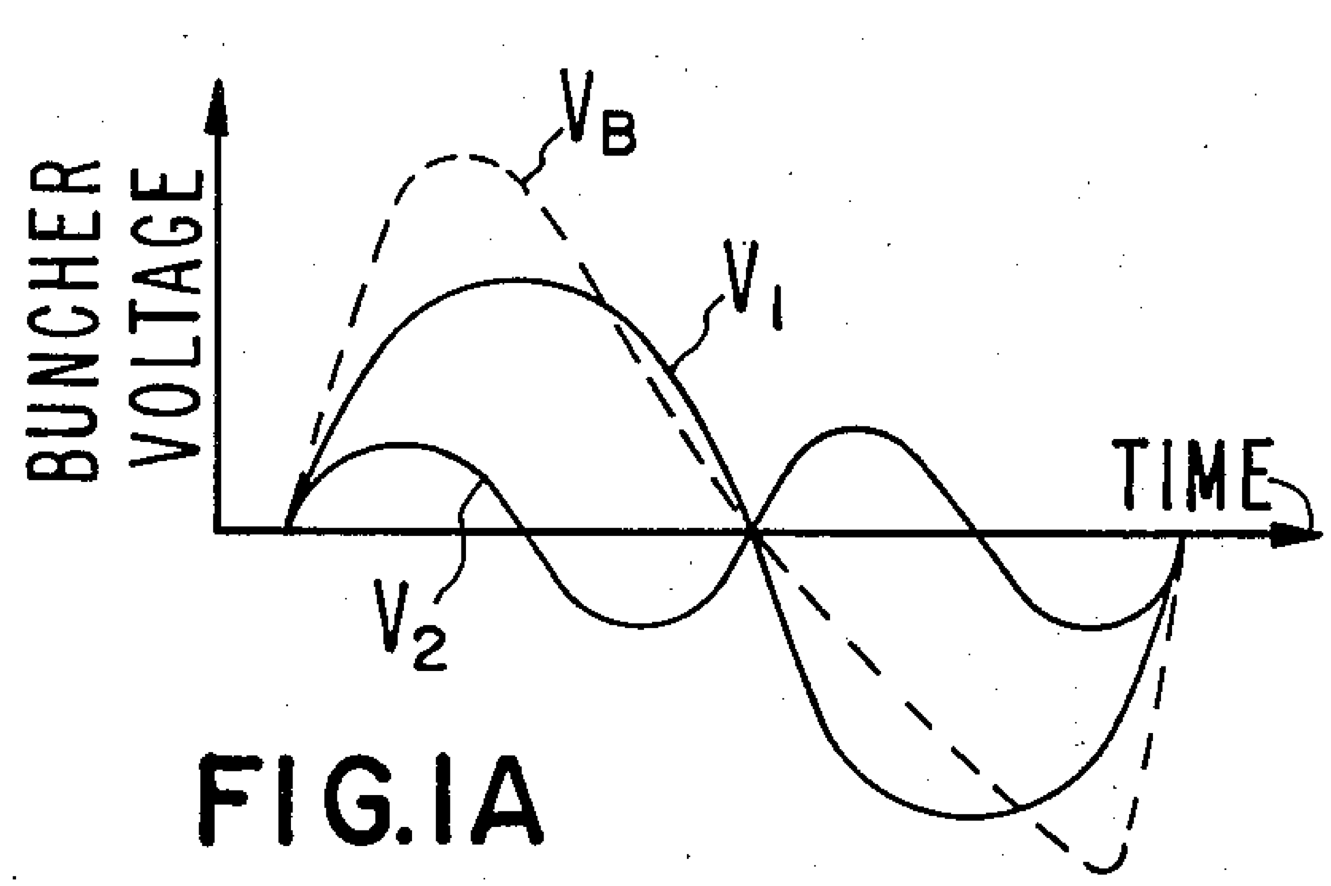


FIG. 1A

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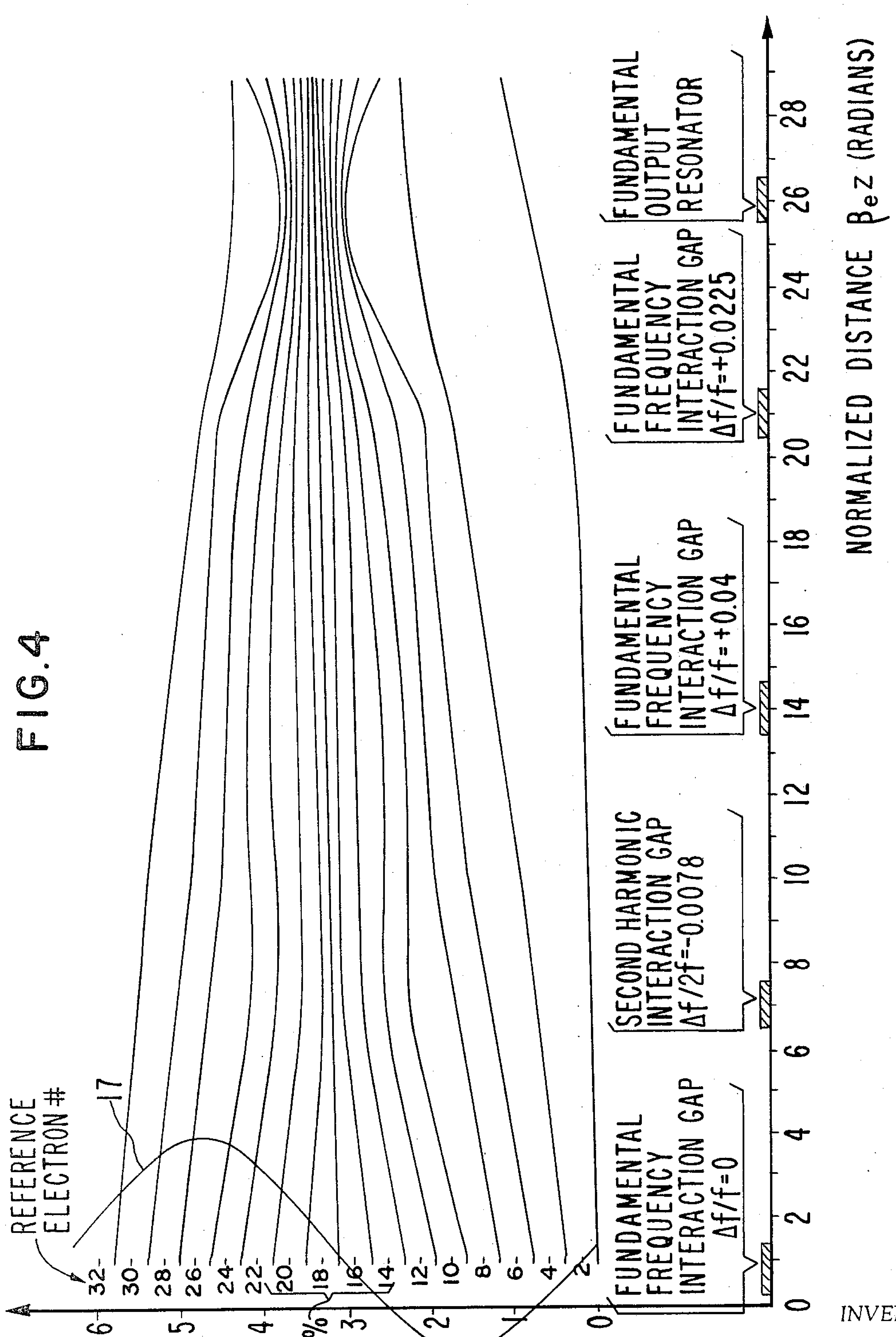

FIG. 4

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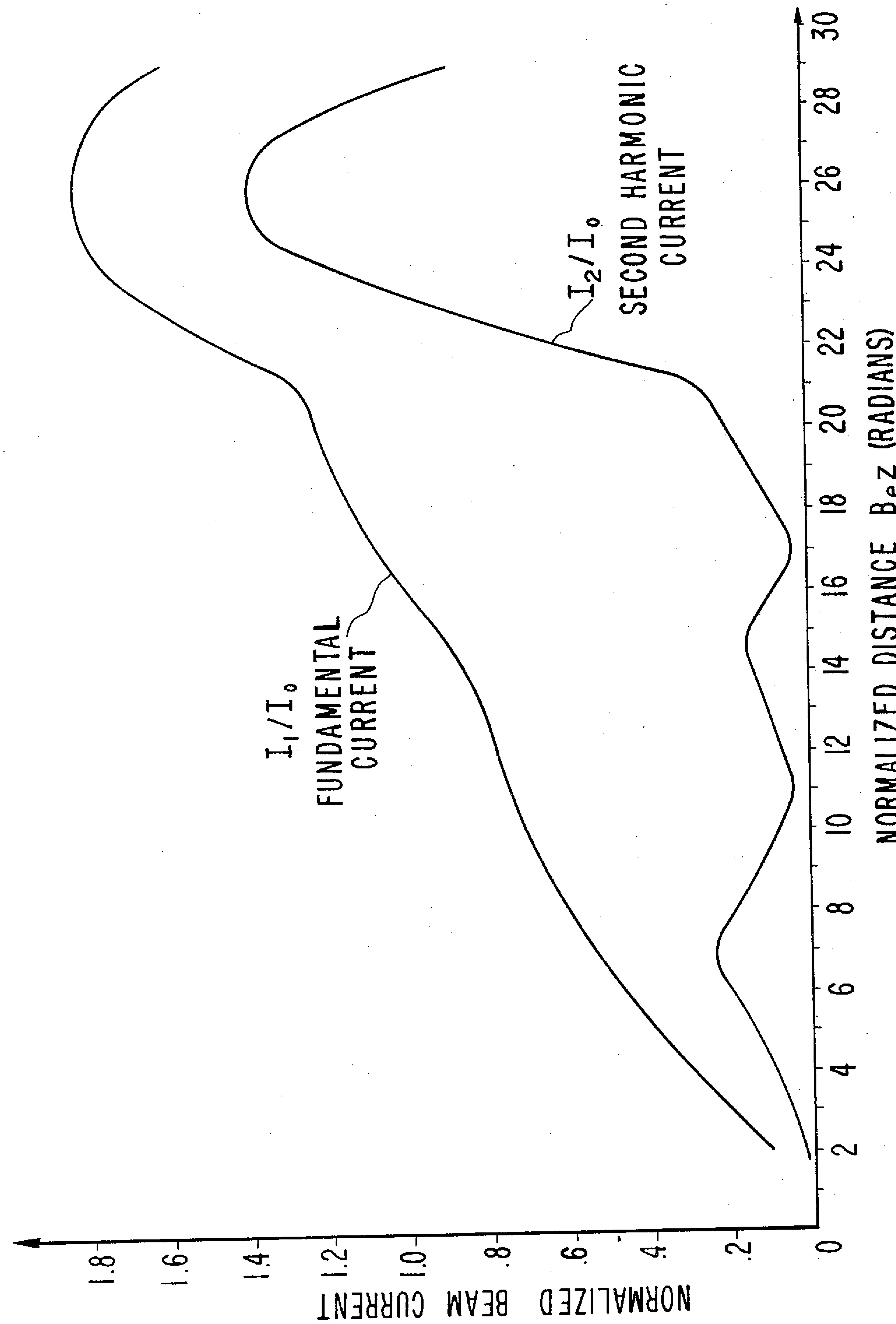

FIG.5

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VELOCITY MODULATION MICROWAVE TUBE EMPLOYING A HARMONIC PREBUNCHER FOR IMPROVED EFFICIENCY

This is a continuation of application Ser. No. 767,774 filed Oct. 15, 1968, now abandoned.

DESCRIPTION OF THE PRIOR ART

Heretofore, it has been proposed to improve the conversion efficiency of a velocity modulation tube (klystron) by making the penultimate resonator a harmonic resonator tuned to the second harmonic of the passband of the tube. A klystron tube utilizing this technique is disclosed in U.S. Pat. No. 2,579,480, issued Dec. 25, 1951. In the prior art tube the function of the second harmonic resonator was to produce a sawtooth type velocity modulation of the electrons to produce the "tightest" possible electron bunches as the beam passes through the interaction gap of the output circuit.

The problem with the prior art tube design is that the buncher arrangements are based upon a pure electron ballistic theory which neglects to take into account space charge forces produced in a tightly bunched high perveance beam. In addition, it has been found that it is generally undesirable to have a velocity spread in the electrons as they pass the output interaction gap. In other words, higher efficiency can be obtained if the electrons within the bunches which pass through the output interaction gap have essentially uniform velocity.

SUMMARY OF THE PRESENT INVENTION

The principal object of the present invention is the provision of an improved velocity modulation microwave tube having improved radio frequency conversion efficiency.

One feature of the present invention is the provision, in a velocity modulation microwave tube, of a floating harmonic prebuncher resonator circuit for interaction with a velocity modulated team for improving the bunching of the beam as it passes from the harmonic prebuncher resonator into a penultimate fundamental frequency final buncher consisting of one or more floating resonators which further bunches the beam before passage thereof into the output circuit, whereby the final stage of bunching is performed by the fundamental frequency final buncher to improve the radio frequency conversion efficiency of the tube.

Another feature of the present invention is the same as the preceding feature wherein the harmonic prebuncher resonator is tuned for a mode of resonance approximately at the second harmonic of the center of the passband of the tube.

Another feature of the present invention is the same as any one or more of the preceding features wherein another harmonic prebuncher resonator is arranged along the beam path upstream of the penultimate fundamental frequency final buncher for further increasing the conversion efficiency of the tube.

Another feature of the present invention is the same as any one or more of the preceding features wherein the harmonic prebuncher resonator is tuned to a frequency slightly lower than twice the operating frequency of the tube.

Another feature of the present invention is the same as any one or more of the preceding features wherein the penultimate fundamental frequency final buncher

resonator or resonators are tuned to a frequency or frequencies slightly higher than the operating frequency of the tube.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic line diagram depicting the prior art klystron,

FIG. 1A is a plot of normalized electron velocity versus time depicting the r.f. phase of the fundamental and second harmonic voltages and showing the sawtooth type velocity modulation obtained in the prior art tube of FIG. 1,

FIG. 2 is a schematic line diagram depicting a velocity modulation tube employing features of the present invention,

FIG. 3 is a schematic line diagram of an alternative prebuncher employing features of the present invention,

FIG. 4 is a plot of electron phase angle versus normalized distance along a beam path depicting the positions of the various interaction circuits and showing the bunching effect and velocity distribution of the bunched electrons in the beam of the present invention, and

FIG. 5 is a plot of normalized r.f. beam current versus normalized distance along the beam path depicting the fundamental r.f. component of the beam current and the second harmonic component of the beam current.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown the prior art klystron 1 as described in the aforecited U.S. Pat. No. 2,579,480. Briefly, the tube 1 includes an electron gun 2 for forming and projecting a stream of electrons 3 over an elongated beam path to a beam collector structure 4 disposed at the terminal end of the beam. Beam voltage is applied to the tube from a supply 5. An input cavity resonator 6 is disposed at the upstream end of the beam 3 for velocity modulating the beam with r.f. energy supplied to the cavity 6 via an input coaxial line 7. The velocity modulation imparted to the beam 3 by the input cavity 6 is converted, in a suitable field free drift space, to current density modulation of the beam at the downstream end thereof. An output resonator structure 8 is provided at the downstream end of the beam to be excited by the bunched electron beam passing therethrough. The r.f. energy is extracted from the output resonator 8 via an output coupling loop and coaxial line 9 and fed to a suitable utilization device. The input resonator 6 and the output resonator 8 are both tuned for a fundamental mode of resonance at the center of the passband of the tube.

A harmonic resonator 11 is disposed along the beam path intermediate the input cavity 6 and the output cavity 8. The harmonic cavity 11 is tuned for a mode of resonance at substantially twice the operating frequency of the tube. The harmonic cavity 11 is a floating resonator which is defined as a resonator which does not have any source of energy external to the klystron and which is not coupled to a load utilizing the output of the resonator; however, a circuit element may be coupled to the floating resonator, solely for affecting some electrical characteristic of the floating resonator such as its Q or frequency.

The function of the harmonic resonator **11** is to produce a bunching voltage having a periodic sawtooth wave form in the manner as shown in FIG. **1A**. More specifically, the input cavity **6** produces a fundamental sinusoidal bunching r.f. voltage V_1. When a second harmonic voltage V_2 is superimposed upon V_1 the total bunching voltage V_b has a periodic sawtooth wave form. Utilizing a pure electron ballistic theory, and neglecting space charge forces, such a bunching wave form produces tight bunches in the output resonator **8**. However, such bunching produces an undesired velocity spread in the electrons as they pass through the gap in the output resonator **8**. In addition, in relatively high perveance beam tubes, i.e., perveance $> 10^{-6}$, space charge forces cannot be neglected and as a result the tight bunching which is desired may not be obtained in practice.

Referring now to FIG. **2**, there is shown a velocity modulation tube **1'** incorporating features of the present invention. The tube **1'** of the present invention is similar to that of FIG. **1** with the exception that a fundamental frequency final buncher section **13** is provided downstream of the harmonic bunching resonator **11** between the buncher resonator **11** and the output resonator **8**. The harmonic resonator **11** together with the input resonator **6** forms a prebuncher section **16**. The final buncher section **13** includes one or more floating resonator circuits tuned for a mode of resonance at a frequency near or preferably slightly above the center of the passband of the tube **1'**. The final buncher section, thus will always include at least a penultimate floating resonator **14** tuned for a mode of resonance near the passband of the tube **1'**. One or more additional fundamental frequency resonators **15** may be included upstream of the penultimate resonator **14** within the final buncher section **13** for increasing the efficiency of the tube.

By providing the final buncher section **13** downstream of the harmonic prebuncher **16**, the electrons are grouped by the prebuncher **16** for a more efficient modulation by the fundamental frequency final buncher cavities **14** and **15** used in the final bunching section **13**. In other words, the second harmonic cavity **11** provides a beneficial phase grouping of the electrons at the entrance of the final buncher stage **13**. The fundamental component of the radio frequency current modulation of the beam I_1 is higher than in the prior art. The efficiency factor:

$$F_1 = [\tfrac{1}{2} I_1 / I_0] \tag{1}$$

of the buncher arrangement of FIG. **2** is typically 0.9 as compared with 0.76 for the buncher of FIG. **1**, where I_0 is the d.c. beam current.

Referring now to FIG. **3**, there is shown an alternative embodiment of the present invention wherein two second harmonic prebuncher cavities **11** and **11'** are provided along the beam path **3** between the input cavity **6** and the entrance to the final buncher section **13**. In the prebuncher section **16'** of FIG. **3**, a larger relative detuning of the second harmonic cavities **11** and **11'** with respect to the second harmonic of the center frequency of the tube is permitted. Therefore, this design is adaptable to velocity modulation tubes **1'** having larger bandwidths than the tubes of the design of FIG. **2**.

The function of the prebuncher **16** and **16'** of FIGS. **2** and **3**, respectively, is to displace the electrons from phase intervals between the main bunches and provide electron bunches typically extending over a phase interval 0.75 times an r.f. period. Ideally, the electron density should be fairly uniform within the bunches and the velocity spread among the electrons should be negligible at the exit of the prebuncher **16**. With the proper selection of the beam drift spaces and r.f. drive levels, the prebunchers **16** and **16'** of FIGS. **2** and **3** will distribute about 95% of the electrons within a phase interval equal to 0.75 of the fundamental frequency period. The electron distribution within the bunch can be made sufficiently uniform and the velocity spread is negligible. The fundamental frequency final buncher cavities **14** and **15** are tuned slightly higher than the center frequency of the passband of operating frequencies of the tube to provide an almost purely reactive impedance to the beam, whereas the harmonic resonator **11** is preferably tuned slightly lower in frequency than the precise harmonic of the center frequency of the passband of the tube.

A map of the electron phase angle versus normalized distance along the beam path for a tube of the type shown in FIG. **2** is shown in FIG. **4**. The map is for a beam having a perveance of 1×10^{-6} and depicts the electron phase angles, (using 32 reference electrons of which 16 are traced in the figure) which are initially distributed uniformly over one cycle **17** of the r.f. fundamental frequency, as depicted on the ordinate. The location and voltages of the interaction gaps are indicated along the abscissa. It is seen from the map that, by the time the electron bunches reach the fundamental frequency output resonator gap, about 90 percent of the electrons are distributed within an r.f. phase angle of approximately 1½ radians (85). Moreover, it is seen by the slope of the electron phase versus distance diagram that the velocity spread of the electrons at the location of the output resonator gap is small. The predicted r.f. conversion efficiency employing a single gap output resonator **8** is 80 percent. In practice, about 70 percent has been realized.

Referring now to FIG. **5**, there is shown a plot of normalized r.f. beam current versus normalized distance along the axis of the beam. It is seen that the maximum normalized fundamental component I_1 of the r.f. beam current produced by the buncher section **13** is:

$$[I_1/I_0] = 1.74. \tag{2}$$

The corresponding value for prior art conventional bunchers is:

$$[I_1/I_0] \approx 1.57. \tag{3}$$

Although the embodiments of the present invention as depicted in FIGS. **2** and **3** employ only a single fundamental frequency resonator in the prebuncher section this is not a requirement. Additional fundamental frequency resonators may be provided along the beam path between the input resonator **6** and the first harmonic cavity **11** or **11'** for providing increased gain of the tube. In addition, it is not a requirement that the harmonic resonators **11** and **11'** be tuned to the second harmonic of the center of the passband of the tube. Such harmonic resonators may be tuned to higher frequency harmonics such as the third, fourth, etc. However, it is definitely preferred that the harmonic cavities be tuned to the lowest frequency harmonic higher than the first (namely the second), since at harmonics higher than the second and especially at frequencies above S-band and at high power levels, an inordinate proportion of the volume of the cavity is occupied by the beam. Moreover, it is not a requirement that the resonator circuits employed in the tube be re-entrant cavity resonators. It is contemplated that other types of resonant circuits may be employed such as, distributed field helical resonators (either the single helix or cross wound helix type may be employed). Moreover, the output resonant circuit **8** may comprise, for example, a slow wave circuit or an extended interaction circuit formed by a plurality of coupled cavity resonators. In other words, the present invention is applicable not only to klystron amplifiers but to velocity modulation microwave tubes in general which employ tuned resonant structures disposed along the beam path for interaction therewith.

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

What is claimed is:

1. In a velocity modulation microwave tube apparatus having a certain operating passband of frequencies, means for projecting a stream of electrons over an elongated beam path, means forming a plurality of wave supportive structures arranged successively along the beam path for successive electromagnetic interaction with the electron stream to produce output microwave energy, said plurality of wave supportive structures including an input circuit, an output circuit, and a penultimate resonator circuit, said penultimate resonator circuit being tuned for a mode of resonance at a frequency above the passband of the tube, the frequency of said fundamental mode of resonance being less than twice the center passband frequency, said penultimate resonator circuit comprising at least one floating resonator for bunching the beam passing into said output circuit, the improvement comprising, means forming a harmonic floating resonator structure disposed along the beam path intermediate said input circuit and said penultimate resonator circuit, said harmonic resonator having a mode of resonance approximately at a frequency corresponding to a harmonic which is an integral multiple of the center frequency of the passband of the tube, whereby the electrons of the beam are prebunched by said harmonic resonator prior to their entering the final stage of bunching performed by said penultimate resonator circuit to improve the conversion efficiency of the tube.

2. The apparatus of claim **1** wherein said penultimate resonator circuit comprises more than one floating resonator tuned for a fundamental mode of resonance at a frequency above the passband of the tube.

3. The apparatus of claim **1** wherein said resonators are re-entrant cavity resonators.

4. The apparatus of claim **1** wherein said harmonic resonator is tuned for a mode of resonance approximately at the second harmonic at the center of the passband of the tube.

5. The apparatus of claim **1** wherein a second one of said harmonic resonators is arranged along the beam path intermediate said input circuit and said penultimate resonator circuit for further increasing the conversion efficiency of the tube.

6. The apparatus of claim **1** wherein the beam has a perveance greater than 0.1×10^{-6}.

7. The apparatus of claim **1** wherein the harmonic resonator is tuned to a frequency lower than the certain higher harmonic of the center of the passband of the tube, and said penultimate resonator circuit is tuned to a frequency higher than the center of the passband of the tube.

8. The apparatus of claim **2** wherein said floating resonators are tuned to frequencies higher than the center of the passband of the tube.

9. The apparatus of claim **1** wherein more than one said harmonic resonator is arranged along the beam path intermediate said input circuit and said penultimate resonator circuit and wherein said penultimate resonator circuit comprises more than one floating resonator.

10. The apparatus of claim **9** wherein said harmonic resonators are tuned to frequencies lower than the certain higher harmonic of the center of the passband of the tube and said floating resonators of said penultimate resonator circuit are tuned to frequencies higher than the center of the passband of the tube.

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