May 26, 1959 E. EVERHART ET AL 2,888,629

VOLTAGE MULTIPLIER

Filed Feb. 25, 1954 4 Sheets-Sheet 1

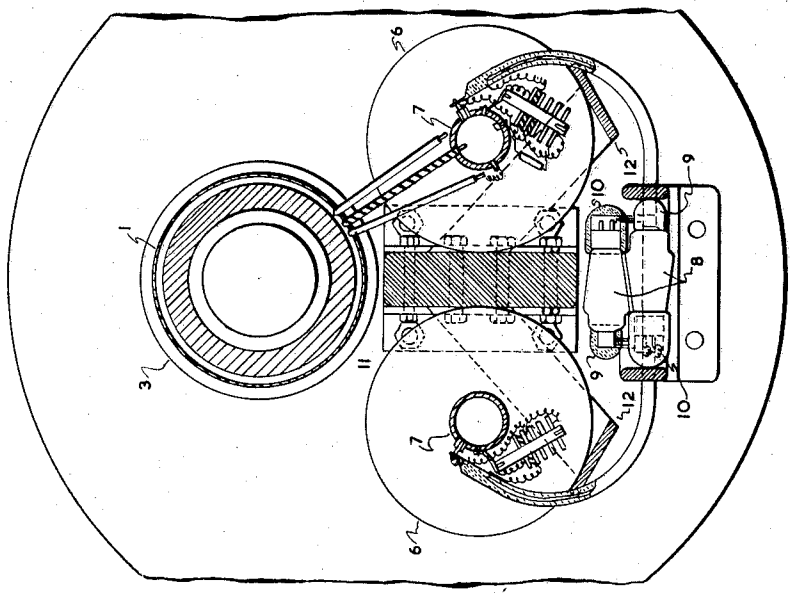


FIG. 2

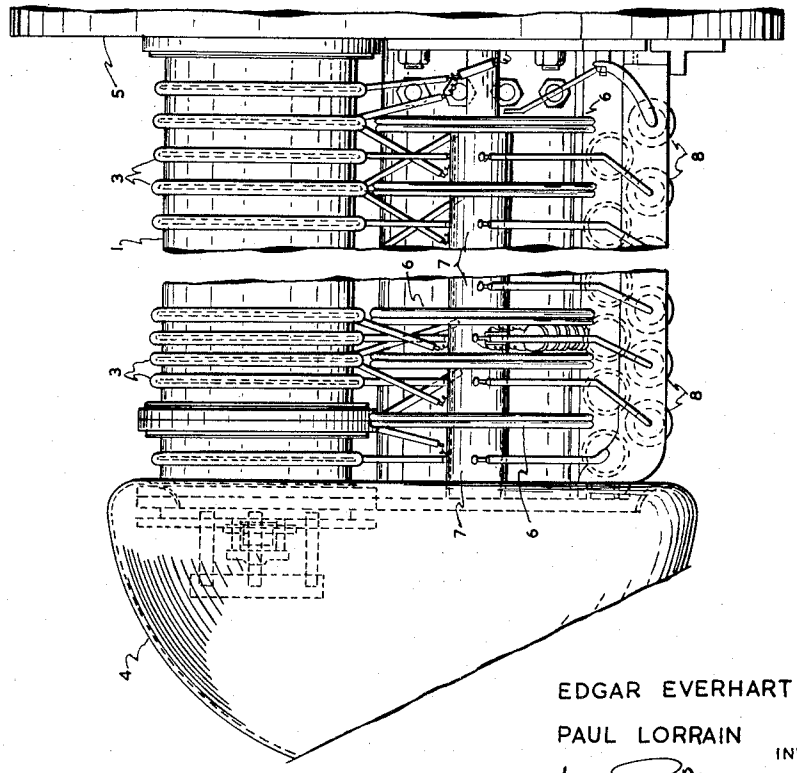


FIG. 1

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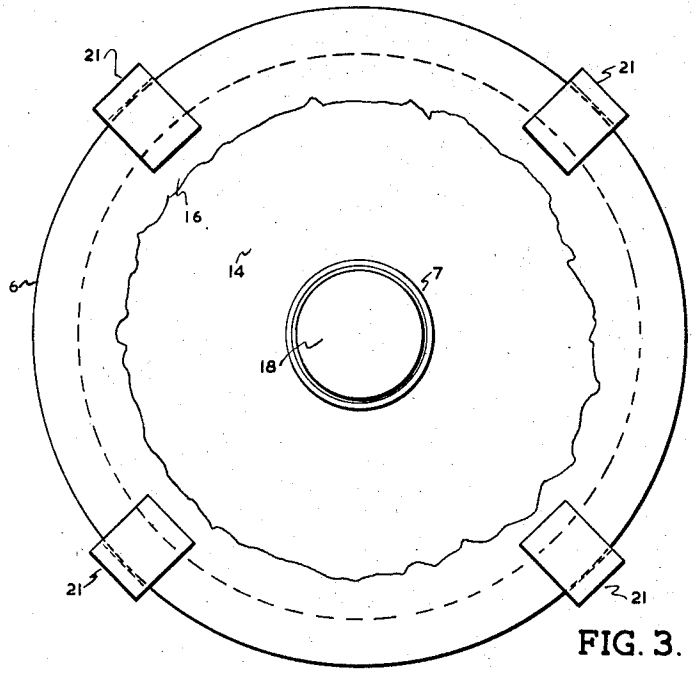


FIG. 3.

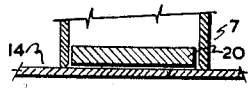


FIG. 4.

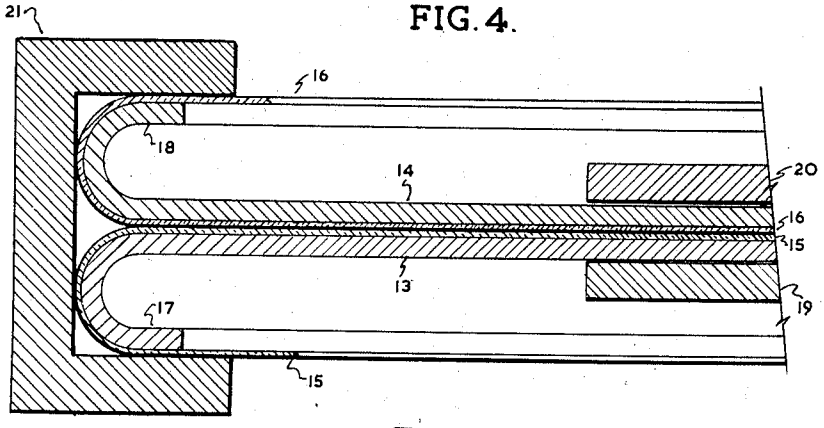


FIG. 5.

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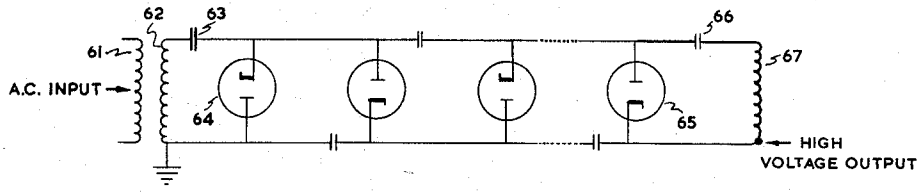


FIG. 6

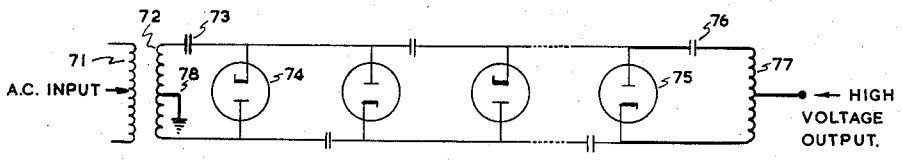


FIG. 7

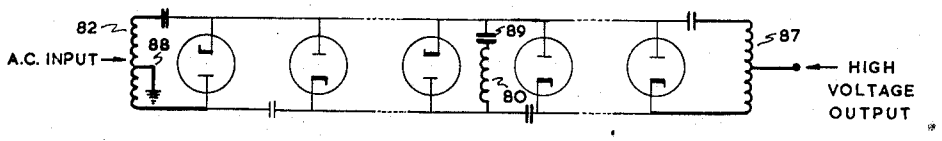


FIG. 8

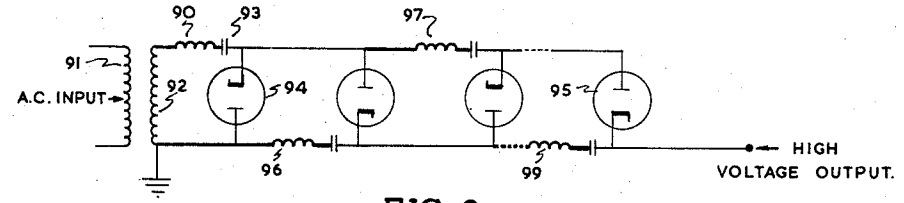


FIG. 9

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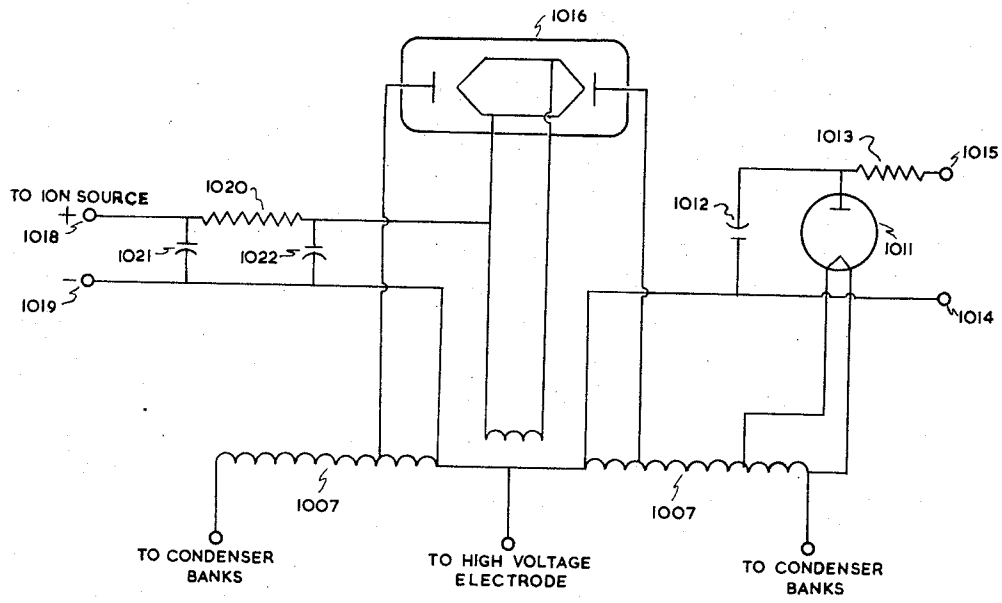


FIG. 10

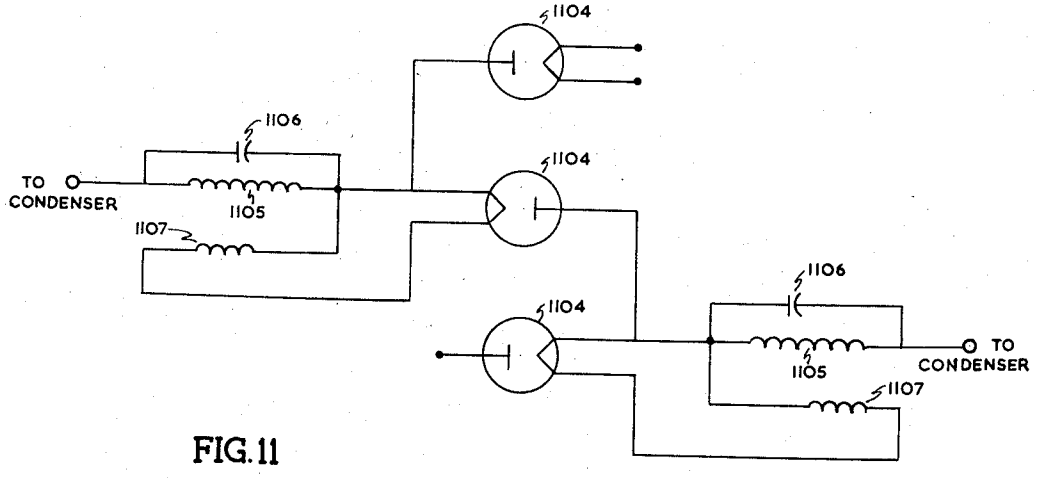


FIG. 11

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2,888,629

VOLTAGE MULTIPLIER

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Application February 25, 1954, Serial No. 412,551

6 Claims. (Cl. 321—15)

This invention relates to a voltage multiplying circuit which is an improvement over the conventional cascade voltage multiplying circuit known in some quarters as the "Cockcroft-Walton" circuit.

The circuit of this general type was first described by H. Greinacher in Zeits. f. Physik (1921), vol. 4, page 195, and has gone into widespread use. As is well known, such a circuit multiplies, rectifies and filters alternating voltage applied thereto. It has however the disadvantage that even when no direct current is drawn from the output, there is an important loss in output voltage caused by circulating currents in the stray capacitances. In addition, where a current is drawn from such a circuit, there is "ripple" or periodic voltage fluctuation in the output, and the circulating currents referred to have the effect of increasing such ripple, which is frequently objectionable.

The present invention has two principal objects, namely, to provide cascade voltage multiplying circuits wherein the output voltage closely approximates the theoretical voltage obtainable from such circuits (i.e. to improve the voltage efficiency), and to minimize ripple in such a circuit.

Other objects and numerous advantages will be apparent to one skilled in the art from an examination of the entire specification and the accompanying drawings.

The theory behind this invention has been set out in an article by the present inventors:

The Review of Scientific Instruments, vol 24, No. 3, pp. 221–226, March 1953, "The Cockcroft-Walton Voltage Multiplying Circuit," by Edgar Everhart and Paul Lorrain.

In examining the above publication, attention is directed to the following points:

(1) In Figure 7 on page 225 of the publication, a capacitor, inductance and resistor are shown in the upper right-hand corner, directly above the terminal denoted as "H.V." While these components are used in the calculations set out in the publication, they are not of any significance, because they are not connected at their right-hand end and accordingly do not have any function in a practical device, and would not be used in an actual circuit.

(2) In Table I on page 224 of the publication, component values are given for a 500 kilovolt voltage multiplier used as an accelerator, but more appropriate and complete values have now been found and will be set out herein, under the heading "Example."

The present invention, while of general application, is particularly suited for providing a high voltage for ion accelerators or for television circuits.

The invention will now be described with the assistance of the accompanying drawings, wherein preferred embodiments are shown. It will be realized that changes can be made without departing from the scope of the invention as defined in the appended claims, and the embodiments shown and described are to be construed by

way of example and not in limitation of the invention.

In the drawings:

Figure 1 shows a side elevation view of an embodiment of an ion accelerator using the cascade voltage multiplying circuit described herein;

Figure 2 shows a cross-sectional view as along the line 2—2 in Figure 1;

Figure 3 shows a side elevation view of one of the capacitors denoted by 6 in Figures 1 and 2;

Figure 4 shows a fragmentary elevation cross-sectional view of the center portion of said capacitors 6 and part of an adjacent spacer denoted by 7;

Figure 5 shows a fragmentary cross-sectional view of substantially one-half of Figure 3, so as to better disclose the construction of capacitor 6;

Figure 6 shows a circuit diagram of one embodiment of the voltage multiplying circuit disclosed herein;

Figure 7 shows a further form of the circuit shown in Figure 6, which is particularly effective in eliminating ripple;

Figure 8 shows a further embodiment of the circuit of Figure 7 where one or more intermediate loading coils are used to further improve the voltage efficiency;

Figure 9 shows another embodiment of the circuit capable of accomplishing the result of that shown in Figures 6, 7 and 8, with almost complete elimination of ripple;

Figure 10 shows the manner in which various power supplies incidental to the device of Figures 1 and 2 may be conveniently obtained from the voltage multiplying circuit which is the subject of the present invention, apart from the high-voltage output to which end the said circuit is particularly intended; and

Figure 11 shows a preferred manner of feeding the filaments of the tubes forming part of the voltage multiplying circuit of the present invention.

Referring now to the drawings, wherein the like parts are denoted throughout by similar reference numerals, and with particular reference to Figure 1, a preferred form of the present invention is shown in association with an ion accelerator. The ion accelerator tube (which forms no part of this invention) is shown at 1 standing on a base denoted by 5. Ion accelerator tube 1 has rings thereon denoted by 3 which are effectual in eliminating corona. A high voltage dome denoted by 4 is attached to the end of ion accelerator tube 1 opposite base 5, the purpose of which is also to eliminate corona.

The voltage multiplying circuit contemplated by the present invention makes use of a plurality of diode electronic tubes and a plurality of capacitors, with certain other components. In Figures 1 and 2, the most important parts of the voltage multiplying circuit are visually evident. The capacitors, denoted by 6, are held in proper spatial relationship with one another by means of spacers denoted by 7. The tubes, denoted by 8 are mounted adjacent capacitors 6, and tubes 8 are provided with suitable anti-corona shields denoted by 9 and 10 which are known in the art.

A source of alternating current is connected to the cascade voltage multiplying circuit about to be described, and from such alternating current the multiplying circuit produces a high voltage direct current which is made use of in the ion accelerator tube 1.

The structural details of the device can be seen with particular reference to Figure 2, wherein it is seen that the elements just described are held in place by means of a beam of dielectric materials such as "Lucite," denoted by 11. Auxiliary guides denoted by 12 are attached to beam 11 for supporting the cascade voltage multiplying circuit.

As can be seen in Figure 2, the voltage multiplier is in the form of two banks of capacitors, with a bank of

tubes along the lower part of the device, and equidistant from the two banks of capacitors.

The capacitors **6** are shown with particular reference to Figures 3, 4 and 5. Condensers **6** comprise two circular metal plates denoted by **13** and **14** separated by two films of dielectric material. The dielectric film attached to plate **13** is denoted by **15** and the dielectric film attached to plate **14** is denoted by **16**.

As seen in the drawings, each of the plates **13** and **14** has a rolled lip denoted by **17** and **18** respectively.

It is contemplated that the dielectric films **15** and **16** attached to plates **13** and **14** respectively, will be in the form of circular envelopes moulded around the said plates. It has been found satisfactory if the dielectric film is made of polyethylene, and for condensers of diameter of the order of nine and a half inches, six layers of polyethylene each of five mils thick have been found satisfactory.

Capacitor plates **13** and **14** are circular in shape, and have attached at their centers smaller circular plates denoted by **19** and **20** which may be merely cemented to plates **13** and **14** respectively, since no electrical connection therebetween is necessary. Spacers **7** are adapted to slide over circular plates **19** and **20**, and it is accordingly possible to stack a substantial row of capacitors **6**, maintaining them in proper spatial relationship.

In order that the capacitance of condensers **6** may be carefully controlled, dielectric clamps denoted by **21**, of a general C-shape are adapted to fit over each pair of capacitor plates **13** and **14** and their associated films, so as to press the plates firmly together.

It is contemplated that four of such clamps **21** will be provided on each capacitor **6**, although the present invention is not in any way restricted to such number, or such construction. It is apparent that adjustable clamps could be used if it should prove necessary to adjust the capacitance of capacitors **6**, which for conditions of operation heretofore experienced, has not been found necessary.

Referring now to Figure 6, one form of the circuit will now be described. The left-hand side of Figure 6 is quite conventional and comprises an input transformer formed of coils **61** and **62**, which are connected to a capacitor denoted by **63** and a tube denoted by **64**. Capacitor **63**, and all other capacitors in this figure may be similar to capacitor **6** already described. There are a number of identical stages, wherein there is always a capacitor connected between the anode of a tube and the cathode of the tube of the following stage, assuming a positive output is required as is the case where the use is in connection with an ion accelerator as shown in Figure 1. It will be realized that if a negative output were required, the circuit would be similar to that shown in Figure 6, except that the anode and cathode of each of the tubes would be reversed.

There may be as many stages as desired, and the present invention is in no way limited to the number of stages except as necessitated by practical considerations. At the last stage there is a tube denoted by **65**.

At the output, between the anode and cathode of tube **65** is connected a capacitor denoted by **66**, and an inductance denoted by **67**. The high voltage output is obtained at the end of inductance **67** adjacent the cathode of tube **65**.

It will be seen that the circuit shown in Figure 6 differs from conventional cascade voltage multiplying circuits in that a capacitance and inductance (**66** and **67**, respectively) are provided across the last tube **65**.

Referring now to Figure 7, it will be seen that this embodiment is similar to that of Figure 6, having elements denoted by **71—77** which are generally similar to elements **61—67**, respectively, of Figure 6, including a transformer coil denoted by **72** and an output inductance denoted by **77**. In Figure 7, transformer coil **72** is center-tapped at **78** and connected to ground, and inductance **77** is also center-tapped. It is from the center-tap of inductance **77** that the high-voltage output is taken. With the present form of the invention, ripple is almost completely eliminated.

Referring now to Figure 8, it will be seen that this circuit is similar to that shown in Figure 7, having elements denoted by **81—88** which are generally similar to elements **71—78**, respectively, of Figure 7. In Figure 8, the transformer coil denoted by **82** is center-tapped at **88** and connected to ground and the output inductance denoted by **87** is also center-tapped, from which point the high-voltage output is taken. The difference from Figure 7 is the provision of an intermediate loading coil denoted by **80** connected as shown substantially midway between the input and output of the circuit. The loading coil **80** has in series therewith a capacitor denoted by **89**.

The use of a loading coil such as loading coil **80** greatly improves the voltage efficiency. It is important to note that more than one such loading coil may be similarly connected between input and output.

Referring now to Figure 9, it will be seen that there are again elements denoted by **91—95** similar to elements **61—65**, respectively, of Figure 6, and also that the present embodiment differs from the conventional cascade voltage multiplying circuit, in that there is provided an inductance denoted by **90** between the secondary of the input transformer denoted by **92**, and the capacitor **93** connected to the cathode of the first tube denoted by **94**.

Similar inductances denoted by **97** and **99** are similarly connected in each stage. Assuming a positive output is required, the high-voltage output is taken from the cathode of the last stage, it having already been mentioned that the polarity of the output can be made negative if the anodes and cathodes of the tubes are reversed with respect to the form shown in the present disclosure.

The embodiments shown in Figures 8 and 9 carry out the principal objects of the invention in providing a voltage output which closely approximates a calculated value being not appreicably decreased by circulating currents, and also materially suppress ripple.

Referring now to Figure 10, a convenient manner of obtaining power supplies for various parts of the ion accelerator of Figures 1 and 2 will now be described. In the type of ion accelerator mentioned, a voltage for the ion source of the order of 1000 volts and a voltage for the extraction electrode of the order of 15,000 volts are required, apart from the high-voltage output for accelerating purposes. The first two are conveniently obtainable with the circuit as shown in Figure 10.

In Figures 7 and 8 the output inductances **77** and **87**, respectively, are center-tapped.

In Figure 10, the inductance shown at **1007** corresponds to inductances **67**, **77** and **87** of Figures 6, 7 and 8 respectively, and while inductance **1007** is shown center-tapped as in Figures 7 and 8, this feature is not necessary to the operation of the circuit of Figure 10.

On the right-hand side of inductance **1007**, a half-wave rectifier is provided, the principal component of which is a diode denoted by **1011**. A capacitor denoted by **1012** and a resistor denoted by **1013** are used in a conventional manner and the output for the extraction electrode is obtained at **1014** and **1015**, being positive and negative respectively.

At the central and left-hand side of inductance **1007**, a full-wave rectifier is provided, the principal component of which is a full wave rectifier tube denoted by **1016**. The filament supply of tube **1016** is obtained from a coil denoted by **1017**, inductively linked to inductance **1007**. The output is taken at **1018** and **1019** being positive and negative respectively, and in the output lines a resistor denoted by **1020** and capacitors denoted by **1021** and **1022** are provided. The output at **1018** and **1019** is for the ion source.

The manner of supplying the filaments of tubes such as **64**, **65**; **74**, **75** and **94**, **95** in Figures 6, 7 and 8, respec-

tively will now be discussed with reference to Figure 11.

In the foregoing figures the cathodes have not been particularly referred to, but it has been found desirable to use ordinary filaments, such as are found in tubes of the 5825 type. The tubes are denoted by **1104** in Figure 11, to indicate the similarity to tubes such as **64** in Figure 6. The filament of each tube **1104** is connected to the cathode of the adjacent tube **1104** and on the same side of the filament, connection is made through the primary of a filament transformer denoted by **1105** to one of the capacitors **6**, the said primary **1105** being tuned to the applied radio-frequency with a capacitor denoted by **1106**. The secondary of the filament transformer denoted by **1107** is connected at one end thereof to the side of the primary adjacent the filament, and the other side of the secondary **1107** is connected to the opposite side of the said filament.

Since the device operates at high frequency, the tubes **1104** pass an appreciable current due to their stray capacitance and this current will flow through primary **1105** and the filament will be fed by the secondary **1107**.

The values of the added components contemplated by this invention will now be discussed.

In Figures 6, 7 and 8, the values of inductances **67**, **77** and **87** respectively, as indicated in the publication referred to above at page **224**, equation (26) are represented by,

$$L_{opt}=\frac{1}{W^2bC}\coth\frac{N}{2b}$$

where L_{opt} is the optimum value for such inductances;

W is the frequency in radians per second of the high frequency applied to the input;

C is the total effective shunt capacitance per stage including the rectifier and stay capacitances; e.g. in Figure 6 in the first stage, C is the interelectrode capacitance of diode **6** plus the stray capacitances;

b is a constant such that the capacity of a condenser **6** is B^2C;

N is the number of stages.

The values of the capacitors **63**, **73** and **83** and the other capacitors in each circuit will now be discussed. It is apparent that this invention contemplates equal series capacitance per stage. Referring to the above publication, particularly Figure 5 thereof and the text in connection therewith, in order to achieve equal series capacitance per stage, capacitor **63** will have double the capacitance of the following or intermediate capacitors which will be equal among themselves. Capacitor **66** will, again, have twice the value of the intermediate capacitors and will have the same value as capacitor **63**.

An example of a practical construction of a device according to Figure 1 will now be given to illustrate the above, as well as other facts which will be apparent.

Example

A device according to Figure 6 was constructed with a 20,000 volt r.m.s. radio frequency input of 34 kilocycles capable of delivering a nominal voltage of 500 kilovolts using 24 stages instead of the four stages shown therein. The diodes such as diode **4** were of the R.C.A. No. 5825 type, and the interelectrode capacitance plus stray capacitance per stage was 6.3 $\mu\mu$f. The series capacitance per stage was 700$\mu\mu$f. It is apparent that with 24 stages, 25 capacitors would be used, and the capacitor corresponding to capacitor **64** in Figure 6 had a value equal to twice the series capacitance per stage, i.e. 1400 $\mu\mu$f. Owing to the commercial unavailability of capacitors having these values, the special capacitors as shown in Figures 3–5 were used.

The value of *b* was thus

$$\frac{700}{6.3},\text{ or }11.1$$

The inductance **67** was made up of two segmental air core coils having an inductance of 0.24 henry, each with one portion short-circuited and as used in the present example, coil **67** was a model 35 kv. coil manufactured by the Spelmann Television Company.

The calculated value of L_{opt} from the equation given above is,

$$L_{opt}=\frac{1}{(2\pi\times34\times10^3)^2\times11.1\times6.3\times10^{-12}}\coth\frac{24}{2(11.1)}$$

$$=0.40\text{ henry}$$

It will be seen that the device herein described is very suitable for producing a high voltage for various uses including accelerator use, and is simple and convenient to build and maintain.

What is claimed is:

1. A voltage multiplying circuit capable of converting energy at low voltage and high frequency to high voltage direct current, comprising a series of stages, each stage consisting of a diode electron discharge device with a capacitor connected to one side of said diode, the input points of each stage being at the side of said diode not connected to said capacitor and at the side of said capacitor remote from said diode, each of said stages being connected to the following stage in such manner that the side of the diode having a capacitor connected thereto of one stage is connected to the side of the diode not having a capacitor connected thereto of the following stage, and comprising in addition an inductance load inserted in the circuit and effectively neutralizing the shunting capacitance of said stages across said high-frequency source to improve voltage efficiency and eliminate ripple.

2. A device according to claim 1 wherein the input to the first stage is the secondary of a high frequency transformer, the device having in addition a capacitor and inductance in series across the diode of the last stage, the last-mentioned capacitor being connected to tha side of the diode of the last stage which is directly connected to the diode of the second-last stage, the last-mentioned inductance being connected between the side of said last-mentioned capacitor remote from said diode of the last stage and the other side of said diode of the last stage.

3. A voltage multiplying circuit capable of converting energy at low voltage and high frequency to high voltage direct current, comprising a series of stages, each stage consisting of a diode electron discharge device with a capacitor connected to one side of said diode, the input points of each stage being at the side of said diode not connected to said capacitor and at the side of said capacitor remote from said diode, each of said stages being connected to the following stage in such manner that the side of the diode having a capacitor connected thereto of one stage is connected to the side of the diode not having a capacitor connected thereto of the following stage, and comprising in addition inductance means inserted in the circuit to improve voltage efficiency and aliminate ripple and having an inductance value substantially equal to

$$\frac{1}{W^2bC}\coth\frac{N}{2b}$$

where W is the frequency in radians per second of the voltage applied to the input, *b* is a constant, C is the total effective shunt capacitance per stage including the diode and stray capacitances and N is the number of stages.

4. A voltage multiplying circuit capable of converting energy at low voltage and high frequency to high voltage direct current, comprising a series of stages, each stage consisting of a diode electron discharge device with a capacitor connected to one side of said diode, the input points of each stage being at the side of said diode not connected to said capacitor and at the side of said capacitor remote from said diode, each of said stages

being connected to the following stage in such manner that the side of the diode having a capacitor connected thereto of one stage is connected to the side of the diode not having a capacitor connected thereto of the following stage, and comprising in addition inductance means inserted in the circuit to improve voltage efficiency and eliminate ripple, said secondary being center-tapped and grounded and the inductance being connected across the diode of the last stage is also center-tapped, the high voltage output being available at said last-mentioned point.

5. A voltage multiplying circuit capable of converting energy at low voltage and high frequency to high voltage direct current, comprising a series of stages, each stage consisting of a diode electron discharge device with a capacitor connected to one side of said diode, the input points of each stage being at the side of said diode not connected to said capacitor and at the side of said capacitor remote from said diode, each of said stages being connected to the following stage in such manner that the side of the diode having a capacitor connected thereto of one stage is connected to the side of the diode not having a capacitor connected thereto of the following stage, and comprising in addition inductance means inserted in the circuit to improve voltage efficiency and eliminate ripple, said inductance means consisting of an inductance in each stage connected to the capacitor of each stage on the side of said capacitor remote from the diode of each stage, the high voltage output being available at the side of the diode of the last stage connected to the capacitor of the last stage.

6. A voltage multiplying circuit capable of converting energy at low voltage and high frequency to high voltage direct current, comprising a series of stages, each stage consisting of a diode electron discharge device with a capacitor connected to one side of said diode, the input points of each stage being at the side of said diode not connected to said capacitor and at the side of said capacitor remote from said diode, each of said stages being connected to the following stage in such manner that the side of the diode having a capacitor connected thereto of one stage is connected to the side of the diode not having a capacitor connected thereto of the following stage, and comprising in addition inductance means inserted in the circuit to improve voltage efficiency and eliminate ripple, wherein there is connected across the diode of an intermediate stage of said series of stages an inductance and capacitance in series, and further including an inductance and a capacitance connected in series, said inductance and capacitance being connected across the diode of an intermediate stage of said stages.

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