Aug. 12, 1958 R. J. VAN DE GRAAFF 2,847,611

APPARATUS FOR VOLTAGE STABILIZATION OF CONSTANT-POTENTIAL HIGH-VOLTAGE GENERATORS

Filed May 21, 1954 5 Sheets-Sheet 1

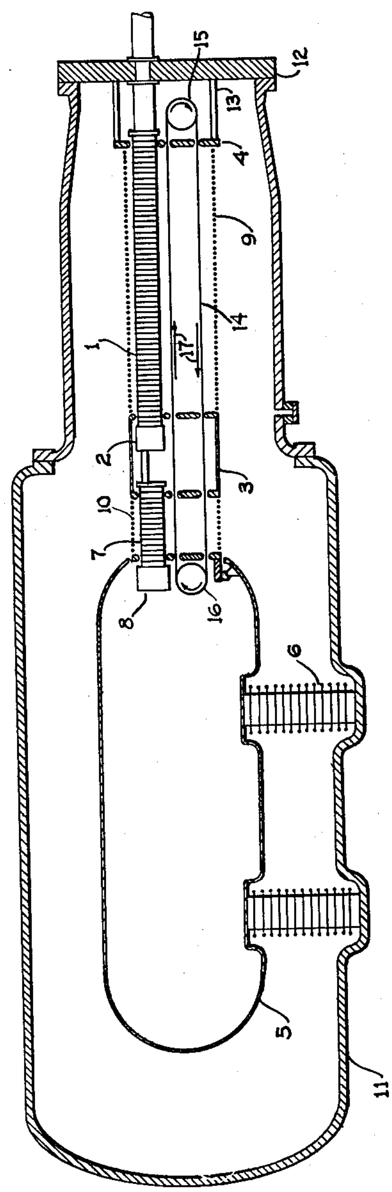
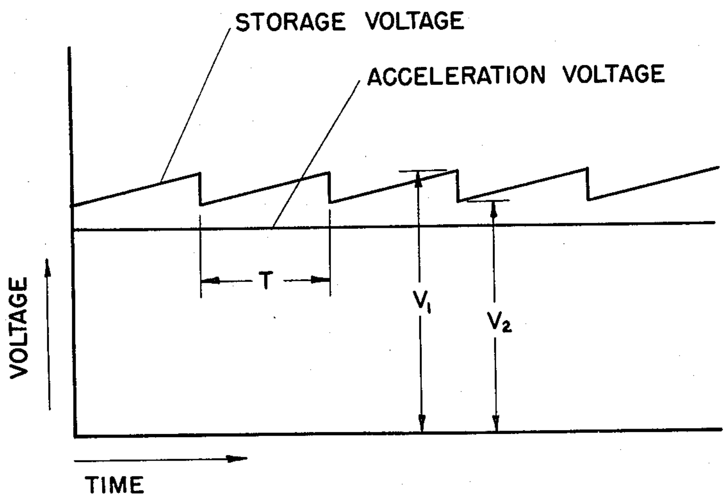
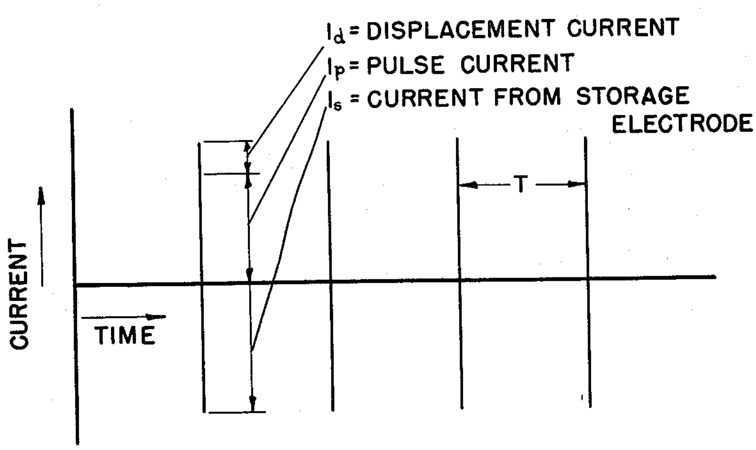


FIG. 1



VOLTAGES AS A FUNCTION OF TIME

FIG. 2



CURRENTS AS A FUNCTION OF TIME
(SAME TIME SCALES AS IN FIG. 2)

FIG. 3

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5 Sheets-Sheet 3

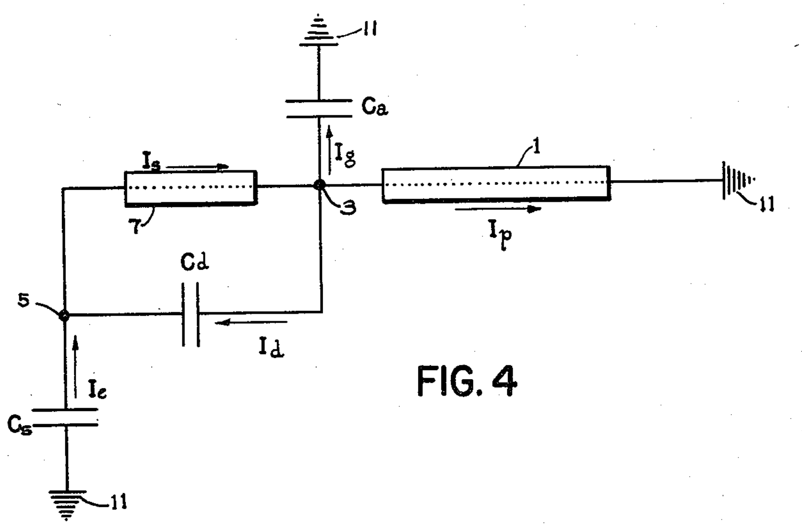

FIG. 4

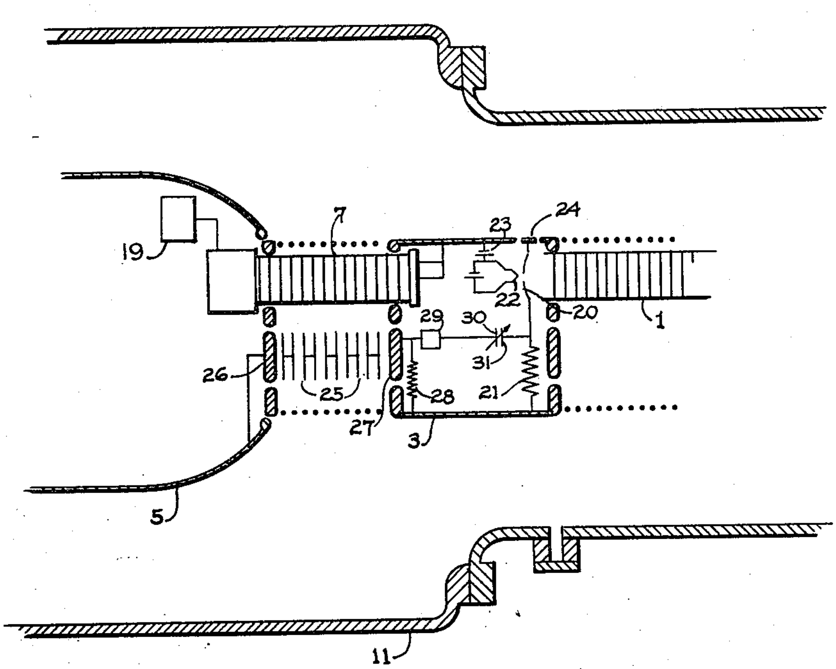

FIG. 5

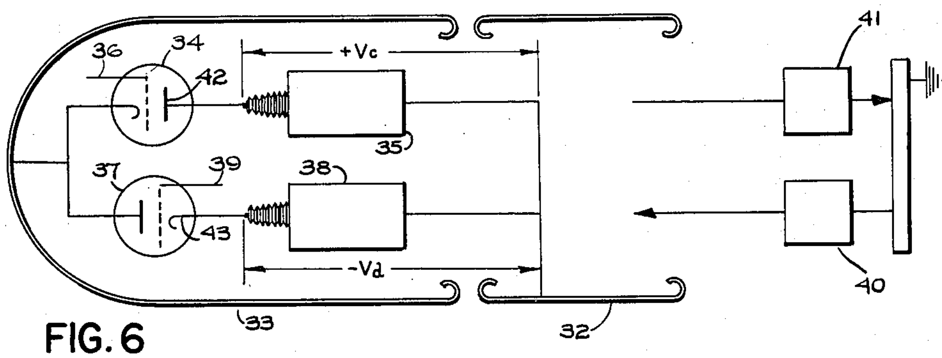

FIG. 6

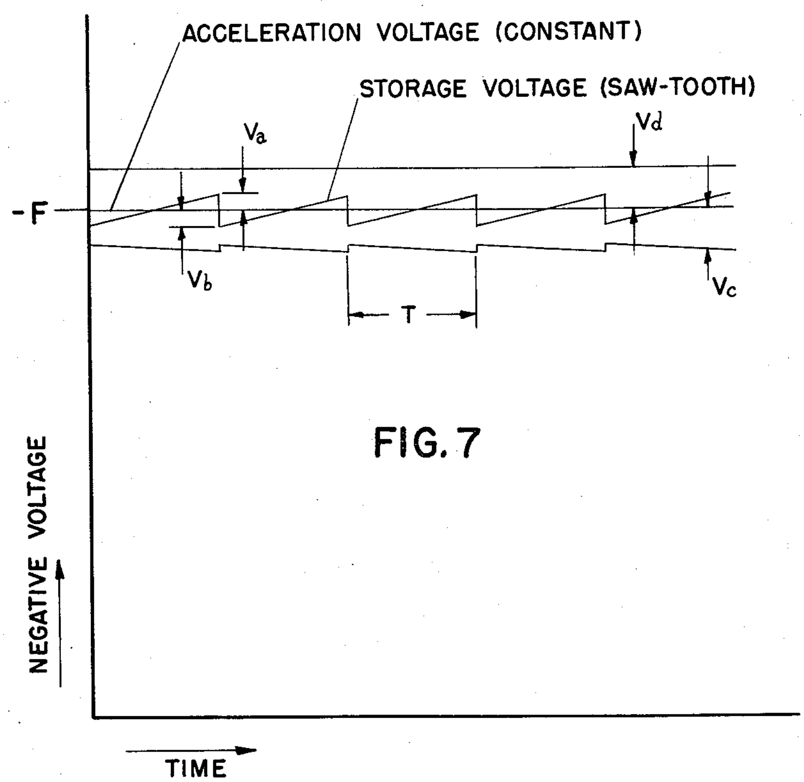

FIG. 7

VOLTAGES AS A FUNCTION OF TIME

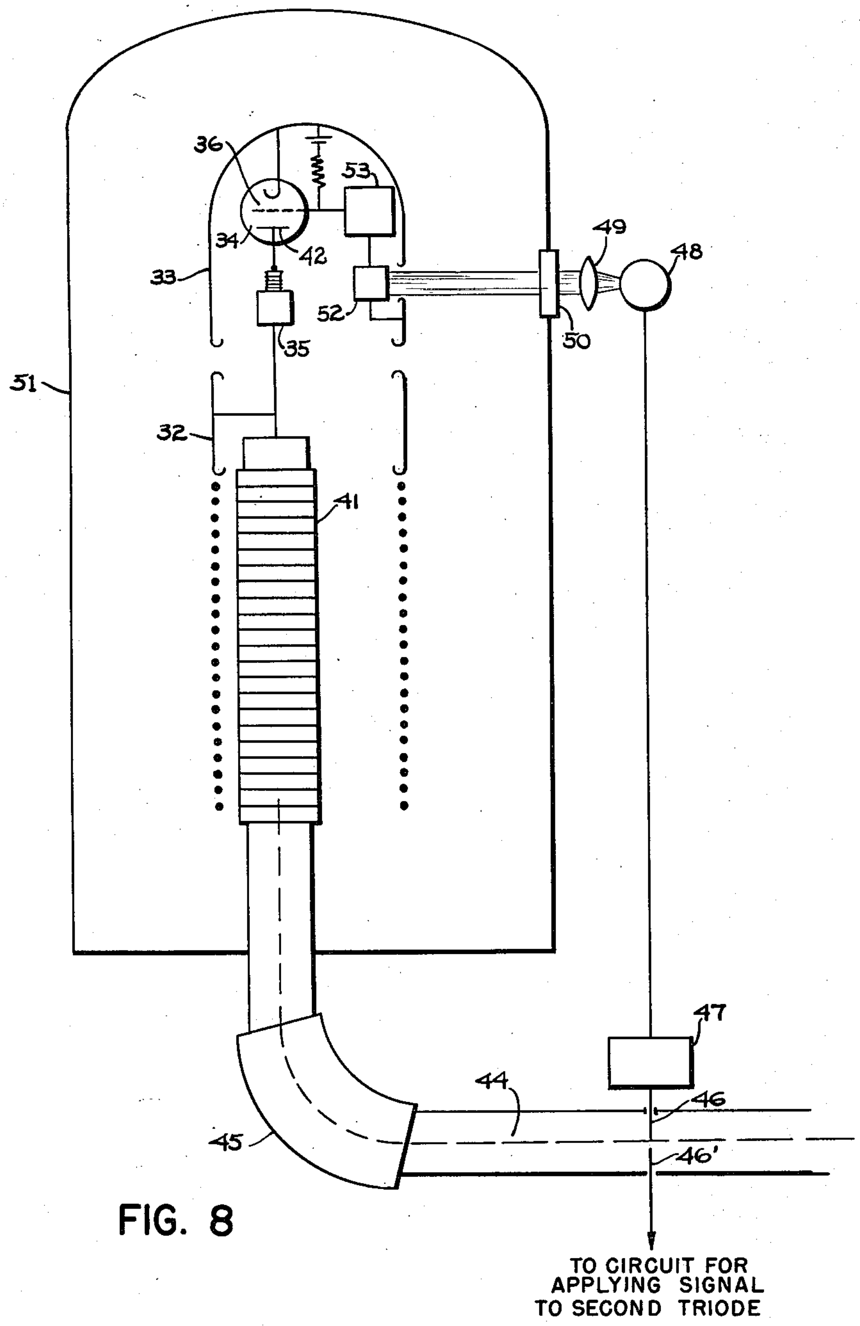
36
53
34
42
33
52
35
49
48
50
51
32
41
47
44
46
45
46'
TO CIRCUIT FOR
APPLYING SIGNAL
TO SECOND TRIODE

FIG. 8

United States Patent Office

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2,847,611

APPARATUS FOR VOLTAGE STABILIZATION OF CONSTANT-POTENTIAL HIGH-VOLTAGE GENERATORS

Robert J. Van de Graaff, Belmont, Mass., assignor to High Voltage Engineering Corporation, Cambridge, Mass., a corporation of Massachusetts

Application May 21, 1954, Serial No. 431,439

11 Claims. (Cl. 315—30)

This invention relates to constant-potential high-voltage generators, and in particular to apparatus for stabilizing the potential of such voltage generators. The invention is especially useful for the stabilization of electrostatic particle accelerators for the production of pulsed or continuous beams.

A constant-potential high-voltage generator includes in effect two main electrodes, one of which is usually a high-voltage terminal and the other of which is usually grounded. The potential of the high-voltage terminal varies with the ratio of the electric charge thereon to the capacitance between the high-voltage terminal and ground. Since it is generally not feasible to alter the capacitance, voltage control is usually effected by controlling the electric charge on the high-voltage terminal. Present methods of voltage stabilization involve the modulation of a current between the two main electrodes (i. e. the high-voltage terminal and ground). Such present methods may be attended by two principal limitations. First, the two main electrodes must, for insulation purposes, be spaced physically a substantial distance apart. Consequently, the rapidity with which electric charge may be transferred from one electrode to the other is limited. Second, the two main electrodes are separated electrically by a large potential drop, so that substantial power is required to effect the transfer of electric charge between them. The instantaneous power required may be very large where a relatively large quantity of charge must be transferred in a very short time interval.

My invention comprehends the introduction of a third electrode whose potential is relatively near that of the high-voltage terminal, and which is positioned physically near the high-voltage terminal. Such an arrangement facilitates the transfer of electric charge to and from the high-voltage terminal to produce voltage regulation of the high-voltage terminal. Less power is required to effect the required charge transfer, because the modulated current passes over less potential difference. Moreover, since the two electrodes involved are close to one another, both in position and electrical potential, conventional sealed-off vacuum tubes may be employed to effect the charge transfer, rather than the corona discharge to ground which is generally required by present methods.

In general, my invention may be used to best advantage in connection with electrostatic particle accelerators, wherein it is particularly desirable to maintain the electrostatic voltage source at constant potential. Although electrostatic accelerators are inherently capable of providing a relatively constant-potential voltage source when operated with a substantially constant-current load, special voltage-stabilization problems arise when such accelerators are operated with a pulsed output. The voltage-stabilization problem may become acute when powerful pulses of monoenergetic particles are required as, for example, when an electrostatic accelerator is used to inject electrons into cyclic accelerators such as synchrotrons or linear accelerators.

The production of powerful pulses of monoenergetic

charged particles by means of a conventional electrostatic accelerator is inherently difficult, because the accelerating voltage depends on the electric charge accumulated on the high voltage terminal of the electrostatic generator. The acceleration of a powerful pulse necessitates a sudden loss of a large quantity of electric charge from the high-voltage terminal of the electrostatic generator, and it is not feasible simultaneously to compensate this loss by conventional apparatus. The resultant potential drop during the pulse prevents the attainment of monoenergetic pulses.

With regard to continuous beams, the present invention may be useful in either of two ways. Its fast stabilization would make possible even greater homogeneity than is now feasible for precision nuclear bombardment. Or, alternatively, the fast stabilization would make possible reasonably good voltage stability even though the generator operation was somewhat unsteady.

Although in the accompanying drawings I have illustrated various embodiments of my invention as applied to electrostatic accelerators, it is clearly to be understood that the use of my invention is not limited to the particular apparatus shown, but may be used to advantage in other cases when it is desired to control the potential of a high-voltage electrode.

In the drawings:

Fig. 1 is a view in vertical section of one type of high-voltage electrostatic accelerator having two high-voltage terminals and embodying one form of the invention;

Fig. 2 is a graph illustrating the variation with time of the voltages of the terminals of the apparatus of Fig. 1;

Fig. 3 is a graph illustrating the variation with time of the various currents to and from one of the terminals of the apparatus of Fig. 1;

Fig. 4 is a diagram showing the equivalent circuit of the apparatus of Fig. 1;

Fig. 5 is a diagram illustrating a possible circuit for obtaining the current relationships shown in the graph of Fig. 3;

Fig. 6 is a diagrammatic view in vertical section of the high-voltage portion of a high-voltage generator, wherein said portion includes two terminals and means for transferring electric charge between said two terminals in accordance with my invention, and illustrates an embodiment of my invention which is particularly suitable for the production of moderately powerful pulses or, alternatively, for fast stabilization in the production of continuous beams;

Fig. 7 is a graph illustrating the variation with time of the voltages of the two terminals of Fig. 6; and

Fig. 8 is a diagrammatic view in vertical section of apparatus similar to that of Fig. 6, and illustrates a circuit for obtaining fast stabilization of the voltage of continuous beams of electrons in accordance with my invention.

Referring to the drawings, and first to Fig. 1 thereof, charged particles are accelerated to high energy within an evacuated acceleration tube **1** by an electric field which is produced by electrically connecting the charged-particle source **2** of the tube **1** to a hollow high-voltage terminal **3** of conducting material and electrically connecting the opposite end portion of the tube **1** to a grounded plane **4** of conducting material. The high voltage of the accelerating terminal **3** is derived from a large storage terminal **5**, which rests on insulating supports **6**. Delivery of electric charge from the storage terminal **5** to the accelerating terminal **3** is effected by an auxiliary vacuum tube **7** which, except for its shortness, is similar to the main acceleration tube **1**. The charged-particle source **8** of the auxiliary vacuum tube **7** is electrically connected to the storage terminal **5**, and the opposite end portion is electrically connected to the accelerating terminal **3**. The accelerating terminal **3** is supported by a main column **9** extending to the ground plane **4** and an auxiliary column **10** extending to the storage terminal **5**. The columns **9**, **10** are of conventional design, and each comprises a series of spaced conducting planes separated by insulating supports. Voltage distribution along each of the two columns **9**, **10** is aided by column resistors (not shown) between adjacent equipotential planes. The entire apparatus is enclosed in a tank **11** containing gas under pressure for the purpose of insulation. The ground plane **4** is supported on the base plate **12** of the tank by conducting members **13**.

An endless belt **14** of insulating material is supported by two pulleys **15**, **16**, one **15** of which is in the electrically isolated space between the ground plane **4** and the base plate **12**, and the other **16** of which is in the electrically isolated space within the storage terminal **5**. The belt is caused to travel continuously in the direction of the arrows **17** by a motor (not shown) which drives the lower pulley **15**. Electric charge is deposited on the belt by conventional means (not shown) in the electrically isolated space between the ground plane **4** and the base plate **12**; and, after being conveyed by the belt **14** to the electrically isolated space within the storage terminal **5**, the electric charge is there transferred to the storage terminal **5** by conventional means (not shown). For the operation of the more conventional aspects of electrostatic belt-type generators, reference may be made to U. S. Patent No. 1,991,236 to Van de Graaff and U. S. Patent No. 2,252,668 to Trump.

As charge is delivered to the storage terminal **5** its potential increases and at the same time the potential of the accelerating terminal **3** increases, but at a rate less than that of the storage terminal **5**. When the potential of the accelerating terminal reaches the desired value, it is held constant by a conventional stabilizing circuit (not shown). The voltage of the storage terminal **5** is then at a corresponding value V_1. (See the graph of Fig. 2).

By means of special circuits, to be described in more detail hereinafter in connection with Fig. 5, the two acceleration tubes **1**, **7** are then so pulsed that the relative magnitudes of the current I_p in the main acceleration tube **1** and the current I_s in the auxiliary tube **7** are such that

$$I_s=I_p+I_d \qquad (1)$$

where I_d will be defined hereinafter. The current relationships are indicated in the graph of Fig. 3, wherein the horizontal time scale is the same as that of the graph of Fig. 2. As shown by the graph of Fig. 3, the synchronous pulses are repeated with a period of T seconds which is much longer than the pulse interval of t seconds, so that the current pulses appear in the graph of Fig. 3 as lines whose thickness represents the pulse interval t.

The principle of my invention may best be understood with reference to an equivalent circuit of the apparatus of Fig. 1. Such equivalent circuit is illustrated in the diagram of Fig. 4, wherein the point **5** represents the storage terminal, the point **3** represents the accelerating terminal, and the ground symbols **11** represent the grounded tank. The storage terminal **5** is electrically associated with the tank **11** through a large capacitance, indicated in Fig. 4 at C_s, and with the accelerating terminal **3** through a smaller capacitance, indicated in Fig. 4 at C_d. The accelerating terminal **3** is electrically associated with the tank **11** through a capacitance indicated in Fig. 4 at C_a.

When the auxiliary tube **7** is pulsed, a current I_s flows therethrough from the storage terminal **5** to the accelerating terminal **3**; and when the main acceleration tube **1** is pulsed, a current I_p flows therethrough from the accelerating terminal **3** to ground **11**. Assuming, for simplicity of discussion only, that the apparatus of Fig. 1 is to deliver electron pulses, the arrows I_s and I_p in Fig. 4 indicate the direction of electron flow through the auxiliary tube **7** and the main acceleration tube **1** respectively.

During the pulse, which involves the transfer of relatively large quantities of charge in a relatively short time, there will be negligible change in the charging current to the terminals **3**, **5** or in currents through resistance paths between the terminals **3**, **5** and the tank **11**. Consequently, the only significant electrical paths between the three electrodes **3**, **5**, **11** are the electronic currents I_p, I_s through the acceleration tubes **1**, **7** and displacement currents through the capacitances C_s, C_d and C_a. Such displacement currents are indicated in Fig. 4 as I_e, I_d and I_g, the arrows indicating the direction of electron flow.

The current I_d in Equation 1 is the displacement current through the capacitance C_d, and is therefore equal to $C_d(V_1-V_2)/t$, where V_1-V_2 is the voltage drop of the storage terminal and t is the pulse interval. For simplicity of discussion, it is assumed that the currents I_p and I_s are constant during the pulse interval t.

Referring to Fig. 4, since $I_s=I_p+I_d$ and since the net current to the point **3** must be zero, the displacement current I_g through the capacitance C_a must be zero. Therefore, since the change in voltage of the accelerating terminal **3** is equal to I_gt/C_a, the accelerating terminal **3** remains at constant potential during the pulse.

As hereinbefore pointed out, if the main acceleration tube **1** were energized in the conventional way directly by a single terminal, the delivery of the pulse current I_p would cause a sudden loss of a large quantity of charge from the terminal, thereby reducing the accelerating voltage during the pulse. By providing a storage terminal **5** separated from the accelerating terminal **3**, and by providing an auxiliary vacuum tube **7** for the transfer of electric charge between these two terminals **3**, **5**, I am able to maintain the accelerating voltage constant during the pulse.

Referring again to the diagram of Fig. 4, the net current to the point **5** must be zero, so that $I_s=I_d+I_e$. Since I_e is the displacement current through the capacitance C_s, and is therefore equal to $C_s(V_1-V_2)/t$,

$$I_s=C_s(V_1-V_2)/t+I_d \qquad (2)$$

Combining equations 1 and 2,

$$I_p=C_s(V_1-V_2)/t \qquad (3)$$

Voltage stability of the accelerating terminal **3** is thus achieved if the net physical current thereto equals the displacement current from the accelerating terminal **3** to the storage terminal **5**. The term "net physical current" refers to the rate at which the net electric charge on the accelerating terminal **3** increases, and in Equation 1 is represented by I_s-I_p.

The relationship of the three currents, I_p, I_d, and I_s, is illustrated in the graph of Fig. 3, where, since t is very much less than T, the current pulses appear as lines whose thickness represents the time interval t. The voltages of the two terminals are shown as a function of time in the graph of Fig. 2, which graph employs the same time scales as the graph of Fig. 3. As shown in the graph of Fig. 2, the negative voltage of the accelerating terminal **3** remains constant at all times, while the negative voltage of the storage terminal **5** drops precipitously from $-V_1$ to $-V_2$ during the pulse interval t.

The operation of the apparatus of Fig. 1 may be illustrated by a numerical example chosen to show the high pulse currents and the high power during pulses that could be obtained from an electrostatic generator of comparatively small size and comparatively small D. C. power output. Suppose that the accelerating terminal **3** may conveniently be stabilized at —2 million volts, and that the storage terminal **5** is designed to operate between a maximum of —2.3 million volts and a minimum of —2.1 million volts. Assuming that C_s is 200 micromicrofarads and that a 5-microsecond pulse is desired, then the pulse current I_p is given by the previously derived relationship:

$$I_p = C_s(V_1 - V_2)/t = 8 \text{ amperes}$$

and the power during the pulse is 16 megawatts. The magnitude of these results show that electrostatic generators of comparatively low continuous power output can in principle be used to supply a pulsed output of extremely high power, it being assumed that vacuum tubes can be made which will supply the high currents needed.

The amount of charge which the belt **14** must deliver to the storage terminal **5** in order to raise its potential from −2.1 to −2.3 million volts between pulses is approximately 40 micro-coulombs. If the net charging current which the belt **14** can deliver to the storage terminal **5** between pulses is 250 microamperes, then the minimum permissible quiescent interval is .16 second

The auxiliary vacuum tube **7** shown in Fig. 1 delivers a pulse from the storage terminal **5** to the accelerating terminal **3** of the same polarity as that of the main pulse. Thus, if the main accelerating tube **1** is delivering a pulsed electron output, the auxiliary vacuum tube **7** will deliver electron pulses from the storage terminal **5** to the accelerating terminal **3**. However, if the main accelerating tube **1** is delivering a pulsed positive-ion output, it will probably be preferable for the auxiliary vacuum tube to deliver electron pulses from the accelerating terminal **3** to the storage terminal **5**, since electrons are easier to produce.

One possible arrangement for providing simultaneous pulses whose currents are related as required is illustrated in Fig. 5, in which are somewhat diagrammatically shown the accelerating terminal **3** and other nearby portions of the apparatus of Fig. 1. For simplicity, it will be assumed that both vacuum tubes **1** and **7** are to deliver electron pulses. In the arrangement of Fig. 5, the pulses are initiated by a conventional trigger circuit **19** which pulses the auxiliary vacuum tube **7**. Just prior to the initiation of a pulse, the auxiliary vacuum tube **7** is non-conducting. A grid member **20** in the main acceleration tube **1** is at the potential of the accelerating terminal **3** to which it is connected through a high resistance **21**. The term "grid member" includes any conductive member which is adapted to control the current flow through the main acceleration tube **1** by virtue of its potential with respect to that of the charged-particle source of the main acceleration tube **1**. By means of a battery **23** which connects the cathode **22** to the accelerating terminal **3**, the cathode **22** of the main acceleration tube **1** is maintained sufficiently positive with respect to the grid member **20** so that no current flows through the main acceleration tube **1**. A pickup electrode **24**, which is exposed to the electric field surrounding the accelerating terminal **3**, is electrically connected directly to the grid member **20**, and is insulated from the accelerating terminal **3** except for the connection via the high resistance **21**.

When the trigger circuit **19** initiates a pulse in the auxiliary vacuum tube **7**, a large quantity of negative charge flows onto the accelerating terminal **3**, thereby tending to raise the negative potential of the accelerating terminal **3**. However, the rise in negative potential of the pickup electrode **24**, which, as far as transient phenomena are concerned, is effectively insulated from the accelerating terminal **3** by the high resistance **21**, lags behind that of the accelerating terminal **3**, so that its potential becomes positive with respect to that of the accelerating terminal **3**, and hence positive with respect to that of the cathode **22**. This positive potential also appears on the grid member **20**, and hence serves to pulse the main acceleration tube **1** before the potential of the accelerating terminal **3** can rise by more than a relatively small amount.

As a numerical example, suppose that the accelerating terminal **3** is to be maintained at −2 million volts with a permissible variation of .1%. This means that the negative potential of the accelerating terminal **3** may permissibly rise −2000 volts to −2,002,000 volts. If the negative potential of the accelerating terminal **3** rises by −2000 volts, that of the pickup electrode **24** will lag behind by an appreciable fraction of −2000 volts, which is a relatively large voltage rise from the point of view of the grid member **20**, and is ample to pulse the main acceleration tube **1**.

Another way of viewing the operation of the apparatus just described, is to consider the flow of electric charge rather than the changes in relative potential. Thus, the pulse of electrons initiated by the trigger circuit **19** results in the deposition of an additional quantity of negative charge on the accelerating terminal **3**, but not on the pickup electrode **24**. However, the increased negative charge on the outer surface of the accelerating terminal **3** induces an increased positive charge on the inner surface of the grounded tank **11**; and this increased positive charge (on the inner surface of the grounded tank **11**) in turn induces an increased negative charge on the outer surface of the pickup electrode **24**, since the pickup electrode **24** is exposed to the electric field surrounding the accelerating terminal **3**. However, since the pickup electrode **24** is effectively insulated, so far as sudden electrical changes are concerned, from the accelerating terminal **3** by the high resistance **21**, the net charge on the unit comprising the pickup electrode **24** and the grid member **20** remains constant. Hence the increased negative charge on the outer surface of the pickup electrode **24** causes an increased positive charge to appear on the grid member **20**, thereby enabling electrons from the cathode **22** to flow into the accelerating field of the main acceleration tube **1**.

This arrangement gives a high degree of stability, and, if the storage terminal **5** were sufficiently remote from the accelerating terminal **3**, the stability would be adequate. However, the proximity of the storage terminal **5** to the accelerating terminal **3** introduces second order effects due to the capacitance between the storage terminal **5** and the pickup electrode **24**. The effect of this capacitance is to cause the large negative charge on the storage terminal **5** to induce a small amount of positive charge on the outer surface of the pickup electrode **24**. When the auxiliary tube **7** is pulsed, a substantial quantity of negative charge leaves the storage terminal **3**, thus releasing some of the induced positive charge from the outer surface of the pickup electrode **24**. The released positive charge then appears on the grid **20**, and hence tends to cause the grid **20** to withdraw more negative charge from the accelerating terminal **3** (via the electron current in the main acceleration tube **1**) than is required for voltage stability of the accelerating terminal **3**.

In order to counteract this second-order effect, a second capacitative connection may be introduced between the storage terminal **5** and the pickup electrode **24**, which second capacitative connection is designed to counteract the effect of the existing capacitance between the storage terminal **5** and the pickup electrode **24**. For this purpose, the following circuit may be employed:

Still referring to Fig. 5, a large capacitance is introduced between the storage terminal **5** and the accelerating terminal **3**, as indicated at **25** by the condensers in series. This capacitance may be provided by the equipotential planes of the auxiliary column **10**, or supplementary condensers may be introduced. One end plate **26** of the series of condensers may be connected to (or indeed form a part of) the storage terminal **5**. The opposite end plate **27** is connected to the accelerating terminal **3** through a high resistance **28**, so that said end plate **28** will in effect be connected directly to the accelerating terminal **3** between pulses but insulated therefrom during each pulse.

When the auxiliary tube **7** is pulsed, the negative potential of the storage terminal **5** drops, so that some of the positive charge which was bound on the end plate **27** is released. This sends a positive pulse into an amplifier

29, since the high resistance 28 prevents the positive charge from immediately flowing to the accelerating terminal 3. The amplifier 29 is designed to amplify this pulse and reverse its polarity, by conventional circuits, so that an amplified negative pulse arrives at the plate 30 of the variable condenser 30—31. This negative pulse induces a positive pulse on the plate 31 of the variable condenser 30—31, and hence draws positive charge from the grid member 20, so as to lessen the net amount of positive charge induced on the grid member 20. (It will be recalled that the effect of the pickup electrode 24 is to induce an amount of positive charge on the grid member 20 which amount is excessive when the storage terminal 5 is close to the accelerating terminal 3.) The amount of positive charge so withdrawn from the grid member 20 may be regulated by adjusting the capacitance of the variable condenser 30—31. Consequently, the pulse current I_p in the main acceleration tube 1 may be regulated to satisfy the requirements of Equation 1.

In addition to the production of substantially monoenergetic pulses, my invention also includes the production of pulses of charged particles whose energy varies in a controlled way. For example, if a relatively long pulse is to be injected into a synchrotron, considerations of orbital stability require that the energy, with which the charged particles are injected, increase during the pulse in a predetermined manner. Such an increase may be provided in accordance with my invention by causing the pulse current I_s in the auxiliary vacuum tube 7 to exceed that necessary for the production of monoenergetic pulses. The pulse current I_s may be regulated as required by means of the variable condenser 30—31, or by means of any other suitable device.

From the above description it will be apparent that quite powerful monoenergetic pulses can be produced by the sort of apparatus shown in Fig. 1. If less powerful pulses are needed, or if extremely fast voltage stabilization is required with a continuous beam the more compact arrangement shown in Fig. 6 may be employed.

Referring to said Fig. 6, therein are shown a main terminal 32 whose voltage is to be stabilized, and an auxiliary or storage terminal 33 which is insulated from the main terminal 32 by being spaced therefrom a short distance.

Transfer of positive electric charge from the main terminal 32 to the auxiliary terminal 33 (or transfer of negative electric charge from the auxiliary terminal 33 to the main terminal 32) is effected via the triode 34 and the power supply 35, and the current involved in such transfer is controlled by the grid 36. Transfer of positive electric charge from the auxiliary terminal 33 to the main terminal 32 (or transfer of negative electric charge from the main terminal 32 to the auxiliary terminal 33) is effected via the triode 37 and the power supply 38, and the current involved in such transfer is controlled by the grid 39. Consequently, electric charge may be transferred very rapidly between the two terminals 32, 33 by suitable control of the potentials of the grids 36, 39.

Although two triodes are illustrated in Fig. 6, under certain circumstances voltage stabilization may be achieved with only a single triode. The apparatus of Fig. 8, to be described in detail hereinafter, illustrates the use of a single triode. Of course, more than two triodes may be employed, and other types of vacuum tubes, such as tetrodes or pentodes and the like, may be substituted for the triodes without departing from the spirit of my invention.

Since my invention may be employed advantageously to stabilize the potential of any high-voltage constant-potential electrode, the means by which such electrode is maintained at high voltage is immaterial to the invention. Accordingly, there is indicated merely diagrammatically at 40 in Fig. 6 means for delivering a charging current to the terminals 32 and 33. Said charging means may comprise an endless traveling belt, as in the apparatus of Fig. 1, or a transformer-rectifier set, or any other appropriate charging device.

Similarly, the use to which the high voltage of the electrode is put is immaterial to the invention, and there is indicated merely diagrammatically at 41 in Fig. 6 a load which draws current from the main terminal 32. Usually the load will comprise an evacuated device for the acceleration of charged particles, but my invention is not limited to such a load; nor is it necessary to my invention that any load be connected to the electrode.

Regarding the apparatus of Fig. 6 as comprising basically three main electrodes (i. e. the main terminal 32, the auxiliary terminal 33, and ground), then it is clear from the previous analysis of Figs. 1 and 4 that the main terminal 32 will remain at constant potential if the net current thereto, including the displacement current between the main terminal 32 and the auxiliary terminal 33, is zero. If the fixed potential of the main terminal 32 is $-F$, and if the plate 42 of triode 34 and the cathode 43 of triode 37 are maintained at potentials of $+V_c$ and $-V_d$ respectively with respect to the potential $-F$ of the main terminal 32, then the potential of the auxiliary terminal 33 may permissively vary between the limits $-F+V_c$ and $-F-V_d$.

To illustrate the operation of the apparatus of Fig. 6 in the production of moderately powerful pulses, suppose that the charging device 40 delivers a constant negative current i to the main terminal 32; and that the load 41 is an acceleration tube adapted to give a pulsed electron output with a negative pulse current I_p, a pulse interval t, and a repetition time T. Then, for voltage stability of the main or accelerating terminal 32, a negative current equal to $i+i_d$ must be delivered from the accelerating terminal 32 to the auxiliary or storage terminal 33 during the quiescent interval (where i_d is the displacement current due to the transfer of charge between the terminals 32, 33), and a negative current equal to $(I_p-i)+(Id-i_d)$ must be delivered from the storage terminal 33 to the accelerating terminal 32 during the pulse. This condition is satisfied if the grid 39 is biased so that the triode 37 passes a constant negative current $i+i_d$ from the accelerating terminal 32 to the storage terminal 33, and if the grid 36 is biased beyond cutoff except during the pulse interval, at which time the grid 36 is pulsed in synchronism with the acceleration tube 41 so as to deliver a negative current I_p+I_d from the storage terminal 33 to the accelerating terminal 32.

Any suitable circuit for pulsing the grid 36, in proper synchronism with the acceleration tube 41 may be employed, such as a circuit of the type illustrated in Fig. 5.

The resultant voltage variation of the two terminals 32, 33 as a function of time are illustrated by the graph of Fig. 7. The accelerating terminal 32 remains at constant potential $-F$, while the voltage of the storage terminal 33 drops from $-F-V_a$ to $-F+V_b$ during the pulse and rises again to $-F-V_a$ between pulses.

The pulse current is given by the relationship

$$I_p=C_s(V_a+V_b)/t$$

Where the apparatus of Fig. 6 is to be employed for fast stabilization of the energy of the charged particles in a continuous beam, any appropriate circuit may be employed to apply suitable signal voltages to the grids 36, 39. For the purpose of illustrating one such circuit, there is shown in Fig. 8 an electrostatic accelerator adapted to produce a continuous beam of electrons. Said accelerator is of the conventional type, except that it is provided with two terminals 32, 33 in accordance with my invention, together with apparatus for fast stabilization of the voltage of the accelerating terminal 32, which apparatus will now be described.

Referring to Fig. 8, the means for transferring electric charge between the terminals 32, 33 is identical to that shown in Fig. 6, except that for simplicity of discussion only one triode 34 is shown in the apparatus of Fig. 8. The load 41 constitutes an acceleration tube adapted to provide a continuous beam 44 of electrons.

After the electrons have been accelerated to full velocity in the acceleration tube 41, they are deflected by a magnetic field of constant intensity, which may be created by conventional means indicated at 45. A slit-edge 46 is supported in the path of the deflected beam 44, so that the electron beam just grazes the slit-edge when the voltage of the accelerating terminal 32 is at its stabilized value. The small electron current thus impinging on the slit edge is amplified by a conventional amplifier 47, and the amplified current is used to energize a light source 48, so that the intensity of light from the light source increases with increasing electron current collected by the slit edge. A portion of the light from the light source is focused by a lens 49, which directs the light rays through a transparent window 50 in the tank 51 and onto an electron multiplier 52, supported within the storage terminal 33, which converts the light signal into a negative-current impulse. This negative-current impulse is then amplified and its polarity reversed by the amplifier 53, so that any increase in the intensity of light from the light source results in a positive impulse on the grid 36.

If the voltage of the accelerating terminal 32 becomes less negative than the stable condition, the electrons in the beam 44 will have less momentum, and the radius of curvature of the path through the magnetic field 45 will be less, so that more electron current strikes the slit edge 46. This makes the grid 36 more positive, thereby increasing the flow of negative current from the storage terminal 33 to the accelerating terminal 32, and hence restoring the potential of the accelerating the terminal 32 to its stable value.

If two triodes are employed, a similar circuit (using a second slit edge 46′, etc.) may be employed to apply a suitable signal voltage to the grid 39 of the second triode 37 of Fig. 6.

Having thus described the principles of my invention together with several illustrative embodiments of apparatus for practicing the invention, it is to be understood that although specific terms are employed, they are used in a generic and descriptive sense and not for purposes of limitation, the scope of the invention being set forth in the following claims.

I claim:

1. Apparatus for controlling the potential of a high voltage electrode comprising a charged body near and substantially insulated from said high voltage electrode, and means for transferring electric charge between said high voltage electrode and said charged body, in at least that direction which tends to increase the net charge on said high voltage electrode.

2. Apparatus for controlling the potential of a high voltage electrode comprising an auxiliary electrode which is substantially insulated from said high voltage electrode and whose position and voltage are near the position and voltage respectively of said high voltage electrode, and means for transferring electric charge between said electrodes, in at least that direction which tends to increase the net charge on said high voltage electrode.

3. Apparatus for stabilizing the kinetic energy with which charged particles arrive at an area in space, comprising in combination: a first charged body; a first vacuum path connecting said first charged body to said area in space; a second charged body adjacent to and substantially insulated from said first charged body and connected thereto by a second vacuum path; and means for transferring charge between said charged bodies through said second vacuum path in such a way that the kinetic energy of charged particles arriving at said area in space from said first charged body via said first vacuum path is substantially constant, despite transient phenomena such as a sudden increase in the charged particle current from said first charged body via said first vacuum path.

4. Apparatus for stabilizing the potential of a high voltage electrode comprising an auxiliary electrode which is substantially insulated from said high voltage electrode and whose position and voltage are near the position and voltage respectively of said high voltage electrode, and means for transferring electric charge between said electrodes at a rate and in a direction such that the net physical current to said high voltage electrode substantially equals the displacement current from said high voltage electrode to said auxiliary electrode, but in at least that direction which tends to increase the net charge on said high voltage electrode.

5. Apparatus for accelerating charged particles to high energy comprising in combination: an evacuated acceleration tube energized by a charged body; a second charged body near said first charged body; means for conveying electric charge to said charged bodies for the purpose of maintaining their potentials at high voltage; at least one auxiliary vacuum tube adapted to provide a current flow between said charged bodies; and means for controlling said current flow so that the kinetic energy of charged particles accelerated in said acceleration tube is substantially constant.

6. Apparatus for producing high-current pulses of charged particles the energy of which increases in a controlled way, comprising in combination: an acceleration tube energized by a high-voltage accelerating terminal; a high-voltage storage terminal near said accelerating terminal; means for conveying electric charge to said terminals for the purpose of maintaining their potentials at high voltage; an auxiliary vacuum tube adapted to provide a current flow between said terminals; and means for pulsing said acceleration tube and said auxiliary vacuum tube, the pulse currents being so related that the energy of the charged particles in the pulse in said acceleration tube increases in a predetermined manner.

7. Apparatus for producing high-current pulses of substantially monoenergetic charged particles comprising in combination: an acceleration tube energized by a high-voltage accelerating terminal; a high-voltage storage terminal near said accelerating terminal; means for conveying electric charge to said terminals for the purpose of maintaining their potentials at high voltage; an auxiliary vacuum tube adapted to provide a current flow between said terminals; and means for pulsing said acceleration tube and said auxiliary vacuum tube, the pulse currents being so related that the pulse in said acceleration tube is substantially monoenergetic.

8. Apparatus for the production of substantially monoenergetic pulses of high-energy charged particles, comprising in combination: an acceleration tube having a source of charged particles at one extremity thereof; a grid member in said acceleration tube adapted to control the flow of charged particles from said source into the accelerating region of said tube; a first charged body from which the accelerating field within said tube is derived, said first charged body including an isolated portion which is electrically separated from the main portion of said first charged body by a high impedance; said source of charged particles being electrically connected to the main portion of said first charged body, and said grid member being electrically connected to the isolated portion of said first charged body; a second charged body near said first charged body; and means for transferring a pulse of electric charge between said second charged body and the main portion of said first charged body, so as to tend to increase the net charge on the main portion of said first charged body, whereby said acceleration tube is caused to deliver a pulse of substantially monoenergetic charged particles.

9. Apparatus in accordance with claim 8, wherein there is provided a capacitative path between said second charged body and said grid member, and means to re-

verse the polarity of electric signals arriving at said grid member through said capacitative path.

10. Apparatus in accordance with claim 9, wherein there is provided means to vary the capacitance of said capacitative path.

11. Apparatus for the production of a continuous beam of substantially monoenergetic charged particles, comprising in combination: an acceleration tube adapted to produce a beam of charged particles; a first charged body from which the accelerating field within said tube is derived; a second charged body near said first charged body; at least one vacuum tube adapted to provide a current flow between said charged bodies; said vacuum tube having at least one grid adapted to control said current flow; means for obtaining at least one signal from the beam of charged particles produced by said acceleration tube, which signal is a measure of the deviation of the kinetic energy of said charged particles from a predetermined value; and means for applying said signal to said grid so as to cause a current flow between said charged bodies of such a nature as to compensate for said deviation of the kinetic energy of said charged particles.

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