Dec. 31, 1957 P. A. PEARSON 2,818,527

PULSE FORMING NETWORK DISCHARGE SWITCH

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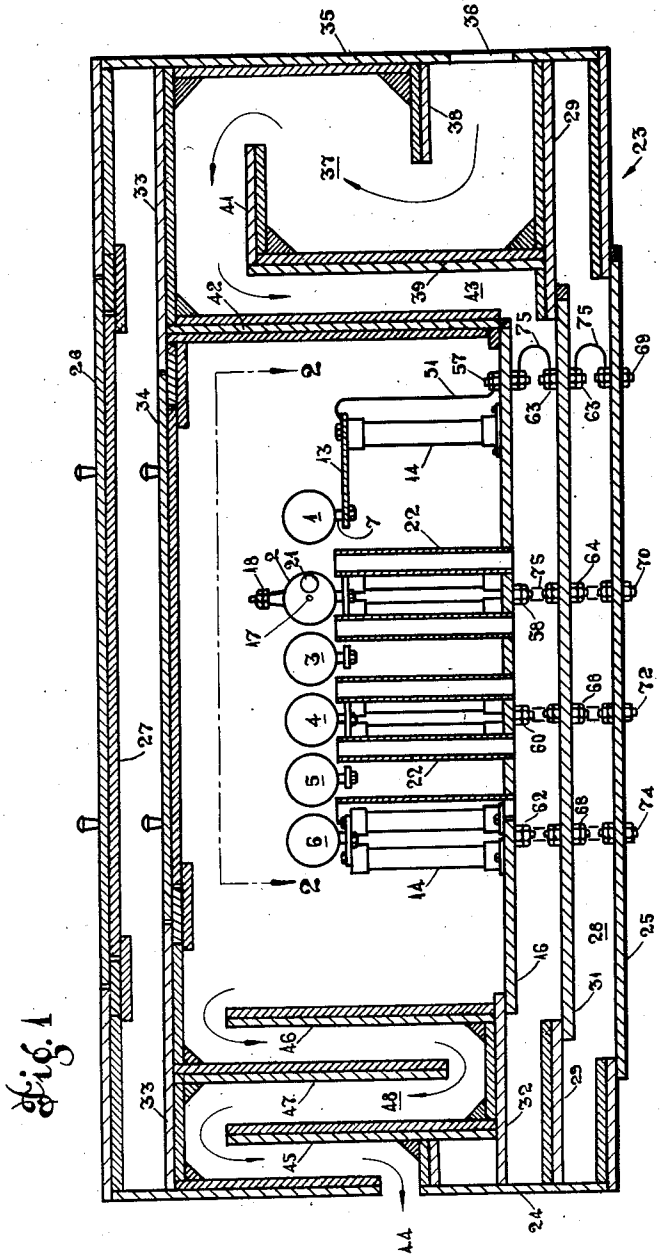


Fig. 1

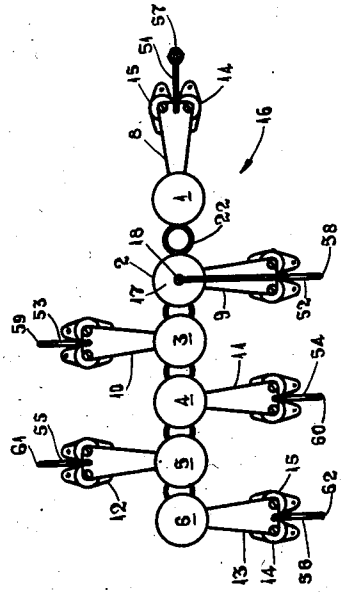


Fig. 2

INVENTOR.
PAUL A. PEARSON
BY Mellin and Hanscom
ATTORNEYS

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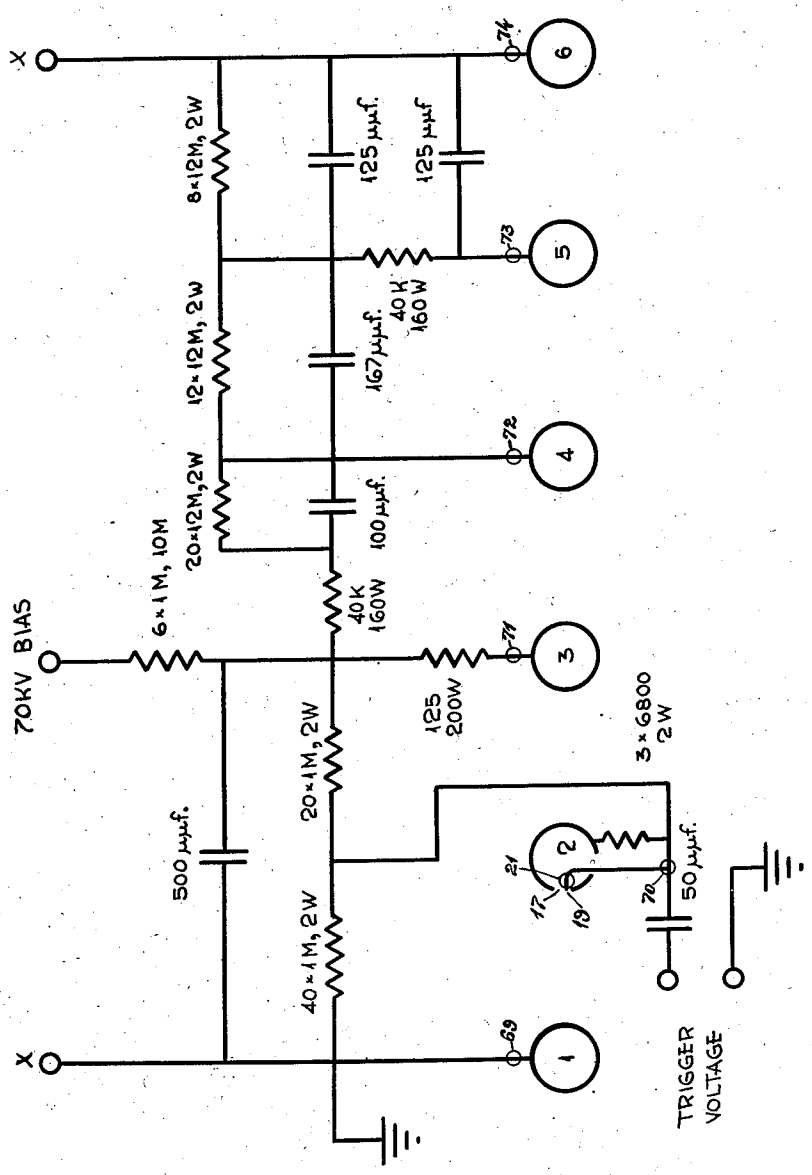


Fig. 3

INVENTOR.
PAUL A. PEARSON

BY Mellin and Hanscom

ATTORNEYS

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PULSE FORMING NETWORK DISCHARGE SWITCH

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Fig. 4

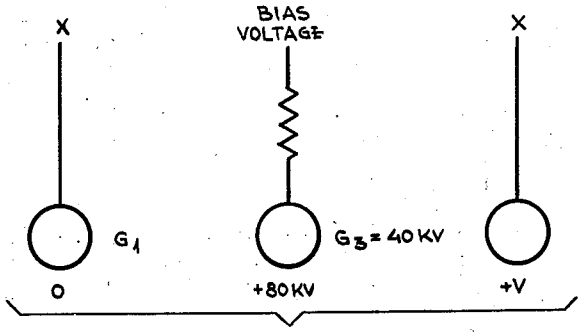


Fig. 5

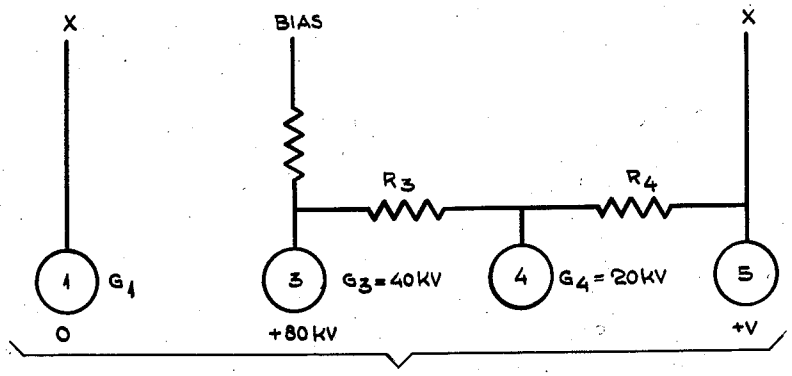
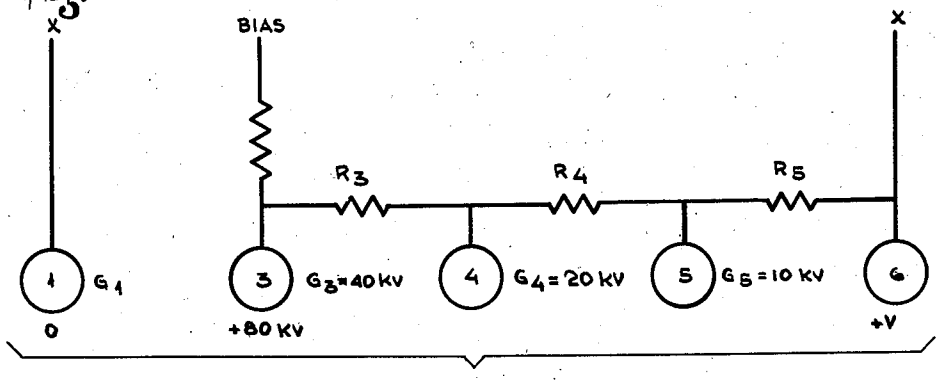


Fig. 6



INVENTOR.
PAUL A. PEARSON

BY Mellin and Hanscom

ATTORNEYS

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Fig. 7

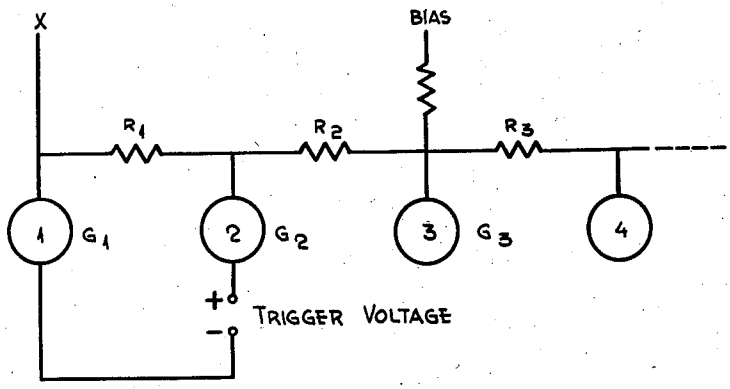


Fig. 8

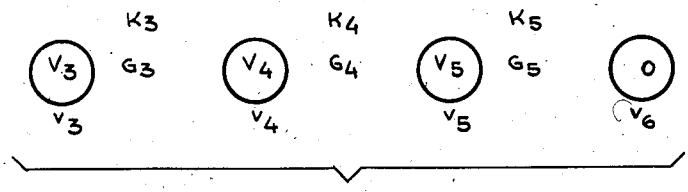


Fig. 9

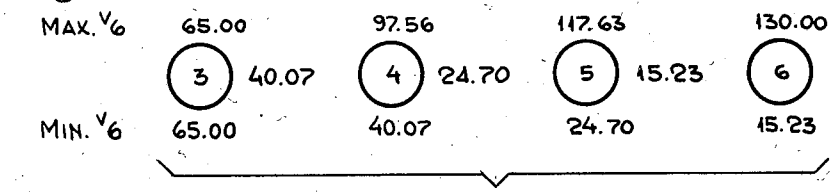
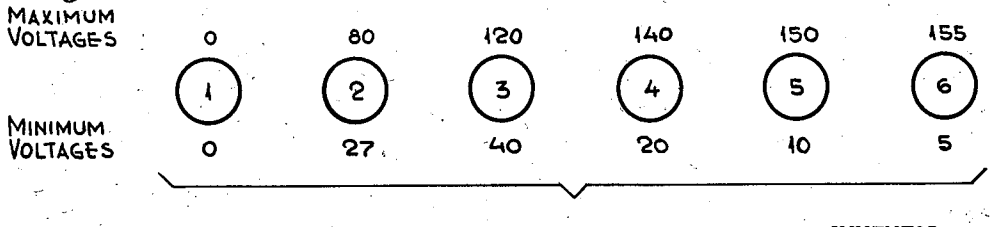


Fig. 10



INVENTOR.
PAUL A. PEARSON

BY Mellin and Hanscom

ATTORNEYS

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Fig. 11

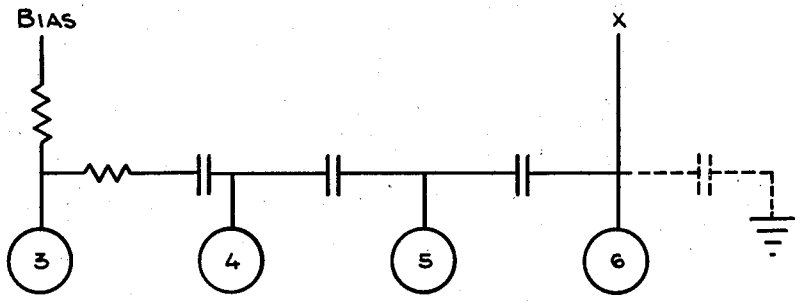


Fig. 12

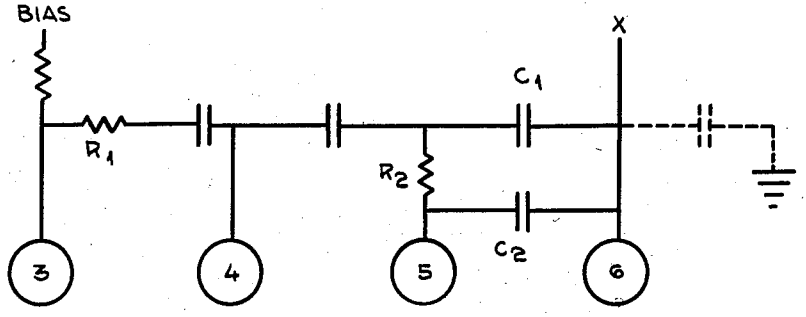
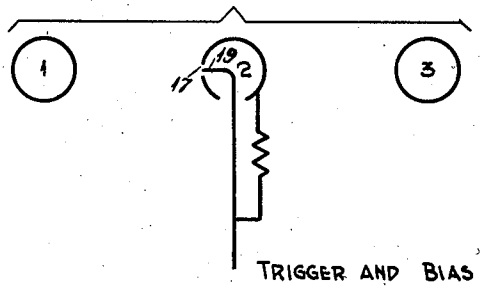


Fig. 13



TRIGGER AND BIAS VOLTAGES

INVENTOR.
PAUL A. PEARSON
BY Mellin and Hanson
ATTORNEYS

PULSE FORMING NETWORK DISCHARGE SWITCH

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Fig. 14

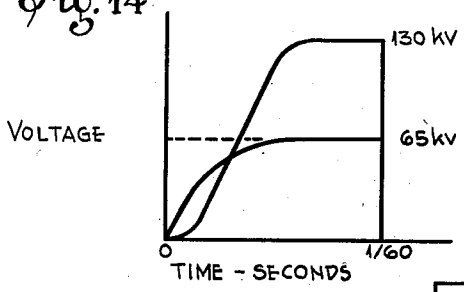


Fig. 15

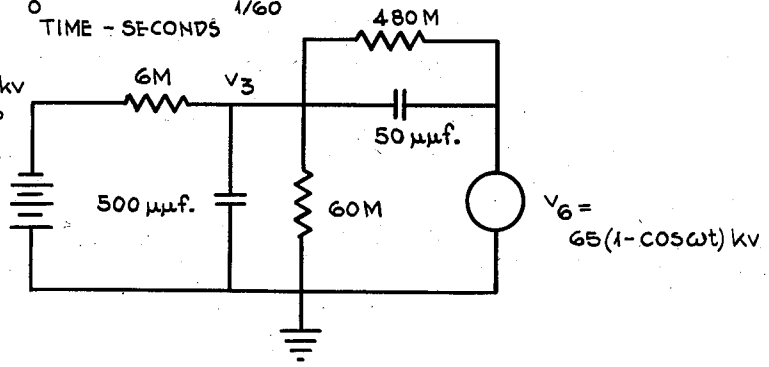


Fig. 16

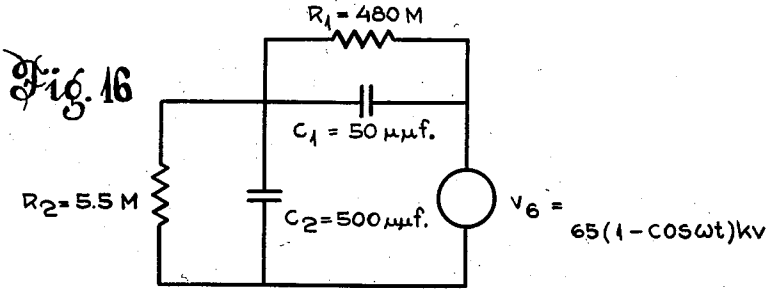
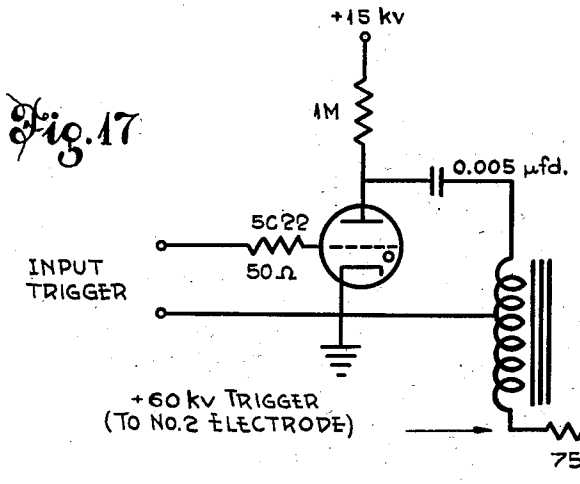


Fig. 17



INVENTOR.
PAUL A. PEARSON
BY Mellin and Hamilton
ATTORNEYS

United States Patent Office 2,818,527 Patented Dec. 31, 1957

2,818,527

PULSE FORMING NETWORK DISCHARGE SWITCH

Paul Alfred Pearson, Palo Alto, Calif., assignor to The Board of Trustees of The Leland Stanford Jr. University, Stanford, Calif.

Application February 23, 1954, Serial No. 411,848

9 Claims. (Cl. 315—36)

This invention relates to and in general has for its object the provision of a discharge switch for pulse forming networks.

More specifically, the object of this invention is the provision of a discharge switch for a pulse forming network suitable for use in conjunction with a linear electron accelerator wherein said accelerator is energized by a series of high power klystron amplifier tubes and wherein each klystron is in turn powered by said pulse forming network, the function of said switch being to close the pulse forming circuit, thus allowing the energy stored in the pulse forming network to be formed into a single pulse of power for each klystron and wherein said switch will open said circuit when the energy stored in said network has been expended so as to then allow the network to recharge.

A further object of this invention is the provision of a switch of the character described capable of withstanding any voltage from zero to 130 kv. without closing spontaneously and capable of closing in response to a control signal with a nominal maximum variation in elapsed time of about 0.05 microseconds from one pulse to another or from one switch to another and which, when closed, will pass currents up to about 2500 amperes for two or three microseconds and then open in such time as not to interfere with the recharging of the pulse forming network and in such time that the charging voltage and current will not interfere with the opening of the switch.

Although various pulse switches, such as hydrogen thyratrons, rotary spark gaps and stationary triggered spark gaps, were available prior to the switch herein described and claimed, none of them are suitable for applicant's purposes.

Hydrogen thyratrons are, within the range of their voltage and current capabilities, excellent switches, but unfortunately, the largest one available commercially was found to be rated at about 40 kv. and 2000 amperes. While the current rating probably was adequate, three or four of these tubes used in series would have been required to meet applicant's demands and the cost thereof would have been over ten times the cost of the subject spark gap type switch. Furthermore, like any other electron tubes, the thyratrons would have a limited life and have to be replaced at staggering costs.

Rotary spark gap type switches depend on the mechanical movement of the gap electrodes to achieve the necessary voltage clearance when conduction is not desired and also to obtain a small gap spacing when breakdown is desired. Unless modified to include triggering voltages, as are used for stationary gaps, this type of switch is useless for use with a linear accelerator since its jitter is in the order of 100 microseconds. Furthermore, the necessity of having moving parts adds other complications.

Stationary triggered spark gaps, until thyratrons have been developed to replace them, are probably the simplest and most satisfactory solution to the pulse switch problem at the voltages and currents under consideration. However, the widest range of maximum to minimum

voltage of all available switches of this type was found to be at best only in the order of three to one. Invariably, these switches take the form of a series of spark gaps and are unacceptable for applicant's purpose for the reason that if the gap spacings are made large enough to withstand the maximum required voltage, they become too large for spark over when the total voltage is considerably reduced.

As a result of working with the latter type of switches, applicant discovered that until the entire string or series of gaps had sparked over and the load current had started to flow, there need not be much current or energy involved in sparking over all but the last of the gaps in series, and it is one of the objects of this invention to provide a switch of this type wherein a series of gaps are so arranged that the high voltage necessary for the breakdown of all but the last gap is derived at least partially from an auxiliary low power source of high voltage.

The invention possesses other advantageous features, some of which, with the foregoing, will be set forth at length in the following description where that form of the invention which has been selected for illustration in the drawings accompanying and forming a part of the present specification, is outlined in full. In said drawings, one form of the invention is shown, but it is to be understood that it is not limited to such form, since the invention as set forth in the claims may be embodied in other forms.

Referring to the drawings:

Fig. 1 is a vertical cross section taken through a switch embodying the objects of my invention.

Fig. 2 is a fragmentary horizontal section taken on the line 2—2 of Fig. 1.

Fig. 3 is a diagram of a complete triggered spark gap switch embodying the objects of my invention and including a capacity shunted between the third electrode and ground and a resistance in series with the bias voltage source.

Fig. 4 is a diagram of an elementary form of a two-gap wide voltage range triggered spark gap switch.

Fig. 5 is a diagram of a gap system similar to that shown in Fig. 4 but wherein an additional gap is resorted to.

Fig. 6 is a diagram of an elementary 15 to 150 kv. triggered gap switch involving four gaps.

Fig. 7 is a diagram of a gap system similar to that shown in Fig. 5 but wherein provision has been made for triggering the first two gap electrodes.

Fig. 8 is a diagram illustrating the potentials and spacings of the gap electrodes.

Fig. 9 is a diagram for voltages and gap spacings for $K=1.23$.

Fig. 10 is a diagram illustrating electrode voltages for a possible very wide voltage range spark gap switch.

Fig. 11 is a diagram illustrating a system for the resistance isolation of the fourth electrode from abrupt voltage changes of the third electrode.

Fig. 12 is a diagram of a circuit for isolating the fifth gap electrode from the abrupt voltage changes of the fourth gap electrode.

Fig. 13 is a diagram illustrating a gap system wherein the fifth electrode is insulated from abrupt changes of the fourth electrode.

Fig. 14 is a diagram of the main and bias voltage wave form of the system illustrated in Fig. 3.

Fig. 15 is a diagram of a circuit for calculating the effect of the main voltage on the bias voltage.

Fig. 16 is a diagram of circuit similar to but more simplified than the circuit shown in Fig. 15.

Fig. 17 is a diagram of a circuit for supplying the initiating trigger voltage for the spark gaps.

Preliminarily, it should be noted that the physical

aspects of applicant's switch are illustrated in Figs. 1 and 2, that the complete electrical circuit used in conjunction therewith and forming a part thereof, is illustrated in Fig. 3 and that the remaining figures are resorted to primarily to illustrate progressively the principles and theory of the circuit illustrated in Fig. 3.

As illustrated in Figures 1 and 2, the objects of this invention have been embodied in a triggered spark gap switch comprising a plurality of aligned, longitudinally spaced copper spherical spark gap electrodes **1**, **2**, **3**, **4**, **5** and **6**, supported on metal studs **7**, these studs mounted on the free ends of brass arms or plates **8**, **9**, **10**, **11**, **12** and **13**. Connected to the outer ends of each of these arms is a pair of upstanding stand-off insulators **14** and **15**, mounted on a ½" thick insulating base **16** made of a phenol condensation product, such as Bakelite. The location of the insulators **14** and **15** on the base **16** should be such as to give approximately the correct gap spacings. Since the supporting arms or plates **8**, **9**, **10**, **11**, **12** and **13** are capable of a little latitude of movement, this provides a further means for adjusting the gap spacings and their final adjustment can be obtained by bending the electrodes on their mounting studs **7**.

Conveniently, three inch diameter, 1/32" thick, spherical float balls, plated with an additional 1/32" of copper, can be used for the gap electrodes **1**, **2**, **3**, **4**, **5** and **6**, for spheres of this size provide reasonably flat sparking surfaces for the gap distances involved. A larger diameter gap electrode, while providing flatter surfaces, would tend to make the string of spark gaps excessively long.

Machined or otherwise formed in the gap electrode **2** in a ring defined by the intersection of a horizontal plane passing through the center of the electrode with the electrode shell are a plurality of peripherally spaced triggering pin holes **17** having a diameter in the order of 5/32". Since the gap electrodes can be rotated on their mounting studs **7**, any selected one of the triggering holes **17** (see Fig. 3) can be positioned to lie on the common longitudinal center line of the gap electrodes **1** to **6**.

Mounted on top of the gap terminal **2** is trigger pin terminal **18** and connected thereto and extending into the spherical terminal **2** is a triggering pin **19** (Fig. 3) terminating on the common center line of the gap terminals **1** to **6** at a point adjacent the inner periphery of its associated spherical gap terminal. Conveniently, the triggering pin can be made of 1/16" diameter copper wire.

Also formed in the spherical gap terminal **2** intermediate any pair of its pinholes **17**, is a larger access hole **21** through which the trigger pin **19** can be adjusted.

Secured to and extending through the Bakelite base **16** intermediate each contiguous pair of spherical gap electrodes is an upstanding cylindrical air or blower tube **22** terminating at its upper end at a point between its associated electrodes and somewhat below their centers.

The gap assembly above described and its base **16** is mounted within a labyrinthed and acoustically treated composite container or box generally designated by the reference numeral **23**. As illustrated in Fig. 1, the box **23** includes an outer shell **24** conveniently made of ½" plywood but provided with a Bakelite bottom panel **25** and with a top plywood door **26** lined with an acoustic sheet **27**. Disposed above the bottom of the outer shell **24** in spaced relation thereto so as to form a dead air chamber **28** is a sub-bottom **29** likewise provided with a central Bakelite panel **31** and likewise lined with Celotex. Similarly disposed above the sub-bottom **29** is a gap assembly supporting inner bottom **32**. Disposed beneath the outer shell top is an inner horizontal plywood wall or top **33** interiorly lined with Celotex and provided with a central Celotex lined door **34**.

Formed on the right end wall **35** of the outer shell **24** is an airport **36** communicating with a tortuous passageway **37** formed by the sub-bottom **29**, an inwardly extending baffle **38**, and upwardly extending baffle **39** terminating at its upper end in an outwardly extending baffle **41**, all of these baffles being acoustically treated. Depending from the inner top **33** and sealed thereto a Celotex lineal vertical wall **42** secured at its lower end to the right hand end of the gap assembly base **16**, this wall being spaced from the upstanding baffle **39** and forming therewith an intervening passageway **43** communicating with and forming a continuation of the tortuous passageway **37**.

Provided on the left hand side of the box assembly **23** is an air outlet port **44** and extending upwardly from the inner bottom **32** are a pair of longitudinally spaced, vertically extending Celotex lined baffle walls **45** and **46**. Secured to and depending from the inner top **33** is a vertical Celotex lined baffle wall **47** interdigitated with the walls **45** and **46** and forming a labyrinthed passageway **48** therewith.

As a result of this construction, it will be seen that any air introduced into the box assembly through the air intake port **36** can escape through the air outlet port **44** along by first traversing the air labyrinth formed in the right hand end of the box assembly, through the air blower tubes **22** and between the spherical gap electrodes **1—6**, and finally through the air labyrinth formed in the left hand side of the box assembly.

Blowing of the spark gaps was found imperative to clear away the ions between each firing. If the ions are not cleared away the gaps have a pronounced tendency to fire erratically at much lower voltages than that at which they would fire if there had been no previous discharge or any appreciable density of ions. Although the proportion of ions left after one-sixtieth of a second is probably quite small, it is still necessary to place a blast of air of about 50 to 100 linear feet per second across the gap. This velocity is sufficient to blow the ion column out of the gap space and away from the electrodes in the time between pulses. Furthermore, the electrodes heat up during operation and blowing serves also to carry away this heat and keep the electrodes cool.

Although the details of construction of the box assembly are not critical, it should be observed that it is highly desirable that it be acoustically treated and sealed against the escape of sound waves for even a small nail hole permits a great deal of noise to escape. If a spark gap assembly of the type under consideration is operated in the open, it produces an ear-splitting roar. The frequency distribution of the current in the spark gap is the usual sin x/x envelope of harmonics spaced sixty cycles apart and extending out into the region of one megacycle. Apparently, the accompanying sound energy has a similar but less extensive distribution. At any rate, the resulting intense sound produced dictates that the gap assembly be housed in a suitably sound insulated receptacle.

Connected to each of the brass arms or plates **8** to **13** respectively are leads **51**, **52**, **53**, **54**, **55** and **56** terminating respectively in terminals **57**, **58**, **59**, **60**, **61** and **62**, fastened to the gap assembly base **16** and extending therethrough. Mounted on the inner bottom **31** in vertical alignment with the terminals **57** to **62** are a corresponding set of terminals **63** to **68** and similarly mounted to the bottom panel is a third set of terminals **69** to **74**, the vertically aligned terminals of these three sets of terminals being respectively connected by copper braid leads **75**.

Although two intermediate sets of terminals above described have been resorted to due to the construction of the gap assembly box, it is to be noted that electrically all that is necessary is to provide a single lead from each gap terminal to the terminals **69** to **74** and that preferably these latter terminals as indicated in Fig. 1 be accessible from the exterior of the box. For this reason and to avoid further complicating the circuit illustrated in Fig. 3, the intermediate leads and terminals have been omitted and the spherical gap terminals **1** to **6** have been shown as each being directly connected respectively to the outer connecting terminals **69—74** by a single lead.

It will therefore be seen that the spherical gap terminal assembly is mounted within its acoustically treated and air-swept container as an integral unit devoid of any associated auxiliary electrical circuits with the exception of the necessary leads from each spherical gap terminal to the outer connecting terminals **69—74** and with the exception of the triggering pin circuit of the spherical gap terminal **2**.

Although the auxiliary electrical circuits associated with the gap assembly above described, together with their various electrical characteristics are fully disclosed in Fig. 3, a rather full discussion of the theory and principles involved in these circuits appears to be beneficial to a proper appreciation of them and such a discussion will now be made by the progressive reference to Figs. 4 to 17, inclusive.

TIME LAG AND JITTER IN OVERVOLTED SPARK GAPS

From available literature on the subject, it seems that the following statements are true:

(1) There is a time lag between application of an overvoltage, and the resulting spark-over.

(2) The higher the overvoltage, the shorter the time lag.

(3) The actual amounts of time required for spark-over has a statistical distribution for a given set of electrode conditions.

(4) The spread of the distribution of time lags becomes narrower as the amount of overvoltage is increased (i. e., jitter is decreased).

(5) The time lag is also affected by the previous history of the gap; whether it had near spark-over voltage on it before overvolting, presence of ionizing radiation, condition of electrode surfaces, etc.

Without trying to be very accurate, the following examples of time lags are given for various overvoltage values for sphere gaps. The percentage overvoltage is the amount over the minimum voltage required for sparking.

	Microsecond
30%	0.1
50%	0.04
100%	0.01

Jitter is approximately one-half these values. No data were available for higher overvoltages, but the trend seems to indicate that the time lag shortens rapidly with increase in overvoltage. From the performance of the series gaps developed for the accelerator the time lags must be in the order of 0.001 microsecond or less for an overvoltage of several times.

A WIDE VOLTAGE RANGE TRIGGERED GAP SWITCH

For explanatory purposes a series of two spark gaps will be used, as shown in Fig. 4. The terminals *x—x* constitute the terminals of the switch. The voltages shown are representative voltages. The +80 kv. is the auxiliary low power voltage, which, for lack of a better name, will be called the bias voltage. It is, for this explanation, fixed, and the 80 kv. value is just a convenient one for the explanation. Suppose that the spacing of a gap G_3 is set at such a distance that it will spontaneously break down if the voltage across this gap equals or exceeds 40 kv. Also suppose that one can make the gap G_1 spark over at will. More will be said about this later, but it is relatively easy to make a fixed voltage gap behave properly. It is now desired to know over what range of voltage +V can vary without causing spontaneous spark-over, and yet spark over reliably when gap G_1 is sparked over. Since G_3 is set at 40 kv. obviously +V can go no higher than 120 kv., nor any lower than 40 kv., without spontaneous spark-over. Now say that G_1 is sparked over. The voltage on the middle electrode

drops to zero. When this happens the entire voltage of +V appears across G_3. Since +V is only allowed to be between +40 kv. and +120 kv., the gap G_3 will be overvoltaged any time G_1 is sparked-over, and it too will spark over. Both gaps are then sparked over and the switch is closed. This then is a spark gap switch of rudimentary form which has a range of three to one in voltage (120 kv. to 40 kv.).

Let another electrode be added to the string, as shown in Fig. 5. Let the ratio of R_3 to R_4 be two to one, as is the ratio of G_3 to G_4. Now it is possible to have +V go as high as 140 kv. and as low as 20 kv. without spontaneous firing of any gap. The voltage on electrode number four has the same voltages as before for the extremes, 120 kv. maximum and 40 kv. minimum, so when G_1 is closed, G_3 will close as before. When G_1 and G_3 are both sparked over, electrode number four is at zero potential. But since +V is somewhere between +20 and +140 kv., G_4 will experience no trouble in breaking down. The triggered gap switch now has a voltage ratio of seven to one. Adding another gap as in Fig. 6, with everything up to electrode number five the same, and with the ratios R_4 to R_5 and G_4 to G_5 equal again to two, there obtains, by the same reasoning, a gap with a voltage ratio of 15 to 1 (10 kv. to 150 kv.). More electrodes could be added until the concept and proper action of a spark gap breaks down because of the low voltage and close spacing of the last gap or gaps.

In this discussion the effect of capacity between electrodes has been neglected. This is not negligible. For instance, when electrode number three drops from 80 kv. to 0 volts, the capacity voltage divider formed by the electrode capacities drops all the subsequent electrode voltages, leaving them not enough voltage at the lower values of +V to allow the remaining gaps to break down. But rather than suffer this loss it is better to put other capacities in the circuit that do not allow this divider action to take place. More will be said about this later. In the meantime, it will be assumed that the effect of the electrode capacities is absent.

CLOSING OF THE CIRCUIT UP TO THE BIASED ELECTRODE

A return will be made to gap number one to consider a convenient means to cause its spark-over at the proper time. For a gap operating at a fixed voltage there are a number of ways in which to initiate a discharge. The one decided on turned out to be actually two series gaps. An electrode was interposed between number one and number three electrodes in the fashion of Fig. 7. The ratio R_1 to R_2 is two to one, as is the break down voltage ratio of gap one to gap two. The gaps are adjusted to something over the steady voltage which is applied to them (e. g., 60 kv. and 30 kv.). Then a sharply rising positive trigger voltage is applied to the middle electrode. This trigger voltage adds to the 53.3 kv. already on the middle electrode and when this voltage has risen to the break down voltage (say 60 kv.) of gap one, then this gap sparks over. Then the right hand gap is greatly overvoltaged, and it too breaks down and the whole gap 1–3 is closed.

If this circuit were considered by itself and the switch terminals were considered to be electrodes one and three, this would constitute a triggered gap switch having a ratio of three to one in voltage without the necessity of any auxiliary voltage. Electrode number three voltage could be as high as the sum of the gap spacings would allow and as low as one-third that value before proper switch action would cease. The trigger voltage would have to be at least ⅓ of the total voltage to get this voltage range.

In its simplified form a six electrode triggered gap switch has now been described which will hold off any voltage over a range of 15 to 1 if it is not triggered, and

if it is triggered it will close for any voltage over this range.

OPTIMUM ELECTRODE VOLTAGES, GAP SPACINGS, AND VOLTAGE DIVISION RATIOS

Zero charging volts and safety factor modifications.—It is convenient, almost to the point of necessity, to be able to apply the bias voltage to the spark gaps without having the main voltage on. Being able to do so greatly facilitates initial and routine testing. This can be provided for by adjusting the gap spacings and the ratios of the dividers which set the electrode voltages. At the same time that this change is being considered, a safety factor can be put in, making the spacings such that the whole series of gaps will actually stand a higher voltage than will normally be applied. This safety factor is useful for a number of reasons, some of which are:

(1) Gap spacing settings need not be made as accurately.

(2) The breakdown voltage of a gap depends partly on the surface condition of the electrodes. A safety factor will help eliminate possible trouble from this source.

(3) There are transients in the system, some known, possibly others that are unknown. The safety factor helps take care of these surges.

(4) The whole system can be tested to a somewhat higher voltage than maximum operating voltage, thus assuring greater reliability for the whole accelerator system.

OPTIMUM DIVISION RATIOS AND RESULTING VOLTAGE RANGES

Increasing the gap spacings to allow the charging voltage to go to zero and to allow a safety factor decreases the maximum voltage range of the switch. In order to compute the proper gap spacings and divider ratios to allow the maximum range in voltage, consider Fig. 8. The computation will be made for the six-electrode gaps which are used with the linear accelerators at the Microwave Laboratory at Stanford University.

K_3, K_4, and K_5 denote the fractional parts of the bias voltage (V_3) that appear across the gaps G_3, G_4, and G_5, respectively, when the charging voltage (the voltage on electrode number six) is zero. In other words, they are the divider ratios. V_3, V_4, V_5, and $V_6=0$ are the electrode voltages for $V_6=0$. The voltages v_3, v_4, v_5, and v_6 are those for the electrodes when v_6 is the minimum that will allow all the gaps to spark over. Now further define K to be the ratio of the maximum voltage that can be placed across electrodes three to six to the maximum voltage that will be normally placed between these electrodes (V_3). K is then a measure of the safety factor.

The values for the gap spacings can now be set down.

$$G_3=KK_3V_3,\ G_4=KK_4V_3,\ G_5=KK_5V_3$$

In order to get the widest possible range in voltage for the whole series of gaps it is necessary that each gap individually be on the verge of being undervoltaged and ceasing to fire for the same minimum value of electrode number six voltage. Therefore,

$$v_4=G_3,\ v_5=G_4,\text{ and } v_6=G_5$$

When the voltage on electrode number six is at its minimum, then the voltage v_4 on electrode number four can be computed.

$$v_4=V_3-K_3(V_3-v_6)$$

Likewise computing v_5,

$$v_5=V_3-(K_3+K_4)(V_3-v_6)$$

Remembering that $K_3+K_4+K_5=1$, the above relations can be solved for K_3 in terms of K, and K_4 in terms of K and K_3. Omitting the algebra:

$$K^2K_3^3+KK_3^2+K_1-1=0$$

$$K_4=\frac{1}{K}\left(\frac{1}{K_3}-1\right)-K_3$$

For $K=1$ (no safety factor),

$$K_3=0.5437,\ K_4=0.2955,\ K_5=0.1608$$

Since the maximum voltage on the sixth electrode is limited to twice the bias voltage, and the minimum is $v_6=K_5V_3$, the range of maximum to minimum is

$$\frac{V_{max.}}{V_{min.}}=\frac{2V_3}{K_5V_3}=12.44$$

For

$$K=\frac{80}{65}=1.231$$

as an example using a reasonable safety factor,

$$K_3=0.5009,\ K_4=0.3087,\ K_5=0.1904$$

The maximum operating voltage is still twice V_3, and the minimum is $v_6=KK_5V_3$, so that the ratio of maximum to minimum is

$$\frac{V_{max.}}{V_{min.}}=\frac{2}{KK_5}=8.54$$

Fig. 9 shows electrode voltages for v_6 a maximum and for v_6 a minimum, with V_3, the bias voltage, set at 65 kv. The gap voltage spacings are also shown.

CHOICE OF SAFETY FACTOR AND TEST VOLTAGES

The safety factor $K=80/65$ was more or less chosen arbitrarily. The 65 is the value chosen for the kilovolts of bias. It is one-half the maximum operating voltage of 130 kv. The series of gaps 3–6 are set to stand as much as 80 kv., this seeming to be a reasonable allowance for safety. The voltage from three to six is 65 kv. when the charging voltage is either zero or 130 kv. For test purposes it should be possible to run the charging voltage up to a maximum of 145 kv. If in addition the bias voltage were raised from 65 kv. to 80 kv., the test might be carried up to 160 kv. This test is not recommended since most of the power supply and other pulser equipment would be overvolted severely. Testing up to 145 kv. is recommended if operation is to be carried on at 130 kv. The bias voltage might also be run up to 75 kv. some time during the test to check its operation. The philosophy here is that in order for equipment to run a long time satisfactorily at a given voltage it should be able to run a short time at a moderate overvoltage.

VERY WIDE VOLTAGE RANGE OPERATION

Wider voltage ranges than those just quoted can be achieved by the following expedient. The bias voltage waveform is made to be very nearly identical to the main charging waveform, and then the bias voltage is raised or lowered as the main voltage is varied, although not over as great a percentage variation around the median value. The voltage between electrodes three to six is thus reduced at all times even though the maximum main voltage may be higher and the minimum voltage is lower. The extent to which this can be carried is limited by the range over which the first two gaps will operate. Since theoretically these are good for a ratio of 3 to 1, it should be possible to get an overall ratio of 30 to 1 with the six electrode structure (dispensing with zero charging voltage and safety factor features). An illustrative example of what the maximum and minimum electrode voltages might be is shown in Fig. 10. Since such an extreme range was not needed and would make the equipment more complex, more expensive, and harder to maintain, this embellishment was not used in the accelerator pulsers.

PRACTICAL FORM OF WIDE VOLTAGE RANGE TRIGGERED SPARK GAP SWITCH

Voltage dividers for electrodes three to six.—A most important circuit consideration for the wide range gaps is the voltage divider which sets the voltages of electrodes

4 and 5. If resistances are used as voltage dividers, as in the previous example, they must be of high resistance in order to keep the divider power loss and the current between main voltage and high impedance bias circuits at sufficiently low values. On the other hand, the resistance must be kept low in order that the capacity between electrodes, between electrodes and ground, and added isolation capacities (discussed later) do not load the divider so that the electrode voltages depart appreciably during charging from the values which would be determined by the resistances alone. If the voltages involved were pure D. C., no problem would exist. But the charging cycle has large A. C. components which must be divided accurately as well as the D. C. component. A pure capacity divider, on the other hand, would divide all A. C. components the same, since the electrode capacities would then become part of the capacity divider. No appreciable power or energy need be expended or comparatively large divider currents handled in this kind of divider since the capacity divider impedance to the charging voltage can be quite high. If there are different amounts of leakage in these divider capacities, as there usually are, the D. C. component of the charging voltage will be divided incorrectly. This, however, can be taken care of by shunting the capacity divider by a high resistance divider. The resistance divider need only draw a current large compared to the divider capacity leakage current or the corona current which might exist along the series circuit. Usually these leakage currents are very small so the resistance divider can be of very high resistance. The divider capacities need only be large compared to the inter-electrode capacities so that the voltage division is determined by the dividing capacities alone and not appreciably affected by the electrode capacities.

ISOLATION OF ELECTRODES FOR ABRUPT VOLTAGE CHANGES

The effect mentioned above under the heading "A Wide Voltage Range Triggered Gap Switch," of having subsequent electrode voltages drop when a preceding electrode sparks over to zero potential is augmented due to the pulse voltage dividing action of capacities added between electrodes for obtaining proper charging voltage division. This problem is solved in the following way:

Electrode number six, although not grounded, has a relatively large distributed capacity to ground because of the pulse forming network that is tied to electrode six. A resistance is placed in series with the divider at electrode number three, as shown in Fig. 11.

The time constant of this new resistance and the capacity from electrode four to electrode six is made very short compared to the charging cycle and very long compared to the time it takes to initiate and complete operation of the switch. This is easy to do since the charging cycle is $\frac{1}{60}$ second in duration while operation of the switch is completed within 0.1 microsecond. When electrode three suddenly drops to zero, the voltages on electrodes four and five do not drop because the divider capacitors are made much larger than the capacity between electrodes three and four. (It should be noted that this resistor must withstand momentarily the full voltage on electrode four.) Yet the division ratio of the capacity divider is not affected by the new resistance because the charging current that flows in the divider capacity does not cause an appreciable drop in the new resistance.

Provision has not yet been provided for eliminating the drop in electrode five when electrode four drops to zero. This can be done by rearranging the circuit of the number five electrode, as shown in Fig. 12.

Again, the newest resistance, R_2, is made small for charging current but the time constant of R_2 and C_2 is made large compared to the time of operation of the switch. The sum of C_1 and C_2 is made to equal the single capacity which they have replaced, so that the charging voltage division ratio remains unchanged. The total capacity from four to six is still large compared to the capacity of electrodes three to four alone. In addition, the total capacity from five to six is large compared to that of electrodes four to five. So the divider is now broken up so that abrupt changes in any electrode voltage does not affect the voltage on any subsequent electrode. Yet the division ratios for the charging voltage is preserved.

The resistance part of the divider does not have an effect on the abrupt changes. It does have an appreciable effect on the division of the charging voltage, but its division ratio is the same as that of the capacity divider, so it has been left out of the discussion.

Current maintaining property of divider condensers.—The voltage divider capacitors serve still another useful purpose beside the ones of dividing the charging voltage properly and isolating the electrodes for abrupt voltage drops. They serve to maintain a high current spark in the gap until succeeding gaps have fired and the load current finally starts flowing. The whole process takes considerably less than 0.1 microsecond, but during this time it is important that each electrode, in its turn, has its voltage dropped to near zero and a conducting path established to the first electrode in order that proper firing be obtained in the succeeding gap.

Condensers for the divider.—The capacity between electrodes is in the order to 8 $\mu\mu$f. It was decided to make the shunting divider condensers about 10 or more times this value, this being a compromise between achieving good abrupt voltage isolation and good charging voltage division on one hand, and keeping the physical size and cost down on the other.

At the present time the condensers being used for the divider are series of barium titanate units, each unit having ratings of 500 $\mu\mu$f. and 20 kv. To achieve the divider ratios calculated in the paragraph above entitled "Optimum Electrode Voltages, Gap Spacings, and Voltage Division Ratios," for the safety factor $K=80/65$, five of these condensers are placed in series from electrodes three to four, three for electrodes four to five, and the equivalent of two across the last gap. For these selections, $K_3=0.5$, $K_4=0.3$, and $K_5=0.2$ The calculated values are 0.5009, 0.3087, and 0.1904. As pointed out in the paragraphs dealing with the circuitry from electrodes one to three, these condensers have been found to be almost completely unreliable for this application. They have not been replaced in the divider circuit from electrodes three to six because at the present klystron voltage levels the difference in voltage between electrodes three and six has not been very great. As the voltage levels are increased, these condensers may have to be replaced by more satisfactory units.

Power loss in divider capacities.—It may be noted that when the gaps spark over that some of the voltage division capacitors are shorted without any current limiting resistances. The energy which is stored in these condensers at the time of discharge probably appears as a damped oscillation, with the capacity of the oscillatory circuit being the voltage division capacitor, the inductance being the inductance of the connecting leads, and the losses of the capacitor, the spark gap itself, and the connecting leads providing the damping. It is not known where most of the energy is dissipated, but even if it were dissipated entirely in the condensers, it would probably be all right. For example, the power involved in the 167 $\mu\mu$f. condenser between electrodes four and five is less than three watts maximum.

First gap trigger pin.—It was found that when the spark gaps were placed in the special soundproofed enclosure made for them, that spark-over of the first gap was not reliable even though the trigger voltage was more than sufficient to do so reliably when the gaps were in another enclosure or in open air. The reason for this phenomenon was not determined. This condition was

corrected, however, by introducing a small initiating spark for the first gap in the face of the second electrode in the fashion of Fig. 13. Because the capacity to ground of number two electrode is fairly large compared to the capacity between the trigger pin and electrode two, a voltage appears across the small gap which faces the first electrode, when the trigger voltage is applied. The gap is small (approximately 3/32 inch) so it sparks over while the trigger voltage is still quite small (approx. 6 kv.). This spark then supplies the initiating influence needed (ultra-violet light probably) for spark over in the first gap space. Once this small spark exists, the trigger voltage is tied directly to the second electrode and straightforward overvolting of the first gap proceeds. Firing is completely reliable with the inclusion of this trigger pin.

The resistor is for the purpose of preventing part of the charging voltage from appearing across this small gap and sparking it over.

Divider for electrodes one to three.—It was found undesirable to use capacity voltage division to obtain the second electrode voltage. The reason for this is that any abrupt voltage change in the capacity divider circuit would then be coupled directly to the trigger pin gap. Since this is a low voltage gap, the voltage change need not be large to cause it to spark over and consequently cause the whole switch to close at the wrong time. These abrupt changes can be caused by a momentary breakdown of a faulty divider condenser, sparking over a dust accumulation, etc. Fortunately a resistance divider does not have the disadvantages here that it would have in the divider for electrode three to six. Electrode two does not need to be isolated for abrupt changes of the voltages of the other electrodes since it is the first electrode to spark to zero volts. Current in this spark can be maintained by the trigger coupling condenser and trigger circuit. Also the incorrect division of a resistance divider during charging (because of the capacity of electrode two and the trigger coupling condenser to ground) does not result in as great a percentage error of the voltage on the first and second gaps as would result for the third, fourth, and fifth gaps, assuming optimum circuit constants and reasonable components in both circuits.

BIAS CIRCUIT CHARGING RESISTANCE AND CAPACITY

Referring to the complete triggered spark gap circuit diagram of Fig. 3, it is seen that a capacity is shunted between electrode three and ground, and a resistance is placed in series with the bias voltage source. The reasons for these components are:

(1) The resistance prevents the bias power supply from being shorted out when the gaps spark over.

(2) The time constant of the resistance and capacity allows the first two gaps time to deionize after a pulse before the bias voltage has risen appreciably.

(3) The discharge of the condenser maintains current in the first two gaps until the whole series has fired.

The values of the components are determined in part by the time constants necessary in the circuit. It has been found that the time constant of the bias charging circuit should be about 3000 microseconds or more in order to allow reliable deionization of the gaps. The time constant of the resistance divider for the second electrode and its 50 $\mu\mu$f. coupling condenser should be several times smaller than this, say 700 microseconds, in order that the voltage on the second electrode will follow the charging waveshape of the voltage on the third electrode. The dividing resistance then has a total value of 60 megohms. The series resistance from the bias supply was chosen to be 6 megohms. This seemed a reasonable compromise between two much bias voltage loss on one hand and too large a condenser on the other. This choice then fixes the bias supply voltage at 70 kv. in order to have 65 kv. on electrode three, and the value of the condenser at 500 μf. in order to get a time constant of approximately 3000 microseconds.

At one time evidence seemed to indicate that the time jitter of the whole gap series improved with increase in the bias condenser size. No effort has been made to verify this early impression because the capacity value is more or less fixed by the other considerations being discussed.

The energy stored in the bias condenser is dissipated in the 125 ohm resistance in series with the third electrode.

Difficulty has been experienced in finding a suitable and inexpensive bias condenser. Commercially available barium titanate condensers were used but found unsatisfactory. These have been replaced temporarily by a 15 foot length of RG–17U coaxial cable. Although rated at 14 kv., lengths of cable have been tested to 90 kv. as bias condensers withut breakdown. Special consideration is given to the ends of the cable to prevent corona and sparkover.

BIAS AND MAIN VOLTAGE RELATIONSHIPS

While a time constant of more than 3000 microseconds would be desirable from the deionization standpoint, it is necessary to have this time short enough so that the difference between bias and main voltages does not exceed the nominal voltage rating (allowing the safety factor) of electrodes three to six. Figure 14 shows the bias and main waveforms for a bias time constant of 3000 microseconds and for the main voltage charging time being considerably short of 1/60 second (corresponding, for instance, to all the charging chokes being in the circuit but only half the total pulse forming network capacity being connected). For this example the difference between the bias and main voltages does not exceed 65 kv. at any time. If the bias voltage had a longer time constant, flexibility in the length of the charging time of the main voltage would be lost.

The bias charging circuit must have a relatively low impedance compared to the circuit between electrodes three and six. This must be so that the current flowing in the divider between electrodes three and six during the charging cycle does not appreciably affect the voltage on electrode three. A quick check can be made to be sure that with the circuit values chosen (Fig. 3) that the third electrode voltage does not rise excessively during the charging cycle. Since the charging cycle is a portion of a sine wave, it is permissible to use ordinary A. C. circuit theory to get an approximation of the voltage developed across electrodes one to three while the total voltage is rising to its maximum. The circuit involved is as shown in Fig. 15.

The behavior of the voltage of electrode three, v_3, is the item of interest. For the sake of simplicity the rise of v_3 due to the A. C. component of v_6 will be calculated. For this the D. C. voltages in the circuit can be dropped. The circuit then simplifies to that of Fig. 16.

Calculation gives:

$$v_3 = v_6 \frac{\dfrac{R_2}{1+j\omega C_2 R_2}}{\dfrac{R_2}{1+j\omega C_2 R_2} + \dfrac{R_1}{1+j\omega C_1 R_1}}$$

Simplifying, and getting the absolute magnitude of v_3,

$$\left| v_{3_{max.}} \right| = v_{6_{max.}} \left| \frac{1}{1+\dfrac{R_1}{R_2}\left(\dfrac{1+j\omega C_2 R_2}{1+j\omega C_1 R_1}\right)} \right|$$

Solving, for v_6=65 kv. peak, and for ω=377 (assuming the charging cycle is cut to 50% of the time between pulses), the maximum value of v_3 is found to be 4400 volts. This is added to the bias voltage of 65 kv. (not actually, since the bias circuit has not charged up completely at the time this v_3 is maximum), to make a

maximum third electrode voltage of less than 69 kv. This can easily be tolerated since the gaps are set with a good safety factor.

HIGH VOLTAGE TRIGGER UNIT

The unit which supplies the initiating trigger voltage for the spark gaps is basically a very simple device. Its diagram is shown in Fig. 17. The 5C22 tube is a hydrogen thyratron capable of passing 300 amperes in pulse duty. On being triggered by an adequate trigger pulse it conducts and connects the condenser across the primary of a 4:1 step-up transformer. An autotransformer, although preferable from a rise-time standpoint, can not be used here because of the need for positive polarity output pulses.

Although a very high voltage output is not absolutely necessary, it is convenient, for it allows a wider spacing of the first two gaps with the added reliability attendant with such a safety factor. There is almost enough voltage output from the high voltage trigger unit to fire the first gap without any bias voltage being on. This can be convenient for trouble shooting, since the trigger unit operation can be checked by merely opening the doors of the gap enclosure and checking the trigger pin sparking and the occasional sparking of the first and second gaps.

The rise-time, which is desired to be short so that the jitter in the firing of the gap will be small, suffers a little from having a transformer in the circuit. The time necessary for the output voltage to rise from zero to 60 kv. is 0.12 microsecond, and the first gap becomes overvolted when the trigger voltage reaches approximately 20 kv. The uncertainty range for firing of the first gap is probably not over 5 kv., therefore the jitter of the first gap is in the order of 0.01 microsecond. This is sufficiently small (and is probably the major contribution to the total jitter of the whole spark gap switch).

The 750 ohm load resistor was chosen to give the lowest impedance circuit the thyratron could handle. This was done to allow the best rise-time to be built into the step-up pulse transformer. The storage condenser capacity was chosen large enough to give a time-constant that worked well with the pulse transformer's limited rise-time characteristic.

The pulse transformer is a small ribbon-wound unit. The core is wound of 2 thousandths hipersil, having a window 2½ inches x $\frac{15}{16}$ inches and a leg cross-section of 1 inch x ⅞ inch. Two identical windings are made for each leg of the core and are connected in parallel. These windings have a total number of turns of 65, tapped at 13 turns. The windings are wound of ¼ of a thousandth inch aluminum foil strip 1¼ inches wide and the turns are insulated by five layers of 1 thousandth inch kraft paper.

Having thus described my invention, what I claim and desire to secure by Letters Patent is:

1. A spark gap switch comprising: a plurality of series connected spark gap electrodes; means for subjecting the first of said electrodes to a reference potential; means for subjecting the last of said electrodes to a potential different than said reference potential; means for subjecting an intermediate one of said electrodes to a selected biasing potential, said biasing potential being independent of the potential applied to the last of said electrodes; means for subjecting the electrodes between the biased electrode and the last electrode to potentials intermediate between the biased electrode and the last electrode; and independent means for effecting a spark-over between said biased intermediate electrode and the reference voltage electrode.

2. A spark gap switch such as defined in claim 1 wherein the biasing potential is applied to the biased intermediate electrode through an impedance.

3. A spark gap switch such as defined in claim 1 wherein the potentials of the electrodes, between the biased intermediate electrode and the last electrode, are provided by a voltage divider between the biased intermediate electrode and the last electrode.

4. A spark gap switch comprising a pair of switch terminals; a plurality of spark gap electrodes connected in series across said terminals; means for subjecting the first of said electrodes to a reference potential and the last of said electrodes to a potential different from said reference potential; means for subjecting an intermediate electrode to a selected biasing potential through an impedance; a voltage divider shunted across the gaps between the biased intermediate electrode and the last electrode; independent means for sparking over the gap or gaps between the first and the biased intermediate electrode.

5. A spark gap switch comprising a pair of switch terminals; a plurality of spark gap electrodes connected in series across said terminals; means for subjecting the first of said electrodes to a reference voltage and the last of said electrodes to a voltage different from said reference voltage; means for subjecting the third electrode to a selected biasing voltage through a resistor; independent means for sparking over the gap formed between the first and second electrodes; a voltage divider resistance shunted across the first and second gaps respectively formed by said first, second and third electrodes and a resistance-capacitance voltage divider shunted across the spark gaps formed by the remaining pairs of electrodes.

6. A spark-gap switch operative over a material range of applied voltages comprising a pair of terminal spark-gap electrodes for connection to a circuit to be controlled, a plurality of intermediate electrodes defining in succession a triggered portion for initiating closure of said switch comprising at least one spark-gap and proportioned to spark-over at substantially one-half of the designed maximum operating voltage of said switch, and a secondary portion comprising a plurality of spark-gaps proportioned to spark-over at successively lower voltages than said triggered portion, a voltage-divider connected across said secondary portion and comprising a series of impedance elements connected respectively across said gaps and substantially proportional in relative value to the spark-over voltage of the gaps across which they are connected, means for applying across said triggered portion a biasing voltage approaching that required to initiate spark-over thereof, and means for applying a triggering potential to said triggered portion to cause such spark-over.

7. A spark-gap switch as defined in claim 6 wherein said triggered portion comprises spark-gap electrodes defining a plurality of series gaps and includes a voltage-divider network connected across each thereof to apply thereto voltages proportional to their respective spark-over voltages.

8. A spark-gap switch as defined in claim 7 wherein the successive spark-gaps counting from said terminal electrodes and included in said triggered portion and said secondary portion are proportioned to spark over at substantially twice the spark-over voltage of the immediately preceding gap.

9. A spark-gap switch as defined in claim 6 wherein the successive spark-gaps of said secondary portion, counting from the terminal electrode thereof, are proportioned to spark over respectively at substantially twice the spark-over voltage of the immediately preceding spark-gap.

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UNITED STATES PATENT OFFICE

Certificate of Correction

Patent No. 2,818,527 December 31, 1957

Paul Alfred Pearson

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 7, line 73, for

$K^2K_3^3+KK_3^2+K_1-1=0$ read $K^2K_3^3+KK_3^2+K_3-1=0$

column 11, line 70, for "two much" read —too much—.

Signed and sealed this 8th day of April 1958.

[SEAL]

Attest:
KARL H. AXLINE,
Attesting Officer.

ROBERT C. WATSON,
Commissioner of Patents.