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August 6, 1963

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ABSTRACT

The construction and operation of a trigger system designed to fire a 30-kV 5000 A spark gap with a minimum delay following the arrival of a small signal pulse is described. In this particular experiment a 150-MeV/c muon is detected with scintillators on three 6199 phototubes, and the output pulse of the attached tunnel-diode triple-coincidence circuit is amplified and used to trigger the gap. Approximately 32 nanoseconds are needed from passage of the muon to the coincidence output, and approximately 25 nanoseconds are required from the coincidence output to the time of complete breakdown of the gap. These delays represent the shortest times that we could achieve with the particular boundary conditions under which the circuit had to operate. Sufficient detail is given to show how additional savings of nanoseconds could be made under different operating conditions.

INTRODUCTION

Considerable lore exists on the construction and operation of spark gaps. Gaps have been made with operating voltages ranging from several hundred volts to several hundred kilovolts and with operating currents from amperes to megamperes. Various combinations of gases, pressures, and conducting and insulating materials have been used, the particular choice in each case being determined by the individual operating requirements. This report describes the construction and operation of a spark gap that had to fit four requirements: (a) stand off 30 to 40 kV dc; (b) pass 5000 A for 15 μsec per pulse; (c) operate at 10 pulses per sec for several hundred thousand pulses; and, most importantly, (d) fire with a "minimum" of delay time following the passage of a muon, the spirit here being that 10 nanoseconds would make a noticeable difference in the associated experiment.

In the application for which this gap was used, a 150-MeV/c muon passed through a counter telescope and the signal from the coincidence circuit on this telescope was amplified and used to trigger the gap (see Fig. 1). The gap, in turn, discharged a 30-kV 0.012-μF condenser into the load. In order to meet other requirements of the experimental setup, it was necessary that the total time delay from passage of the muon through the telescope to the top of the current rise in the load be as short as possible, and certainly no more than about 130 nsec. The severity of this basic requirement was increased by the fact that the load was primarily inductive so that a finite current rise time was unavoidable. Considerations of high-voltage engineering around the experimental apparatus together with a required load current of 5000 A fixed this load rise time t_R at 60 nsec, leaving 70 nsec for t_D, the time between passage of the muon ($t = 0$) and the start of the current rise in the load (see Fig. 2). (In Fig. 2, t_p time pulse.) Since the elements of the electronic chain that lead from the muon passage to the final current in the load form as vital a part of this delay-time problem as the spark gap itself, the complete chain is described in some detail in the next section.

Very briefly, the counter telescope seen in Fig. 1 consists of three 6199 phototubes that feed a tunnel-diode coincidence circuit (RCA TD119). The 1-V 20-mA output of this circuit is amplified by an avalanche transistor-planar triode combination that delivers a 12-kV 20-A pulse with a rise time of 9 nsec onto the trigger pin of a three-element spark gap, which, in turn, discharged the high-voltage condenser into the load. In Table I a summary of the delay times through each element of this system is given.

DESCRIPTION OF APPARATUS

As the signal pulse is followed through the system, each piece of apparatus is described in turn. Because of a 30-kG field in which the scintillators were situated, it was necessary to carry the light from the plastic scintillators out through Lucite pipes 3-feet long to a region where the type 6199 phototubes could be magnetically shielded. This took about 5 nsec. (A triple coaxial iron-cylinder shield reduced the residual field from ≈ 1 kG to less than 1 G.) It was necessary, in the experiment, to keep the multiple scattering of the muon in the scintillators to an absolute minimum. Consequently scintillators #2 and #3 were only 0.010 in. thick so the number of photons reaching the type-6199 cathodes was very small, resulting in anode pulses that were buried in the noise. The type-6199 tubes were specially selected for best signal-to-noise characteristics and were run at 2500 volts. A cathode-to-anode time of 23 nsec was measured.

Threefold and twofold coincidences of signals from the photomultiplier anodes were made with the circuit shown in Fig. 3. Each anode signal is handled by a two-stage tunnel-diode discriminator; the input diode sets a triggering level, and the output diode shapes the signal to produce an output pulse whose length and height are independent of input-pulse heights. Two discriminator outputs are added resistively in a tunnel diode biased to select double coincidences. Transistor amplifiers are used to give decoupled outputs, one for external timing circuits in different parts of the experiment and the other to make a subsequent coincidence with the third input discriminator. The output of the triples coincidence diode is shaped by a second diode and drives a transistor output amplifier. The use of germanium tunnel diodes makes unidirectional coupling by germanium diodes impossible because the 200-mV output of these tunnel diodes will not switch the regular diodes. Signals are therefore directed by the use of asymmetrical resistive coupling and by an emitter follower after the doubles coincidence.

This circuit follows an earlier design[1] except for a few changes that reduce the over-all delay from 11 nsec to about 4 nsec. The changes include (a) the use of germanium tunnel diodes (RCA TD 119), which can switch in 0.3 nsec if not limited by the external circuit; (b) the use of resistive interstage coupling at all points where it will not result in unstable operation; (c) extremely compact circuit construction. Most of the improvement comes from (a). In normal use the input discriminators were set to a 1-mA threshold. Delays were measured with a 4-mA input signal of negligible rise time; the delay was measured between 50% level points on the input and output signals with a sampling unit (Tektronix type N). Typical coincidence curves using light pulses were 7 nsec wide, full width at half maximum. The signal amplitude at any tunnel diode in the circuit is about 200 mV as viewed by the Tektronix type N unit. The delay of 4 nsec from input to triples output is equally divided between input discriminator, doubles emitter follower, triples coincidence discriminator, and the output amplifier. The output amplifier delivers 1 V into 50 ohms; it can be dispensed with if a 200-mV output is adequate.

The general characteristics of an amplifier suitable for carrying the above 1-V 20-mA pulse up to a level where it would satisfactorily trigger the 30-kV spark gap with a minimum time delay are determined by the gap operating voltage as well as by the impedances seen by the gap. For reasons to be described later, a three-element gap was used here. In order to minimize t_R in the inductive load, one should use as high a voltage as possible on the pulse-producing network. As stated previously, general considerations of high-voltage engineering around the experimental apparatus resulted in a choice of about 30 kV and this resulted in the aforementioned 60-nsec rise time. General experience indicates that one needs something like one-half of the gap operating voltage on the trigger pin of a three-electrode gap if nanosecond breakdown times are to be achieved. To bring the output of the phototube coincidence circuit up to 12 kV at 20 A, the amplifier shown in Fig. 4 was constructed. Other combinations of small spark gaps, transistors, and tubes were investigated, but the final choice was as shown. This unit was found to be extremely reliable and, with coaxial heavy solid-metal shields compartmentalizing each amplifier section, showed no deterioration with operation even though 30 kV at 0.5 ohm appears on the trigger pin for about 30 nsec when the gap fires, and this pulse moves back, through the 210-Ω current-limiting hv resistor, to the DP 30 anode. However, it was found necessary to magnetically shield the planar triodes from the 1-kG field in which they were located before the unit would operate properly.

It takes approximately 11 nsec from the start of the 1-V input pulse into this amplifier to the time when the DP 30 is turned on and starts to deliver current to the gap trigger pin. About one-third of this is needed to fire the avalanche transistors--and this was for the fastest ones in a batch of about 10. The total shunt capacitance seen by the DP 30 anode looking into the spark-gap trigger pin was about 15 pF, and since this tube will deliver about 20 A it takes 9 nsec for the DP 30 to raise the voltage on the trigger pin up to 12 kV. Thus a total of about 20 nsec is required to bring the input 1 V at 20 mA pulse up to 12 kV at 20 A on the trigger pin of the gap, and if the gap is properly designed it should begin to avalanche at or before this time.

To fire any spark gap quickly, two things must be done. Generally speaking, enough electrons must be liberated from one of the elements of the gap to locally overcome the capacity of the gas to absorb them and, at the same time, the electric-field distribution in this region must be increased enough to initiate avalanche breakdown in the gas. One common method of initiating gap breakdown is to sharpen the tip of a centrally located trigger pin in a three-electrode gap and then put a high enough voltage pulse on this pin to liberate electrons either by field emission or by the ultraviolet radiation from the corona at the tip. This method requires a relatively high trigger-pin field or a sharp tip that would be subject to erosion by the plasma (or both); neither of these is consistent with minimum t_D operation for thousands of pulses. Similarly, the technique of firing a two-electrode gap by pulsing a trigger pin (usually a fine wire) just inside one of two electrodes depends for its operation on the motion of the trigger plasma with sonic speeds out into the gap where it both supplies the electrons and distorts the field. Again this technique is too slow for our purposes.

It has been known for some time that an ultraviolet source near the gap aids in gap breakdown, presumably because of the photoelectrons produced at the electrodes. It should be noted, however, that diffusion of the electrons produced in the uv source out into the gap may also play a significant role in this technique. An auxiliary gap near the main one as well as a steady uv source have been used in the past. The auxiliary gap suffers from the same delay problems as the main one, and in addition needs quite a bit of power on the scale involved here. This power would have to come from the amplifier described above, and this takes time. A steady uv source, on the other hand, simply results in the necessity of having to reduce the main gap voltage well below the "clean" spontaneous breakdown point, the difference that must be supplied by the trigger-pin pulse--which again takes time. The best arrangement was found to be a small power-pulsed uv source constructed by pressing the end of a 3-mil tungsten wire against the face of a 0.5-in.-diameter titanate disk. This ceramic wafer is made by sawing in half a 500-μμF 10-kV ceramic condenser. The pulser that drives this uv light source is shown in Fig. 5. It delivers about 5 A at 3 kV, and the pulse length was chosen to be about 50 nsec. This circuit is basically just the front end of the main amplifier and needs only about 10% of the current at point T (Fig. 4) to trigger it. The uv light output rises to its maximum value about a nanosecond after the 7698 tube starts to conduct (about 2-pF shunt capacitance with 5-A maximum current). Although the uv light output from this source was not measured, individual pulses appear to be "quite bright" when observed by eye during the daytime.[2] The spectral distribution of this lamp is not known. This uv flasher was placed about an inch from the gap and could "see" all three electrodes (Fig. 6). Its effectiveness in liberating electrons into the gap is indicated by the observation that when the gap was operated at a somewhat reduced voltage of 20 kV and held to within a few percent of the spontaneous breakdown point, this uv light pulser would fire the gap by itself, i.e., with <u>no</u> field-distorting pulse on the trigger pin. However, the delay in breakdown was appreciable, and as the gap voltage was raised the breakdown became sporadic, until at 30 kV the ultraviolet flasher alone would not fire the gap. With use, the white ceramic became covered with a brown deposit of residues manufactured by the plasma during the gap discharge, but its performance did not appear to be appreciably affected by this coating.

Under normal operating conditions, the delays in the circuitry were such that the uv lamp was pulsed on 19 nsec after the 1-V signal entered the "gap amplifier," and this time corresponds to the top of the rise of the voltage pulse on the trigger pin, as previously described. As far as could be seen with the present setup, onset of gap breakdown was immediate at this point (i.e., < 5 nsec) as is seen in Fig. 7. These scope pictures were taken with a voltage probe at the throat of the load (pt L on Fig. 1) and with the gap discharging a 0.012-μF 30-kV condenser through the load coil. The small initial pulse is the 1-V 20-mA pulse at the entrance to the amplifier--taken by double exposure. Both parts of Fig. 7 were taken under identical conditions with two different vertical scales, and this allows one to see in Fig. 7(a) the voltage at the load rise to the full 30 kV and to see in Fig. 7(b) the trigger-pin voltage rise to 12 kV (and appear on the probe by capacity feedthrough), followed by the sharp vertical rise that appears when the uv lamp comes on. The time between onset of gap breakdown [vertical rise in Fig. 7(b)] and the top of the voltage rise at the load is ≈ 15 nsec. Since there was an unavoidable impedance mismatch on the two sides of the gap, the full voltage at the load could be reached only after several reflections down the feed line (Fig. 1). A rough estimate indicates that $\gtrsim 10$ nsec should be required. Consequently, it is estimated that $\lesssim 5$ nsec is required for the avalanche in the gap plasma to develop to the stage where the current flowing is limited by the external impedances. On the time scale of these photos, a jitter time of a few nanoseconds was observed. Both the breakdown time and jitter increased with use, but this was basically due to the fact that as the electrodes became pitted and chemical deposits formed on them, it was necessary to back off the high voltage on the gap to prevent too many sporadic spontaneous breakdowns. The figures given here are for the gap in new condition, and after something like 100 000 pulses an additional firing delay of 5 to 10 nsec would be observed with a few more nanoseconds of jitter. However, removal and cleaning of all electrodes would restore the gap to "new condition."

By means of trial and error, we discovered that the center electrode should be shaped like a horseshoe, as shown in Fig. 6. Other shapes resulted in misfiring, longer delays in breakdown, and more rapid deterioration of the gap with use. The successful performance of this shape of pin is attributed to three factors. First, the uv lamp illuminates a comparatively large area (the center of the horseshoe) at normal incidence. Second, the spark "walking around" the horseshoe from pulse to pulse results in slow electrode erosion (in contrast with a point pin that was soon eroded away by the plasma). Third, the low voltage or "second half" of the gap breakdown--i.e., that half whose electrode is the same sign as the trigger-pin pulse--is directly illuminated through the open part of the shoe by the plasma of the first half of the breakdown. Molybdenum and copper were used for the electrodes because of their low work functions. No comparison was made with other materials such as platinum, which has a higher work function but is a more chemically stable material.

Several gases were tried and a mixture of about 90% N_2 and 10% CO_2 was finally used. The gap was pressurized and operated at 50 psi with a constant flow at a rate that emptied a standard large 2000-psi tank of N_2 in about 24 h. Pure N_2 was unsatisfactory because the gap would not shut off, i.e., the power supply that recharged the high-voltage condensers would feed current in a semicontinuous discharge through the gap after it had fired. Increasing the impedance that isolated the supply made the recharge time too long. Also, considerable spontaneous breakdown occurs with pure N_2.

On the other hand, using pure CO_2 cured the spontaneous breakdown problem, but it also noticeably increased the firing and jitter time of the gap (10 to 15 nsec). A combination of the N_2 and CO_2 resulted in stable, fast operation as described above. These observations are consistent with the known properties of these two gases. In pure N_2 the electron "temperature" is relatively high, i. e., the mean free path is comparatively long. (Electron-drift velocity ≈ 1 mm/nsec under the conditions in this gap.) The capture cross section for a free electron is comparatively small, so that it takes relatively few electrons to initiate an avalanche. After the discharge has taken place, both the positive and negative ions that are left have a drift velocity of about 1 cm/msec at the residual voltage of a few tens of volts across the gap. Both types of ions are quite stable and drift around, diffusing out of the high-recharging field region of the gap. When one of these N_2^+ ions strikes the cathode, the chances are high that it will liberate an electron into the gas from the cathode. As previously mentioned, it was found necessary to keep voltage off the gap for about 10 msec to prevent a semicontinuous discharge from occurring in N_2, and this is presumably the "ion-clean-up time" in the gas. Using pure CO_2, on the other hand, lowers the electron temperature considerably because of the large inelastic-collision cross section for electrons on CO_2. In addition, the electron-capture probability, to form CO_2^-, is also relatively high. Consequently, pure CO_2 results in poor breakdown performance. On the other hand, when the CO_2^+ ions remaining after the discharge strike the cathode, the probability of an electron's being emitted is considerably less than for N_2 and, indeed, pure CO_2 showed no tendency to multiple fire, even when the recharge cycle was initiated within 100 μsec. When the two gases are used together, the charge-exchange cross section between N_2^+ and CO_2 is such that after a few thousand collisions all N_2^+ has disappeared--being replaced by CO_2^+. The magnitudes of the cross sections involved in these various processes are such that 90% N_2 and 10% CO_2, under the conditions described here, result in domination of the breakdown phase by the electron avalanche in N_2, whereas the CO_2 ions dominate during the recovery phase.

Operating the gap under pressure reduces the firing time somewhat and this is here limited by mechanical convenience and by observing that the spacing between electrodes (about 1 mm here) should be large compared with the irregularities caused by plasma erosion and chemical deposit.

An additional point of interest should be noted in the operation of this circuitry. Since the load is basically inductive and the required current is as shown in Fig. 2, once the current has reached I_0, considerably less power is required to maintain it. Consequently, a low-voltage gap is crowbarred on about 60 nsec after the breakdown of the high-voltage gap, as shown schematically in Fig. 8. As seen from this figure, the 2 kV line delivers I_0 to the load from the crowbar time on, with the residual energy in the high-voltage section being trapped in the high-voltage gap region and eventually dissipating in the high-voltage condensers (C). The interesting point is in the mode of operation of this low-voltage gap, which is of the two-electrode buried-trigger-pin variety operating in air at atmospheric pressure. Even though the voltage across this gap is decreasing rapidly as shown in Fig. 7, the motion of the plasma from the trigger wire out into the gas dominates its breakdown performance. Its firing point (in time) was determined by adjusting the separation D as well as the recessed depth of the trigger wire, and once adjusted it operated with < 10 nsec jitter so long as the electrodes were kept clean.

Finally, it is to be noted that Table I shows that the phototube delay is the slowest element in the chain. Since it was necessary, in the application of this equipment, to extract a minimum amount of energy from the muon, all 10 stages of gain in the type-6199 tubes were needed. In applications for which plenty of light is available and one is still interested in keeping the over-all delay to a minimum, about 2.5 nsec/stage can be gained by moving down to the dynode where 1 volt becomes first available.

ACKNOWLEDGMENTS

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FOOTNOTES AND REFERENCES

[*] This work was supported by the U. S. Atomic Energy Commission and carried out at the Lawrence Radiation Laboratory, University of California, Berkeley.

[†] Now at University of California, Santa Barbara.

[‡] Now at CERN, Geneva, Switzerland.

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2. Quentin A. Kerns and Gerald C. Cox, A Triggered Nanosecond Light Source, Lawrence Radiation Laboratory Report UCRL-9269, 1960 (unpublished) and Nucl. Instr. Methods 12, 32-38 (1961).

Table I. Time delays through trigger system.

	Delay (nsec)
Muon passage to 6199 photocathode (light pipe time)	5
Photocathode to anode	23
Anode to coincidence output	4
Coincidence output to start of rise of pulse on trigger pin of spark gap	11
Rise time of 12-kV pulse on trigger pin of spark gap	9
Spark-gap breakdown (time required for plasma current to build up until limited by external impedances	$\lesssim$ 5
	$\approx$ 57

FIGURE CAPTIONS

Fig. 1. Block diagram of apparatus.

Fig. 2. Idealized current waveform.

Fig. 3. Coincidence circuit. All tunnel diodes are TD 119 (RCA). All transistors are Philco 2N769. Trim "L" for desired pulse length 1 μH or less. T_1 has 10-turn primary, 5-turn secondary, which are Trifilarwound on Ferroxcube 102 core.

Fig. 4. Trigger-pin amplifier.

Fig. 5. Ultraviolet light pulser.

Fig. 6. Spark gap.

Fig. 7. Voltage pulse at load. (Time scale, 50 nsec per division).

Fig. 8. Crowbar circuit.

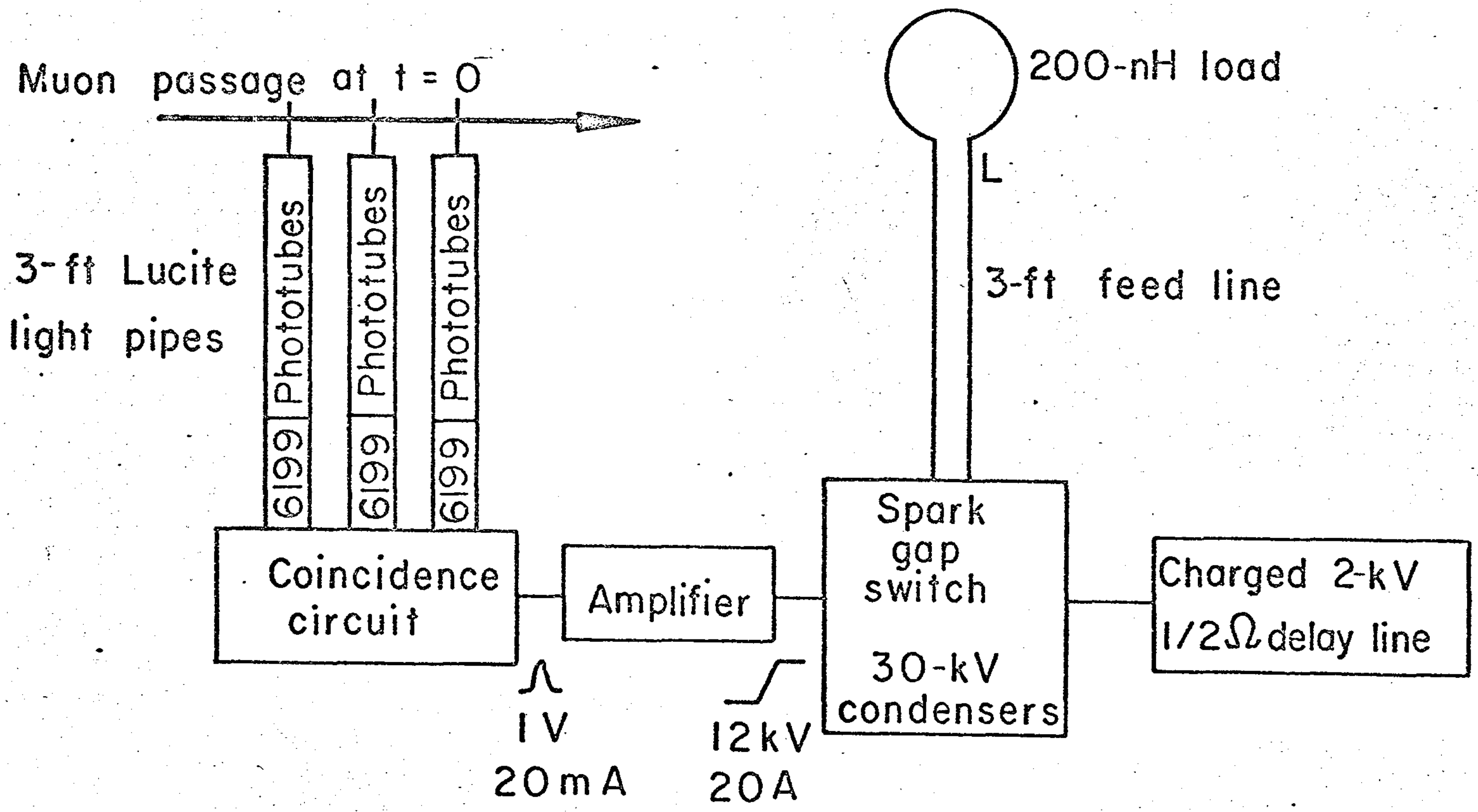

Fig. 1

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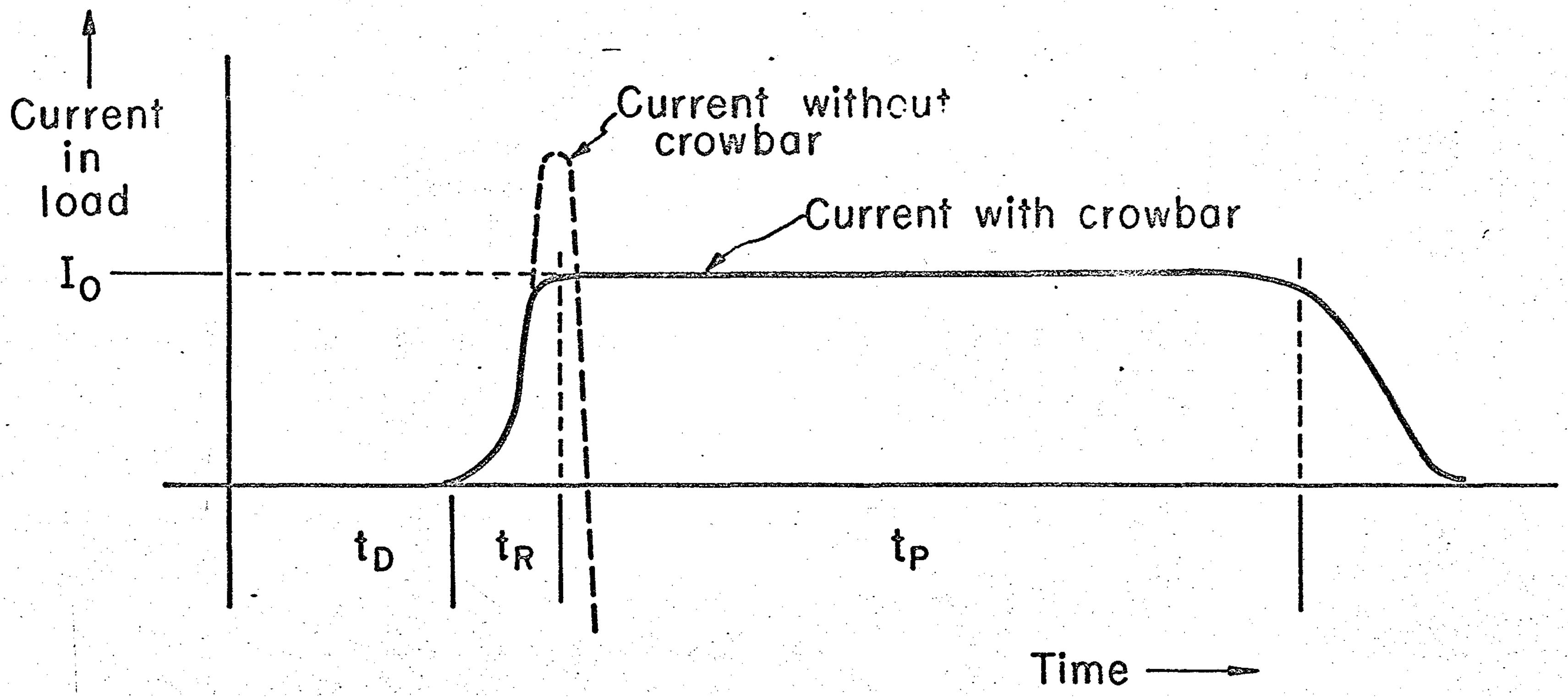
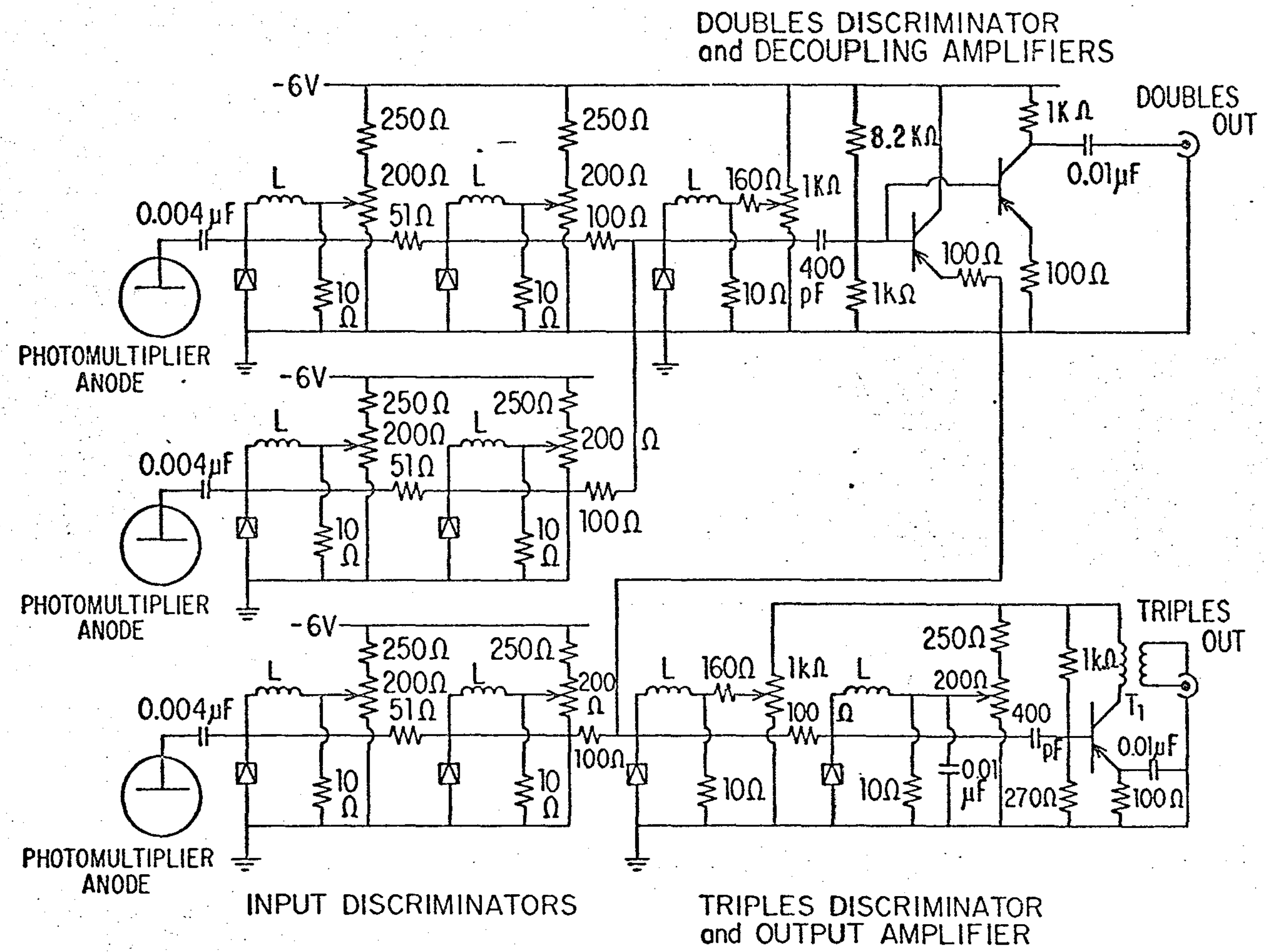


MU-31403

Fig. 2



All Tunnel Diodes are TD 119 (RCA). All Transistors are Philco 2N769. Trim "L" for desired pulse length 1uH or less.

T_1 has 10-turn primary, 5-turn secondary, which are Trifilar wound on Ferroxcube 102 core.

MU-33194

Fig. 3

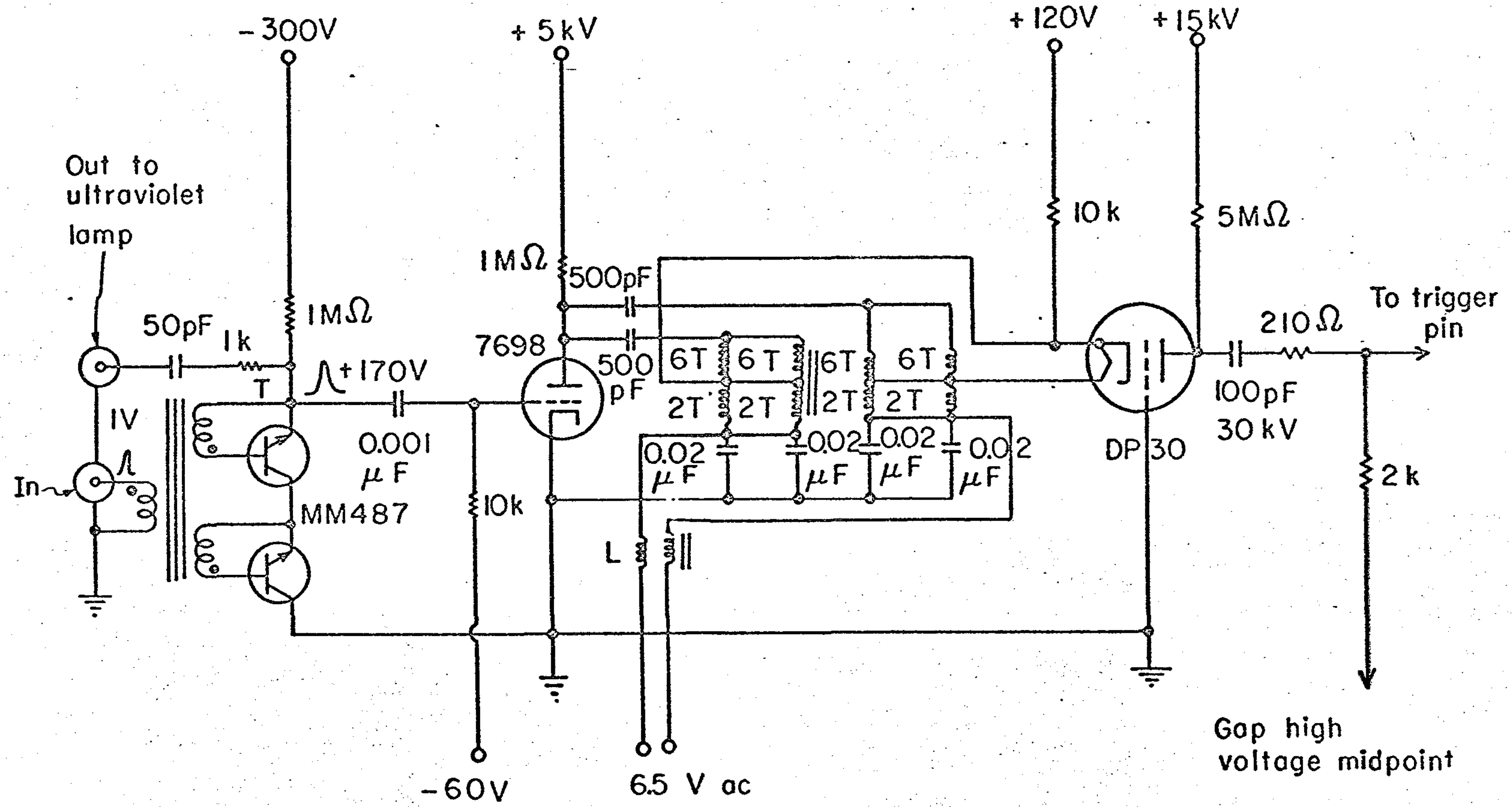


Fig. 4

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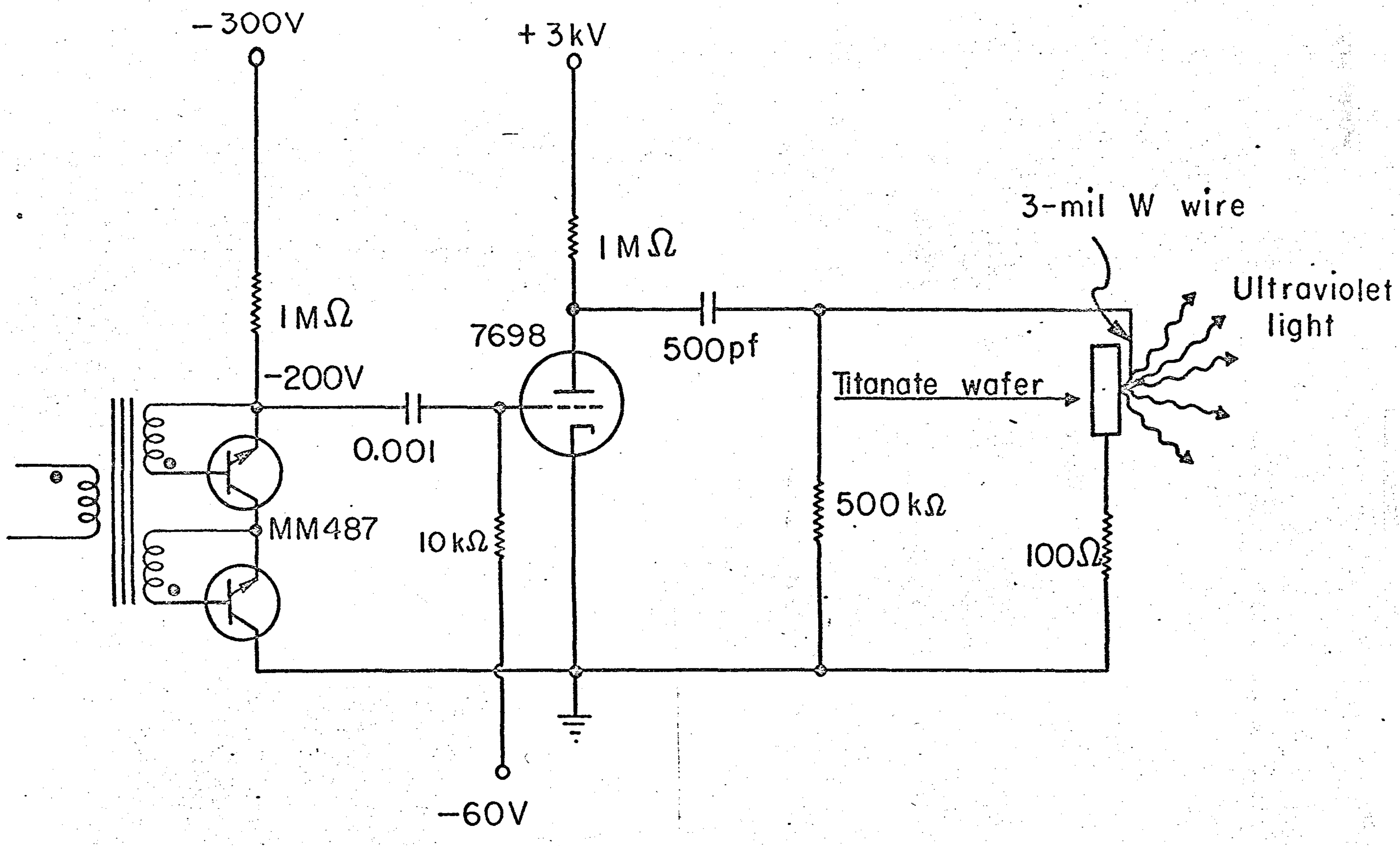

Fig. 5

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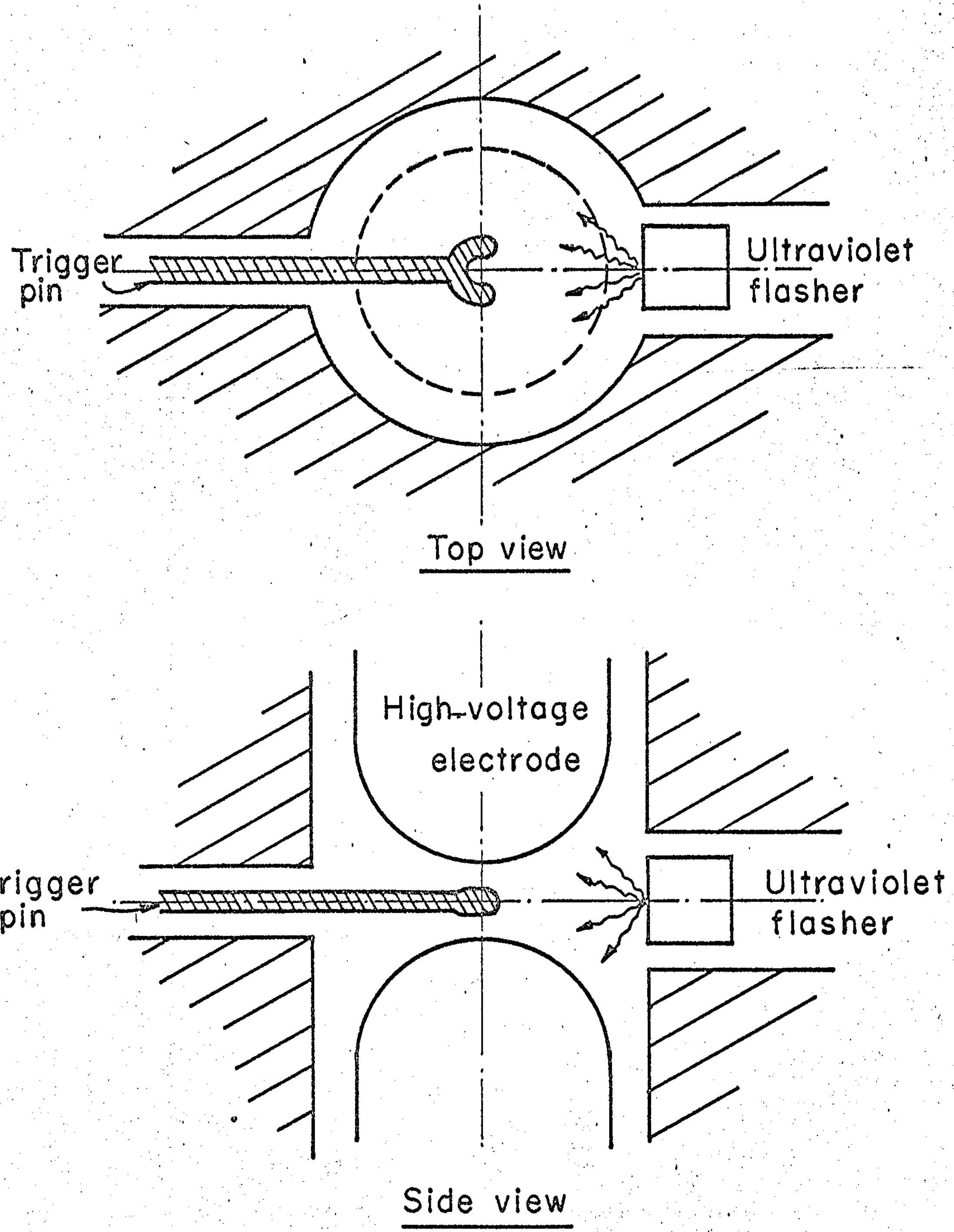

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Fig. 6

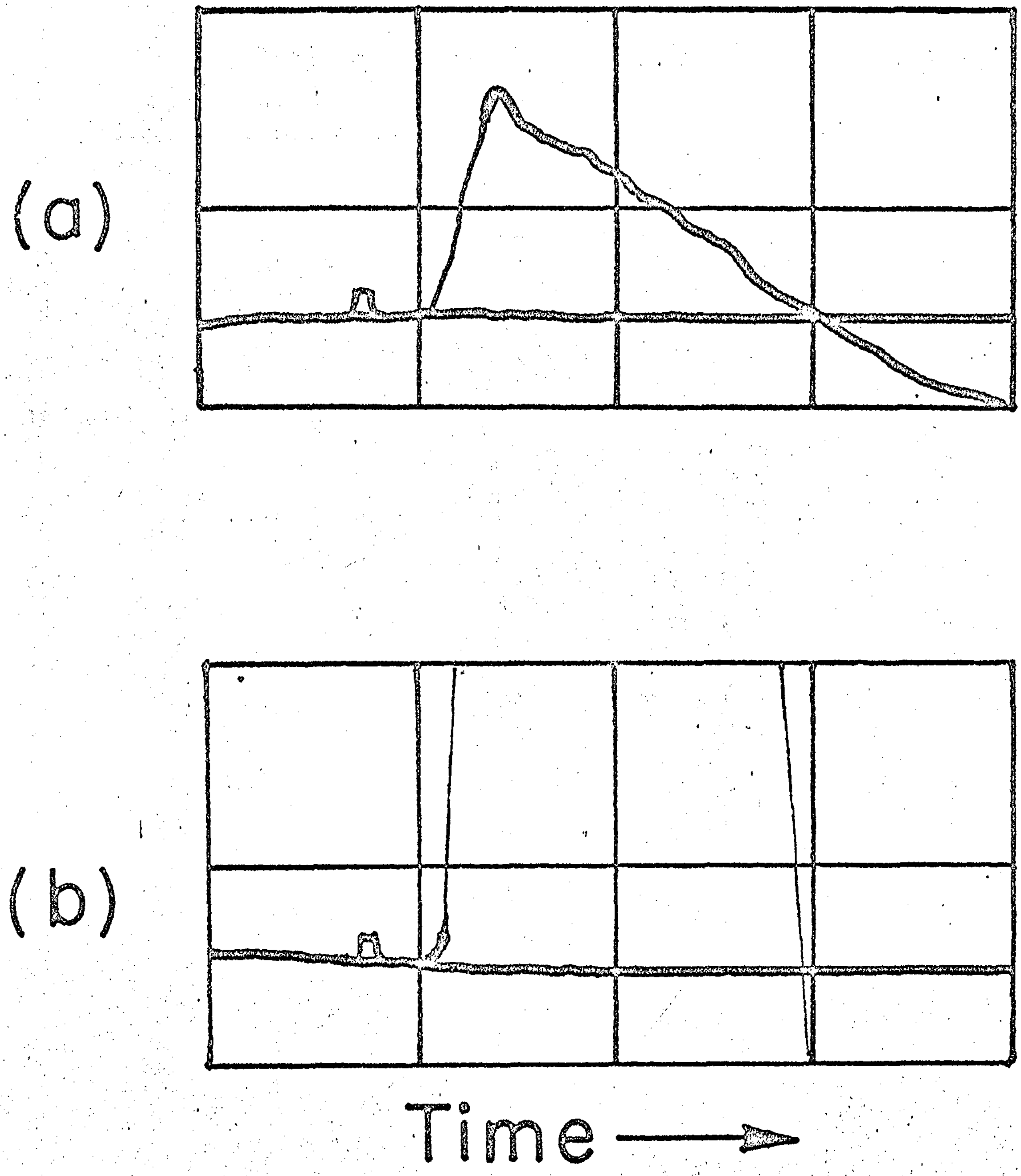

Fig. 7

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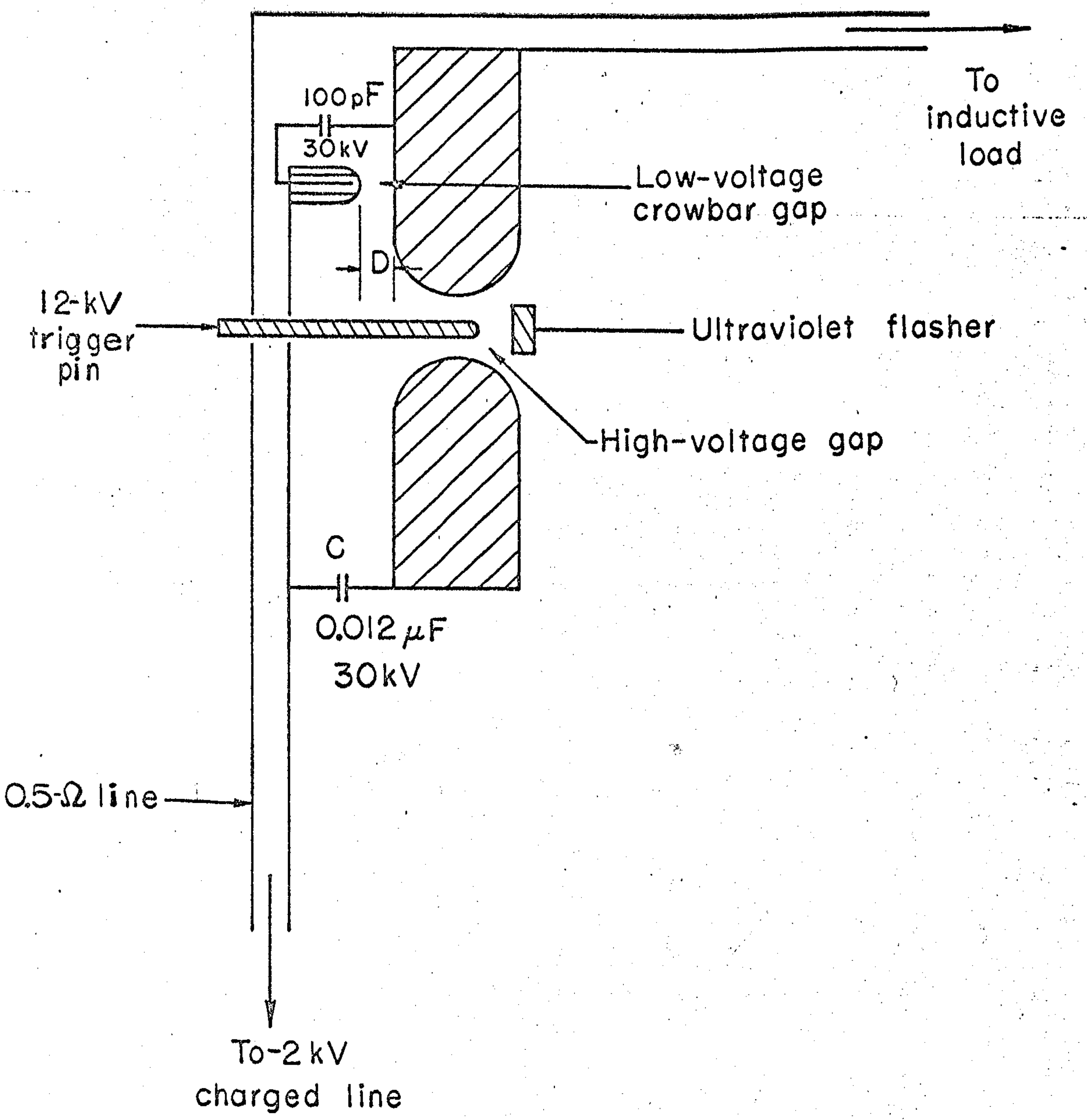

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Fig. 8