Switching Notes

Note 26

August 1977

Four Element Low Voltage Irradiated Spark Gap

J. C. Martin
Atomic Weapons Research Establishment
Aldermaston
England

Approved for public release; distribution unlimited.

Originally published as
SSWA/JCM/778/514

1 INTRODUCTION

The higher the working voltage of a gap, the easier it is to trigger and the smaller the fraction of the DC volts the trigger pulse needs to be. The difficulty is usually to stop a high voltage gap working. For low voltage gaps (which the reader should be warned have always been a hang up of mine) the difficulty is to trigger it quickly and reliably with a small trigger pulse. This difficulty is largely, if not completely, associated with obtaining electrons from the electrodes to start off the various breakdown processes.

Traditionally, field distortion gaps are useful for voltages of 20 kV and above and these derive their initiating electrons by field emission from whiskers on protruberances on the sharp edge of the trigger electrode. These gaps can be made to work at 10 kV, but need trigger pulses of greater than 15 kV and, even so, when used to pass quite small quantities of charge may become erratic in operation, after a while. This is because either the thin trigger edge gets blunted, or because the whiskers get chemically rotted off and the rather low field on the trigger edge ceases to cause electron emission quickly enough.

The corona gap, which works down to a few kV, obtains the initiating electrons by producing a large field between a thin trigger strap and another electrode from which it is separated by one or two thou. (US mil.) of mylar. These initiating electrons avalanche across the plastic surface and irradiate or inject electrons into the main gaps which are between the trigger electrode and other electrodes. This gap, properly designed, works well but still needs a kV or two to trigger it, has a fairly large input capacity, and has the disadvantage for high current use that the discharge passes through the thin trigger strap.

Having a week or so to spare, a little while ago, I decided to indulge myself and look at other designs of gap. Desirably these should have more or less uniform field electrodes, so that they could pass reasonable quantities of charge in use, have a wide operating range, need a small trigger pulse into a lower capacity, be fast, and have a low jitter. Because of the 'uniform field' requirement they would have to be u.v. irradiated, and the other objectives suggested that three electrode gaps would not be optimal for operation at 10 kV or lower.

This note briefly summarises the result of a few days' hurried work, so the arrangements tested have not been well optimised. In addition, four element gaps have an extra degree of freedom, compared with three element ones, so only a few of the possible arrangements were looked at, and for only two of these are results given below. Lastly, my notebook was even more inscrutable than usual and while this would not have mattered if I had been able to write up the results straight away, this was not possible. Returning to the notebook after a couple of months has been a sobering experience (to be compared with an archaeological dig) and while I am sure the results quoted were obtained with the mechanical configuration described, I am decidedly less certain that the particular values of the resistances given were actually in the circuit at the time of the tests; my apologies. Thus this note should be read as a description of a certain class of gaps, the results given as examples of what can be achieved, and the circuit values as possible examples of what actually were used.

2 MODE OF OPERATION OF GAP

Figure 1A shows a schematic of the switch, which has four electrodes and three gaps. These gaps are numbered from the bottom, as shown. Also shown in Figure 1A is the ratio of the DC breakdown voltages of the three gaps, 1, 2, 1 in this case, and a resistor chain not shown keeps the individual gap voltages at these ratios. This particular arrangement is typical of a gap requiring about 5 kV to trigger it quickly for 8 kV operation, but also having a wide operating range. The spacings (in mm) of the gaps for breakdown at 10 kV DC are about 0.45, 1.2 and 0.45. The firing order of the gaps is G2, G3 and then G1.

I have an awful feeling that the nomenclature of this note is going to get out of control, but I will attempt to be consistent and follow the above pattern. Thus a fully specified switch would be: 1,2,1/0.45,1.2,0.45/3,1,2. This means that the bottom first gap has one-quarter of the DC volts on it, its spacing is 0.45 mm, and it is the third gap to close. In general, only the first set of numbers will be given in describing the switch, the others being included only occasionally. Hopefully all the circuits will be drawn for the switch so that gap No. 2 fires first, No. 3 next, and No. 1 last. This corresponds in the notation to 3,1,2 as the last set of three numbers. The perceptive reader will readily understand the potential pitfalls, but other methods of numbering seem to me to have even worse troubles.

Figure 1B shows a distinctly idealised sketch of the voltages existing on the four electrodes (unnumbered; I've given up) as functions of time after the trigger pulse arrives. The circuit is arranged so that the volts of G1 and G3 go to zero and reverse, allowing a substantial pulsed voltage to appear on G2. Before either G1 or G3 can fire, G2 reaches its breakdown voltage and closes. Ideally the circuit should be arranged so that all the trigger pulse plus the DC voltage on G2 should now be applied to G3 (the dashed line). However in real life, where fast triggering is required, stray capacities, inductances, etc. mean that this does not happen and the electrode voltages follow the full line curves. G3 then fires and ideally the full DC volts appear across G1 (the dashed line again). However in real life, for quick operation, the potential of the electrodes follows the full lines again and less than the DC voltage appears promptly on G3.

In real life there are two further complications. The first and obvious one is that for a gap which can be triggered fast over a wide range of DC voltages, the standing voltage across each gap (and hence the total voltage applied to G2 and G3) alters as the DC voltage on the switch is changed. Thus the gap spacings should ideally be changed whenever the working voltage is altered. However, reader, take heart: in practice a gap self-breaking at 10 kV can be triggered quickly down to 4 kV with the above 1,2,1 arrangement, and even wider operation achieved with other DC breakdown ratios.

The second and more subtle way in which Figure 1B is idealised is that it assumes the spark closure is well behaved and merely has an inductance and time-varying resistance, as is shown in Figure 3A. In practice all gaps, I believe, have the breakdown characteristics shown in Figures 3B and 3C. What happens is that an initiating electron (usually from an electrode) avalanches and produces a brief period of spatially non-uniform glow discharge. After a while the region where the initiating electron occurred gets warm, its pressure rises, and the gas expands. The combination of a gas density below ambient and glow discharge current necking in the region leads to it reaching plasma temperatures very much faster than would be the case if the glow discharge were uniform in cross-section across the gap and no hydrodynamics occurred in the gas. The front of the plasma spike then propagates across the gap and finally plasma channel closure occurs, the gap voltage falls, and the resistive phase formula can be applied.

The current passing before final plasma channel closure is known as 'fizzle' in the spark gap world, and in the world of the gas laser as 'pumping'. (One man's meat is another man's poison.) The phenomenon is most clearly seen (for uniform field switches) for rapidly pulse charged atmospheric air dielectric gaps with large spacings (Ref. 1), in particular where these are very well irradiated by u.v. Such gaps have a voltage waveform such as is shown in Figure 3B. After reaching a field where the ionisation multiplication rate is very fast, the voltage falls to a level above but close to the DC breakdown level where the multiplication rate is low. After a period, which is longer the more intense and uniform the u.v. irradiation is, plasma channel closure takes place and the remaining gap voltage collapses. As is indicated, there is a jitter in the time of this final voltage collapse. For a uniform gap which is pressurised to a couple of atmospheres, the glow discharge phase still exists, but is much shorter, as is indicated in Figure 3C. In addition, if the impedance of the pulse generating circuit is low, the glow discharge phase is shorter.

All the above applies to irradiation with u.v. which is only energetic enough to give rise to photo-electrons from the electrode. If u.v. of a wavelength small enough to provide a suitable level of ionisation in the gas is used, the gap volts can collapse very quickly, as was shown by Laird Bradley, but these rather special conditions are not likely to be relevant to this note.

In the present experiments the atmospheric air gaps were weakly irradiated by longish u.v. and were also very quickly pulse-charged by relatively high impedance circuits, so the gap breakdown behaviour sketched in Figure 3B is very likely to occur on the few nanosecond timescale. This means that the pulsed voltage waveform that, say G3 sees after G2 fires may come in two bits. If the total of DC standing and pulse voltage is enough to fire the gap on the rapidly falling portion of the waveform, the jitter is very good. If, however, the gap closure occurs during the slowly falling portion of the wave, the jitter is very bad. If, however, the gap has to have most or nearly all the pulsed voltage, the jitter, while poorer than in the first case, is better than in the second. This I believe accounts for the occasional observation that lowering the DC standing voltage on the gap can improve its jitter.

Another way around the difficulty would be to pressurise the gap to two or three atmospheres, but firstly the spacings are already rather small, and secondly the gap loses its simplicity of construction, which is a practically nice feature of working in air. Reader, again take heart: the jitter of the gap was frequently sub-nanosecond in practice, without any care being taken. The above section is only included to account for surprising behaviour and to explain why the jitter is not in the tens to one hundred picosecond range, which calculationally it ought to be. It also gives hints as to how the design might be altered to achieve very small jitters indeed.

In designing a gap it is desirable to make the times for the three gaps to break down about the same; this seems to lead to the least jitter as well as the shortest operating time. Where a gap with a wide operating range is aimed at, then the above condition should be met for an operating voltage in the middle of the design range. For a low trigger voltage version, such as is next described, the condition should be achieved for an operating voltage of about 0.8 or 0.9 of the DC breakdown voltage. Using Figure 4 (discussed briefly at the end of this section), it is relatively simple to do the initial gap design, although the final circuit components may have to be experimentally varied in order to get the best operating conditions. In addition, it is desirable to monitor the gap closure times to make sure they are approximately the values calculated.

Figure 2A gives a sketch of a gap designed to operate with a near minimum trigger pulse. In this case it is a 5,2,3/1.15, .35,.60/2,1,3 gap. Figure 2B gives a sketch of the waveforms, again showing how after firing G2 the pulse is used to help to over-volt G3, as before. After G3 fires most of the DC gap volts are applied to G1.

The observant reader will have spotted that the ratio of the gap voltages is not much like the ratio of the spacings. This is because the DC uniform breakdown field for air at one atmosphere is given by

$$F = 24.5 + 6.7/d^{1/2} \text{ kV/cm}$$

where d is the spacing in centimetres. Thus for a 1 mm gap, the breakdown field is nearly double that of a large gap, even with uniform field conditions, and for smaller gaps it is even higher. This is shown in Figure 4, which is taken from Reference (2). Reference (2) was written shortly after the period of experimentation with the gaps described in this note and provides the input data necessary to calculate their performance. The data given in Figure 4 and Reference (2) is not of the highest accuracy, but is adequate for the purpose for which it was obtained.

In Figure 4 it is seen that the DC breakdown field curve is far from linear and in addition the pulsed breakdown curves intersect it. Thus for a gap of about 0.5 mm spacing, a pulse voltage equal to the DC breakdown voltage with irradiation will cause it to break down with a t_{eff} of about 10 ns. (t_{eff} is the time width of the pulse at 89% of peak amplitude.) To make the gap break in a time of 2 1/2 ns only needs about a 3.5 kV pulse, while its DC breakdown level is about 2.7 kV, i.e., a pulse to DC ratio of about 1.3. For a centimetre gap with a DC breakdown of about 31 kV, a pulsed voltage of around 60 kV is needed to break it down in the same time, that is, a ratio of about 2.0. Thus small gaps need significantly less fractional pulsed volts to trigger them quickly. This is not so much that the pulse voltage requirement is down as that the DC breakdown voltage is high for small spacings. This phenomenon would not be expected to be observed for gases such as SF_6, where the data suggests that there is very little gap length dependency of the DC breakdown field.

3 DESCRIPTION OF GAP AND UV IRRADIATION

It should be stated at the outset that the gap was just botched together and worked well enough that there was no cause to change it, and that it could be greatly improved. For instance, it is at least twice as long as it need be for operation at 10 kV and in addition its inductance could easily be halved from the present value of about 40 nH. In addition, the method of adjusting the gap was very inferior and this could and should have been improved. The DC breakdown of the gap was quite stable, except when dirt got into it, and some simple housing to exclude this would be useful.

With all these reservations, Figure 5A gives a sketch of the gap. The two bent rod electrodes were made out of 1/8" brass, while the outer two electrodes were made of slightly thinner copper, suitably rounded. Under the gap was a reasonably low inductance strip line feed to a home-made condenser of about 1.5 nF capacity. Figure 5B shows a cross-section of the gap with this feed. As the electrodes were rail ones and the maximum spacing about 1.2 mm for a rod radius of 1.6 mm, there was little field enhancement on them.

The pulsed irradiator was also highly unoptimised. The first version is shown in Figure 5C and the surface flashover from it used to provide the uv irradiation of the main gap when it was about 3 cm away. The electrodes were mounted on a 3/4" OD perspex rod and a thin copper sheet acted as a backing plate or electrode. Two thou. mylar was placed between this and a tensioned 2 thou. thick, 2 mm wide, steel strap. The tensioning was provided by squashing a small slab of sponge rubber under the steel and away from the gap. This meant that if the steel expanded slightly, the tension in it was not lost. In the case of the irradiator shown in Figure 5C there was no need to keep the capacity low or to make it work with the lowest possible trigger pulse: hence the backing plate was about 3 mm wide and the length of mylar over which the surface discharge took place was about 1 mm. Thus the capacity before the discharge started was some 3 pF and the pulse volts needed to flash it over in a few ns about 4 kV. The irradiator was driven from a 50 ohm cable unterminated.

Figure 5D shows a sketch of the very low capacity uv irradiator which was designed to require the minimum trigger energy to operate. In this, 1 thou. mylar was used and the area in contact with the backing rod was about 1 mm^2. Thus the starting capacity was about 1 pF plus the lead strays. The mylar overlap was about 0.3 mm and the irradiator needed some 1.2 kV to flash it over in a few ns. The backing metallic rod had a diameter of about 3 mm and was half sunk into the perspex rod. The metal rod stopped just under the edge of the strap and was replaced by a perspex rod of the same diameter.

In operation, this irradiator was placed about 2 cm above the gap and positioned so that the uv could irradiate the cathode of G2 at its closest point. This did not seem to be very important, but appeared to have a marginal advantage.

4 PERFORMANCE OF GAPS

4.1 Wide Operating Range Version

This had approximately the following characteristics: 1,2,1/.45,1.2,.45/3,1,2. Figure 6 shows the believed circuit parameters, the trigger volts being provided by a 50 ohm cable; and also the pulsed trigger volts applied to the electrodes of G2 to fire it. The pulsed voltage required in the cable was roughly 0.7 of that shown in the figure. In the actual test set-up the trigger pulse had a rather poor rise time (∿ 8 ns to 70% of peak), which is not of course necessary. Because of this, the circuit values were optimised for a rather slowly rising pulse. If these were re-optimised and an adequately fast rising trigger pulse provided, it is calculated that G2 could be fired in not much more than 2 ns. Because of this the observed delays have been reduced by the delay in firing G2 minus 2 ns; that is, the delays shown in Figure 6 are based on G2 firing in about 2 ns.

As can be seen from the figure, operating at 0.8 of the DC breakdown voltage of 10 kV, the firing delay can be around 8 ns, using a trigger pulse rising very quickly to about 5 kV. The version shown here triggered down to a bit less than 4 kV. A slightly different version (1,3,1 probably) triggered down to 3 kV for a 10 kV self break, but with slightly longer delays at higher operating voltages.

4.2 Small Trigger Voltage Version

This had the following characteristics: 5,2,3/1.15,.35,.60/3,1,2. Figure 7 gives the circuit values used and the pulsed trigger volts needed across G2 to fire it. In this case the pulse in the cable was about 0.6 of that shown in the figure. Once again the observed delays have been reduced to show what would have been the gap firing time if G2 fired after 2 ns. For operation at 0.9 of the 10 kV DC breakdown of the gap, the delay is about 17 ns and a 550 volt fast rising trigger pulse on G2 is needed to achieve this. If this is generated in a 50 ohm cable, the pulse voltage required in the cable is some 330 volts.

Table I gives the observed times for the gaps to fire, in nanoseconds. Δt_1 is the time for gap 1 to fire after gap 3 has fired, etc.

TABLE I

Self Break of Gap ∿ 10 kV
Volts in kV; Times in ns

Operating Voltage 10 kV	Trigger Volts $t \to \infty$	G2 Firing Voltage	Δt_2	Δt_3	Δt_1	Gap Firing Time (Fast Trigger)
0.9	0.9	0.55	7	7.5	5	17
0.8	1.0	0.67	10	9.5	9	22
0.69	1.1	0.85	16	20	17	41

From Δt_2 the time the trigger pulse took to rise to the triggering voltage is subtracted and 2 ns added, to give the numbers in final column. No notice should be taken of fractions of a ns in Table I; the monitoring was not capable of resolving these, really. The actual numbers were obtained by averaging a number of individual measurements; hence the fractions.

The total capacity across G2 in this version was about 6 1/2 pF, including the strays of the blocking capacitors. By building a half length version and tidying up the feeds, this capacity could easily be reduced to 3 pF.

Such a gap, at 0.9 of its self-break would need 550 volts into 3 pF to fire it quickly, whereas even the low capacity irradiator (shown in Figure 5D) needed 1.3 kV into around 1.2 pF to operate it so as to close the surface discharge in a spark. It would work as a uv irradiator (without a faint closure spark appearing) at under 1 kV, but I would be reluctant to use it in such a mode, as the mylar might charge up and it could become irregular in performance. Thus the gap needs 1/2 microjoule to trigger it, while the uv irradiator needed about 1 microjoule, a most annoying outcome. In addition, the uv irradiator needed about 5 ns to provide sufficient uv to reduce the time jitter in operation of the gap to a low value (∿ 1 ns). This was partly because of the slow rate of rise of the pulse supplied to the uv irradiator (it was the same pulse rise time as the trigger pulse). Thus with a faster pulse operating the uv irradiator gap probably there would be no need to delay the gap trigger pulse. Even if this were not so, only a couple of ns need be added to the times shown in Figures 6 and 7 to get adequate uv irradiation in the gap by the time it was needed.

In some applications it might be possible to provide a trigger pulse a few tens or hundreds of ns before the time the gap needed to be fired; however, from the point of simplicity this is obviously undesirable. Thus when I left the work I was contemplating improved uv irradiators, i.e., ones needing less volts and energy to make them operate more quickly.

When the trigger pulse was larger than the minimum required, multichannel operation was frequently observed. This was particularly true of the 1,2,1 gap, which when operated at around 0;7 to 0.9 of its self-break, would have a few channels in G2 and about 10 each in G1 and G3. As the capacity across the gap was only 1 1/2 nF, the multichannelling might not be so spectacular for larger capacitors and longer switched pulses.

While both gaps were fired many thousands of times, they were only tested with the small value of load capacitor, so questions as to electrode erosion, etc. were not addressed in the tests. However, because of the constancy of operation at peak currents of up to 2000 amps ringing on for quite long times, it is not expected that erosion will be a significant problem for most applications.

With regard to the jitter in gap firing time, there were operating regimes where the standard deviation was 0.3 ns or less, particularly with the 1,2,1 version. In general, the standard deviation was less than 1 ns, except for peculiar operating modes or where the trigger pulse amplitude was marginal. As was mentioned earlier, there were occasionally operating modes where the time jitter was relatively poor and where this improved considerably as the DC voltage on the gap was actually reduced.

5 POSSIBLE VARIANTS

As has been mentioned earlier, there are various obvious improvements to be made to the first experimental gap, notably to build it about half the length over the electrodes and considerably less over the whole length. Where there is a trigger pulse available intermediate in amplitude between 1/2 and 5 kV, the spacings can be re-optimised to take advantage of this fact, to obtain an improved operating range and faster closure time than the 5,2,3 results.

I think the gap can be scaled down to work at 4 to 5 kV with reduced trigger volt requirements, but I have not shown this.

If there are trigger volts to spare and multichannelling can be confined with larger load capacitors, a very much lower inductance feed can be devised than is shown in Figure 5B. Under these circumstances it may be possible to build a version with an inductance of significantly less than 10 nH, and switch currents of 5 kA or more rising in 5 ns or so. The latter estimate assumes that the full gap fizzle phase is short, which would probably--but not necessarily--be the case. Pressurising the gap to two or three atmospheres should certainly achieve this, or better.

Mr. Storr has devised an elegant version of the gap, where he has combined the uv irradiator and one of the electrodes of gap 2. This he has done by providing a corona gap version of this electrode, by making the current-carrying electrode a ring of 2 thou. metal separated by mylar from the rod underneath. The gaps are staggered out of a single plane, so all see the corona. This arrangement has the great advantage that no separate irradiator circuit is required: the trigger pulse provides the corona as well as over-volting G2. There is a minor disadvantage in that the gap will be somewhat limited in the coulombs it can pass, as the discharge current passes through the thin metal ring.

He has also built a small avalanche transistor circuit, so that the system operates with a 20 volt input. He has shown overall delays slightly shorter than those shown in Figure 7, with very good jitter and the ability to run at modest rep. rates. Anyone interested should write to him and get details. (That should lumber him with writing it up.)

6 CONCLUSIONS

A four element uv irradiated gap of simple construction has been tested in a few of its many possible versions. With a suitably fast trigger pulse, one version can trigger down to 0.3 of its DC breakdown voltage, and at 0.9 of this fire in about 8 ns. The other version of interest requires only 0.55 kV to trigger a 10 kV DC breakdown gap operated at 9 kV in about 17 ns. Both versions have quite good jitter ($\sigma < 1$ ns) which can almost certainly be improved for a given set of operating conditions by tinkering. Low inductance versions of it are very likely to be constructable and with some air flow and short output pulse operation, versions of the gaps can probably be operated at 50 pps or more.

7 ACKNOWLEDGMENTS

It is, as always, a great pleasure to thank Vikki Horne, who has been typing out a series of notes for me over the past two weeks, this one being the last. I fear the strain of straightening out my syntax, pruning my punctuation, and doing major surgery on my spelling, for so long may have been too much for her. This is because as she handed me the typed script for part of this note, she snorted and said: "Archaeological dig, indeed," as she retired in good order. My apologies, Vikki, and my heartfelt thanks. I promise next time I'll use the word 'excavation'.

REFERENCES

(1) An Auto Irradiated Pulse Charged Divertor Gap. T. H. Storr and J. C. Martin. Switching Note 25, May 1977.

(2) High Speed Breakdown of Small Air Gaps in Both Uniform Field and Surface Tracking Conditions. J. C. Martin. Switching Note 24, April 1977.

Schematic Waveform for 1,2,1, Version

For $V_{OP} \sim 7$ kV
$V_{SB} \sim 10$ kV

- - - No Stray Waveform

—— Real Life Waveform

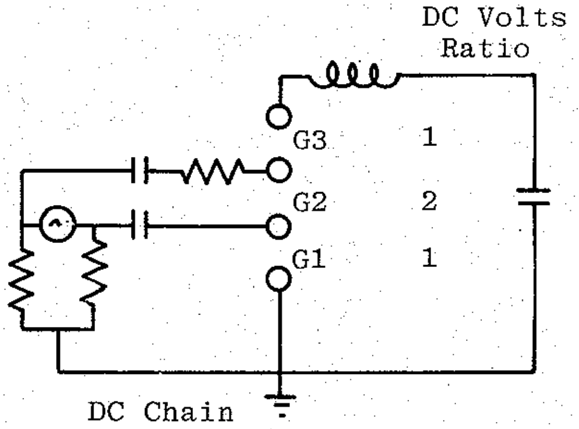


Fig. 1A

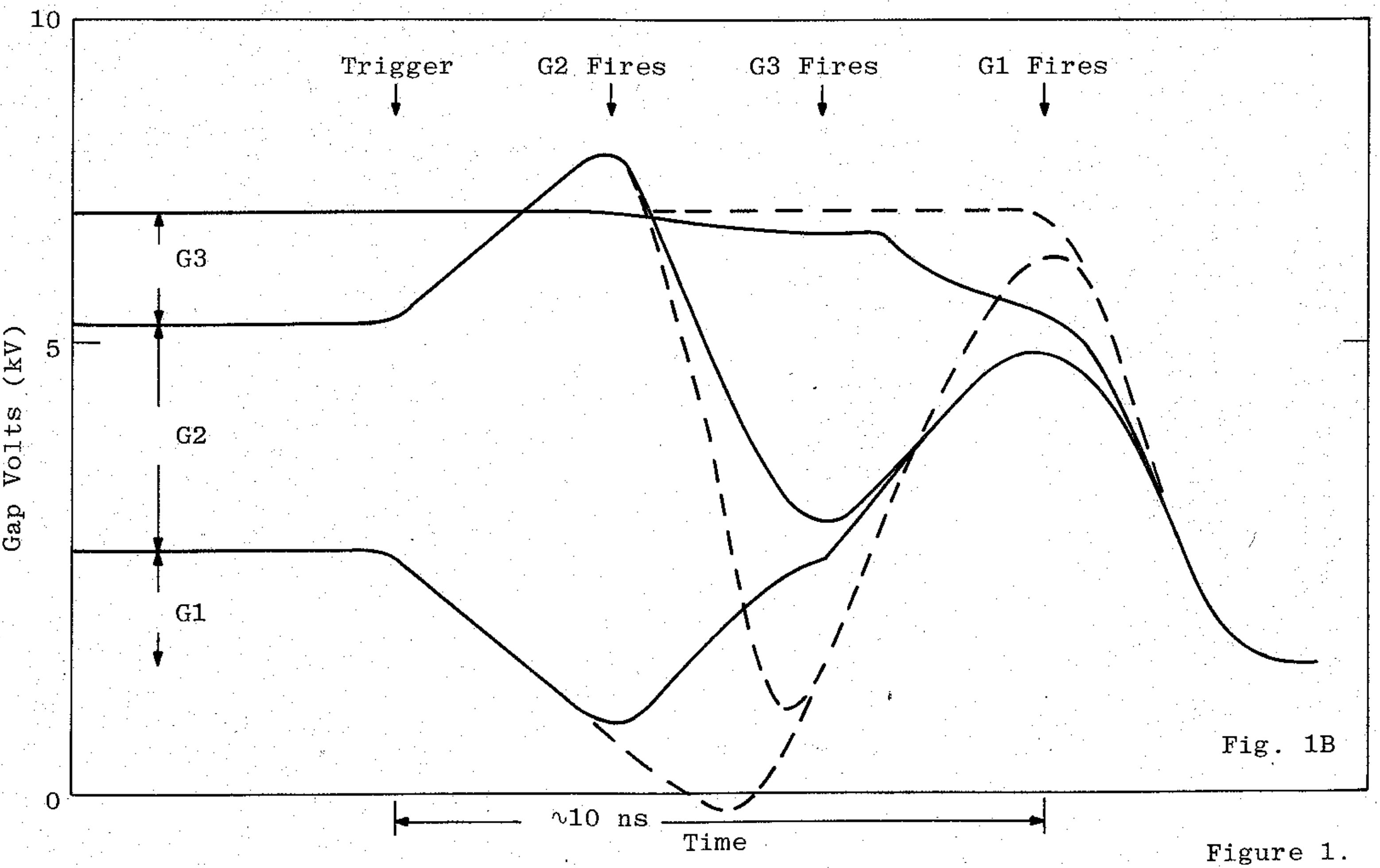
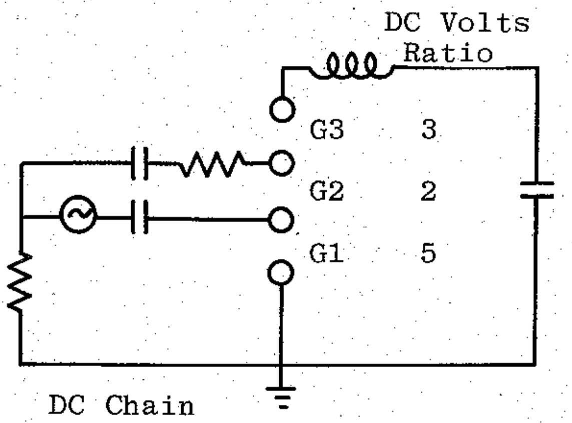


Figure 1.

Schematic Waveform for 5,2,3 Version

For $V_{OP} \sim 9$ kV

$V_{SB} \sim 10$ kV



DC Chain
Not Shown

Fig. 2A

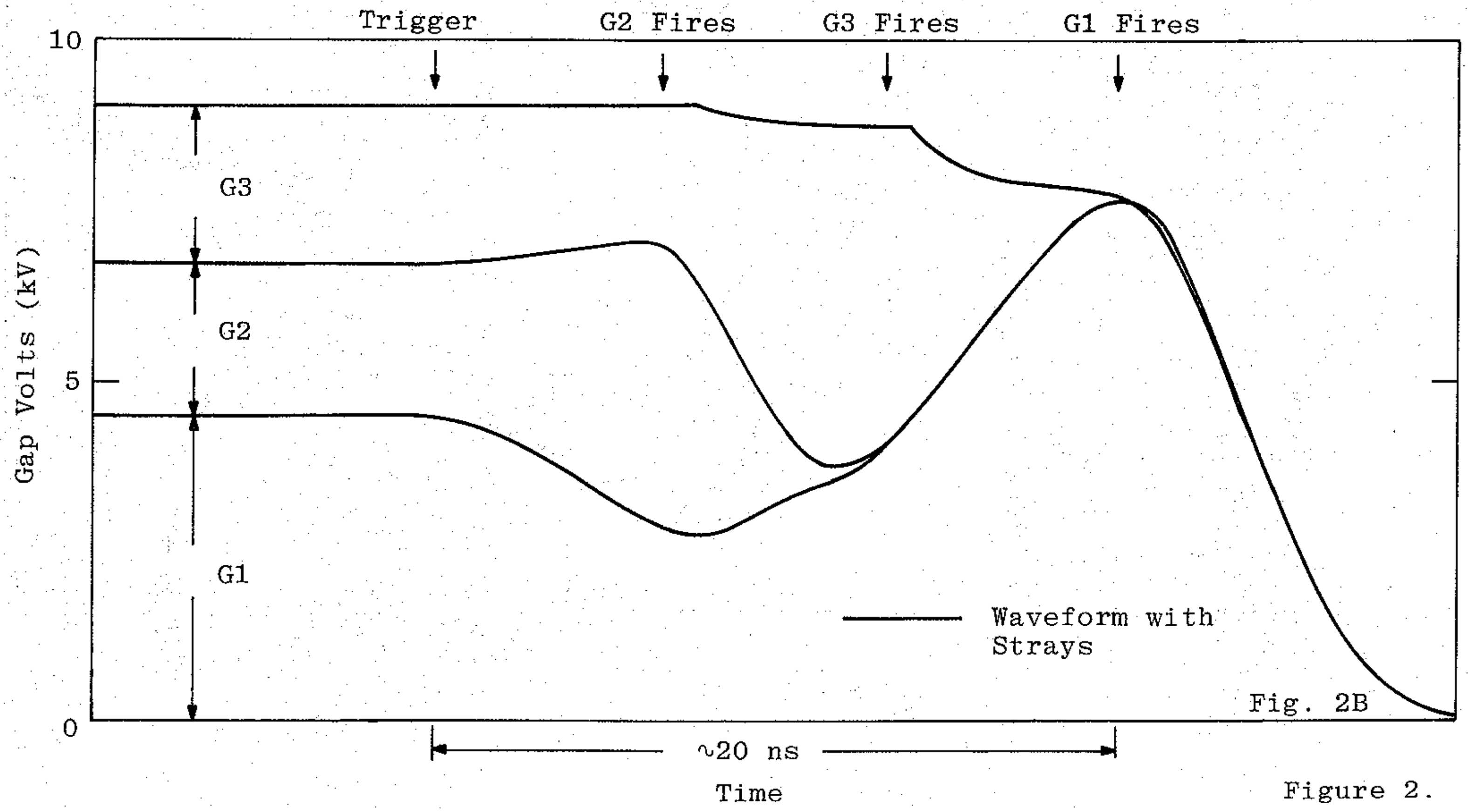
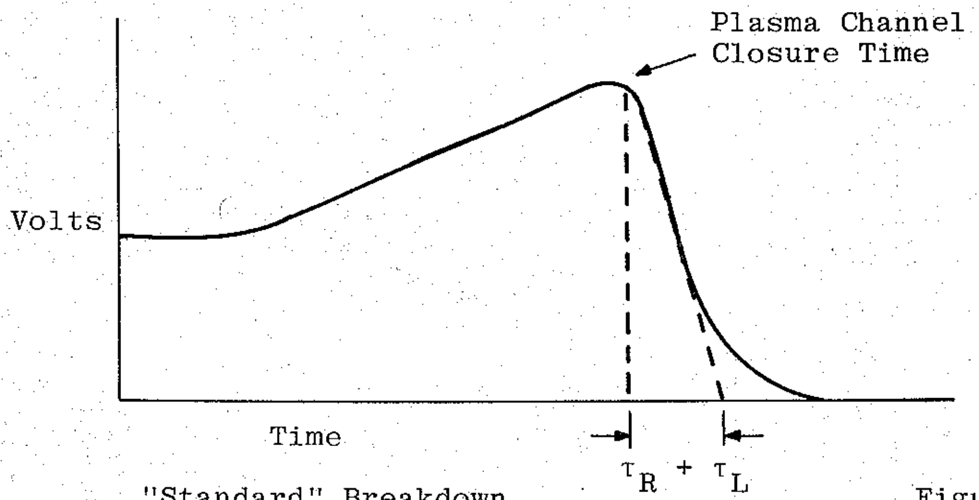


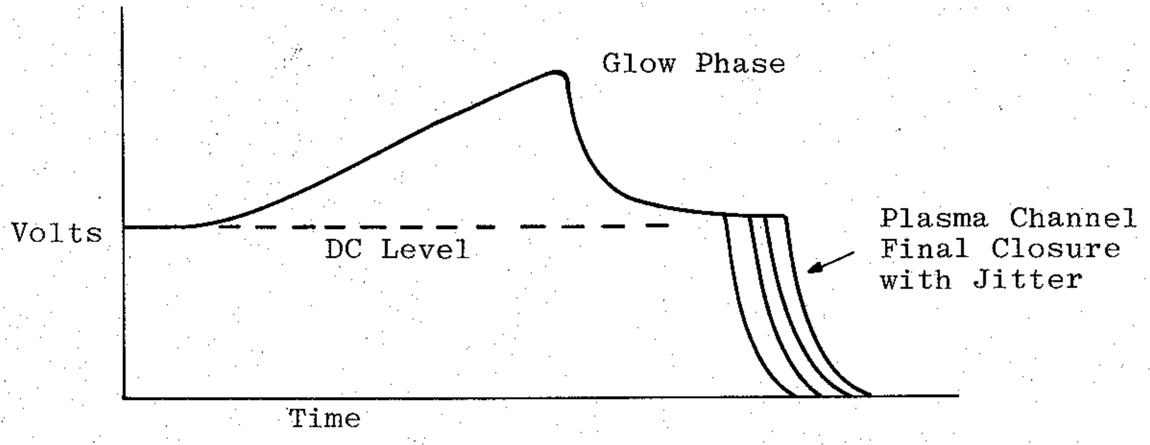
Fig. 2B

Figure 2.

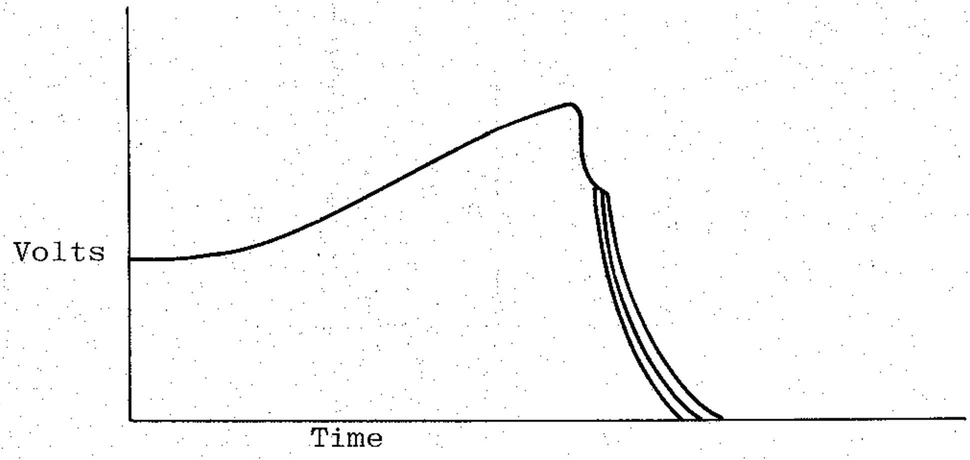
Pulse Charged Gap Breakdown Waveforms



"Standard" Breakdown Figure 3A



Fast Breakdown of Air at 1 Atm. Figure 3B



Fast Breakdown of Air at 2-3 Atm. Absolute Figure 3C

Irradiated Pulse and DC Breakdown Voltage of Atmospheric Air Gap

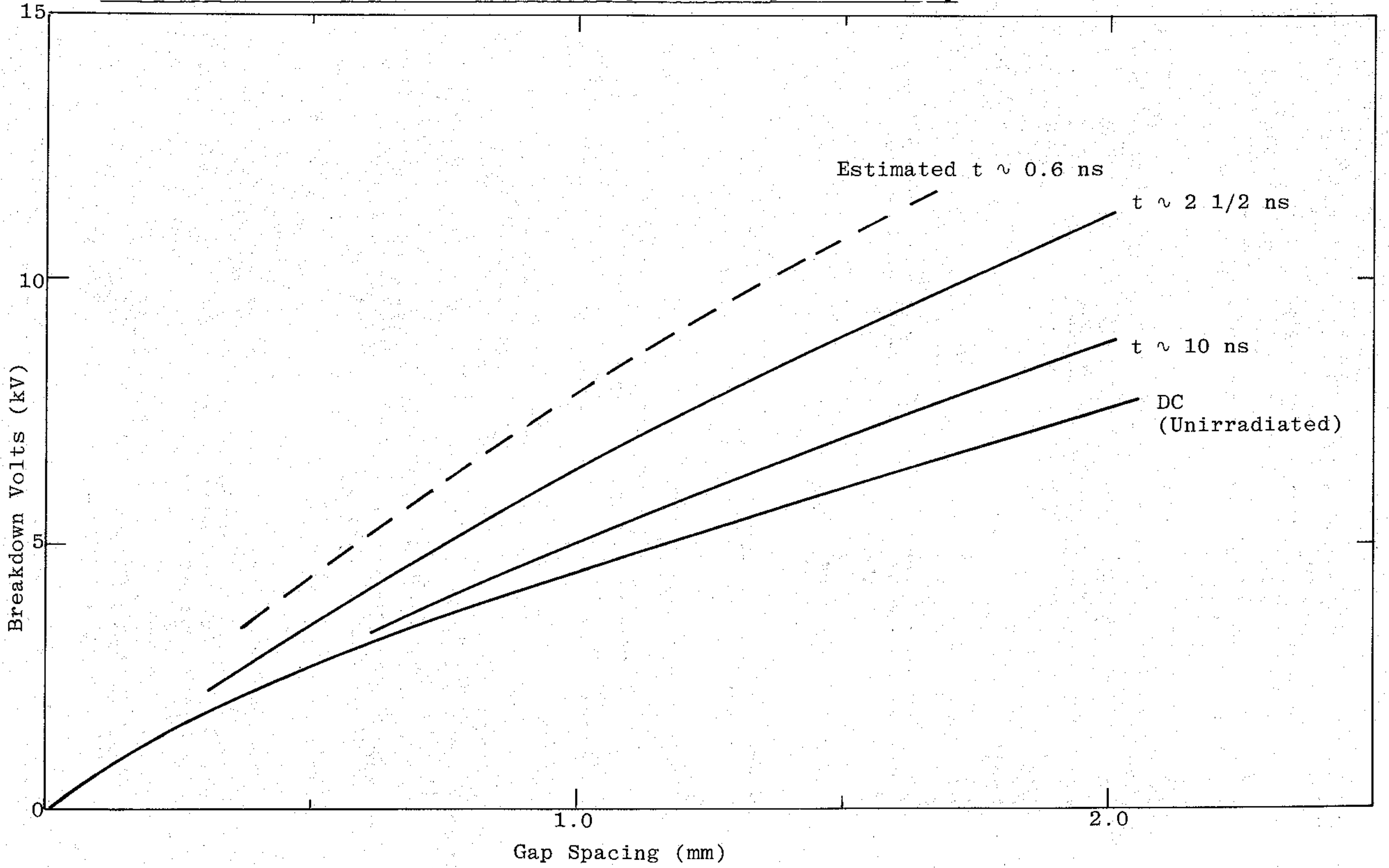
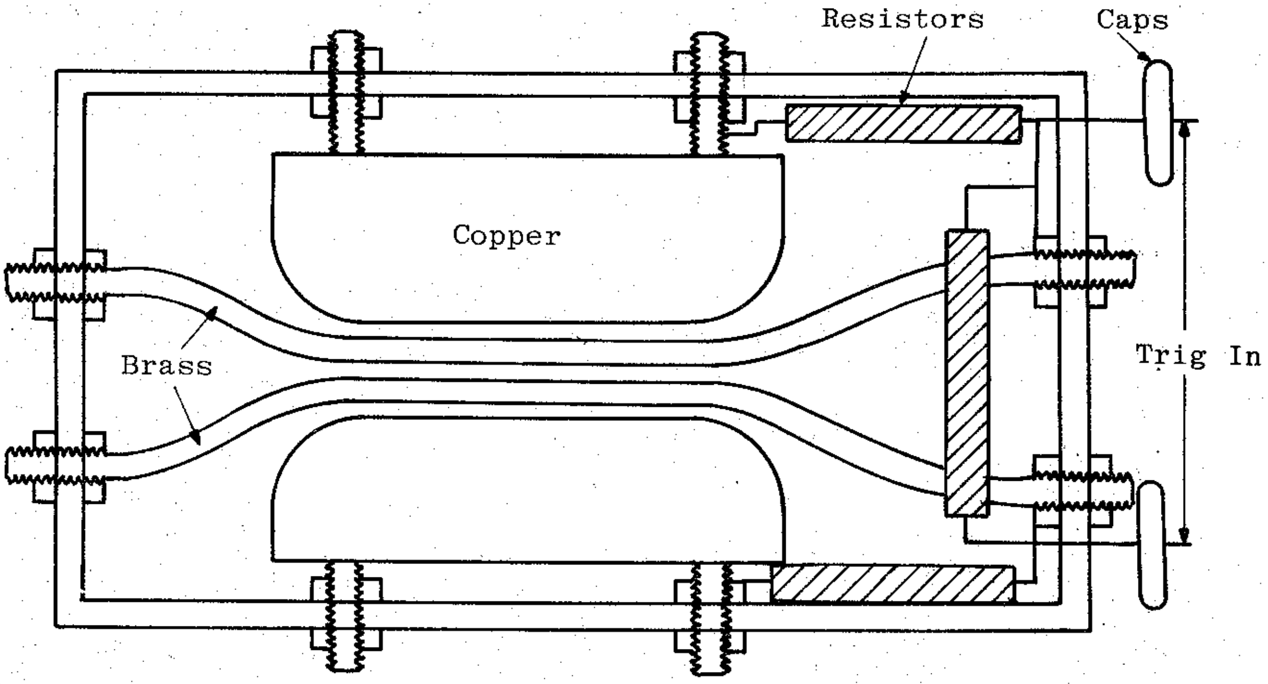
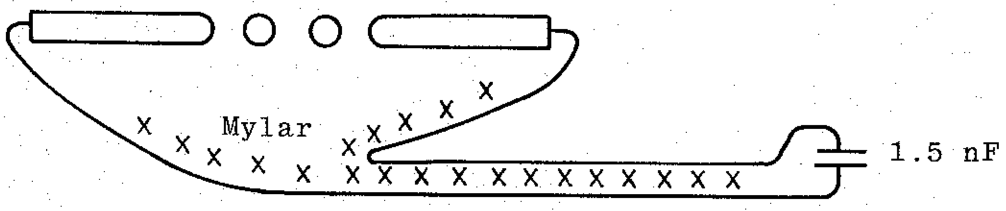


Figure 4.



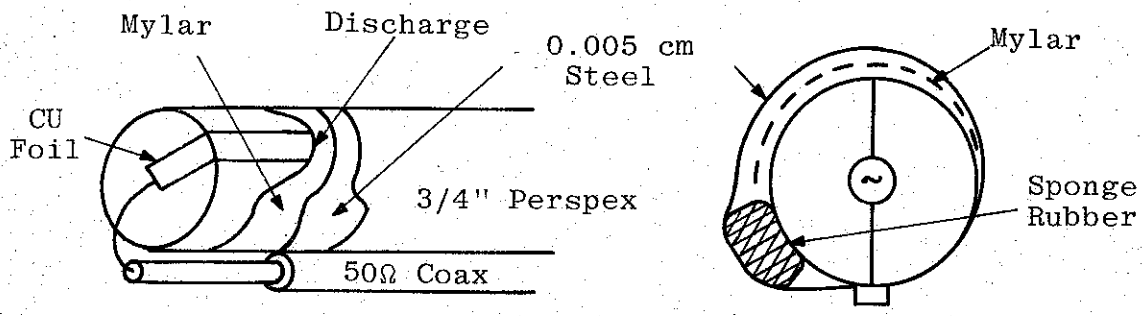
Plan View Appoximately Full Scale

Figure 5A



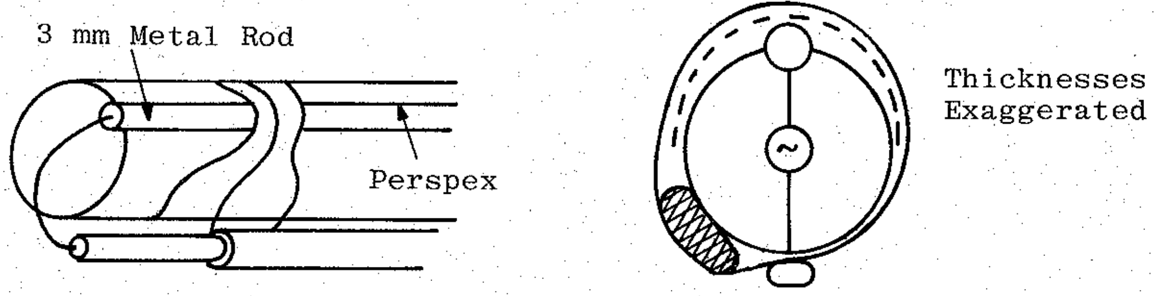
Cross Section of Gap

Figure 5B



First u.v. Irradiator

Figure 5C



Second u.v. Irradiator

Figure 5D

Figure 5.

Wide Operating Range Version 1,2,1/.45,1.2,.45/3,1,2

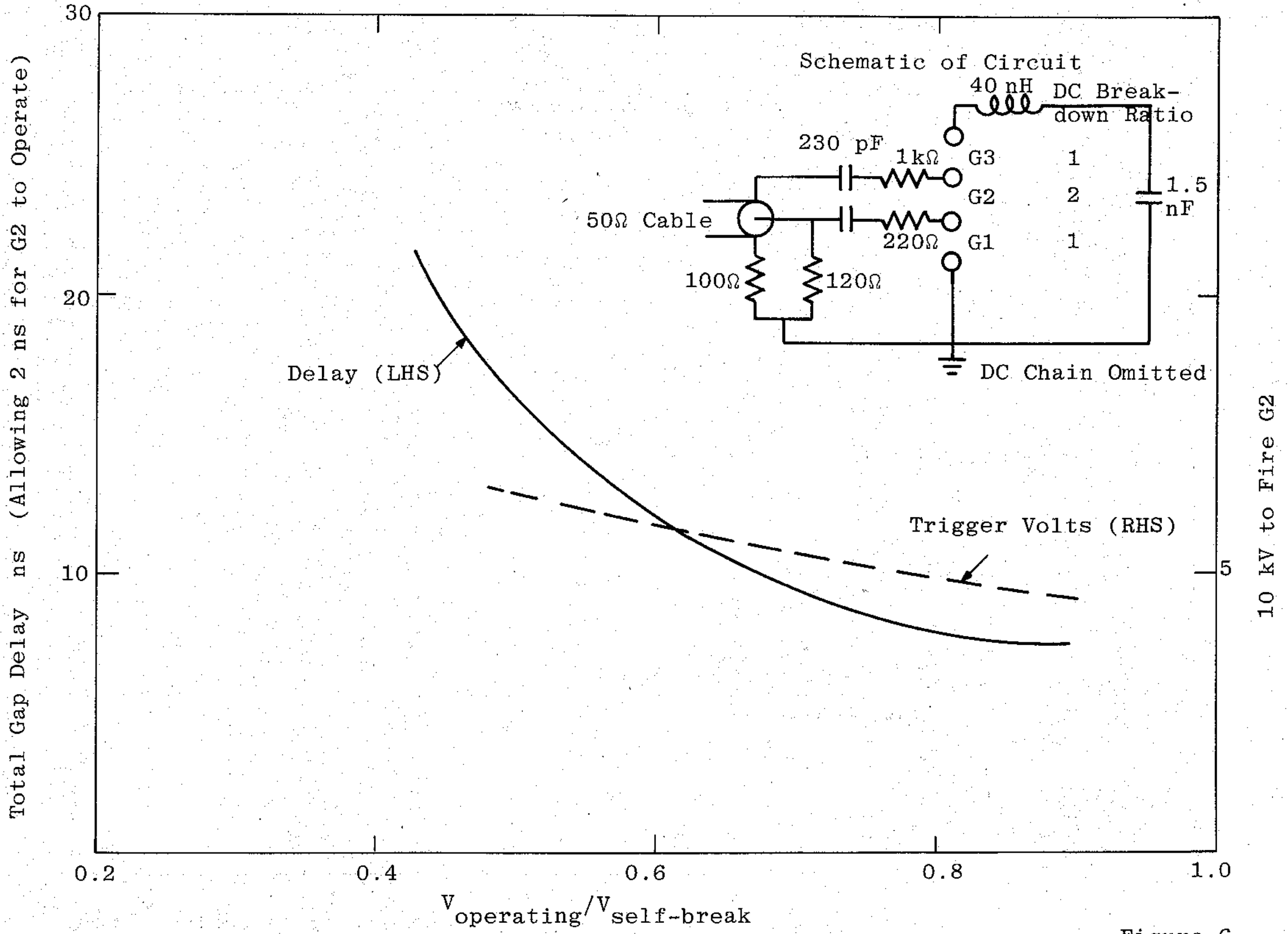


Figure 6.

Small Trigger Voltage Version 5,2,3/1.15,.35,.60/3,1,2

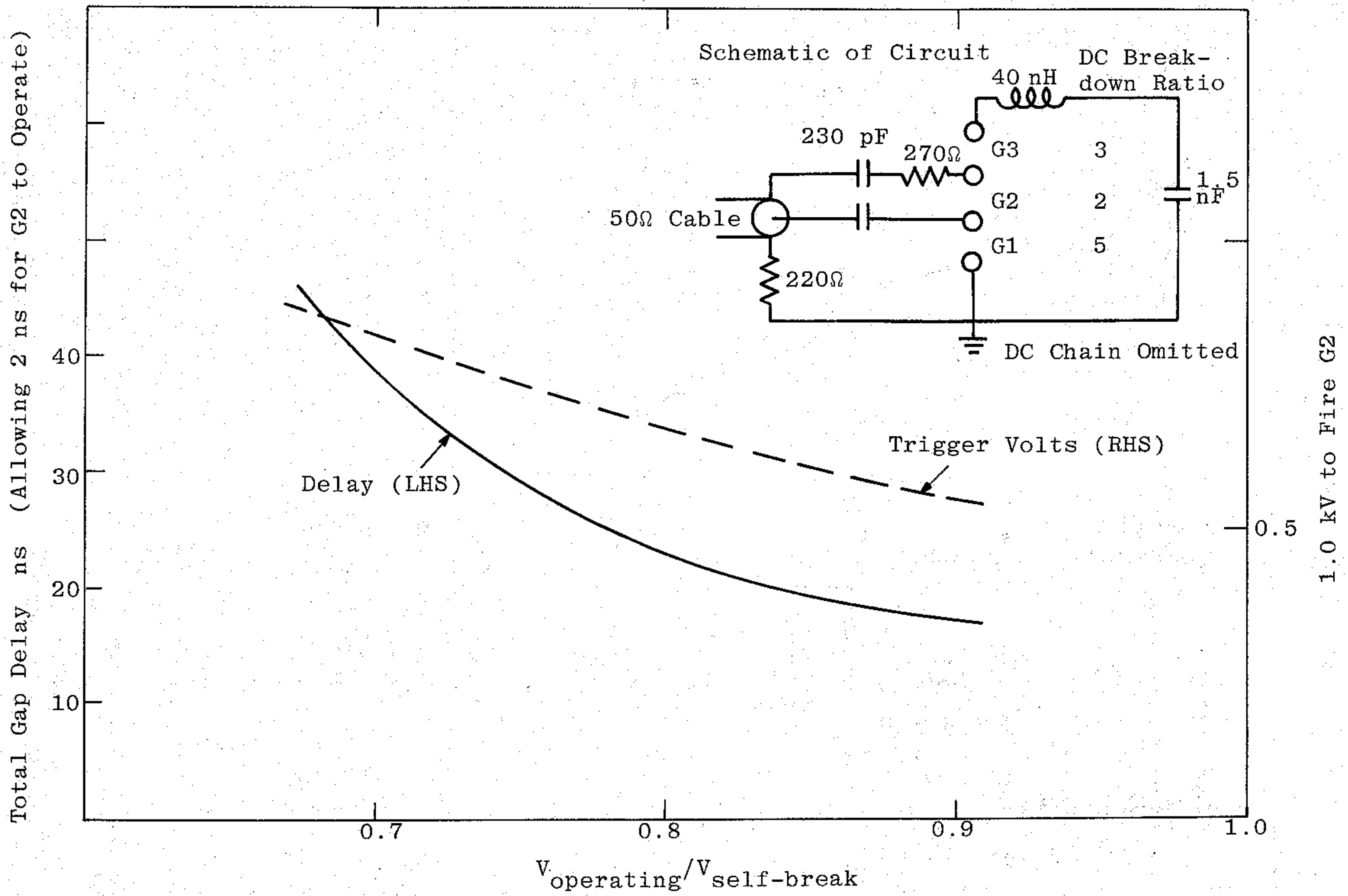


Figure 7.