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Since the first trigatron spark gap was described by J. D. Craggs, M. E. Haine, and J. M. Meek [J. Inst. Electr. Eng. **93A**, 963 (1946)], there has been controversy about the physical mechanism responsible for triggering the devices. In this letter we present experimental evidence that directly shows the sequence of physical events responsible for triggering in the gap we studied, and we present a model for trigatron triggering based on this information. We believe this model to be general and discuss it in light of existing literature. We briefly discuss the implications of the model for the engineering design of trigatron gaps.

The trigatron spark gap was invented in the early 1940's to serve as a switch in high-power modulators for radar,[1,2] and has found wide application as a high voltage, high current switch. A trigatron spark gap has three electrodes, two of which form the main gap. The third, the trigger pin, is located inside a hole in one of the main gap electrodes. In operation, a voltage less than the static main gap breakdown voltage, V_{SB}, is applied to the main gap and breakdown is triggered by the application of a voltage pulse to the trigger pin. There is disagreement about the physical mechanism responsible for triggering breakdown of the main gap. The most common view in the technical literature is that the breakdown of the main gap is initiated *after* the gap between the trigger pin and the adjacent main gap electrode breaks down, and is the result of the action of this spark.[1-9] Another viewpoint is that breakdown occurs as a result of the formation of a streamer in the distorted field around the trigger pin tip *before* the formation of the trigger spark.[10-15]

This long-standing controversy is due in part to the fact that both viewpoints are based mostly on indirect experimental evidence such as current and voltage traces which must be interpreted in terms of a specific model. In this letter we present recent experimental results which clearly and directly support the second viewpoint, and clarify the detailed succession of events occurring during the initial stages of triggered breakdown. We believe our conclusions to be general and to impact directly several design questions for trigatron spark gap switches as well as other types of triggered spark gap switches.

Figure 1 shows a schematic drawing of our experimental apparatus. A trigatron spark gap was placed inside a metal housing which could be evacuated and then back filled. Gap spacing was adjustable, but for most experiments was set at 2.5 cm, resulting in $V_{SB} = 62$ kV for a 700 Torr N_2 fill. The gap was designed to appear as a 50 Ω constant impedance transmission line. Voltage was supplied to the gap by a d.c.-charged, 50 Ω, 20 ns coaxial cable, and the gap discharged into a matched load. The trigger generator consisted of an 800 ns, 50 Ω, d.c.-charged coaxial cable switched by a laser-triggered spark gap. The rise time of the trigger pulse at the trigger pin tip was 10–20 ns. Capacitive voltage probes with ≈2 ns rise time monitored trigger pin and main gap voltages. A low inductance current viewing resistor in the load provided a monitor of load current. Optical events in the gap were recorded with a high sensitivity streak camera and a locally constructed two-dimensional shutter camera capable of about 5 ns temporal resolution.

Figure 2 shows a typical two-dimensional shutter photograph of streamers in the trigatron gap obtained under conditions listed in the caption. Figure 3 shows a typical streak photograph obtained under the same conditions, along with the gap current for the same shot. The photos show very clearly a luminous front crossing the gap. This front was the first optical event observed in the main gap, and is certainly a record of the passage of a streamer. Several streamers are launched from the trigger pin, each with a diameter of about 2 mm, and propagate with a speed varying between about 10^8 and more than 10^9 cm/s. In almost all cases, however, the arc forms from only one of these streamer channels. The intensity of the emission from these fronts is very weak. Much more intense emission is observed later as the streamer channel heats and the arc starts to form.

Except for the arrival of the trigger pulse, current associated with this front is the first electrical event observable in the main gap. Starting within a few ns of the time the streamer appears at the trigger pin tip on the streak photo, the gap current starts to rise. This current is the result of the motion of free electrons in the streamer tip, ahead of the streamer (produced by photoionization or photoemission), and inside the streamer body. The plasma of the streamer tends to shield the streamer interior from the external field, but is only partially successful because of the rapidly changing conditions produced by the propagating streamer tip. The gap current rises primarily because the number of free electrons inside the streamer body increases as the streamer channel lengthens. As the streamer nears the distant electrode, shielding of the interior becomes increasingly difficult because the external circuit maintains a constant potential

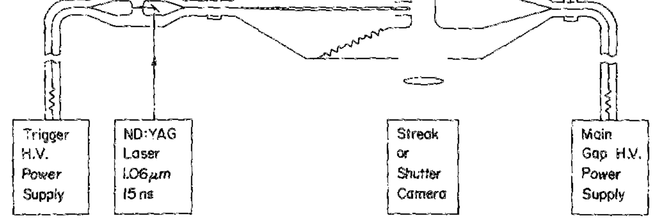

FIG. 1. Schematic diagram of the experimental setup.

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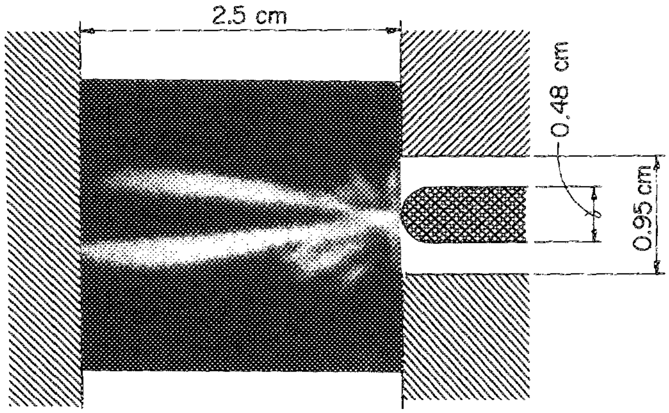

FIG. 2. Two-dimensional shutter photograph showing streamers in the gap. The conditions were −60 kV charging voltage, +10 kV trigger voltage, and 700 Torr N_2 fill. The shutter was open for ≈5 ns, and closed at a time roughly corresponding to 10 ns on the current trace in Fig. 3. Arc formation and gap closure occurred 20–30 ns later.

drop between the trigger and main gap electrodes. Some of the current increase may, therefore, also be due to a decrease in shielding efficiency.

In most cases, the gap current jumped simultaneously (±1 ns) with the streamer arriving at the opposite main gap electrode. When the streamer contacts this electrode, the requirement of constant potential drop is inconsistent with significant shielding of the main streamer body, and the field inside the streamer must rise.[17] This effect is seen in the electrical diagnostic as this current jump, and in the optical

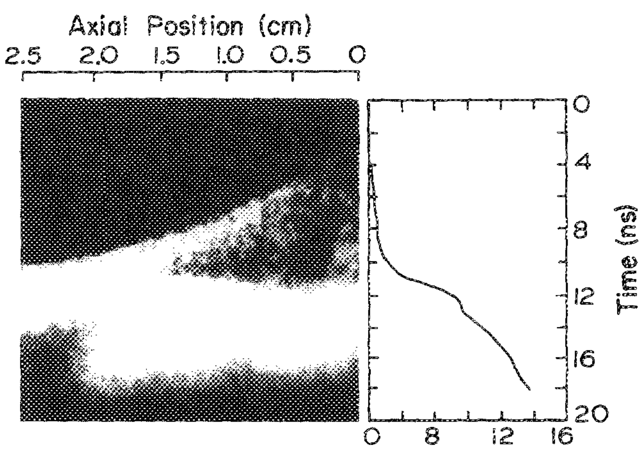

FIG. 3. Streak photograph and corresponding current trace associated with a streamer propagating across the gap. Conditions were the same as in Fig. 2. The streak camera viewed a 1.2-mm-wide slit containing the gap axis. The current trace was obtained by measuring the voltage at V_{GAP} in Fig. 1, and is nearly independent of the trigger gap current before main gap breakdown. The synchronization of the time scales of the streak photo and the current trace is accurate to within 1 ns.

diagnostic as a sudden increase in luminosity. Neglecting any voltage drop across the electrode-plasma interfaces, we estimate the resistance of the streamer channel at this time to be somewhat larger than 6 kΩ, and the average free-electron density in the streamer channel to lie in the range 10^{14}–10^{15} cm^{-3}, in good agreement with theoretical expectation.[18]

The experimental results we have obtained show that triggered breakdown of our trigatron spark gap occurs through the following sequence of events. Upon arrival of the trigger pulse at the trigger pin streamers form after a short delay and propagate across the gap. One or more streamer channels then connect the trigger pin to the opposite main gap electrode through a high resistance (≈10 kΩ), and the switch is still open. The applied field causes the ionization density in these streamer channels to rise, decreasing this resistance. Concurrently, as seen in two-dimensional shutter photographs not shown here, the gap between the trigger pin and the adjacent main gap electrode also undergoes a streamer/channel-heating breakdown process. The detailed sequence of events beyond this point is complex, depending on the relative timing of these two breakdown processes, the source resistance and pulse length of the trigger generator, and the main gap charging voltage. In most cases the final result is two thermalized arcs connecting the trigger pin to the opposite main gap electrode and the adjacent electrode, but other final configurations are probably possible, and control of this stage provides the engineer with an opportunity to optimize gap performance.

Physically, the breakdown is a two-step process. First, one or more streamers form and propagate across the main gap. Second, the resulting ionization density, driven by the applied field, increases until the arc channel forms and the switch is closed. The enhanced field at the trigger pin tip is needed only to launch the streamer. Once the streamer has bridged some fraction of the gap, the presence of voltage on the pin may aid the breakdown process, but it is not needed for breakdown to occur.

These conclusions have important implications for the design of trigatrons, and the question of the generality of our observations naturally arises. We have performed similar experiments for N_2 fills between 250 and 900 Torr; synthetic air and H_2 fills at 700 Torr; trigger pin diameters between 0.08 and 0.5 cm; rounded, squared-off, and ring-shaped pin tips; pins flush with and recessed below the host electrode surface; charging voltages between ≈25 and 99% of static self-break voltage (15–62 kV for 700 Torr N_2); trigger pulse voltages between 5 and 25 kV; and both heteropolar charging configurations (+ trigger, − main gap, and vice versa). Except for very low charging voltages or very short trigger gaps, breakdown of the main gap was always initiated by a streamer launched from the trigger pin before breakdown of the trigger gap.

Shkuropat studied the dependence of gap current and voltage traces on the polarity configuration and trigger gap conditions in trigatrons, and concluded that breakdown is initiated by field distortion at the trigger pin tip.[11] He later presented photographic evidence showing several generations of luminous filaments in the gap before the breakdown of the main gap, and concluded that breakdown occurs in two stages.[13] Martin has described a phenomenological model for breakdown in high voltage gaps which he has applied to trigatrons, and concluded that breakdown consists of a sequence of events similar to those we report.[14] Very recent experimental results by Wells[16] also support our model.

Most other workers have attributed triggering to effects of the trigger spark that forms between the trigger pin and the adjacent main gap electrode.[1-9] The principal argument they use is based on excluding field distortion mechanisms, and implicitly assumes that breakdown is a single-step process. Since the main gap is often found to break down after the trigger gap, field distortion mechanisms are excluded by reasoning that when the trigger gap breaks down the trigger voltage collapses, removing the field distortion, and terminating the main gap breakdown process if it has not already been completed. The breakdown mechanism we suggest is a two-step process, and such arguments cannot be used to exclude it. We therefore believe the model to be consistent with most published experimental results on trigatrons.

The results we present here have several implications for the design of trigatrons. For example, high fields near the trigger pin tip are probably needed to reduce delay and jitter in the formative time of the streamer, but the trigger gap must be designed so that it does not break down at least until the streamer is well on its way. The deleterious effects of too short a trigger gap or too high a trigger voltage have been reported by several authors.[11,13,14,16,19] Further, through careful choice of voltage waveform on the trigger pin, it may be possible to encourage the main arc to form directly between main gap electrodes, rather than through the trigger pin tip as an intermediary. Our results also clarify some of the issues involved in operating trigatrons at charging voltages well below V_{SB}. More work is needed to understand better the streamer formation process and the channel heating processes as they apply to triggered breakdown.

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