NRL Memorandum Report 1831

Multichannel Switching for High Power Discharges

IHOR M. VITKOVITSKY

Plasma Physics Branch
Plasma Physics Division

October 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

SEE INSIDE OF FRONT COVER FOR DISTRIBUTION RESTRICTIONS

ABSTRACT

Preliminary experiment to establish the feasibility of multichannel switching by overvoltaging water dielectric is described. It is shown that under the conditions of the experiment, the dominating factor in determining multichannel operation is the inherent scatter of the water breakdown strength. Up to three channels have been switched with jitter time between channels of less than 2×10^{-7} sec when operating voltage of 250 kV was used.

PROBLEM STATUS

This is a preliminary report.

AUTHORIZATION

NRL Problem H02-26A
Project DASA 08.0132

Manuscript submitted October 1967

The work reported on in this memorandum was funded by the Defense Atomic Support Agency

MULTICHANNEL SWITCHING FOR HIGH POWER DISCHARGES

Development of high power electrical pulse technology has been spurred by a wide range of applications, such as radar, light sources, and accelerators. More recently, laser developments (1) and plasma heating experiments (2) attempt to exploit newly available electrical energy storage systems capable of delivering submicrosecond pulses at 10^{11} watt levels. These pulsers work at relatively high voltage (100 to 500 kV range) and utilize breakdown of solid insulators to achieve high power levels. Such switching, requiring 10^{12} V/sec trigger pulses is not convenient for frequent pulsing, for repetitive pulsing, or in systems which store the energy in liquid dielectrics; however, its very low inductance, low energy dissipation and ability to determine spatial current distributions in the discharge are important advantages. Work on development of switches free of the above disadvantages has been initiated at U. S. Naval Research Laboratory. It is based on the data of J.C. Martin (3) and co-workers at Atomic Weapons Research Establishment at Aldermaston, U.K. It indicates that controlled multichannel breakdown in water is possible. A switch based on this mechanism will considerably alleviate the abovementioned disadvantages.

The purpose of this note is to review briefly the laws of electrical breakdown of liquids, indicate the design criteria for multi-channel switches and summarize the preliminary results obtained in operation of such multichannel switching.

Fig. 1 reproduces data from ref. (3) indicating a generalized breakdown curve for water as function of the electrode area (defined as that area over which field strength is 90% or more of the maximum). It has been generalized for: (1) all electrode shapes (by introducing a factor* α which accounts for the departure of the electric field strength F_{max} on the electrode surface from the mean field F_{mean} between the electrodes) and (2) any monotonically rising pulse shape of duration**, t_{eff}, (defined as the time during which the voltage applied to the electrodes is 63% or more of the breakdown voltage). It is seen that a polarity effect exists, permitting higher stressing of negative electrodes, the advantage of which is indicated below.

Once the breakdown occurs, then the time required for the switch to close is the time taken for the breakdown channel to lower its impedance below the effective impedance, Z_o (ohms), of the generator supplying the gap voltage.

This spark impedance has both a resistive and an inductive component. J.C. Martin (3) has found that for a variety of conditions the duration of the resistive phase in solids and liquids can be represented by the relation

$$t_R = \frac{5}{Z_o^{1/3}\ F^{4/3}} \text{ (nsec)} \qquad (1)$$

* Factor α does not exceed a value of 1.2 for most electrode configurations.

** The test pulse duration used in establishing curves of Fig. 1 has not exceeded 10^{-6} sec.

where F (MV/cm) is the maximum interelectrode field. The duration of the inductive phase of the voltage drop is determined from the switch inductance, L (nH), to be

$$t_L = \frac{L}{Z_0} \quad \text{(nsec)} \qquad (2)$$

For voltages of the order of a megavolt and fields of the order of a megavolt/cm, $t_R \approx 5/Z_0^{1/3}$ and $t_L \approx 10/Z_0$. If the switching is accomplished by multiple spark channels the effective impedance presented to each channel is proportional to the number of channels.

As this number increases, t_L decreases linearly, whereas t_R is reduced by the cube root of the number of channels. Thus for generator impedances less than three ohms, the switching time can be profitably reduced by parallel switching. In any instance it is seen to be advantageous to work at high field strength to achieve fast closing. Therefore, the asymmetric breakdown indicated in Fig. 1 is exploited by making the negative electrode have small area to maintain high voltage strength and have small radius of curvature to achieve large F_{max}. This is somewhat inconsistent with the low inductance requirement and a compromise must be determined for a given switch.

A typical configuration of a three-channel switch is shown schematically in Fig. 2 along with three time integrated photographs of its operation. This switch has the initial breakdown at the negative electrode. This is achieved by approximately tripling the field strength at the negative electrode relative to the mean field strength. This requirement is consistent, according to Eq. (1), with the requirement for fast closing. The switch configuration is based on the following criteria:

1. Flat plates of the switch must have sufficiently large separation, a + b, to prevent initiation of breakdown from the positive electrode. The breakdown strength is a function of the plate area and is given in Fig. 1.

2. The gap separation, a, is determined by the enhanced field at the negative electrode due to its small radius of curvature and by the area over which the stress is 90% of the maximum.

3. Radius of curvature must provide sufficiently large enhancement of the field, so that negative breakdown occurs first.

This switch was operated near 250 kV with gap spacings of 0.50 cm and 0.61 cm (measured within 5%). The peak voltage varied from 185 kV to 255 kV and t_{eff} varied from 200 nsec to 850 nsec due to the wide variation of the breakdown point of the switch in the primary circuit of the pulse charging transformer. Of 23 tests only in 3 cases did all three channels not establish some conducting path.

Fig. 2 (first frame) shows a closing of two of the gaps while a streamer (bright channel that does not completely span the electrode gap) is seen to start on the middle one. The start of a streamer at the negative electrode is a check on the correct choice of electrode curvature and electrode spacing.

The streamer mechanism, its propagation velocity and length depend on the applied fields. Their duration has been studied by J.C. Martin (3). The appearance of such streamers indicates that very high fields may exist at the sharp streamer end. Measurement of the streamer brightness, related very insensitively by the Stefan-Boltzman law to streamer temperature indicates that Spitzer conductivity is sufficiently high to be neglected in the estimate of the fields. Taking a radius of curvature of 0.03 cm, the field strength is of the order of 10^9 V/m. The corresponding streamer electrode area is about 3×10^{-3} cm^2 which according to the data of Fig. 1 should support breakdown at much lower field values. Thus, it is construed that multichannel closing such as that seen in the first two frames of Fig. 2 corresponds to main current flow in the brightest channel. Late, lower amplitude voltage oscillations tend to close the remaining channels.

To study the difference between channels of different brightness a streak camera was used to observe the time of initiation of luminescence of the channels. Fig. 3 shows four examples of the performance of a four-channel switch operating at near 250 kV. Both time integrated and streak photographs are shown. The number 4 test shows simultaneous closing (within 10 ns resolving time) of the two adjacent channels. It should be noted that the time-integrated brightness is the same in both channels. Two tests (1 and 2) in Fig. 3 show that a second channel closing may occur as late as 150 ns after the first channel has closed and started to conduct. The amount of energy carried by the second channel is small; as indicated by its luminosity. The third test also shows that streamer seen in one of the channels starts late (~100 ns) after first channel closing. The time delay between channel closings approximates the half period of the discharge. This indicates that channel breakdown occurs as a result of reversal (wrong polarity on field enhanced electrode) or initial streamer is driven to breakdown.

The representative data in Fig. 3 shows, that while all three channels can be made to close, the jitter time is given by the voltage reversal in the discharge. The simultaneous switching has been demonstrated, but it has not been possible to determine experimentally, in the preliminary work reported here, what parameters must be controlled to achieve this. The demonstration of simultaneous closing of channels without triggering and the data on the behaviour of breakdown of water (Fig. 1) provides further indication of the requirements for the simultaneous switch closing. If it is taken that the information of channel closing (i.e. vanishing of the voltage difference immediately across the electrodes) propagates to the next channel (distance ℓ away) in time

$$T = \frac{2C}{\sqrt{\epsilon \ell}} , \qquad (3)$$

(ϵ = dielectric constant of water, C = velocity of light) then the voltage difference across neighboring gap will vanish in time $T+T_R+T_L$. Here T_R+T_L represents the switch closing time. Assuming, initially, no deviations of breakdown strength from the curve of Fig. 1, the only cause for preferential closing of a given channel would be the increased electric field on the channel whose electrode are spaced more closely. The inaccuracy in spacing that can be tolerated is therefore governed by the data of Fig. 1, i.e.

$$F^-_{max} = k\ t^{-1/3}, \quad k = \text{constant}. \tag{4}$$

It follows that

$$\frac{dF^-_{max}}{dt} = -\frac{1}{3}\ t^{-1}\ F^-_{max} \tag{5}$$

If dt represents the time $T+T_R+T_L$ and t is the effective time, t_{eff}, then permissible variation, δ, in electrode spacing is

$$\delta = \left| \frac{dF^-_{max}}{F^-_{max}} \right| = \frac{1}{3} \cdot t^{-1}_{eff} \cdot (T+T_R+T_L). \tag{6}$$

In the experiments described here (where the switch was driven by 2.2 ohm line) the computed value of δ was about 1% ($t_{eff} \cong 500$ ns $T_R \cong 2.5$ ns/channel*, $T_L \cong 1.0$ ns/channel*, $T \cong 6$ ns), while electrode spacing was held to within 5%.

*T_R is estimated from Eq. 1, T_L is estimated by assuming channel diameter of 10^{-2} cm. (See J. C. Martin work, Ref. 3).

It must also be assumed that scattering in breakdown data will influence the channel closing simultaneity. This imposes risetime requirement on the voltage applied to the gap, since the spread in breakdown voltage ΔV must be spanned in time shorter than the signal propagation time between channels, $T+T_R+T_L$. If dV/dt represents the voltage rise across the switch, then

$$\frac{dV}{dt} \geq \frac{\Delta V}{T+T_R+T_L} \quad . \qquad (7)$$

Since no preference for a given gap closing has been observed, the statistics of simultaneous breakdown in the experiment described here is then dominated by the intrinsic value of the scatter in the breakdown voltage. Indeed the observed mean value ΔV of 9% indicates that $\frac{dV}{dt}$ is too small to satisfy the inequality (7).

Ref. 3 indicates that somewhat lower deviation of 7% was observed in data plotted in Fig. 1 (significantly better than 12% deviation found for oil and polyethelene). It is therefore expected that 1 MV pulser with 3×10^{12} V/sec charging rate will be sufficient for simultaneous switching of channels 20 cm apart in a switch with main plates separation (a + b of Fig. 2) being 2.5 cm if 50 ohm/channel generators is used.

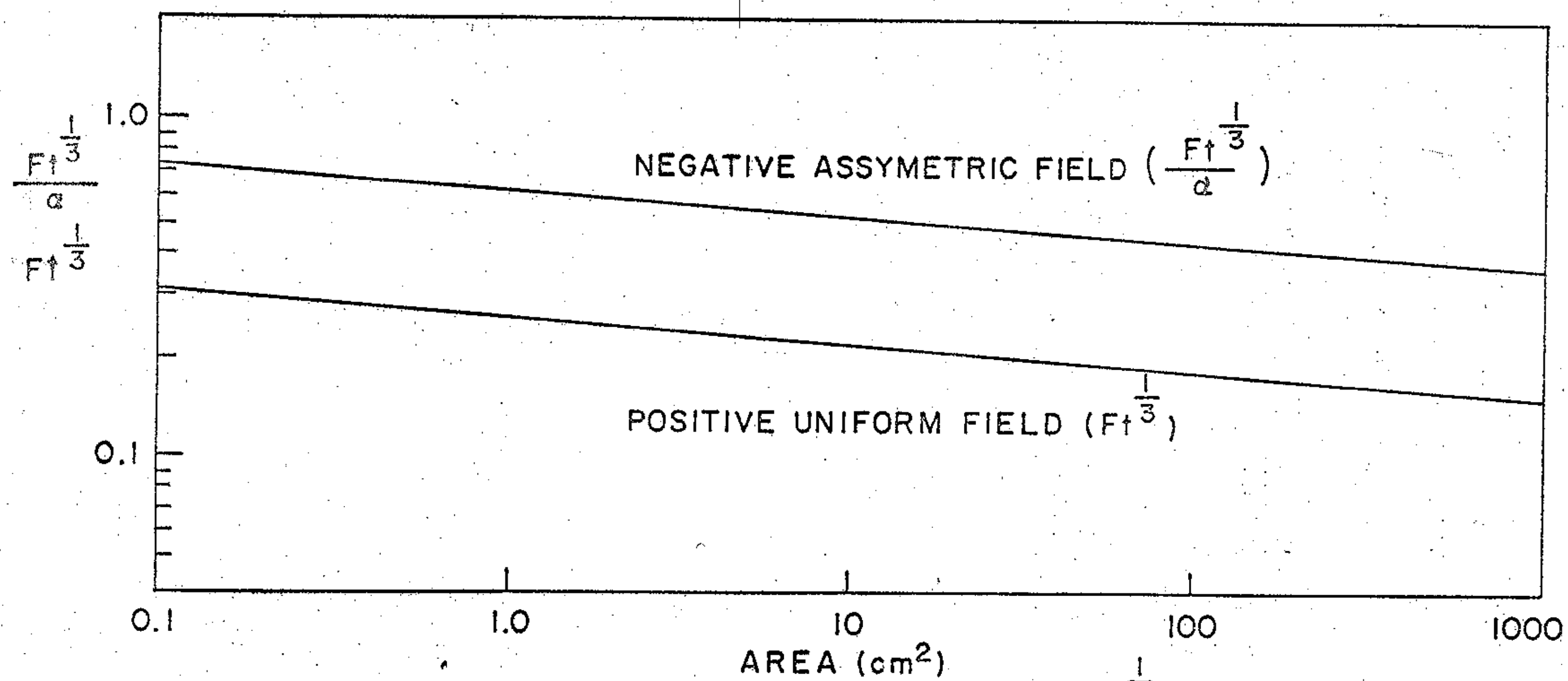
Further work on effective parallel closing of switches therefore must await the construction of pulser that will have shorter t_{eff} (about 100 ns) and will operate at 1 MV, requiring larger gap length, and permitting better control of δ.

REFERENCES

1. J. D. Shipman, Jr. Appl. Phys. Lett. 10, 1 Jan, 1967

2. I. M. Vitkovitsky, 4th Symposium on Engineering Problems in Thermonuclear Research, Rome, 1966.

3. J. C. Martin, Cornell University Seminar on High Voltage Technology, November, 1966.



$$\frac{Ft^{\frac{1}{3}}}{\alpha} = \text{CONSTANT}$$

$$\alpha = 1 + 0.12\left(\frac{F_{MAX}}{F_{MEAN}} - 1\right)^{\frac{1}{2}}$$

Figure 1 - Impulse breakdown of water

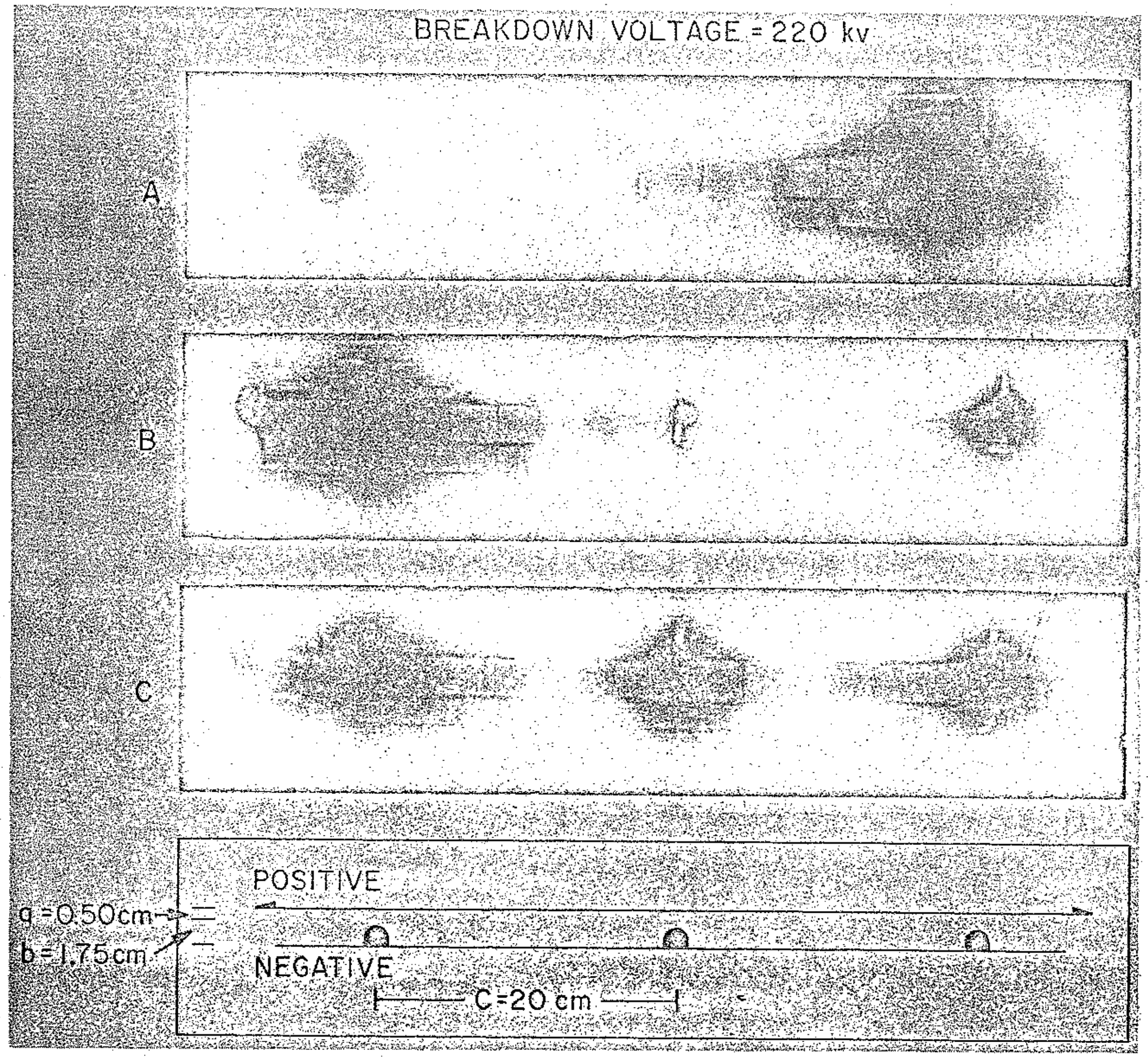


Fig. 2 - Time exposure photographs of the switch channel closing

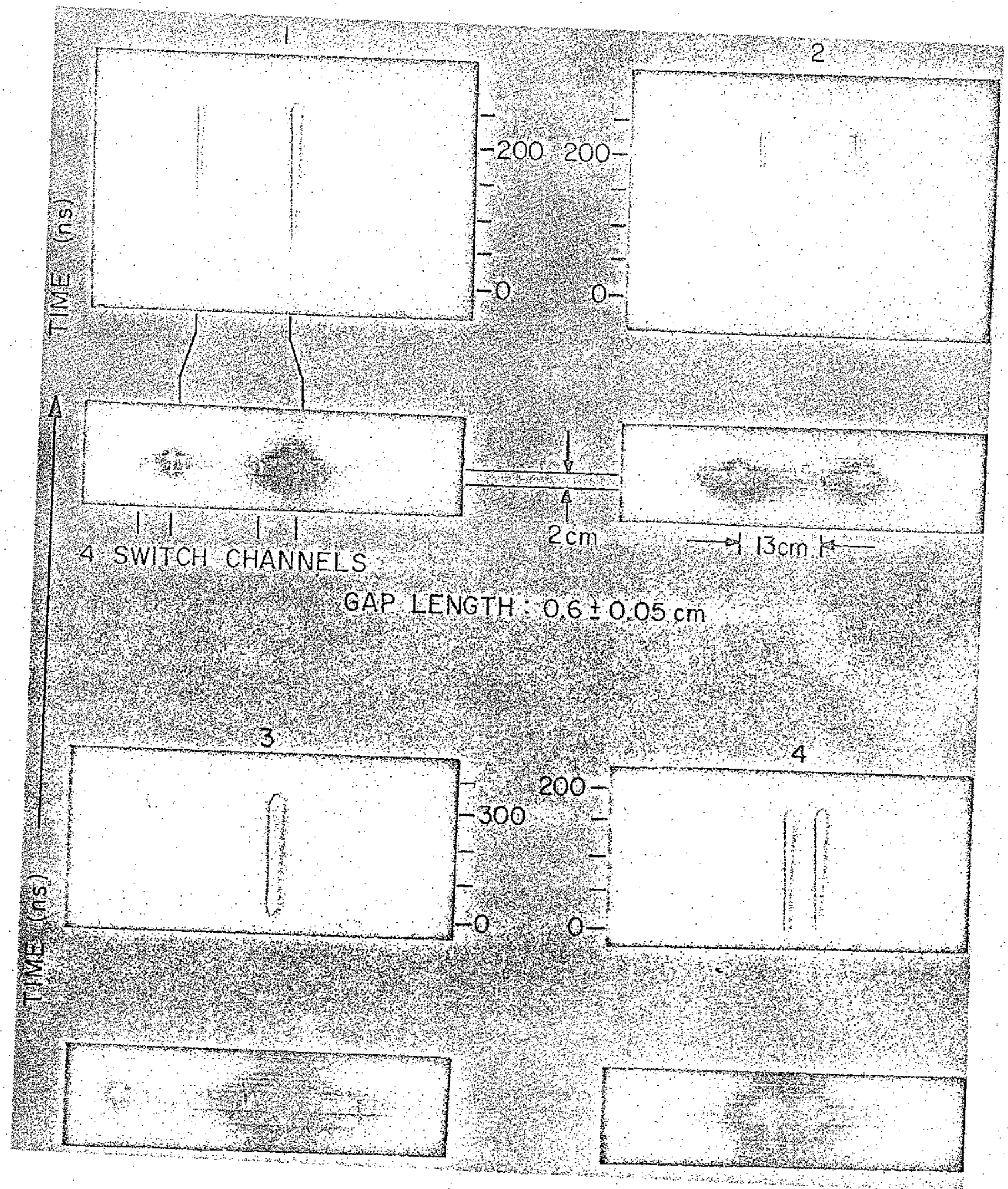


Fig. 3 - Streak and time exposure photographs of switch channel closing