Conf-750335--1

UNTRIGGERED WATER SWITCHING*

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ABSTRACT

MASTER

Short Pulse Relativistic Electron Beam Accelerators Based on Untriggered Water Switching, J. PACE VAN DEVENDER, and T. H. MARTIN, *Sandia Laboratories*. --Recent experiments indicate that synchronous untriggered multichannel switching in water will permit the development of relatively simple, ultra-low impedance, short pulse, relativistic electron beam (REB) accelerators. These experiments resulted in the delivery of a 1.5 MV, 0.75 MA, 15 ns pulse into a two-ohm line with a current risetime of 2×10^{14} A/sec. The apparatus consisted of a 3 MV Marx generator and a series of three 112 cm wide strip water lines separated by two edge-plane water-gap switches. The Marx generator charged the first line in less than 400 ns. The first switch then formed five or more channels. The second line was charged in 60 ns and broke down with 10 to 25 channels at a mean field of 1.6 MV/cm. The closure time of each spark channel along both switches was measured with a streak camera and showed low jitter. The resulting fast pulse line construction is simpler and should provide considerable costs savings from previous designs. Multiples of these low impedance lines in parallel can be employed to obtain power levels in the 10^{14} W range for REB fusion studies.[1]

*Work supported by the U.S. Atomic Energy Commission.

[1] G. Yonas, et al., Nuc. Fusion, 14, No. 5 (1974).

INTRODUCTION

High current electron beams capable of delivering 10^{13} to 10^{14} W for 10 to 20 nsec will be required to investigate the feasibility of thermonuclear fusion of pellets with intense electron beams.[1] The pulsed power technology required to produce these beams efficiently involves switching of low impedance lines with very small inductive and resistive risetimes, τ_L and τ_r. These parameters are given by J.C. Martin[2] as:

$$\tau_L = L/NZ \qquad (1)$$

$$\tau_r = \frac{5}{N^{1/3}Z^{1/3}E^{4/3}}$$

in nanoseconds with L the inductance per switch channel in nanohenries, N the number of channels, Z the impedance of the line feeding the switch, and E the mean electric field in the switch in megavolts/cm. In the past, the switching problem has been alleviated by switching a high impedance pulse forming line and then transforming the pulse down to a low impedance output.[3,4] An alternative scheme is to use multichannel switching to obtain N channels across the switch. The number of channels N is given by the semi-empirical relation[2]

$$2\sigma \frac{V_{BD}}{dV/dt_{BD}} \approx 0.1\tau_{tot} + 0.8\tau_{trans} \qquad (2)$$

where σ is the fractional standard deviation of breakdown voltage V_{BD} on the switch, dV/dt is the voltage charging rate evaluated at the time the switch breaks, τ_{tot} is the total risetime of the current, and approximately equals

$\tau_R + \tau_L$, and τ_{trans} is the transit time between channels given by $\frac{\ell\sqrt{\epsilon_r}}{Nc}$ for a switch of width ℓ in a dielectric with relative dielectric constant ϵ_r. The speed of light in vacuum is c.

A favorable dielectric for high power lines is water because of the large energy density and the slow wave velocity which results in very compact low impedance systems. Multichannel switching in water has the disadvantage that the electric field breakdown strength E_{BD} is less than that in oil, another good dielectric, for typical charging times of 300 nsec to 2 μsec. This fact causes the duration of the resistive phase in Eq. 1 to be longer in water than in oil. Experiments were reported[4] on the characteristics of water breakdown with a three channel, water-switch which gave a σ of 3 to 10% for a 100 nsec charge time (depending on the field enhancement at the positive electrode), and a 25% improvement in the relatively slow risetime (from 60 nsec to 45 nsec) of the output pulse as the number of channels was increased from 1 to 3 over a total switch circumference of 82 cm.

We report the results of a new experiment called RIPPLE which features self-breaking water switching of a 2 Ω transfer capacitor and of a 2 Ω pulse forming line. Charging voltages range up to 3 MV with charging times of 200 to 500 nsec and 40 to 60 nsec for the transfer capacitor and pulse forming line, respectively, on the 112 cm long switches.

Typically, five channels are obtained with charging times of 200 to 500 nsec on the first switch, and 10 to 20 channels are obtained on the second switch with the fast charging pulse. The value of σ in the second gap is measured with a streak camera to be 3 percent which reflects the intrinsic jitter in the breakdown and the effect of 10 nsec jitter in the gap feeding the pulse forming line.

The results show that the electric field in the gap is sufficiently large to reduce the τ_L on the current's risetime. Pulses of 1.5 MV, 0.75 MA, with a risetime of 3 nsec and a pulse width of 13 nsec have been achieved by this approach with an overall efficiency of 50 percent (output energy/Marx energy).

APPARATUS

A low impedance, 3 MV, 6.2 nF Marx generator charges a transfer capacitor in 200 to 500 nsec as shown in Fig. 1. The transfer capacitor is switched to a 2 Ω pulse forming line by a 112 cm long edge-plane switch in water. The Ripple lines evolved as a joint effort of the authors and R. S. Clark who provided the line design. The pulse forming line is charged in 40 to 80 nsec and is then switched into a 2 Ω output line through a second, 112 cm wide edge-plane water switch. The field enhancement factor of the edge is ~ 6. The output line is terminated in a load resistor which is transit time isolated from the output monitor during the experiment. The voltage waveforms on the line are monitored by resistive dividers located at the center of each line as shown in Fig. 1. The closure time for each streamer in each gap is monitored with a streak camera viewing space 1/8 to 1/4 of an inch in front of the small gap electrode. The recorded luminosity was time correlated with the rise of the current in the gap to within 1 nsec. The jitter in the closure times of the streamers in each gap and in the total jitter in the time between the Marx's erection and the output pulse is obtained from the streak records and the voltage waveforms. Time integrated photographs are also taken for comparison with the streak camera records.

RESULTS AND DISCUSSION

Sample output waveforms, streak records and open shutter photographs are shown in Fig. 2. This output pulse was 1.5 MV, 750 kA, with a 10-90% risetime of 3 nsec and a pulse width of 13 nsec. The energy in the output pulse was 13 kJ with 25 kJ initially in the Marx generator. The streak camera and the open shutter photograph showed that 15 channels carried significant current in the second gap and the average breakdown field was 0.8 MV/cm. The calculated values of τ_r and τ_L were 1.7 nsec and 0.4 nsec, respectively, from Eq. 1. The calculated 10-90% risetime is $\simeq 2.2\ (\tau_r) = 3.7$ nsec compared to 3 ± 0.5 nsec observed risetime.

The fast risetime of the pulse is thus related to the large values of E_{BD} and N that are obtainable in the second gap. A plot of E_{BD} vs t_{eff} is shown in Fig. 3, where E_{BD} = the voltage at breakdown divided by the gap spacing and t_{eff} is the time during which the gap voltage was above 63% of the breakdown voltage. Gap separations of 2.5 cm to 1.25 cm and 5.7 cm to 4.1 cm were used in the output and transfer gaps, respectively, and voltages of 1 to 2 MV were used for this data. It is evident that the negative edge can hold off up to twice the breakdown voltage of a positive edge. Although more channels were formed when the edge electrode was positive at the same breakdown voltage, a negatively charged edge gave a better switching performance because of the larger electric fields in the gap with a negative edge.

The superior performance of the gap with a negative edge when the resistive phase dominates the risetime means that the customary procedure of having the field enhancement on the positive electrode[4] should be changed.

Fig. 3 also contains the predicted curves of E_{BD} vs t_{eff} which were derived from the relationships for the average streamer velocity U given by J. C. Martin[5] for $V \leq 1$ MV as follows:

$$\begin{aligned} &\text{Negative Edge:} \quad U = \frac{d}{t_{eff}} = \frac{16\ V^{1.1}}{t_{eff}^{1/3}} \ \text{cm}/\mu\text{sec} \\ &\text{Positive Edge:} \quad U = \frac{d}{t} = \frac{8.8\ V^{0.6}}{t_{eff}^{1/2}} \ \text{cm}/\mu\text{sec} \end{aligned} \qquad (3)$$

for a gap separation d and effective time t_{eff} (the time during which the voltage on the gap is greater than 63% of the breakdown voltage V in megavolts).

These relations can be rearranged to give the breakdown voltage as a function of $t_{eff\ BD}$ as follows:

$$\begin{aligned} &\text{Negative Edge:} \quad E_{BD} = \frac{0.0625}{t_{eff}^{2/3} V^{0.1}} \ \text{MV/cm} \\ &\text{Positive Edge:} \quad E_{BD} = \frac{0.027 d^{0.667}}{t_{eff}^{0.83}} \ \text{MV/cm} \quad . \end{aligned} \qquad (4)$$

Since the data in the recent experiments was taken in the regime, $1 \text{ MV} < V \leq 2$ MV, the relations need not be valid in this regime. Nevertheless, the relations for streamers originating on the negative electrodes provide a reasonable fit to the data for $t_{eff} < 50$ nsec. For $t_{eff} > 50$ nsec, the breakdown field is approximately 60-80% more than predicted. The positive relations, on the other hand, provide a reasonable description of the data for $t_{eff} > 200$ nsec. For shorter times, the relations overestimates E_{BD} by as much as 100%. More appropriate, empirical formulas for the present data were found to be:

$$\text{Negative Edge:} \quad E_{BD} = \frac{0.13}{t_{eff}^{0.5}} \text{ MV/cm}$$

$$\text{Positive Edge:} \quad E_{BD} = \frac{0.11}{t_{eff}^{0.4}} \text{ MV/cm} \quad . \qquad (5)$$

The breakdown data of gaps is often presented in the form of average streamer velocity d/t_{eff} as a function of the gap voltage V, the pulse duration t_{eff}, and the gap separation d, as presented in Eq. 3. Such relations may be applied directly with the 63% criteria of t_{eff} or may be used in a differential form with a given voltage waveform. In the latter case the streamer is assumed to start at $t \approx 0$. The two approaches are equivalent for breakdown of a linearly rising voltage waveform in oil, with t_{eff} defined as time during which $V > 0.63\ V_{BD}$. There is no similar t_{eff} for which the two approaches are equivalent using Eq. 3 for water breakdown. The disagreement between the two treatments may be due to the fact that the streamer does not leave the edge electrode until $t \approx$ 75-80% of the breakdown time as shown in streak photographs in Fig. 4.

A detailed comparison of the streak camera data, the positions of backlighted streamers that did not close (from open shutter photographs), and the rise of the current in the gap indicates that the streamer luminosity closely correlates with the streamer's position as it crosses the gap. Consequently, the tip of the luminosity is considered the tip of the streamer as it crosses the gap. It is interesting to note that this correlation may not hold for streamers propagating in transformer oil since spectra taken of the light emitted from the streamers in water show that the light associated with the initial streamer formation is predominately of wavelength shorter than

4000 Å. This is the range of wavelengths that is very strongly absorbed in transformer oil and, hence, the light associated with the initial streamer in transformer oil may well be absorbed in the dielectric.

After the streamer leaves the edge electrode, it propagates across the gap with a velocity that increases with the applied voltage. The negative streamer remains at the edge electrode twice as long as the positive streamer for comparable waveforms $V = V_0 t/\tau_0$ and, therefore, holds off twice the voltage of the positive streamer. The negative streamer then crosses the gap at approximately 60% of the velocity of the positive streamer with the same driving voltage V. The velocities of the streamers were 90 cm/μsec and 140 cm/μsec at $V \approx 2$ MV and $d = 5.7$ cm for the negative and positive streamers, respectively. This compares to the average streamer velocity (the ratio of the gap separation to t_{eff}) of 32 and 58 cm/μsec for the negative and positive streamers, respectively. The long delay phase for both positive and negative streamers suggest that the breakdown field (the field at which the streamer propagates across the gap) may be relatively independent of the field enhancement at the edge electrode (and the field at which the streamer actually forms). Thus, one can have edge electrodes with sufficiently large field enhancement to give a small jitter in the streamer formation time and still maintain large breakdown fields in the gap. Consequently, one can improve the number of channels formed without increasing the resistive phase's risetime. Preliminary experiments support this hypothesis. Multiple point-plane gaps had breakdown fields approximately equal to those achieved with edge-plane gaps and the jitter in the channel closure was reduced by as much as 50%, as shown in Table II.

The number of channels that is formed in a gap is given by Eq. 2 which reduces to:

$$N = \frac{0.4L\ \varepsilon_r}{c\tau_0}\ \sigma \qquad (6)$$

for a linearly rising pulse $V = V_{BD}\ t/\tau_0$ and $\tau_{tot} << 8\ \tau_{trans}$, which was appropriate for the present experiments. The value of N is the number of channels that carry 45% or more of the current carried by the channel with a maximum current. This corresponds to those channels that close when approximately 85% or more of the maximum voltage is still on the gap.[2] It was not possible to monitor the current in each channel. In lieu of this information, the risetime of the current in the gap, the relative positions of the streamers and the relative closure times of the streamers were correlated with the brightness of the channels in open shutter photographs. It was found that: (1) when the voltage at the root of the streamer had fallen to 90% of its maximum value, the two streamers were equally bright; (2) when the voltage had fallen to 80% of its maximum value, there was a clearly observable difference between the two images. Consequently, only the streamers with brightness approximately equal to the brightest streamer were counted as an approximate value of N. This was normally about half of the total number of streamers that closed.

For charge times of 200 to 400 nsec (i.e. the data in the first gap) the value of σ obtained from Eq. 6 was 1.4% with no significant difference for positive or negative streamers. Consequently, the larger number of streamers obtained with a positive edge arises from the shorter charging time τ_0 for positive streamers and not from the intrinsic standard deviation of positive streamer breakdown.

The waveform on the second gap (i.e. the output gap with charge times of 40 to 80 nsec) was not a linearly rising pulse and the simple relation in Eq. 6 does not apply. In these pulses the dV/dt was nearly zero or even negative, so a value of σ was difficult to determine accurately. Using Eq. 6 to give an upper limit of σ, one finds σ is $\leq 3.0\%$ for both positive and negative streamers in the second gap. These values of σ given by Eq. 6 from N measured with open shutter photography can be compared to the σ of the closure times as measured with the streak cameras. Sample data is shown in Table I.

TABLE I

t_c	Time Integrated Data		Time Resolved Data		
	N	$\sigma_{eq.3}$	N_{tr}	$\sigma_{isolated}$	σ_{all}
220	6	1.0%	5	3.2%	3.9%
220	5	1.2%	3	0.4%	4.7%
220	6	1.2%	5	3.0%	4.8%
45 nsec	9	3.0%	6	6.2%	5.5%
50 nsec	8	3.0%	6	4.6%	5.0%

If the closure time of each of the streamers in the first gap is measured, the standard deviation σ_{all} is typically 3-5% (which corresponds to 6-10 nsec). If the same measurement is made of all independent streamers (i.e., streamers which are transit time isolated from each other), the fractional standard deviation $\sigma_{isolated}$ of the isolated streamers is less than σ_{all}. However, $\sigma_{isolated}$ is approximately two to three times the value given by Eq. 6 although the value of N measured with Equations 2 and 3 assume that all channels that close within a time interval of 2σ V/dv/dt contribute to N, while the present experiment indicates that only those that close within $\sigma\tau_0$ contribute to N and determine the switch risetime.

A similar treatment of the streamers in the second gap gives σ_{all} as typically 5% (3 nsec for a 50 nsec charge time). The appropriate $\sigma_{isolated}$ for independent streamers is still $\sim$ 5%. A detailed analysis of the closure time of the streamers shows that the variation in closure time along the first gap is reflected in the closure time along the second gap.

If a single streamer closes in the first gap, a wave is launched into the second line. The voltage begins to rise at a point on the second gap when the wave front reaches a point on the gap. For the present experiment, with a single channel in the center of the first gap, the wavefront reaches the center of the second gap after 20 nsec. Thus, if a channel in the first gap closed with zero jitter when the voltage reached a value V_0 locally, the measured jitter in the second gap would by $\sim \frac{10 \text{ nsec}}{2} \cong 5$ nsec. When the jitter in the first gap is comparable to the difference in transit times to points along the second gap from the channels in the first gap, the effect is still present but is ameliorated by the addition of many wafefronts. When N = 5 and the jitter in the first gap is 10 nsec, the jitter in the second gap is 3 nsec. This jitter is the resultant of the intrinsic jitter plus the ameliorated effect of the jitter in the first gap.

For large accelerators many lines would be fired simultaneously. For this scheme to be practical, the total jitter between the Marx's erection and the closure of the second gap must be much less than the desired 20 pulse length. The charge time of the transfer capacitor was varied by adding an inductor between the Marx and the capacitor and the total time between Marx's erection, and the output pulse was measured for 5 to 7 shots for each charge time. (The jitter in TRW and streak was < 0.5 nsec.)

TABLE II

Charge Time nsec	V_{output}	σ_{ns}	Gap #1
260	1.0 MV	10	edge/plane
380	1.4 MV	18	"
430	0.7 MV	21	"
500	1.0 MV	20	"
400	0.8 MV	10	6 point/plane

Apparently the jitter for a slow charge time with edge-plane gaps increases suddenly when the charge time is more than 300 nsec. Nevertheless, even for a charge time of 260 nsec, the overall jitter was too large to allow the unsynchronized operation of many units to form a 20 nsec pulse. Therefore, either the first gap will have to be triggered or the transfer capacitor must be charged in ~ 100 nsec.

CONCLUSION

We have examined multichannel switching in water and found that the standard deviation in breakdown time is 2-3% of the charging time for a linearly rising voltage waveform. The generally used relation for calculating the number of channels N should be modified to reflect that only streamers that close within σ_{τ_0} of each other carry significant current. The value of N so obtained can be measured equally well with open shutter photography or streak photography. For $N > 3$ on a 112 cm long edge-plane gap, the rise-time of the current is adequately described by the usual relation of Eq. 1. The closure of the luminosity of the streamer corresponds to the beginning of the current rise in the gap. When the knife edge electrode is negatively charged, the breakdown fields for 1 MV $<$ V $<$ 2 MV are adequately described by the empirical relation based on data for V $<$ 1 MV for short charging time. When the knife electrode is charged positively, the corresponding relation overestimates the breakdown voltage by as much as 100 percent. Alternative empirical relations are presented.

Preliminary results indicate that the breakdown electric field is a weak function of the field enhancement at the knife electrode while the jitter and the number of switch channels formed is a strong function of the field enhancement. In general, better switching performance is obtained with a knife edge electrode charged negatively.

Current risetimes of dI/dt in excess of 2 x 10^{14} amps/sec have been achieved.

ACKNOWLEDGEMENTS

We wish to acknowledge fruitful discussions with J. C. Martin on self-breaking water switches and William Moore for technical assistance in performing and assembling the experiments. Special acknowledgement is due R. S. Clark for developing the pulse lines between the inception period through the delivery. The low inductance Marx gnnerator was provided by Physics International, San Leandro, California, under a development contract to Sandia Laboratories which was directed by D. L. Johnson.

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Fig. 1 - SIDE VIEW OF APPARATUS

The lines extend 120 cm into the paper. A is the transfer capacitor section; B is the pulse forming line; C is the output line terminated in a load resistor D. E and F are edge-plane gaps and G represent resistive voltage monitors that are uniformly graded in the high field region between the lines. The gaps are viewed through screens or slits in the upper line.

Fig. 2 - SAMPLE DATA

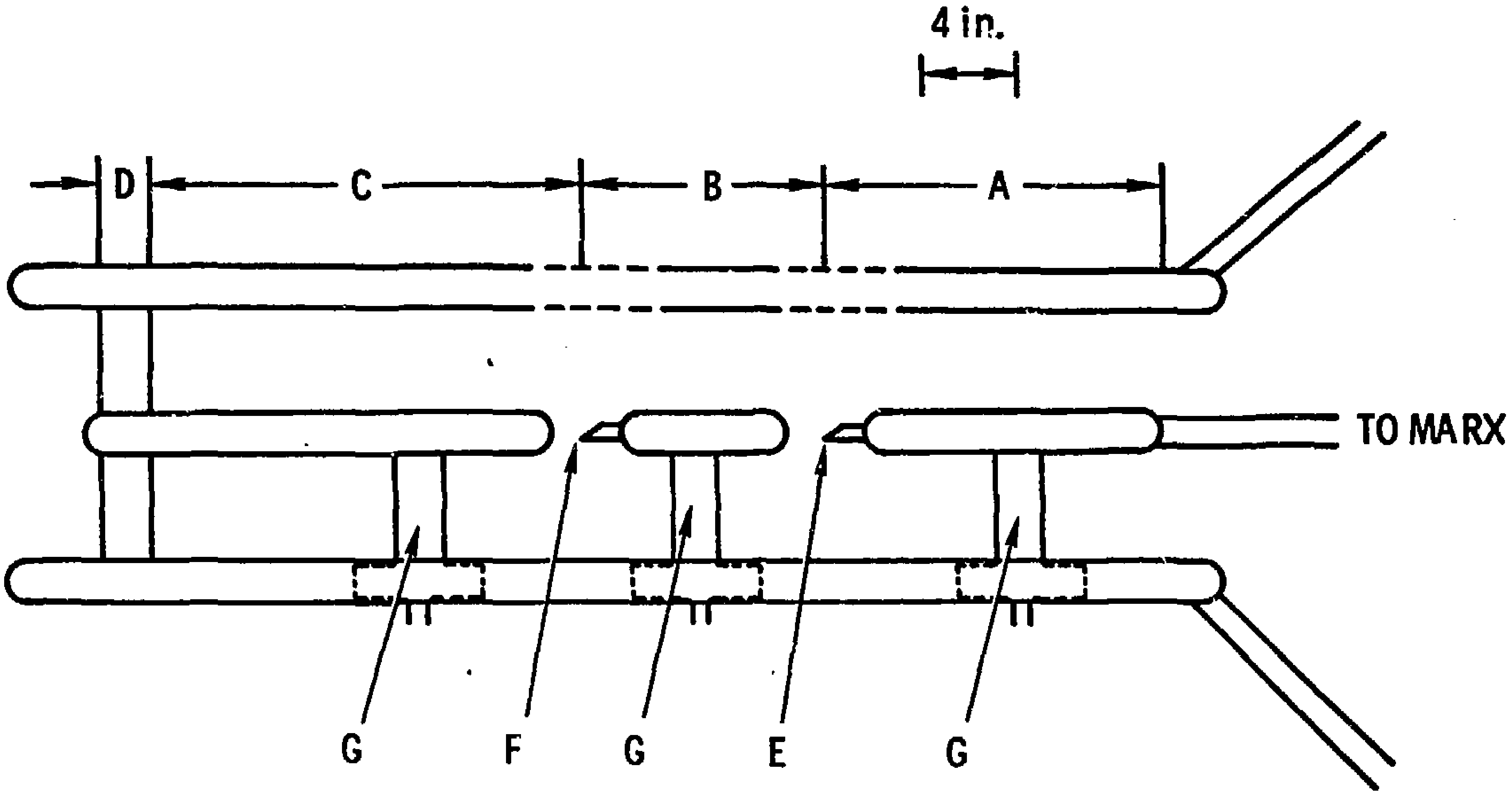
The output waveform at 1.6 MV/div corresponds to 800 kA/div in the 2Ω line. The streak record first records the streamers in the first gap (A) and then the streamers in the second gap (B). The open shutter photograph of the slits is also shown for comparison with the streak record

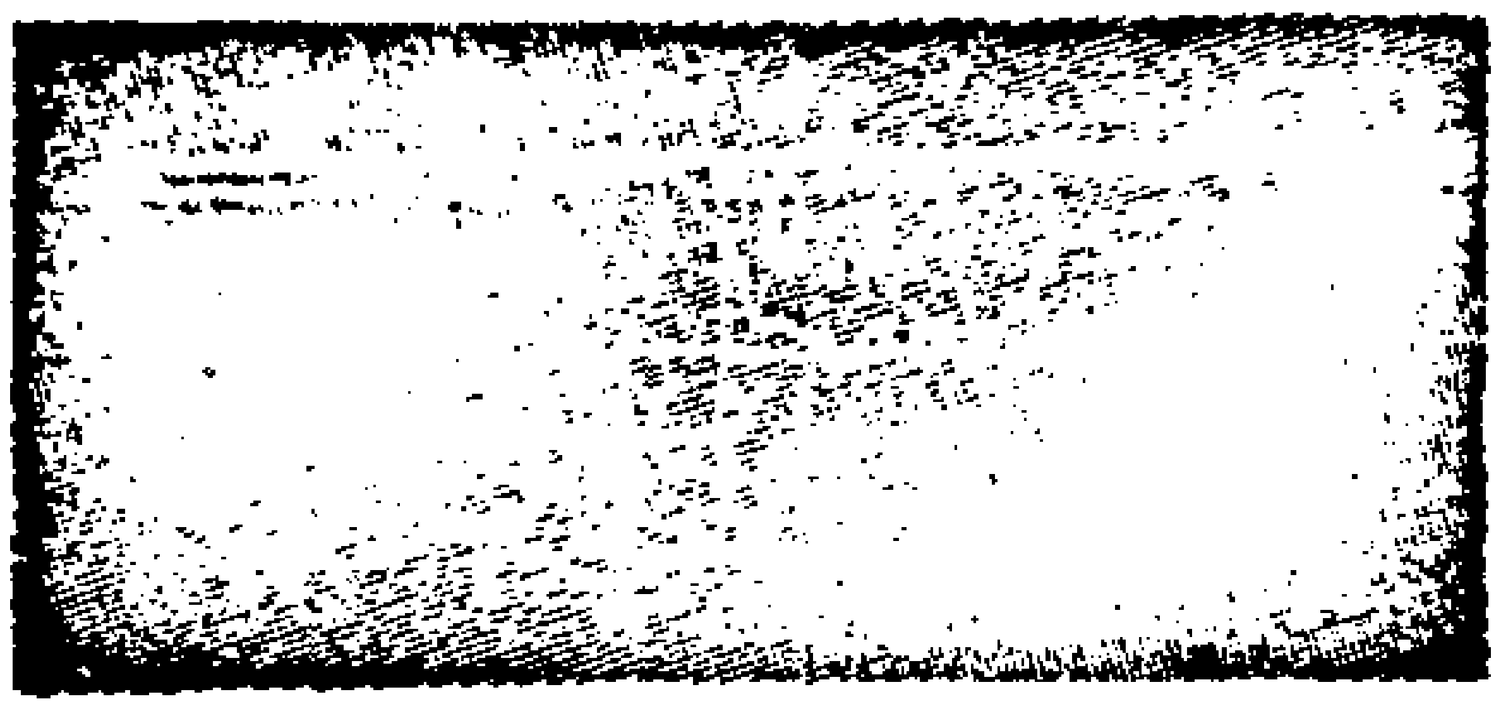
Fig. 3 - BREAKDOWN ELECTRIC FIELD AS A FUNCTION OF THE EFFECTIVE BREAKDOWN TIME

The data taken with a negative edge (+) and with a positive edge (⊕) are shown. The error bars represent the spread in the data over many shots, gap separations and voltages. The solid lines A and D are the relations in Eq. (5) for the negative and positive edges, respectively. The dashed lines B and C are the relations in Eq. (4) for the positive and negative data, respectively.

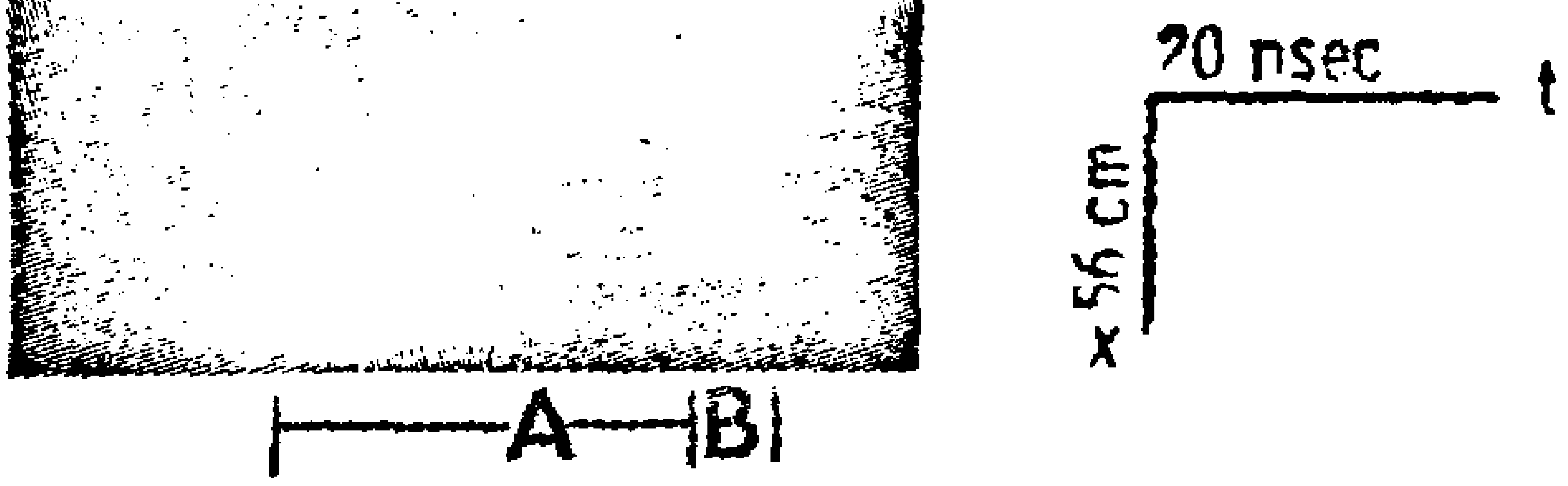
Fig. 4 - STREAK PHOTOGRAPHS OF A SINGLE STREAMER CROSSING THE FIRST GAP.

The luminosity from the rounded edge of the blade is visible as an apparent "backward going" streamer in both photographs. The velocity of the positive streamer is much faster at V = 1.4 MV than the negative streamer at V = 1.8 MV.


4 in.
D
C
B
A
TO MARX
G
F
G
E
G

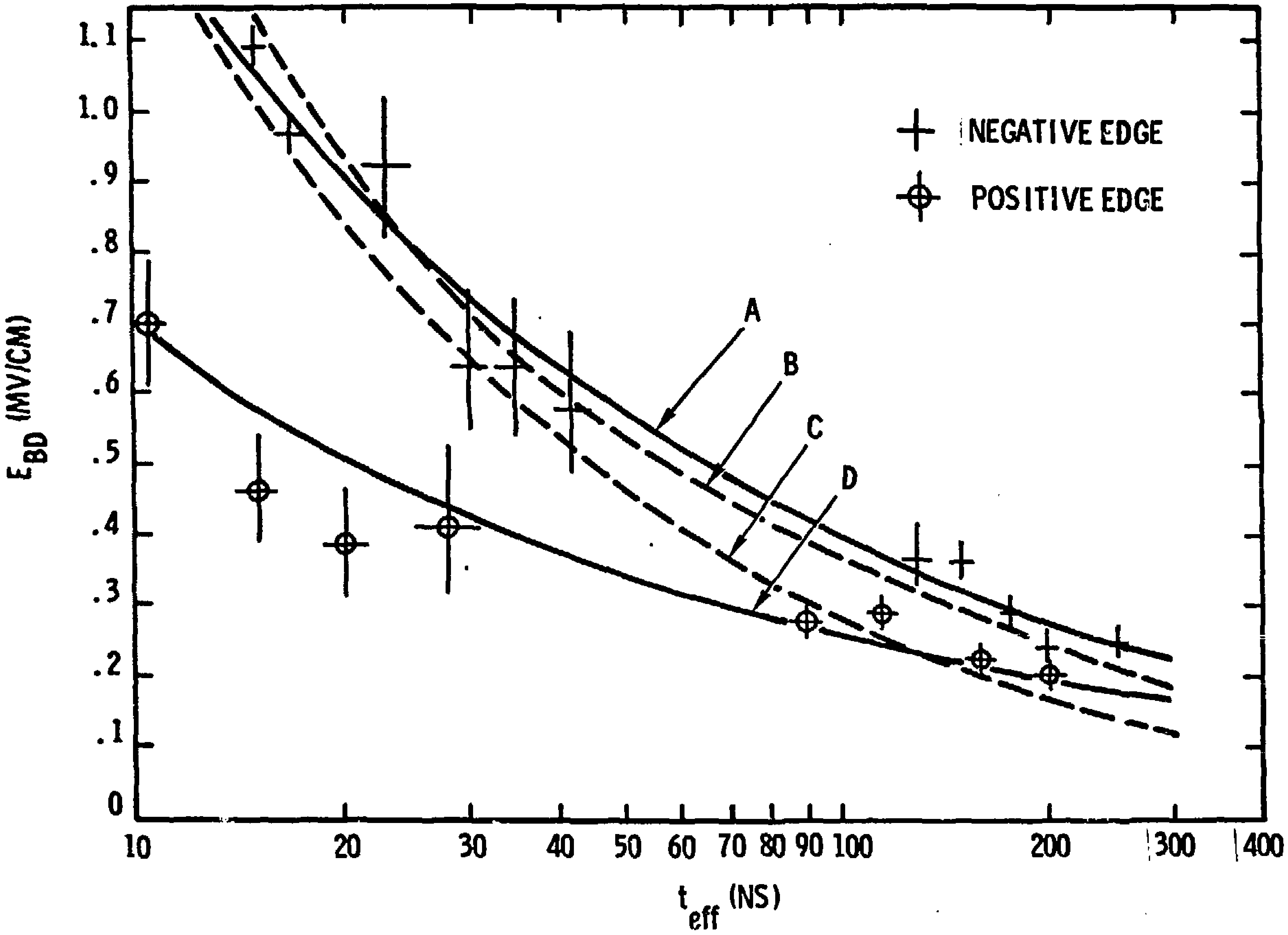


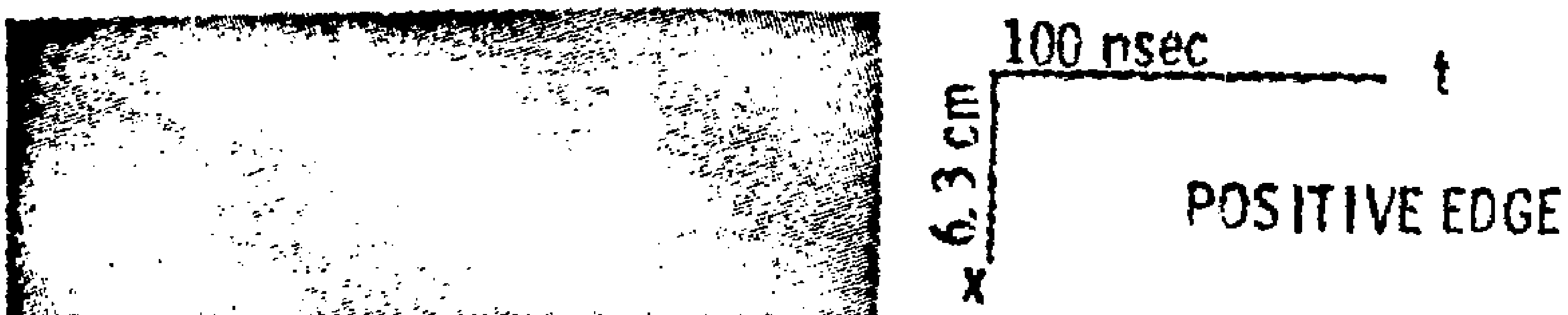
OUTPUT WAVEFORM
1.6 MV/div 10 nsec/div

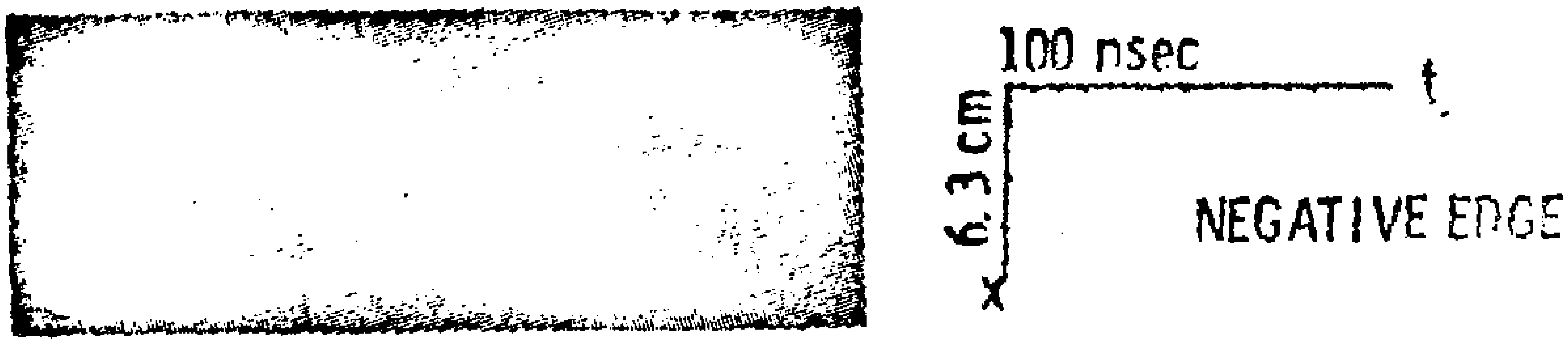


STREAK RECORD

OPEN SHUTTER PHOTOGRAPH


E$_{BD}$ (MV/CM)
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
70
80
90
100
200
300
400
t$_{eff}$ (NS)
NEGATIVE EDGE
POSITIVE EDGE
A
B
C
D


100 nsec
t
6.3 cm
x
POSITIVE EDGE


100 nsec
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6.3 cm
x
NEGATIVE EDGE