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UNTRIGGERED WATER SWITCHING†

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Summary

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 2 Ω 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 2 edge-plane water-gap switches. The Marx generator charged the first line in < 400 ns. The first switch then formed 5 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 cost 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.‡

Introduction

High current electron beams capable of delivering 10^{13} to 10^{14} W for 10 to 20 ns will be required to investigate the feasibility of thermonuclear fusion 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 as:[2]

$$\tau_L = L/NZ$$
$$\tau_r = \frac{5}{N^{1/3}\, Z^{1/3}\, E^{4/3}} \qquad (1)$$

in ns with L the inductance per switch channel in nH, N the number of channels, Z the impedance of the line feeding the switch, and E the mean electric field in the switch in MV/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]

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

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 $\frac{\ell\sqrt{\epsilon_r}}{N c}$ for a switch width ℓ in a 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 ns to 2 μs. 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. In those experiments the switch risetime was dominated by the inductive risetime τ_L and the field enhanced electrode was charged positively. Recent experiments at Sandia[5] with edge-plane water dielectric gaps resulted in successful multi-channel switching at voltages up to 1 MV.

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 ns and 40 to 60 ns for the transfer capacitor and pulse forming line, respectively, on the 112 cm long switches. In these experiments, the risetime of the current in the switch was always dominated by the resistive risetime. Both positive and negative charged edges were used in the gaps.

Typically, five channels are obtained with charging times of 200 to 500 ns 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 ns which reflects the intrinsic jitter in the breakdown and the effect of 10 ns 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 ns and a pulse width of 13 ns 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 ns, 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 60 ns 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 ~12. 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

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with a streak camera viewing space 1/8 to 1/4 inch in front of the plane electrode. The recorded luminosity was time correlated with the rise of the current in the gap to within 1 ns. 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.

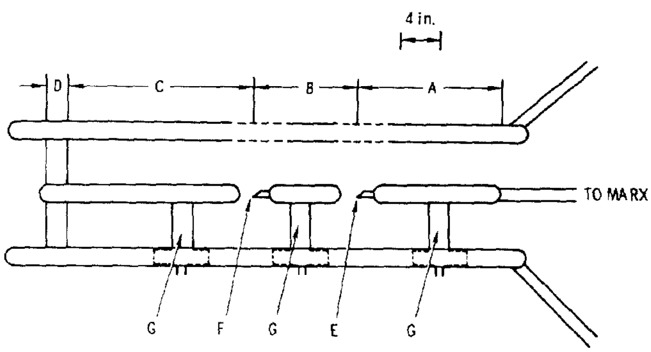

Figure 1. - Side View of Apparatus

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 represents 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.

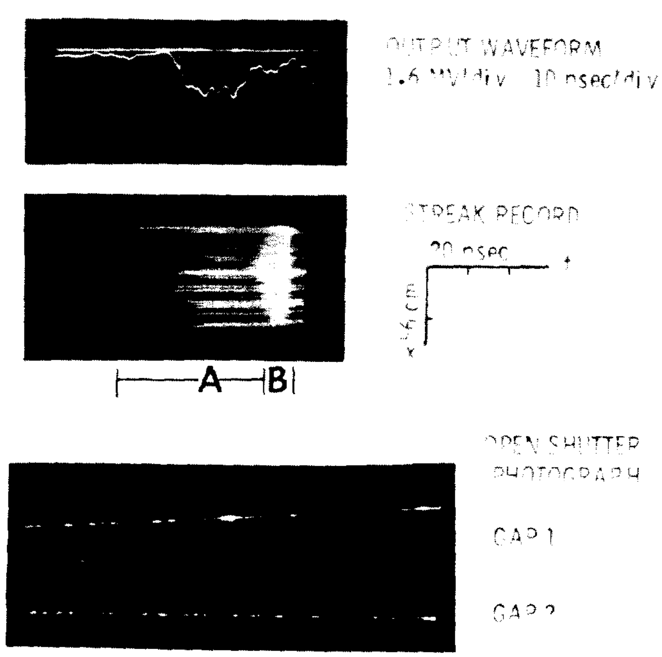

Figure 2. - Sample Data

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

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 percent risetime of 3 ns and a pulse width of 13 ns. 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 ns and 0.4 ns, respectively, from Eq. (1). The calculated 10-90 percent risetime is ≈ $2.2\ \tau_r = 3.7$ ns compared to 3 ± 0.5 ns 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} equals the voltage at breakdown divided by the gap spacing and t_{eff} is the time during which the gap voltage was above 63 percent 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 should be changed.[4]

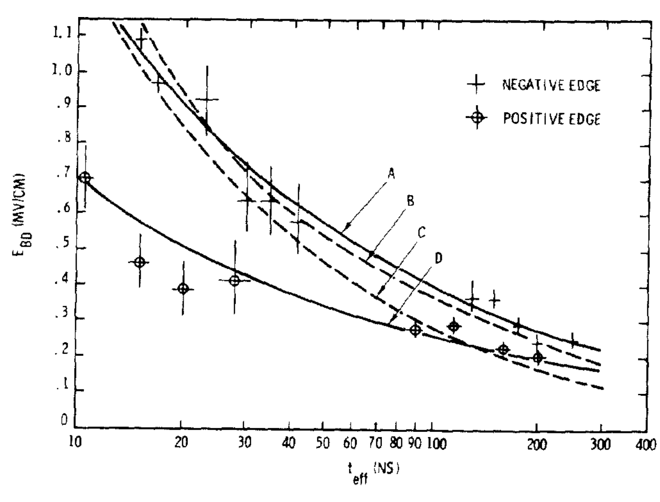

Figure 3. - Breakdown Electric Field as a Function of the Effective Breakdown Time

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. (4) for the negative and positive edges, respectively. The dashed lines B and C are the relations in Eq. (3) for the positive and negative data, respectively.

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

$$\text{Negative Edge:}\quad E_{BD} = \frac{0.0625}{t_{eff}^{2/3}\,V^{0.1}}\ \text{MV/cm} \tag{3}$$

$$\text{Positive Edge:}\quad E_{BD} = \frac{0.027d^{0.667}}{t_{eff}^{0.83}}\ \text{MV/cm}$$

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

Since the data in the recent experiments was taken in the regime, 1 MV < V ≤ 3 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 $t_{eff} < 50$ ns. For $t_{eff} > 50$ ns, the breakdown field is ~ 60-80 percent more than predicted. The positive relations, on the other hand, provide a reasonable description of the data for $t_{eff} > 200$ ns. For shorter times, the relations overestimate E_{BD} by as much as 100 percent. More appropriate, empirical formulas for the present data were found to be:

$$\text{Negative Edge:}\quad E_{BD} = \frac{0.13}{t_{eff}^{0.5}}\ \text{MV/cm} \tag{4}$$

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

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 percent of the velocity of the positive streamer with the same driving voltage V. The velocities of the streamers were 90 cm/μs and 140 cm/μs at V ≈ 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/μs for the negative and positive streamers, respectively.

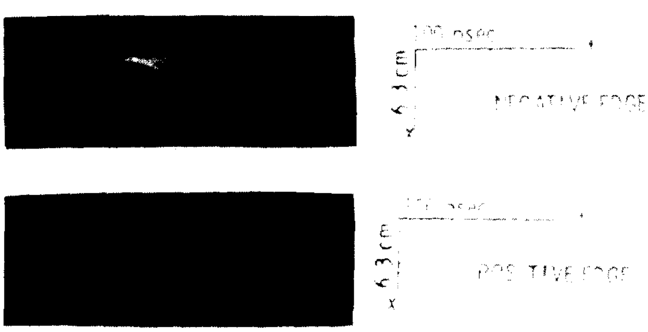

Figure 4. - Streak Photographs of a Single Streamer Crossing the Gap

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.

The relationship between the number of channels N and the intrinsic jitter σ is given by Eq. (2). The value of N is the number of channels that carry 45 percent or more of the current carried by the channel with a maximum current. This corresponds to those channels that close when approximately 85 percent 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 percent of its maximum value, the two streamers were equally bright; (2) when the voltage had fallen to 80 percent 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 the total number of streamers that closed.

For charge times of 200 to 400 ns (i.e., the data in the first gap), the value of σ obtained from Eq. (2) was 1.4 percent 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 ns) was not a linearly rising pulse. Since dV/dt was nearly zero or even negative, a value of σ was difficult to determine accurately. Using Eq. (2) to give an upper limit of σ, one finds σ is ≤ 3.0 percent for both positive and negative streamers in the second gap. These values of σ given by Eq. (2) from N measured with open shutter photography can be compared to the σ of the closure times of transit-time isolated streamers as measured with the streak camera. Sample data is shown in Table I.

TABLE I

τ_c (ns)	Time Integrated Data		Time Resolved Data	
	N	$\sigma_{Eq.(2)}$	N_{tr}	$\sigma_{isolated}$
220	6	1.0%	5	3.2%
220	6	1.2%	5	3.0%
45	9	3.0%	6	6.2%
50	8	3.0%	6	4.6%

The value of σ measured with the streak camera is two to three times that given by Eq. (2). The discrepancy apparently lies in the assumption, implicit in Eq. (2), 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.

The larger, fractional standard deviation σ for streamers in the second gap is attributed to the long timescale required for the voltage on the second gap to equilibrate along the entire length of that gap. Since the single-transit time along the gap length is comparable to the charging time, the voltage varies along the gap. This voltage variation increased the apparent jitter in the second gap over the intrinsic jitter of the same gap with a uniform voltage along the length.

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. Since the reference time t = 0 was taken from the time at which the erecting Marx waveform reached a set voltage, the value of σ includes the variation in t = 0 caused by transients in the Marx. Thus, σ is an upper limit to the intrinsic jitter in the gaps.

TABLE II

Charge Time (ns)	V_{output}	σ_{ns}	Gap #1
260	1.0 MV	10	edge/plane
350	1.4 MV	18	"
430	0.7 MV	21	"
500	1.0 MV	20	"

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

Conclusion

We have examined multichannel switching in water and found that the standard deviation in breakdown time is 2-3 percent 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_{T_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 risetime of the current is adequately described by the usual relation of Eq. (1). When the knife-edge electrode is negatively charged, the breakdown fields for 1 MV < V < 3 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. In general, better switching performance is obtained with a knife-edge electrode charged negatively. Current risetimes of dI/dt in excess of 2×10^{14} A/sec have been achieved.

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