New low inductance gas switches for linear transformer drivers

J. R. Woodworth,[1] W. A. Stygar,[1] L. F. Bennett,[1] M. G. Mazarakis,[1] H. D. Anderson,[2]
M. J. Harden,[2] J. R. Blickem,[3] F. R. Gruner,[4] and R. White[5]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*National Security Technologies, Inc., Los Alamos, New Mexico 87544, USA*
[3]*Ktech Corporation, Albuquerque, New Mexico 87123, USA*
[4]*Kinetech, LLC, The Dalles, Oregon 97058, USA*
[5]*L3 Communications, Pulse Sciences Division, San Diego, California 92111, USA*

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We have developed two new gas switches that are designed to be used with linear transformer drivers. The switches, which can be DC charged to 200 kV and triggered with less than a 2-ns 1-σ jitter, have overall inductances ranging from 69 to 85 nH. When transferring 400 J of energy per shot, the switches have lifetimes in excess of 5000 shots. The two switches are insulated with 130–270 PSIA of air and are submerged in transformer oil during operation. These switches should allow development of linear transformer drivers that are more compact and have higher peak power.

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I. INTRODUCTION

Linear transformer drivers (LTDs) are a new pulsed-power architecture that may dramatically reduce the size and cost of high-voltage, high-current pulsed-power accelerators [1–7]. LTDs, however, place stringent demands on gas switches, requiring switches that can be charged to 200 kV DC, be triggered with a 1-σ jitter of 5–10 ns, be low inductance, have very low prefire and no-fire rates, and have lifetimes of at least several thousand shots when transferring ~400 J of energy per shot. Multimegavolt, multi-mega-ampere LTD drivers for controlled fusion, dynamic materials experiments, or flash radiography may require more than 10 000 gas switches. Hence, it is essential that these switches be very reliable. We have previously reported tests on four switches designed for LTDs [8]. Based on the results of that previous work, we designed the two new, lower inductance and more robust LTD switches that are reported in this work. We compare the performance of these new switches with a baseline LTD switch designed by researchers at the High Current Electronics Institute (HCEI) in Tomsk, Russia [9–11].

LTDs can achieve compactness and low cost by discharging a large number of DC charged capacitors in parallel directly into a water or vacuum transmission line, generating a ~100 ns pulse without the need for any of the pulse compression circuits typically needed in large pulsed-power systems. The basic building block of an LTD system called a "brick" typically consists of two capacitors, a triggered switch, toroidal rings of magnetic material, and a magnetically insulated transmission line [12] in vacuum. Figure 1 shows a typical LTD brick. Two capacitors are charged to opposite polarities with a gas switch between their high-voltage terminals. When the switch is triggered and conducts current, a voltage pulse is induced on the opposite ends of the capacitors. This voltage pulse attempts to drive current around a loop formed by the metallic case of the LTD brick. The toroidal magnetic cores, however, block current from flowing in this loop until the magnetic cores saturate. The result is that a large, fast-rising voltage pulse is impressed on the transmission line in the center of the accelerator.

The rise time of the voltage pulse at the transmission line is controlled primarily by the components in the green dashed box in Fig. 1: the capacitors, the switch, and the associated current busses. Minimizing the inductance of these components will result in a faster rise time on the power pulse at the transmission line. As an example, if two 40 nF capacitors are used in the brick, the inductance of the capacitors, switch, and leads must be no more than 245 nH to achieve a zero-to peak rise time of 70 ns into a matched load.

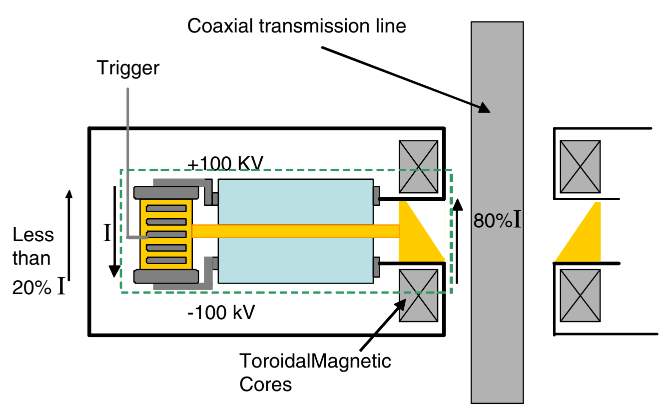

FIG. 1. Electrical schematic of a single LTD brick in an accelerator. The rise time of the pulse delivered to the load depends primarily on the inductance of the switch, capacitors, and current busses in the green box. The toroidal magnetic cores block the return current path for the brick. This results in a high-voltage pulse at the load until the cores saturate.

FIG. 2. Picture of the LTD-II cavity with 20 bricks stacked around a common load.

Typically, many bricks are stacked around a common cavity as shown in Fig. 2. Figure 2 shows the LTD-II cavity, containing 20 bricks around a central resistive load. This cavity was initially fabricated at the High Current Electronics Institute in Tomsk, Russia and recently rebuilt by researchers at Sandia Laboratories [7]. This cavity develops a 100 kV, 0.5-MA power pulse across a resistive load in the center of the cavity and can be fired repeatedly at a rate of 0.1 Hz. In LTD-II, the ~120 nH inductance of each switch accounts for half of the total inductance of each brick. We are testing switches with lower inductances to increase the LTD cavity's peak power and decrease its rise time.

II. APPARATUS

We tested three different LTD switches in the apparatus shown schematically in Fig. 3. In this apparatus, the toroids and the central transmission line have been replaced by a flowing resistive load. The system is heavily instrumented with current, voltage, and optical monitors and has been described previously [8]. Our trigger system delivered a 120-kV trigger pulse with a rise time of 18 ns to the switch being tested. These relatively short low-inductance switches utilized DC electric fields on the outside of the switches on the order of 20 kV/cm. While the switches were submerged in transformer oil, we still found it necessary to provide a minimum radius of 1.6 mm on the external edges of all metal parts exposed to these DC electric fields to prevent breakdown arcs from occurring in the oil.

Figure 4 shows the three switches we tested in these experiments: the baseline Russian switch developed by

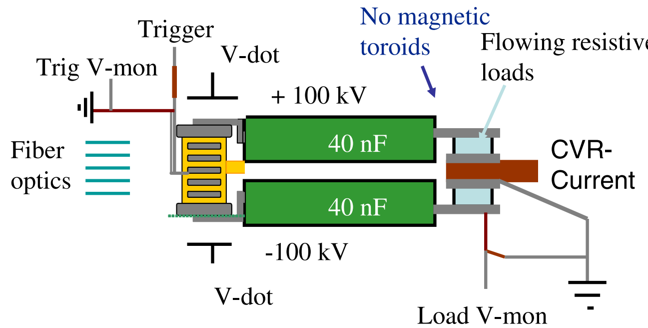

FIG. 3. Schematic of our single brick test setup. The magnetic cores and coaxial load have been replaced by a simple flowing liquid resistive load. Monitors measure load current and voltage as well as the voltage across the switch.

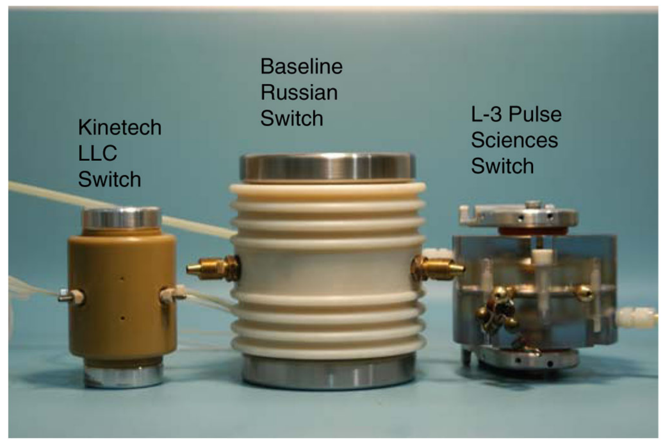

FIG. 4. Picture of the baseline (HCEI) Russian switch, the Kinetech switch, and the L-3 pulse sciences small-diameter switch.

researchers at HCEI in Tomsk and used in LTD-II [7]; the switch developed jointly by Kinetech, LLC and Sandia (Kinetech-2); and the switch developed jointly by L3 Pulse Sciences and Sandia (L-3 small diameter).

Table I summarizes the physical parameters of these three switches and a large diameter L3 switch reported previously. All the switches are insulated with dry air and submerged in transformer oil during use.

The HCEI switch has been described in the literature previously [4,10]. Figure 5 shows cross-sectional drawings of three switches all at the same scale. Figure 5(a) shows the original Kinetech switch reported previously. Figure 5(b) shows the Kinetech-2 switch tested in this work. Both Kinetech switches had a 7.5-cm overall diameter. The switches had four each 3-millimeter diameter tungsten trigger pins at the midplane between the two copper-tungsten main electrodes. The main change between the two Kinetech switches is that the relatively long, narrow electrode stalks in the old switch have been replaced by shorter, larger diameter stalks in the Kinetech 2

TABLE I. Switch parameters for these experiments.

Switch	Gaps	Operating pressure (psia)	Overall switch diameter (cm)	Switch height (cm)
Russian (HCEI)	6 each 6 mm	40–62	7.8–20[a]	15.9
Kinetech 2	2 each 5 mm	230–270	7.3	11.7
L3 small diameter	2 each 6.4 mm	100–150	11.7	7.6
L3 large diameter[b]	2 each 12.8 mm	40–80	15.3	7.6

[a]Diameter varies with current-carrying requirements.
[b]Previous work [8].

switch. This significantly lowered the overall switch inductance. In addition, the plastic compression fittings used to seal the trigger pins in the old switch have been replaced by O-ring seals which have proved more reliable.

Figure 5(c) shows a schematic cross section of the L3 small-diameter switch (part # 40264-200SD), which had an 11.7-cm diameter, and had two flattened-hemispherical brass electrodes spaced 6.4 mm from opposite sides of a brass midplane. The small-diameter L3 switch had a smaller diameter than the older large diameter L3 switch (11.7 versus 15.3 cm) and smaller gaps (2-each 6.4 mm versus 2-each 12.8 mm). Both of these changes tended to lower the inductance of the switch in our application. The midplanes in both L3 switches had small holes at their centers to allow for a UV preionization pin. The trigger pulse to the switch was forced to flow through the UV preionization pin and across a small air gap in the center of the switch before it could reach the switch's midplane. The UV preionization significantly improved the switch's triggering behavior.

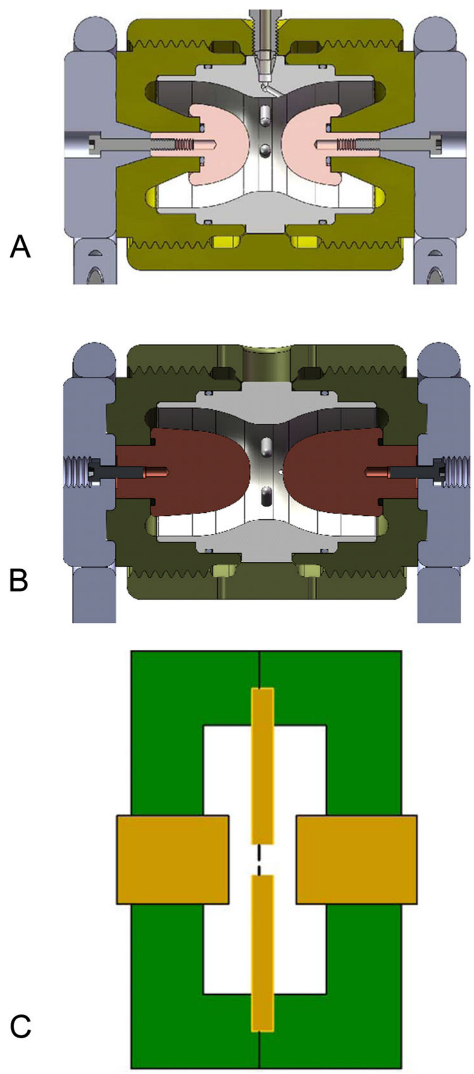

FIG. 5. Cross sections of three LTD switches: A: original Kinetech switch with narrow electrode stalks; B: Kinetech 2 switch with low-inductance large diameter electrode stalks; C: Schematic cross section of small-diameter L3-Sandia switch.

III. RESULTS

A. Self-breakdown curves

Figure 6 shows two self-breakdown curves for the L3 small-diameter switch. The blue self-break curve is for a new switch. As the switch conditions, the self-break curve gradually moves up as shown in the figure. Note that when we operate the switches at a 200 kV charge, we must use

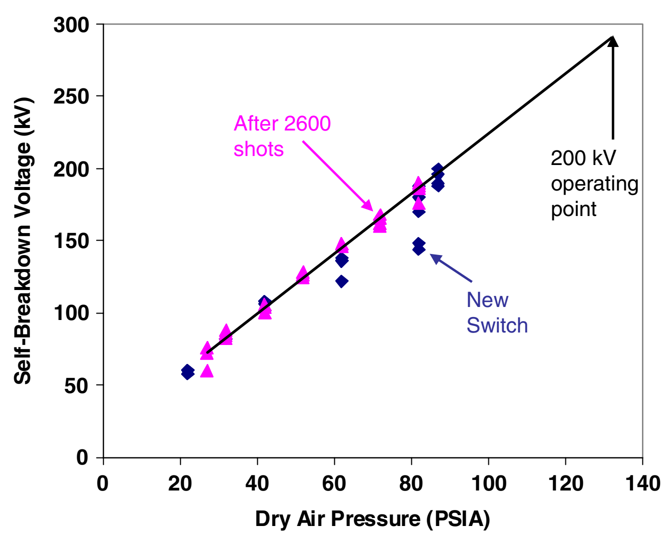

FIG. 6. Self-breakdown curve for the L-3 small-diameter switch. Note that we actually operated the switch at a significantly higher pressure than our data points.

pressures higher than any of the pressures used in making the self-breakdown curves.

Figure 7 shows self-breakdown curves for a new Kinetech-2 switch and a switch after 1700 shots had been taken. While this switch had only slightly smaller gaps than the L3 switch, it had higher field enhancement in the gaps and, hence, operated at a much higher dry air pressure.

B. Triggered switch performance—current waveforms

Figure 8 shows current waveforms of the test brick shown in Fig. 3 when we used the Kinetech-2 switch, the small-diameter L3 switch, and the baseline HCEI switch. All three cases show the current delivered to a matched resistive load. The L3 small-diameter switch and the Kinetech-2 switch both have matched-load peak currents of 40–41 kA while the HCEI switch has a matched-load peak current of 36 kA. All of these measurements were taken with two 40.5-nF double-ended capacitors in our LTD brick. Table II summarizes the peak currents, rise times, and triggering behavior of the three switches tested in this work and compares them to results reported previously [8]. Note than in the current work our new brick has 40.5-nF capacitors while in the previous work, the brick had 38-nF capacitors. When the HCEI switch was tested in our new brick with 40.5 nF capacitors, it had a 36 kA peak current into a matched load. The matched-load value changed from one switch to another but typically was between 1 and 2 Ω.

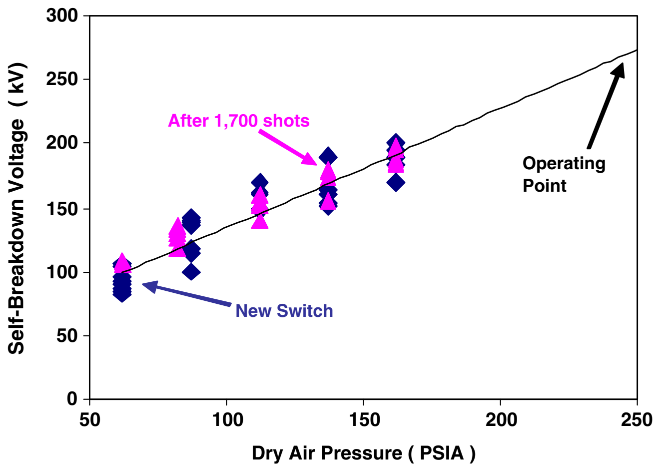

FIG. 7. Self-breakdown curve for the Kinetech-2 switch. Note that the curve changed only slightly after 1700 shots.

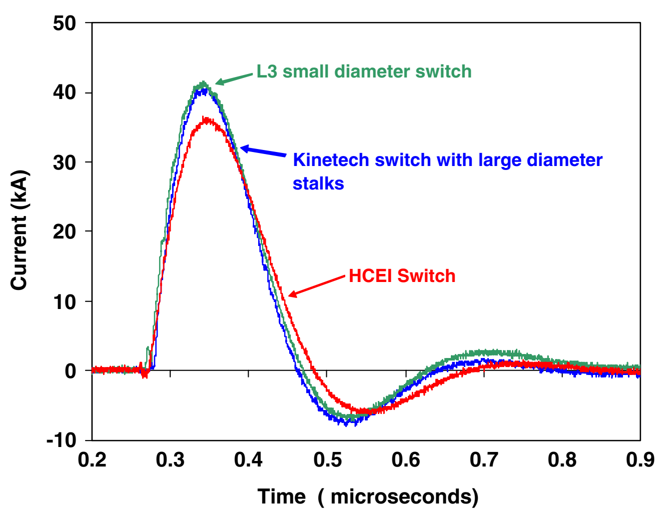

FIG. 8. Current waveforms for our brick charged to plus and minus 100 kV and discharged into matched loads.

In order to measure the effective switch inductances, we fired the switches into a short circuit load at a reduced charge voltage of 120 kV and measured the system ringing period. This allowed us to determine the overall system inductance for each switch. Subtracting the known inductances of the capacitors and current busses leading to the (shorted out) resistive load allowed us to determine the overall inductance that each switch added to the circuit. These results are shown in Table III. Note that the switch inductances listed in Table III are the total inductance the switch and its power feeds add to the system, not just the inductance of the breakdown arcs inside the switch. All the switches we tested have lower inductances than the baseline HCEI switch. The Kinetech-2 switch has an inductance about 30 nH lower than the Kinetech-1 switch. This is due entirely to the increase in diameter of the electrode stalks in the second Kinetech switch. Because of its smaller diameter and shorter electrode gaps, the L3 small-diameter switch also has an inductance ~8 nH lower than the original L3 200-kV switch.

Figure 9 shows current waveforms for the L3 small-diameter switch with 20, 40, and 80 nF capacitors in our LTD brick. These tests were all performed with 200 kV across the switch, the switch operating at 70% of its self-breakdown voltage, and the circuit being discharged into a matched load. In all three cases, the switch had a jitter of 1.5-ns or less. The switch withstood over 700 shots with the 80-nF capacitors without any damage. Table IV lists the peak currents and rise times for the circuit with the three different sets of capacitors.

Accelerators used for flash radiography [13] typically operate in a critically damped mode to decrease the accelerator rise time and increase the accelerator voltage. Figure 10 compares voltage wave shapes generated by the L3 small-diameter switch and 20 nF capacitors in our brick to the voltage wave shape generated by one module of the LTDR accelerator [14] that uses 20 nF capacitors and HCEI switches. The LTDR waveform is the total voltage a ten-brick LTDR module delivers into a critically damped load. This waveform will include losses such as eddy current losses in the magnetic toroids, but we do not expect these losses to change the voltage waveform. The use of the L3 small-diameter switches produces a

TABLE II. Operating parameters of LTD gas switches into matched loads at 200 kV charge voltage.

	This work; with 40.5 nF capacitors		Previous work; with 38 nF capacitors		
Switches	L3 small diameter	Kinetech 2	L3 large diameter	Kinetech 1	HCEI
Peak current (kA)	41.1	40.6	37	36	33.4
T-rise 10%–90%	41	39.5	47	45	47
Delay (ns)	38	30	62	43	42
1-σ jitter (ns)	0.5–1	1–2.4	1.2	3.3	1.8
% SBV	70	70	81	68	67
Lifetime	>7400	>5300	1500	>2000	2000

TABLE III. Short circuit LTD switch parameters at 120 kV charge voltage.

	This work; with 40.5-NF capacitors		Previous work; with 38-NF capacitors		
Switches	L3 small diameter	Kinetech 2	L3 large diameter	Kinetech 1	HCEI
Ringing period (ns)	352	333	352	358	373
System L (nH)	155	139	164	171	185
Approximate switch L (nH)	85	69	93	100	115

significantly narrower voltage pulse (blue curve). Our brick with the L3 small-diameter switches has a 47-ns wide voltage pulse at 80% of the peak voltage. The LTDR accelerator with the HCEI switches has a 64-ns wide pulse at 80% of the peak voltage. Width at 80% of peak voltage is often used as a figure of merit in radiography experiments due to the strong nonlinearity of x-ray yield with voltage.

C. Switch delay and jitter

The delay between the trigger pulse and the switch breakdown is defined somewhat arbitrarily as the interval between the time the trigger pulse exceeds 27 kV and the switch current exceeds 21 kA. Figure 11 illustrates the timing sequence in a triggered shot of the L3 small-diameter switch when it was charged to 200 kV. At 0.250 μs, the main trigger pulse starts. At 0.256 μs, the

TABLE IV. Matched-load circuit parameters using L3 small-diameter switch and 20, 40, and 80 nF capacitors in brick.

Capacitors in brick	Peak current (kA)	10%–90% rise time (ns)
20 nF	28.7	31
40.5 nF	41.1	41
80 nF	53.9	62

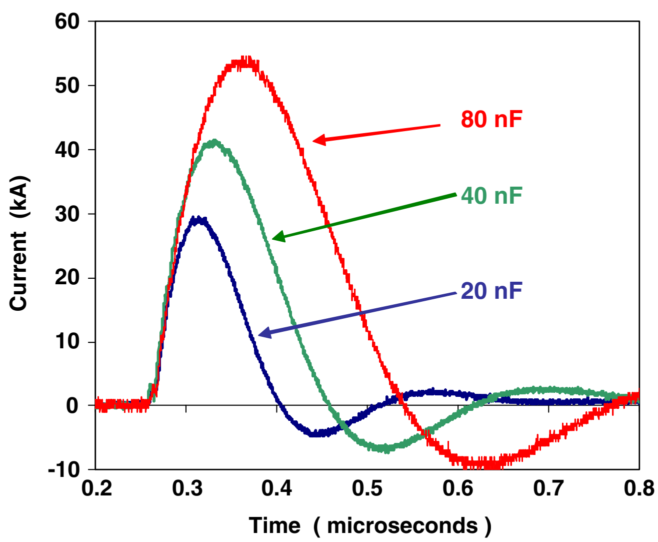

FIG. 9. Current waveforms for our bricks with L-3 small-diameter switches and 20, 40, and 80 nF capacitors when discharged into matched loads.

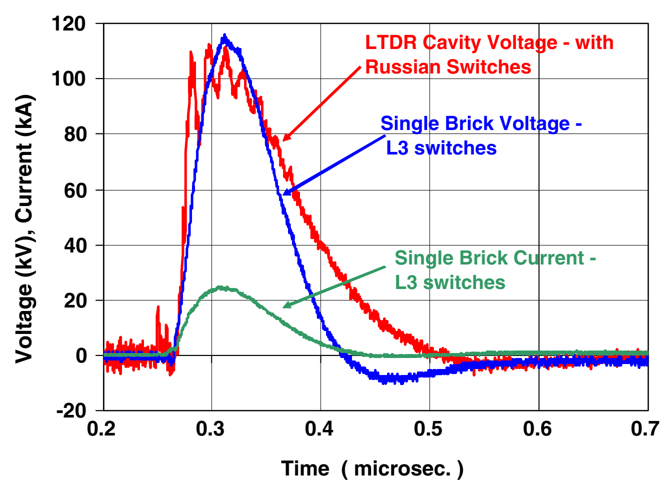

FIG. 10. Comparison of voltage waveforms for an LTDR accelerator cavity with 20 nF capacitors and HCEI switches with a waveform for our test brick using 20 nF capacitors and the L-3 small-diameter switch.

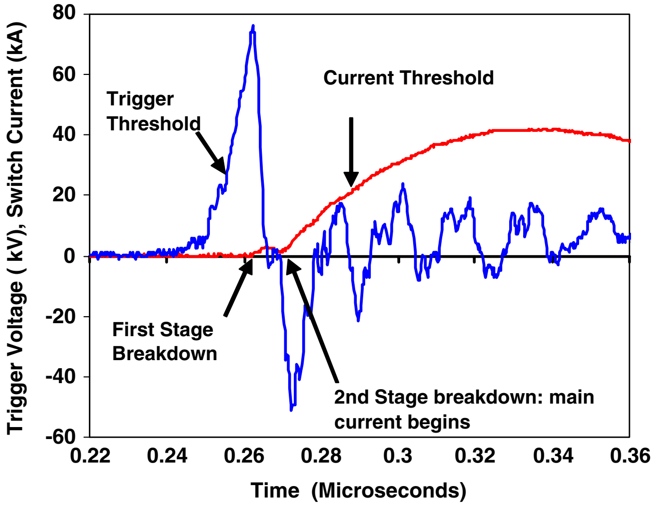

FIG. 11. Timing sequence of trigger voltage and switch current during triggering of L-3 small-diameter switch.

trigger rises above 27 kV and the timing sequence begins. At 0.262 μs, the triggered stage of the L3 small-diameter switch breaks down, causing the trigger pulse to collapse. A small displacement current flows through the triggered half of the switch until the second half of the switch breaks down at 0.270 μs, starting the main current pulse. The main current pulse crosses 21 kA at 0.288 μs, stopping the timing sequence. In this case, the delay from the start to the end of the timing sequence was 35 ns.

Figure 12 shows a plot of delay versus shot number for the Kinetech-2 switch when it was charged to 200-kV and insulated with 252 PSIA of dry air, which meant it was nominally operating at 70% of its self-breakdown voltage. The switch initially had a ~32-ns delay and a 1.05-ns 1-σ jitter. Over the course of 5000 shots, the delay gradually increased to ~43 ns and the jitter increased to 2.4 ns. Examination of the switch after the run showed that the tungsten trigger pins had worn back about 0.5 mm, which may account for the gradual increase in delay and jitter.

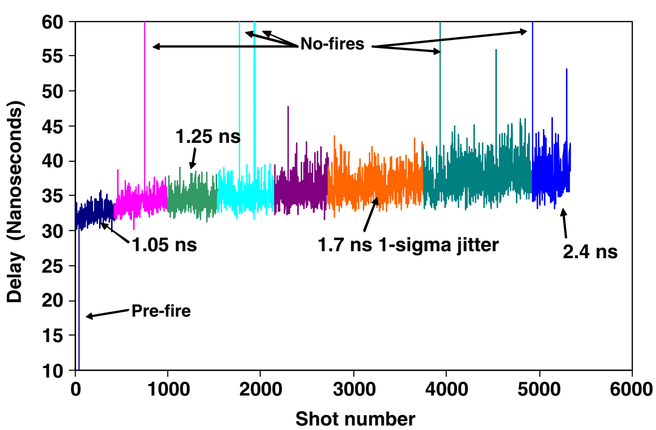

FIG. 12. Plot of delay versus shot number for 5400 shots taken on eight successive days for the Kinetech-2 switch.

The Kinetech-2 switch also had one prefire on the first day of the tests and failed to fire about once in every thousand shots.

Figure 13 shows a plot of delay versus shot number for the L3 small-diameter switch which it was charged to 200 kV and insulated with 142 PSIA of dry air, which also meant that it was at 70% of its self-breakdown voltage. The switch initially had a ~38-ns delay and 1.1-ns 1-σ jitter. The delay slowly decreased to about 36 ns after 7000 shots and the jitter actually decreased to 0.47 ns by the end of the 7400 shot run. The switch prefired once on the first day. A failure of the gas supply system caused another prefire on the 7th day. The switch never failed to fire on any of the 7400 shots.

Figure 14 shows how the delay and jitter of the L3-small-diameter switch vary as a function of charge voltage for switch pressures of 135, 112, and 102 PSIA. When the capacitors were charged to 200 kV and the switch was at these three pressures, the switch was approximately at 72%, 84%, and 91% of its self-breakdown voltage, respectively. At all three pressures, the switch had a 1-σ jitter of

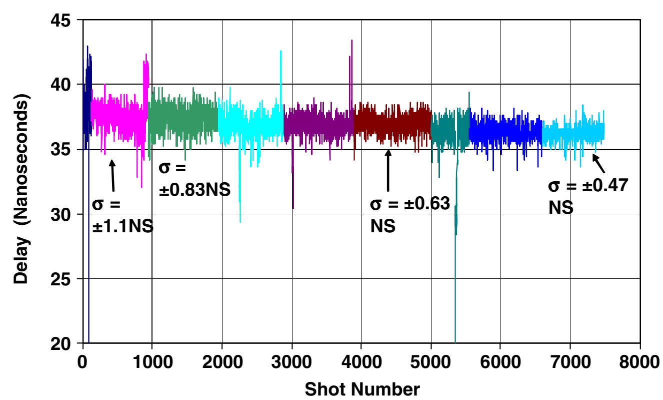

FIG. 13. Plot of delay versus shot number for 7400 shots taken on nine successive days for the L-3 small-diameter switch.

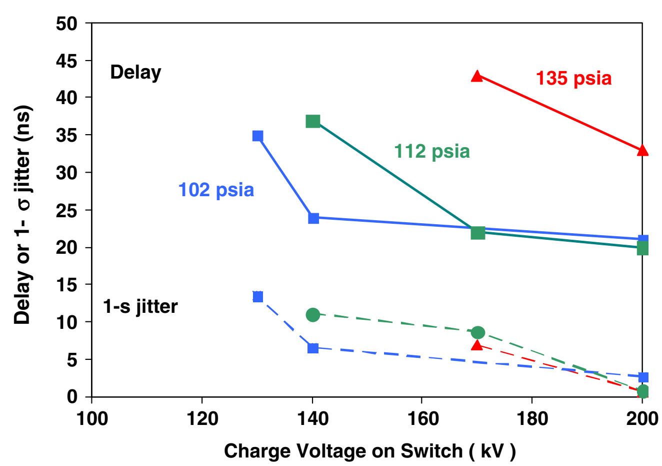

FIG. 14. Delay and jitter of the L-3 small-diameter switch as a function of charge voltage for three different switch pressures.

2 ns or less when the switch was charged to 200 kV. At 135 PSIA, however, the switch would not trigger below a 170 kV charge. At 112 PSIA, the switch would not trigger below a 140 kV charge and at 102 PSIA, the switch would not trigger below a 130 kV charge. The switch jitter typically was 5–12 ns at the switch's lowest triggerable voltages. The triggered gap in the switch consistently broke down at lower voltages than are shown in Fig. 16, but in these cases, the untriggered half of the switch, which was below 55% of its DC self-breakdown voltage before the triggered gap fired, failed to break down.

The baseline HCEI switch requires about 1000 "conditioning" shots before it achieves a low prefire mode [10]. This requirement may be due to conditioning of the tips of the corona needles that are used to grade the electric fields inside these six-stage switches. This requirement for conditioning shots could cause problems in large multimodule accelerators.

D. Comparison of circuit currents under different conditions

We are undertaking this research to attempt to raise the peak current and power delivered to a load by LTD accelerator systems. Figure 15 compares currents delivered by a variety of LTD bricks in our test stand with the current per brick delivered to a load in the LTD-II module. In all cases, the LTD bricks had two 40.5-nF capacitors and were discharged into matched loads. The lowest (red) curve peaking at 24.2 kA is the current per brick delivered to a matched load by the LTD-II accelerator module [7]. Estimates at HCEI [15] suggest that losses in the magnetic toroids in this accelerator module lower the peak current by about 12%. Thus, without the magnetic toroids, LTD-II might have delivered ~27.2 kA peak current as indicated in the figure. To perform a direct comparison between our test stand results and LTD-II, we tested a brick with the same single ended 40-nF capacitors and the HCEI switch used in LTD-II. This test (pink curve) yielded a peak current of 32.4 kA, significantly higher than the 27.2 kA we expected. We do not understand this discrepancy but it may indicate that the toroid losses in LTD-II are greater than 12%. We then installed double-ended capacitors in the brick with the HCEI switch (green curve); this increased the peak current to 36.1 kA. This increase is caused because the double-ended capacitor design allows us to pack the circuit more tightly, lowering its overall inductance. Finally, we plot the peak current through the brick with double-ended 40-nF capacitors and the L3 small-diameter switch (orange curve). This final test yielded a peak current of 41.1 kA, which is a ~70% increase in peak current from the LTD-II results. We intend in future accelerator module experiments to determine how much of this 70% increase in current and power we can realize in real accelerator cavities through use of improved switches, improved capacitors, and improved magnetic toroid materials.

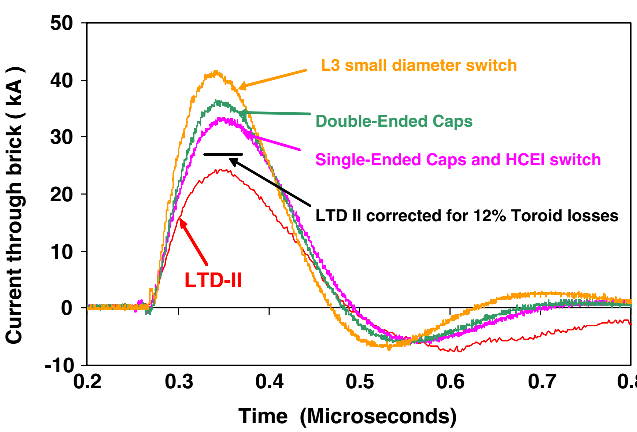

FIG. 15. Comparison of currents into matched loads for LTD-II brick and several improvements of capacitors and switches. The peak current we observed is 70% higher than the peak current in LTD-II.

E. Impedance of the L3 small-diameter switch

The L3 small-diameter switch has been chosen for upgrades of the LTD-II cavity [7] and the LTDR radiography accelerator at Sandia [16]. We therefore felt it was worthwhile to examine the impedance behavior of the L3 small-diameter switch in some detail. Using the capacitive voltage monitors above and below the switch, we were able to measure the voltage (V) across the switch during the current pulse through the brick. Using the current pulse (I) and Ohm's law, we were able to arrive at a first order estimate of switch impedance versus time. Because there is significant inductance (L) in the switch arc, Ohm's law gives accurate results only at peaks of the current pulse when $dI/dt = 0$. To estimate the switch arc impedance at other times, we need to modify Ohm's law to read

$$V - LdI/dt = IR. \quad (1)$$

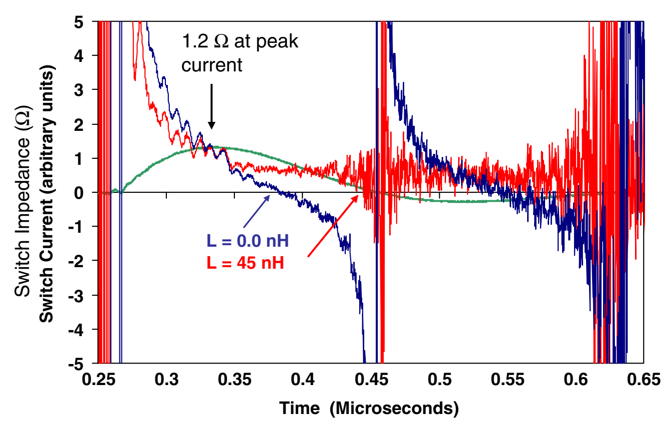

FIG. 16. Impedance of the L3 small-diameter switch with and without a correction for the ~45 nH inductance of the switch arc.

TABLE V. Switch impedances at times of peak current.

Capacitor size	Circuit setup	Impedance at peak current (Ω)	Approximate inductance
20 nF	Critically damped	2.2	
20 nF	Matched load	1.7	
40 nF	Matched load	1.2	45 nH
80 nF	Matched load	0.5	45 nH
40 nF	Short circuit	0.95 (0.35 on 2nd peak)	

We were only able to obtain clean enough current and voltage traces to estimate switch inductance and, hence, the LdI/dt correction on a few traces. Figure 16 shows our estimated switch impedance with and without a 45 nH LdI/dt correction for the L3 small-diameter switch and 40 nF capacitors when the switch was charged to 200 kV. The 45 nH inductance was chosen to produce a relatively flat asymptotic impedance at late times, particularly as the impedance passed through the first current zero. Note that this 45 nH is the inductance of the breakdown arcs alone and does not include the inductance of the switch and its current busses as listed in Table III.

Table V shows switch impedance for a number of cases *at peak current* through the L3 small-diameter switch, when we do not need to make LdI/dT corrections. The impedances we measure range from 2.2 Ω for 20 nF capacitors and a critically damped load to 0.5 Ω for 80 nF capacitors and a matched load. This agrees with our previous conclusion [8] that the impedance of the switch is controlled primarily by the balance of circuit. Furthermore, the switch impedances we measure are not negligible. They are large enough to affect the performance of large LTD accelerator modules. As an example, LTD-II operated at ~0.5 MA and 100 kV or an impedance of 0.2 Ω with 40 nF capacitors in each brick. Since there were 20 bricks in LTD-II, each brick discharged into an effective 4-Ω impedance. The switch impedance of 1.2 Ω was in series with the 4-Ω impedance per brick, which would lower the current into the 4 Ω load by more than 20%.

IV. SUMMARY

We have demonstrated two new 200-kV air-insulated switches for LTD's that have inductances less than 90 nH. When operated at 70% of their self-break voltages, the switches have 1-σ jitters of 2 ns or less. In an extended lifetime test at 70% of its self-break voltage, the L3 small-diameter switch had only two prefires and zero no fires in over 7400 shots. The impedance of the L-3 small-diameter switch at peak current appears to be controlled by the balance of the circuit, with switch impedances ranging from 2.2 Ω for a brick with 20-nF capacitors that was discharged into a critically damped load, to 0.5 Ω for a brick with 80 nF capacitors discharged into a matched load. These impedances are not negligible and may lower peak currents achieved in LTD cavities by 20% or more.

Because of its simple design, low prefire rate, and relatively low operating pressure (142 PSIA of dry air), the L3-small-diameter switch has been chosen for tests in a 0.5-MA LTD cavity at Sandia Laboratories. We have demonstrated 41 kA peak currents from a brick with 40.5 nF capacitors charged to plus and minus 100 kV. This is a 70% increase over the peak currents observed in the 0.5-MA LTD-II cavity, which used 40 nF capacitors and HCEI switches. This 70% increase is due partly to the use of improved capacitors and switches in our test system and partly due to the absence of magnetic toroids in our test system. By using improved switches and capacitors along with toroids made of Metglas™ [17] amorphous iron, we intend to see how much of this 70% increase in peak current can be realized in an upgraded version of the LTD-II cavity in the near future.

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[17] Metglas is a trademark of metallic glass products manufactured by Allied-Signal Corporation.