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Field-Distortion Air-Insulated Switches for Next-Generation Pulsed-Power Accelerators

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Abstract

We have developed two advanced designs of a field-distortion air-insulated spark-gap switch that reduce the size of a linear-transformer-driver (LTD) brick. Both designs operate at 200 kV and a peak current of ~50 kA. At these parameters, both achieve a jitter of less than 2 ns and a prefire rate of ~0.1% over 5000 shots. We have reduced the number of switch parts and assembly steps, which has resulted in a more uniform, design-driven assembly process. We will characterize the performance of tungsten-copper and graphite electrodes, and two different electrode geometries. The new switch designs will substantially improve the electrical and operational performance of next-generation pulsed-power accelerators.

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1. INTRODUCTION

Next-generation pulsed power machines may be composed of an arrangement of "bricks", which is an in-series combination of two capacitors and one switch. The brick drives a transmission line connected to the side of the brick opposite the switch.

To realize these machine designs, there is need for a 200-kV, 50 kA spark gap switch. Such a switch could function as the building block of many different architectures, such as linear transformer drivers, Marx generators, and trigger pulse generators.

1.1. Previous Work

The Kinetech 200-kV gas switch, Sandia's original brick switch, reduces the size and inductance of the LTD architecture considerably. Unfortunately, this switch does not lend itself to reliable, repeatable performance in large quantities. While its small size and electrode geometry result in lower switch inductance, the complexity of the entire switch assembly precludes reliable, repeatable operation, due to a lack of documentation and control of the fabrication, cleaning, assembly, and operating specifications. Furthermore, a complex design is expensive in terms of fabrication and assembly time.

1.2. Project Objectives

A switch is needed which can meet all requirements for a next-generation pulsed power accelerator which uses brick-based pulsed power. A switch that meets our requirements had not yet been developed by the international pulsed power community. This is a 60-year-old problem, as there is no paper that describes how to design a low-inductance, 200-kV, 5-GW brick, and there is no paper that describes how to design a switch that can function in such a brick.

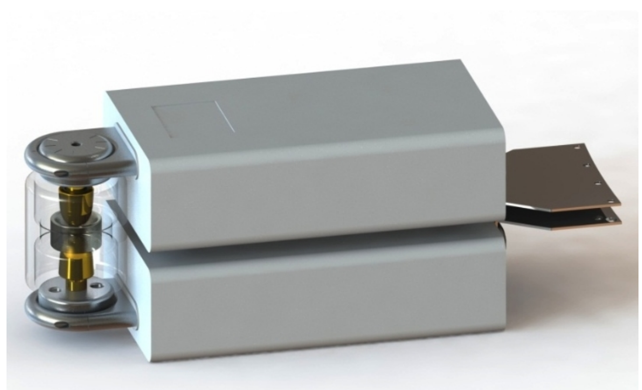

Figure #1. Illustration of the 5-GW LTD brick.

A brick is an in-series combination of two capacitors and one switch (Fig. 1). Although this LDRD was at first proposed as a switch-development LDRD, the problem is broader, since a switch test is not possible without a brick in which to test the switch. The absence of literature on either a brick or switch appropriate to next-generation pulsed power required an approach which developed the switch and the brick as one unit. As a result, this report lists specifications for a brick for next-generation pulsed power machines. Since the switch is a core component of the brick, these specifications, by default, include switch specifications.

2. BRICK REQUIREMENTS

The requirements for a next-generation brick are driven by next-generation pulsed power accelerator concepts, such as those posed in the references [1-4]. These specifications are listed below:

- The brick should operate at a high voltage (up to ±100 kVDC).
- The brick should have a high stored energy (800 J).
- The brick should be triggerable with a small fraction of machine energy (< 2%).
- The brick should have a low prefire rate (≤ 0.4%).
- The brick should have a low misfire rate (≤ 4%).
- The brick should be easy to trigger (runtime jitter ≤ 4 ns).
- The brick should sustain high current (≥ 50 kA).
- The brick should sustain high power (≥ 5 GW), and should do so reliably (≤ 5%).
- The brick should have a low nominal inductance (≤ 160 nH).
- The brick should have a low effective series resistance (≤ 0.3 Ω).
- The brick should have a nominal capacitance of 40 nF (two 80-nF capacitors in series).
- The brick should be compact (length ≤ 46 cm, width ≤ 16 cm, height ≤ 16 cm).
- The switch should be filled with filtered, dry air, as opposed to sulfur hexafluoride (SF_6).
  - Avoid greenhouse gases (e.g. SF_6): the 100-year global-warming potential of SF_6 is a factor of 23,500 greater than that of CO_2.
  - Avoid asphyxiation hazards: SF_6 is an asphyxiant.
- The brick should be electrically triggered to avoid eye hazards posed by laser triggering.
- The brick's switch should use tungsten copper electrodes.
  - Tungsten copper has been correlated with a low prefire rate [5].
  - Tungsten copper does not contain lead, which is a neurotoxin.
- The brick should have a long lifetime (≥ 3,000 shots).

3. SWITCH DESIGNS

3.1. Baseline

We added engineered quality controls to the original Kinetech switch, and this served as our starting point for the switch tests. This switch was adapted from an early switch design originated by Sandia Labs and Kinetech, LLC through a collaborative design process [6-7]. This switch suffered complications in assembly, required oil impregnation of voids in the housing assembly, and exhibited electrode movement when pressurized. This switch became the Sandia baseline switch when Sandia updated the switch's drawing package to correct the electrode movement problem. Figure 2 illustrates this baseline design.

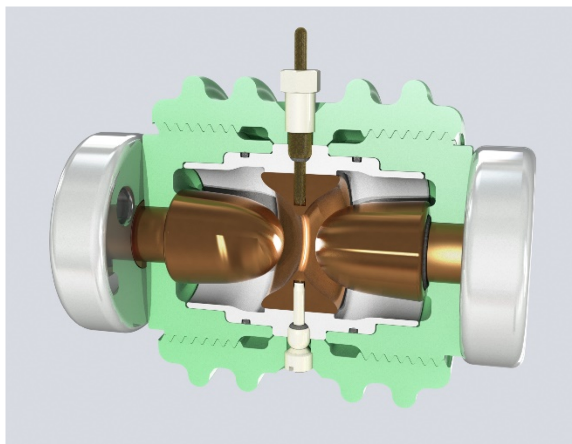

Figure #2. Computer rendering of the baseline switch design.

3.2. Clamshell A

We maintained the physics package of the baseline switch, but the housing design was simplified with a "clamshell" housing. Doing this eased switch assembly considerably, and applied more precise tolerances to the electrode position by virtue of the housing geometry. By contrast, the baseline design allowed for electrode position adjustment, a degree of freedom which was not desired for the brick switch. Figure 3 illustrates this first version of the clamshell design.

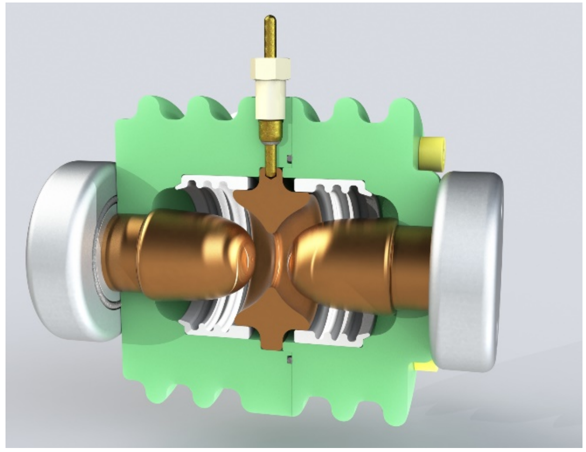

Figure #3. Computer rendering of the Clamshell A switch design.

3.3. Clamshell B

We made additional modifications to Clamshell A to reduce cost, mitigate surface tracking, and further simplify the design. In particular, we eliminated the heat shield surrounding the electrodes, which was composed of expensive polychlorotrifluoroethylene (PCTFE, colloquially known as Kel-F®). We also increased the inner diameter of the switch and added a series of scalloped grooves on the surface to increase the surface tracking length. The test using this switch design yielded the most successful result. Figure 4 illustrates this design.

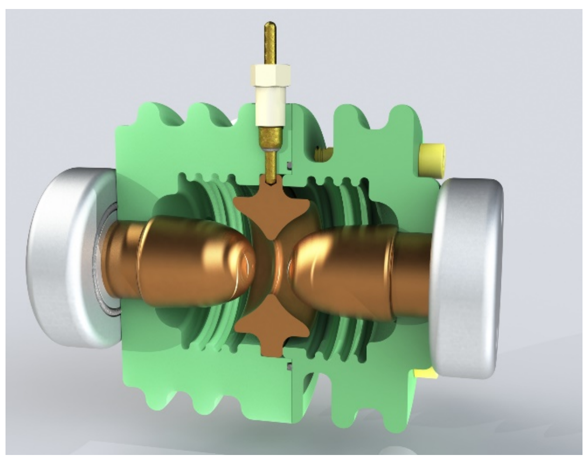

Figure #4. Computer rendering of the Clamshell B switch design.

3.4. Clamshell C

We adjusted the electrode profile of the Clamshell B design to improve performance. Part of the LDRD approach was to design and field novel electrode profiles, which this design revision did. Although the test did not result in drastic performance improvements, inspection of the switch's internal surface following its test sequence revealed surface tracking near the trigger midplane. This may have contributed to the less-that-optimal performance, and suggest an avenue for future work. This electrode design, having a larger electrode-to-electrode gap, operates at a lower pressure, making this switch design safer. Figure 5 illustrates this design.

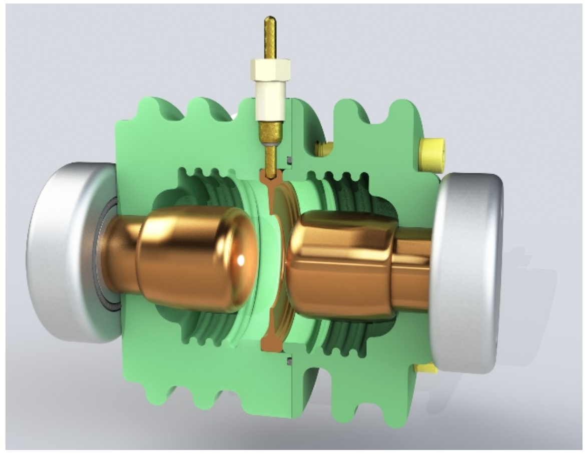

Figure #5. Computer rendering of the Clamshell C switch design.

4. EXPERIMENT SETUP

4.1. Single brick test facility

To test the performance of the LTD brick, we designed, assembled, and commissioned a single brick test facility (Figs. 6-7). This test facility comprises an oil-filled test chamber, charge and trigger circuits, load current monitors, load and trigger voltage monitors, data acquisition, a variable-resistance saltwater load, air pressure control manifold, and a computerized control system that manages the test automatically.

For each shot, the control software uploads the raw test data to a network repository, which a MATLAB analysis program accesses when performing post processing. The processed data is transferred to an Excel spreadsheet for easy access, plotting, and statistical analysis. The statistics collected are compared with the brick requirements to determine the brick's performance quality.

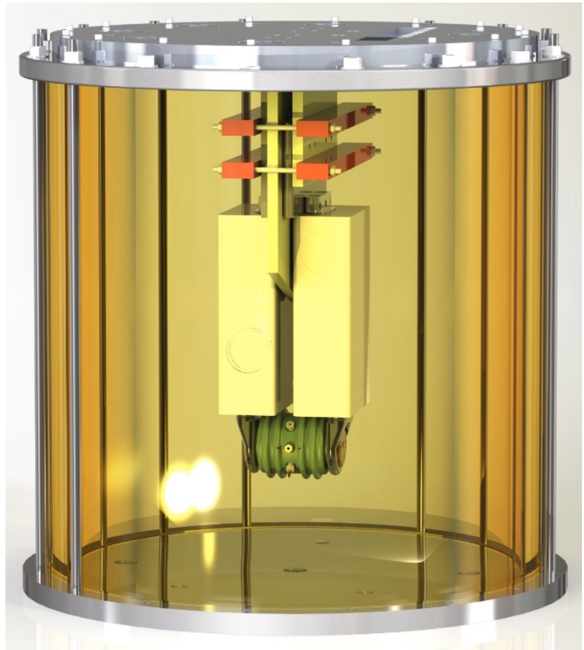

Figure #6. Computer rendering of the single brick test facility.

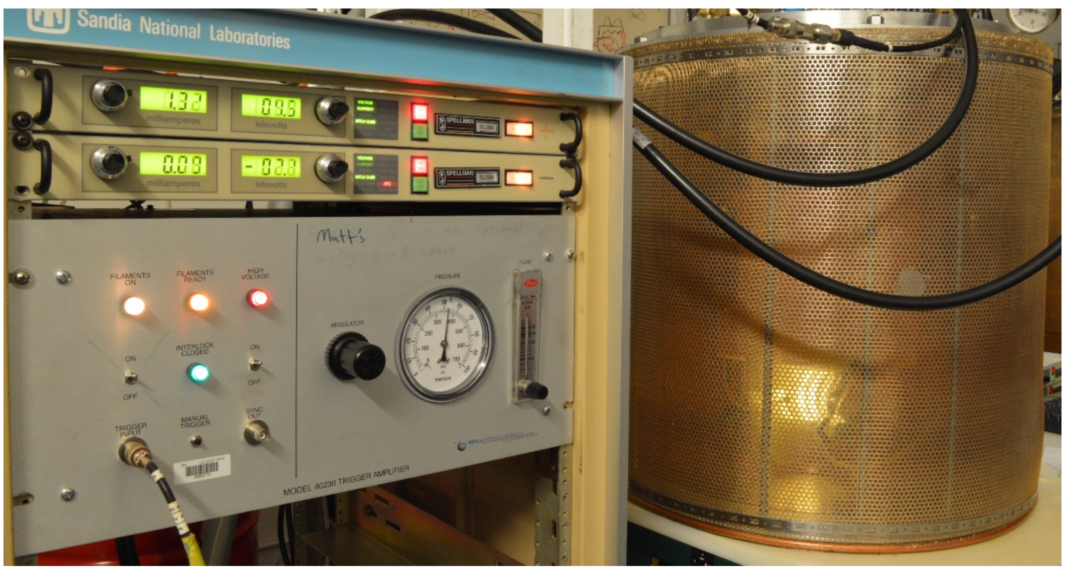

Figure #7. Illustration of the single brick test facility, as installed at Sandia National Laboratories.

4.2. Brick components

Two high-voltage storage capacitors and a high-voltage gas switch are the main components of the brick, pictured conceptually in Fig. 1. The capacitors used in the brick varied, and included General Atomics model 35484, NWL Capacitors model 13321, and CSI Technologies model 100PPM0009L. Regardless of make or model, all capacitors used in these tests had nominal specifications of 80 nF capacitance and 100 kVDC maximum voltage. The double-ended design of these capacitors allows for optimal packing of components, which helps minimize brick inductance. For the anticipated ≤10% voltage reversal, the designed lifetime of the capacitor is specified to be at least 40,000 charge/discharge cycles. When operating the brick, each capacitor is charged to the same voltage, but with opposite polarities. As such, the voltage across the gas switch will be twice the charge voltage. In the tests reported here, the charge voltage was ±100 kV.

4.3. Switch operating parameters

The switch uses Zero-grade, clean, dry air as the fill gas. The switch's hold-off voltage will increase with increasing gas pressure in the switch. The approximate self-break and operating curves for the switch are given in Fig. 8. We typically operate the switch at ~60% of its self-break voltage at a given pressure in order to minimize the occurrences of prefires and misfires.

Immediately after every shot, we flow air freely through the switch, which purges the air inside and reduces particulate contamination inside the switch. In early tests, we found that a 10 second flow-through purge helps maintain a prefire rate of less than 1 prefire per 1000 shots (<0.1%). Without purging, the switch's internal components quickly become contaminated, resulting in frequent prefires and misfires.

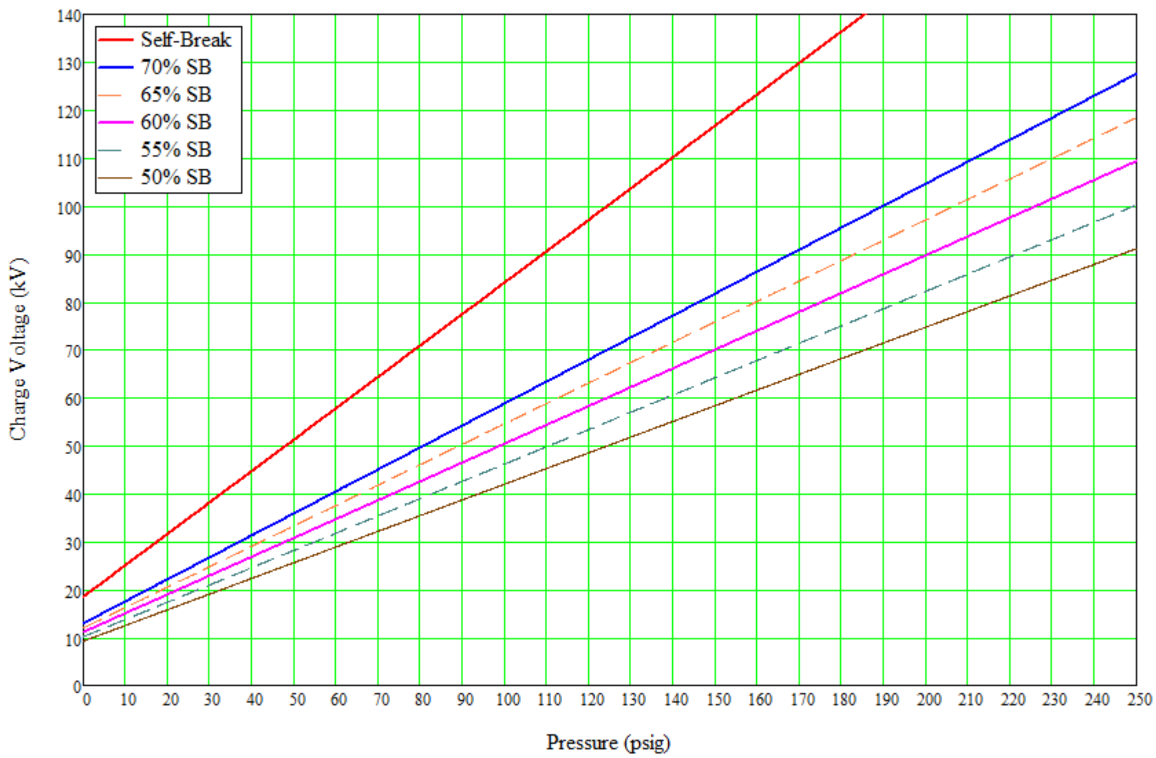

Figure #8. Self-break and operating pressure curves for the Kinetech spark gap switch. In terms of electrodes design, this switch is physically similar to all switches tested.

4.4. Triggering circuit

The switch is triggered by applying a fast-rising voltage pulse from an L-3 42030 Trigger Amplifier to the trigger midplane electrode. The output pulse has a forward-going peak voltage of 64.8 ± 0.6 kV, with a 10%-90% rise time of 7.3 ± 0.1 ns into a Dielectric Sciences 2121 coaxial cable (59 Ω). The trigger pulse couples into the switch's midplane through a 233 pF capacitance composed of three TDK FHV-10AN capacitors in series. Once the trigger pulse arrives at the open switch, the open-circuit reflection approximately doubles the trigger voltage at the midplane and initiates switch closure. To discharge any residual voltage on the trigger line, a 110 kΩ pull-down resistor grounds the trigger line, as does a large-value inductor internal to the trigger amplifier.

4.5. High voltage charge supplies

A pair of Spellman SL130 high-voltage power supplies, one for each charge polarity, charges the brick capacitors with a 1.3 mA (current-limited) current. Each power supply has a 160 kΩ charge resistor between it and the capacitors to reduce the effect of transients. A computerized control system monitors the current and voltage of the power supplies and aborts operation if a charge current or voltage imbalance occurs. In the test configuration presented, the brick fired at a repetition rate of 0.05 Hz, or about 20 seconds per shot, 10 seconds of which was switch purge time.

4.6. Brick insulators

Ancillary components include switch and capacitor mounting brackets, and a set of middle insulators that separate the capacitors. The primary insulator extends from the lid of the brick test chamber to halfway down the switch's diameter, and is physically integrated into the brick. Additionally, a Mylar skirt fits around the switch to obstruct oil breakdown on the DC-charged side of the brick.

4.7. Load resistor

On the end of the brick opposite the switch, a saltwater solution flows through a slot in the primary insulator and serves as the load resistance. The saltwater's conductivity is readily adjustable, which allowed us to scan resistances to maximize peak power at about 2.2 Ω. Capacitive and inductive probes monitor load voltage and current. Table I summarizes the 5 GW brick's performance.

5. EXPERIMENT RESULTS

The bricks and their switches met the specifications listed in the Requirements section. Table I compares the performance of a single brick against the requirements, and Table II lists the performance of each brick tested. Each switch design was tested at least once. Operating parameters were also optimized; disentangling these parameters to attribute the relative significance to each is the topic of future work.

Table #1. Summary of 5 GW brick performance (test designation: Clamshell B, Kinetech electrodes).

Specification	Requirement	Actual
Capacitor charge voltage	±100 kV	±100 kV
Stored electrical energy	800 J	800 J
Trigger energy % of brick energy	< 2%	< 1%
Prefire rate	≤ 0.4%	< 0.1%
Misfire rate	≤ 4%	< 1 %
Runtime jitter	≤ 4 ns	< 3.5 ns
Peak current	≥ 50 kA	51 kA
Mean peak electrical power	≥ 5 GW	5.2 GW
Standard deviation of peak power	≤ 5%	1.5%
Nominal inductance	160 nH	160 nH
Nominal resistance	0.3 Ω	0.4 Ω
Nominal capacitance	40 nF	41 nF
Length	≤ 46 cm	45 cm
Width	≤ 16 cm	16 cm
Height	≤ 16 cm	16 cm
Fill gas (dielectric)	Filtered, dry air	Zero-grade, pure, dry air
Trigger	Electrical	+65 kV into 50 Ω
Electrode material	Tungsten copper	Tungsten copper
Brick lifetime	≥ 3,000 shots	≥ 5,000 shots

Table #2. Summary of each switch and brick tested.

switch style	Prefire rate	Misfire rate	Pressure (psia)	Charge voltage (kV)	Jitter (ns)	Peak current (kA)	Peak power (GW)
Baseline, Kinetech electrodes	0.03%	0.0%	242	200	1.8	49 ±0.7%	5.0 ±0.8%
Baseline, Kinetech	0.07%	0.0%	242	200	2.1	48 ±0.7%	5.0 ±1.0%

electrodes							
Clamshell A, Kinetech electrodes	0.0%	0.0%	242	180	1.5	46 ±1.0%	4.2 ±0.8%
Clamshell A, Kinetech electrodes	0.0%	0.0%	242	180	3.5	47 ±0.5%	4.2 ±1.0%
Clamshell B, Kinetech electrodes	0.0%	0.8%	266	200	3.1	51 ±0.8%	5.2 ±1.5%
Clamshell C, low-field electrodes	0.1%	1.8%	206	200	4.6	50 ±2.8%	5.0 ±2.4%

6. SUMMARY

The results of this LDRD are encouraging to the future of pulsed power, and present a path forward to a brick suitable for next-generation machines. All the specifications listed for next-generation pulsed power were met. Additional testing should be done to improve the certainty of reliability, which will allow design risk to be calculated confidently. At this time, the sample size of each tested switch is low, however, the parameters and designs used in these experiments direct us toward a solution which can be refined with additional testing. This inspires follow-on work to further refine the design from the point achieved by this LDRD.

7. FUTURE WORK

With the result of this LDRD, we have created several point designs from which we can grow a well-defined switch model. Of all possible paths, the most beneficial approach would be one that repeats the same test many times over to establish some statistical certainty of the results. Once this new baseline model is established, the effect of additional improvements to the design will become distinguishable as we are able to attribute some statistical significance to design changes.

The several switch designs presented here are all valid starting points for improvement, but given the good performance of the *Clamshell B, Kinetech electrodes* test article in Table #2, combined with its simplified design, this design is the recommended starting point for establishing this new, statistically-quantified baseline design. As such, this design will be the new starting point for future switch designs that will seek to improve the switch design further.

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