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EXPERIMENTAL RESULTS FROM THE 1.2 MA, 2.2 M DIAMETER LINEAR TRANSFORMER DRIVER AT SANDIA NATIONAL LABS

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Abstract

Herein we describe the design, simulation and performance of a 118-GW linear transformer driver (LTD) cavity at Sandia National Laboratories. The cavity consists of 20 to 24 "Bricks". Each brick is comprised of two 80 nF, 100 kV capacitors connected electrically in series with a custom, 200 kV, three-electrode, field-distortion gas switch. The brick capacitors are bi-polar charged to a total of 200 kV. Typical brick circuit parameters are 40 nF (two 80 nF capacitors in series) and 160 nH inductance. Over the course of over 10,000 shots the cavity generated a peak electrical current and power of 1.19 MA and 118 GW.

I. BACKGROUND ON LTD DEVELOPMENT AT SANDIA

Sandia and other pulsed power laboratories around the world have been developing high-current LTDs for more than two decades [1]–[5]. The motivation for this research has been to determine if this technology is a viable alternative to the primary pulsed power stages and pulse compression techniques often used in mega-Volt, mega-Ampere drivers with output rise-time of order 100 ns.

A high-current LTD cavity typically contains 20 to 48 "bricks", with each brick being composed of two low-inductance, high-voltage capacitors with a gas switch connecting them in series. All brick components, charging circuitry and trigger circuitry are typically enclosed in a cylindrical metal vessel, which is commonly referred to as the "cavity". The output of a single high-current LTD cavity is typically 80 to 100 kV and 700 kA to 1 MA into an under-matched load. Target applications for LTD technology typically require output voltage greater than 1 MV; in these cases many cavities would be stacked in series (voltage adding) to form an LTD "module" with the desired output voltage; Ursa Minor [6] was a 21-cavity LTD module.

The primary challenges to fielding LTDs in this application space are reliability, scalability and cost. The research presented in this manuscript focuses on analysis and improvements to LTD reliability at the single-cavity scale.

II. RELIABILITY SCALING

All scales of high-current LTD-based pulsed power drivers, including single-cavity (10^{11} W), multi-cavity voltage adder module (10^{12} W), and multi-module current adder (10^{13} W), are built from the same fundamental "brick" (10^{10} W) as described in Sec. I with additional detail provided in [1], [3]–[5], [7]. In the ideal case we would be able to extrapolate system reliability, regardless of scale, from brick reliability derived from exhaustive single-brick testing. In fact, exhaustive single-brick testing and design refinement have been carried out at Sandia since 2010. However, in practice, single-brick reliability is a necessary but insufficient condition to achieve satisfactory system reliability at larger scales.

The primary differences between the single-brick and single-cavity operational environments are: the presence of neighboring bricks, packing fraction, physical orientation, and visibility to the operator.

A. Neighboring Bricks

In a single-brick test chamber a switch misfire event (prefire, late-fire or no-fire) generally has no harmful effects on any of the brick components. This is certainly not the case when neighboring bricks are present, and

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especially when the bricks are in as close a proximity as possible to achieve a high packing fraction. For example, a prefire in an LTD cavity will put far more stress than normal on charging resistors and trigger circuit isolation components, and can damage the prefiring switch if the entire cavity (all brick capacitors) discharges through the offending switch.

B. Packing Fraction

The high DC charge voltages at which these systems are operated necessitate that they be submerged in transformer oil; consequently, they reside in some form of oil tank. For convenience and forward compatibility with larger test objects the oil tanks used for single-brick tests are generally significantly larger than the volume of the brick, i.e. the packing fraction is low. In this case the standoff distances between the brick components and the surrounding vessel (oil tank) are much larger than required to prevent DC electrical breakdown. Additionally, should any contaminates such as large particulates or air bubbles be carried in by the oil circulation system (or any other route) there is at least a fair chance that they will not be deposited in regions of extreme field stress. Neither of these beneficial conditions exist inside an LTD cavity where the packing fraction is as high as possible by design.

C. Brick Orientation

The mentality behind single-brick reliability testing is generally to evaluate the reliability of brick components under best-case conditions. The additional complexity that would be imposed on a test stand to evaluate secondary concerns like brick orientation is comparable to the effort required to construct an entire cavity. Naturally, investigation of effects induced by such things as brick orientation are deferred to single-cavity testing. Should any of the various brick orientations present in the single-cavity be less reliable than the sole orientation found in the single-brick experiment then an unaccounted bias in system reliability could be introduced. As will be seen in the following experimental results capacitor failures are correlated with brick position inside the cavity (at least for the configuration under examination).

D. Experiment Visibility

At Sandia the experimental volume of a single-brick test stand is much smaller than a single cavity and single brick testing is done inside a glass oil tank. Under these circumstances the environmental conditions of the single-brick experiment are enormously more transparently visible to the operator than in the single-cavity experiment. This disparity in visibility leads to fundamentally different methods of operation between single-brick and single-cavity testing.

First let us consider operations with the highly visible single-brick test stand. Should a potentially harmful circumstance be visible to the operator, such as a tiny air bubble stuck to a capacitor, the operator will probably pause experiments to clear the bubble; after all the intent here is to evaluate component reliability under best-case circumstances. The issue may or may not have caused a problem and there is no telling if the problem would have been fatal or simply degrading in a moderate, mild or temporary way. Additionally, if the operator chose not to address the potential issue and it did result in a significant outcome then it is at least known with some confidence what the source of the issue was, i.e. characteristic of brick or an external factor.

Now consider the black-box-like single-cavity reliability testing environment. Under normal conditions (with metal “lids” installed, see [7], Fig. 2) the operator has zero visibility of the conditions inside the cavity. The reliability test is only paused after a failure has occurred. Component failures usually occur while charging so shot diagnostics generally provide no information as to the failure. To address the failure the cavity must be drained of oil and opened (lid removed). Usually the failed component can be identified by visual inspection. However, unlike the single-brick experiment, the cause of the failure is usually open to speculation. Perhaps the failure was a latent effect of an issue that occurred one or more shots ago; we have no way of knowing. This naturally leads to substantial uncertainty in estimation of reliability at the single-cavity level because it is unclear which failures should be considered characteristic of the cavity design and its internal components as opposed to external factors.

These distinctions between single-brick and single-cavity experiments, along with the supposed distinctions between single and multi-cavity experiments, etc., demonstrate the need to conduct reliability testing for each scale of high-current LTD pulsed power driver. The differences between the scale of experiments is not limited to the number of components involved; one must also understand the impact of operational and maintenance procedures when assessing system reliability.

III. LTD CONSTRUCTION

The construction of this LTD cavity is presented in detail in [7]. The only modification that has occurred since the publication of [7] is the addition of four bricks, which fills the cavity to its designed capacity. The 24-brick configuration is illustrated in Fig. 1.

As mentioned in [7], significant improvements were made to the charging and trigger circuits of this LTD over previous configurations [4]. The cavitys internal charging resistors are now made from solid, carbon composition, high-voltage, axial-package resistors. Six 10 kΩ resistors connected in series (to form a 60 kΩ chain) connect neighboring charge terminals, as shown in Fig. 1. Previous LTDs used aqueous charging resistors ranging in value from 1 to 10 kΩ. Should a prefire occur, the high-

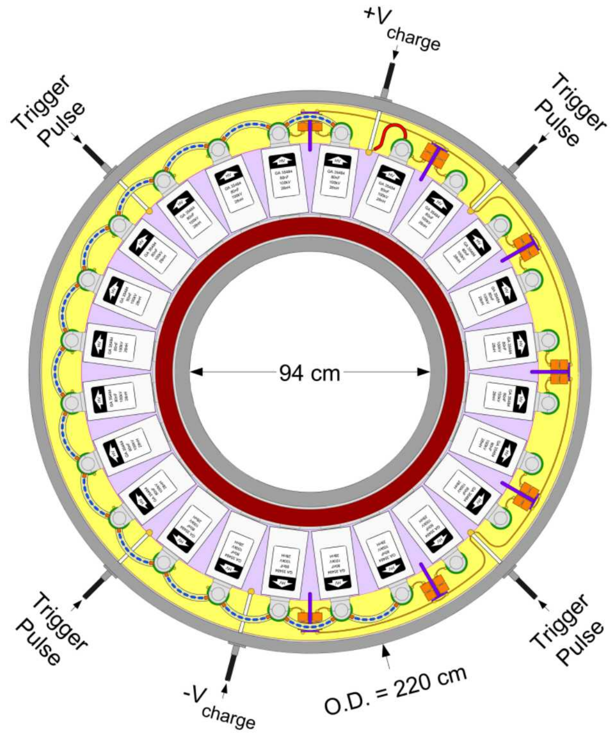

Figure 1. Illustration of the 24-brick cavity with the lid removed. Right half of illustration shows original capacitively-coupled trigger circuit layout. Left half of illustration shows charging resistor configuration.

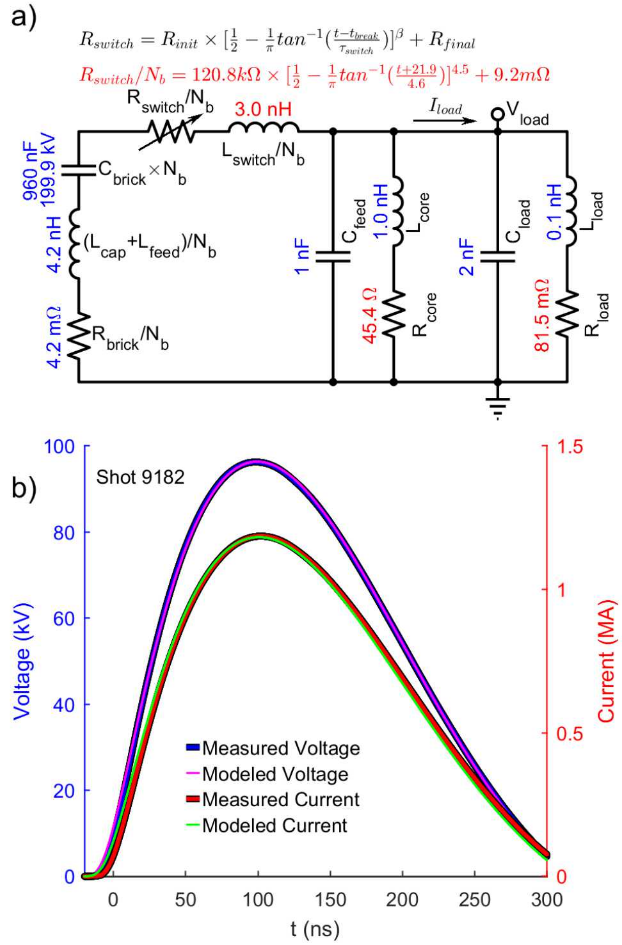

Figure 2. Sample simulation and experimental results. A) lumped element circuit model of 24-brick LTD with fixed component values (blue) and best fit component values (red) determined by Genetic Algorithm optimization. N_b is the number of bricks in the cavity (24). B) Experimental voltage (blue) and current (red) along with simulation results from circuit model and parameters shown in upper diagram.

impedance (60 kΩ) resistor provides sufficient current limitation to prevent charge in neighboring bricks from being discharged through the switch that prefired (there is insufficient current to maintain the arc in the switch).

The original trigger circuit of this LTD used ceramic door knob capacitors to provide DC isolation between the trigger generator and each switch trigger terminal. Trigger connections are cascaded to all switches from four nominally identical trigger input pulses on 58 Ω coaxial cables as shown in Fig. 1. The capacitive isolation provided very little isolation between pairs of switches that are connected to the trigger bus at nearly coincident locations. This created a system that was sensitive to switch jitter of about 2 ns and resulted in a high rate of switch late-fires. Replacing the ceramic capacitors with wire-wound inductors of about 5 μH essentially eliminated switch late-fires. Note, caution must be exercised with an inductively isolated trigger circuit such as this. In the event of a switch misfire, a long pulse at full charge voltage of either polarity could be sent from the cavity to the trigger generator.

IV. LTD PERFORMANCE

Typical 24-brick LTD output current and voltage when driving an under-matched, purely resistive load, with $R_{load} = Z_{LTD}$ (0.08 Ω), are plotted in Fig. 2b for $V_{chg} = \pm 100\ kV$. Maximum output current achieved was 1.19 MA.

V. LTD CIRCUIT ANALYSIS

Circuit simulations of this LTD cavity have been performed using a combination of nominally-known and best-fit values for circuit parameters. The simplified, lumped-component circuit is shown in Fig. 2a.

Several circuit parameter values were determined by best fit to experimental data. Circuit parameter fitting was accomplished by Genetic Algorithm (iterative) optimization with sensible initial guesses and no bounds constraining the parameters being optimized. The only parameters with significant variability between experiments that were nominally identical were switch dynamics and magnetic core loses. Dynamic switch parameters primarily serve to match the simulation to LTD output early in time; core loss parameters are most significant in matching the tail of the output pulse.

Sample simulation results along with the experimental data that they were fit to are shown in Fig. 2b. The average disagreement between experiment and optimized-fit-simulation output is typically less than 1% of peak current and voltage.

VI. LTD Cavity Reliability

The majority of the experiments performed with this LTD cavity were conducted with 20 bricks and charge voltage of 100 kV; the associated reliability metrics were reported in detail in Ref. [7]. To summarize the previously reported results: switch prefire probability was reduced to 10^{-4} to 10^{-5}, switch late-fire and no-fire probabilities were reduced to less than 10^{-5}, capacitor failure rate was about 5×10^{-6} (one failure), resistor failure probability was about 5×10^{-5} and there was zero switch mortality or degradation over the course of 6,556 shots conducted over a ten-month time frame.

The new results reported here come from the same LTD cavity but with four new bricks added. The layout of the 24-brick configuration is illustrated in Fig. 1. Also, whereas all of the previously reported work was conducted with 100 kV charge voltage, the new experiments utilized various charge voltages to investigate the effect of electrical stress on system reliability; this was the primary motivation for the new experiments.

The results from 24-brick experiments are shown in Fig. 3, where we plot the peak output current of each experiment along with system malfunctions and component failures.

Output performance of the 24-brick configuration exhibited good consistency at all charge voltages once reliable triggering had been re-established around shot 6900 ("Trigger gen. rebuild" in Fig. 3). Switch misfire event probability decreased somewhat with lower charge voltages.

Zero component failures occurred while operating at 90 kV charge. At least one capacitor failed in every campaign with V_{chg} above 90 kV. However, the first three capacitor failures occurred in an environment where air bubbles were being generated inside the cavity by a faulty charge cable connection. The discovery and elimination of this issue are indicated in Fig. 3 around shot 7850. Charging waveforms show conclusively that the faulty charge connection was present from the beginning of 24-brick operation. Since the failed capacitors were generally near the top of the cavity (positions 23 & 24), where bubbles would certainly pass, and all were on the same side as the faulty charge connection (negative terminal), it seems likely that the capacitor failures were induced by

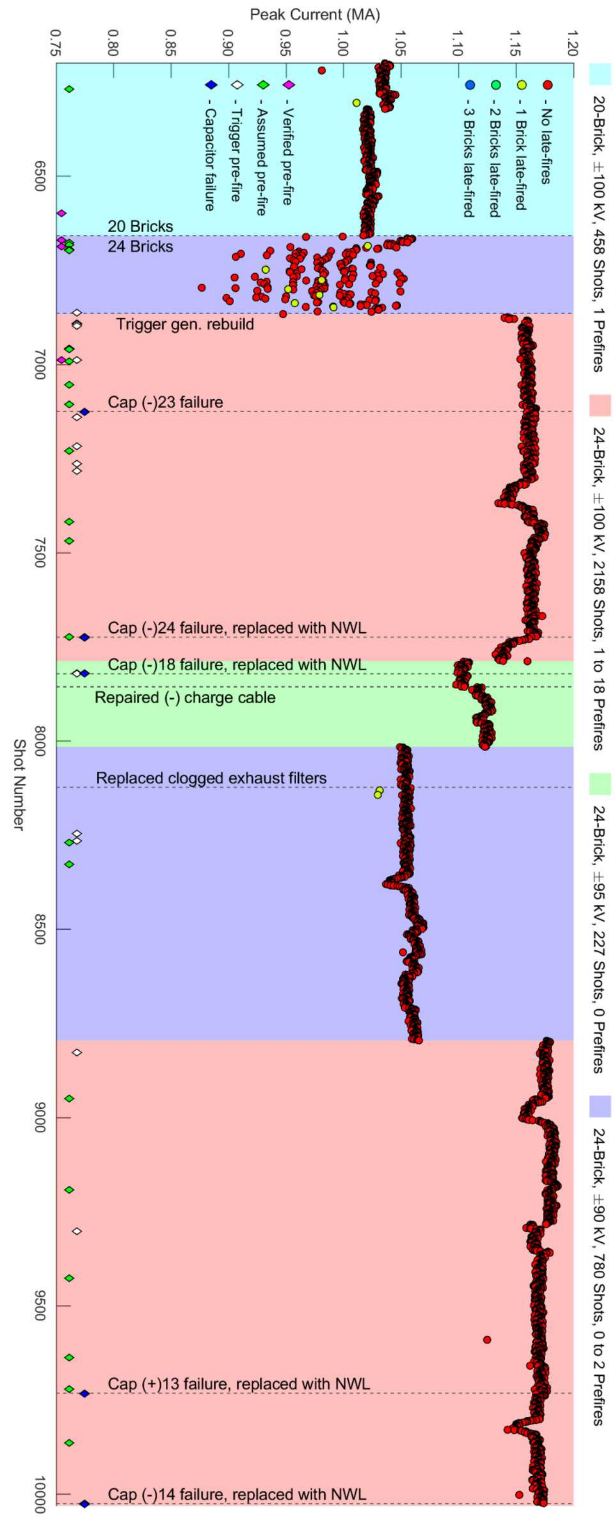

Figure 3. Peak output current from LTD cavity (round markers). Background color indicates number of bricks and charge voltage according to legend at right. Diamond markers near shot number axis indicate malfunctions and capacitor failures. Color of round markers indicates number of late-firing switches.

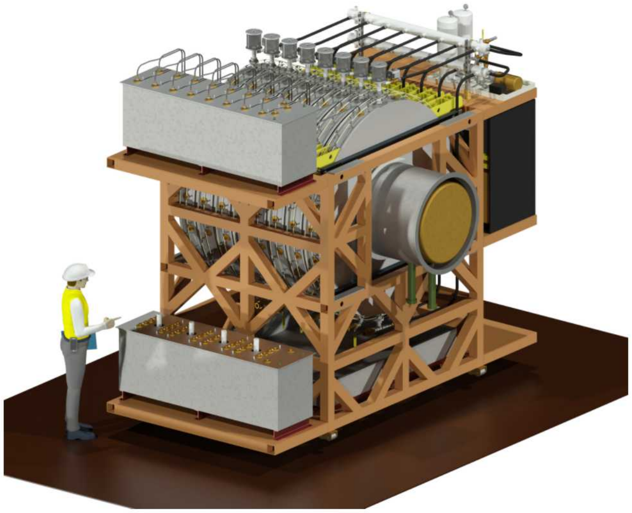

Figure 4. Conceptual model of an 8-cavity module presently in design and procurement.

air bubbles. Additionally, one of the capacitor failures that occurred at 100 kV charge after the charge connection was repaired was in a capacitor that had nearly 10,000 shots on it, which is the expected normal lifetime for these units and operating conditions. Hence, the claim that operation at reduced stress is beneficial to component reliability is somewhat tenuous, at least for the level of stress reduction implemented in our experiments. Based on the results presented here it would be fair to conclude that the reduction in component stress by decreasing the charge voltage from 100 kV to 95 kV does not substantially decrease the sensitivity of this LTD to unfavorable operating conditions, i.e. air bubbles. Given that no component failures occurred over a span of about 1,000 shots at 90 kV, perhaps the threshold for reliable operation in practically achievable operating conditions is in the 90 kV charge voltage regime.

VII. CONCLUSIONS

Our investigations of high-current LTD reliability at the single-cavity level have been carried out with objectivity and transparency. Assuming that design improvements to charge cable connections eliminate unfavorable oil conditions, then by our estimation the system reliability sufficient to justify an investigation into the reliable and practical operation of a multi-cavity module has been demonstrated.

The design and procurement of components to construct an 8-cavity module based on the LTD presented here is presently underway. A conceptual model of this driver is shown in Fig. 4.

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