

PERFORMANCE ENHANCEMENTS AND RESULTS OF TESTING A NEW 6.7 MV LASER-TRIGGERED GAS SWITCH SYSTEM ON THE REFURBISHED Z ACCELERATOR*

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Abstract

As the last command-triggered switch in the Refurbished Z accelerator at Sandia National Laboratories (SNL), the laser-triggered gas switch (LTGS) system is instrumental in the overall performance of Z and allows for flexibility in pulse shaping for various experimental campaigns. It is desirable to push the operating envelope of the switch to higher voltages and currents to allow for a higher peak power to be delivered to the load while at the same time reducing jitter and pre-fire rate for increased precision and reliability. We have accomplished this in a version of the LTGS that we call the C1.1 with the constraint of keeping the overall switch size consistent with physical space available. The C1.1 LTGS consists of laser-triggered and cascade portions which has been reported on previously.[1] However, the C1.1 eliminates the trigger plate and supports the cascade section in a cantilevered fashion. Improvements to this iteration of the LTGS were mainly mechanical in nature. Other minor electrical improvements were made to reduce regions of electric field enhancement and to reduce the likelihood of tracking by adding scalloping to the center support rod. Materials choice for the center support rod was important due to both the mechanical and electrical requirements placed on this component. Mechanical shock testing of the improved switch was performed on a shaker table available at SNL prior to installation on Z and showed that the improvements resulted in less displacement of the cantilevered end and less rotation of components in the cascade section. All electrical testing of the improved LTGS was performed on the Z machine. To date, we have accumulated 377 shots on C1.1 switches

without a pre-fire. Runtime statistics are determined after each shot and show that the C1.1 switches are very tolerant to voltage and pressure variations exhibiting median runtimes of 43.9 ns with a jitter ($1-\sigma$) of 5.4 ns for all switch closures. The modifications made to and the performance results of the improved LTGS system are detailed in this manuscript.

I. INTRODUCTION

The Sandia National Laboratories' Z accelerator requires nanosecond synchronization of up to 36 pulsed power driver modules arranged in parallel to deliver mega-ampere level current to its load. Z's architecture consists of many stages of energy storage and switching for temporal and spatial energy compression in order to deliver very high power densities to loads of interest. Energy is first stored over several minutes in Marx banks that, when switched, charge intermediate storage capacitors on a microsecond time scale. The intermediate storage capacitors are discharged into pulse forming lines (PFL) by sulfur hexafluoride (SF_6) filled laser-triggered gas switches (LTGS) that are immersed in mineral oil. The water-filled PFLs transport energy to self-closing water switches which deliver energy to a water-vacuum interface. Power then flows to the load via magnetically insulated transmission lines (MITL). This architecture allows for generation of mega-ampere load currents on a sub-microsecond time scale.

There is a mismatch in the erected capacitance of the Marx banks and the intermediate storage capacitor on each module of Z. As such, for a ± 95 kV charge on the 30 stages of the bipolar Marx bank (5.7 MV erected) the

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voltage seen across the LTGS could be as high as 6.7 MV. To allow for higher load currents to be attained on Z and as a result achieve higher material pressures and higher X-ray yields the Marx banks must be charged to 90-100 kV. In addition to pulse forming line upgrades and a planned water-vacuum interface stack upgrade, the LTGS is a key element that will allow Z to achieve higher load currents.

II. THE C1.1 LASER-TRIGGERED GAS SWITCH

The C1.1 laser-triggered gas switch (LTGS) is an evolution of the Rimfire switch reported on some time ago [2] and the “A” series switch reported on in [1 and 3]. The C1.1 LTGS consists of a laser-triggered portion and 22 self-breaking gaps. C1.1 switch is unique from previous versions of the switch in that the internal electrode components of the switch are supported in a cantilevered fashion. A cross-sectional view of the C1.1 LTGS is shown in Fig. 1.

After extensive testing of the switch in a high voltage test bed, the first installation of a C-type LTGS in Z was in 2010. The initial C1 switch suffered from failures due to unanticipated flashing of the center support rod which was later found to be due to metallic debris from the tensioning mechanism infiltrating into the annular SF₆ filled region surrounding the center rod.

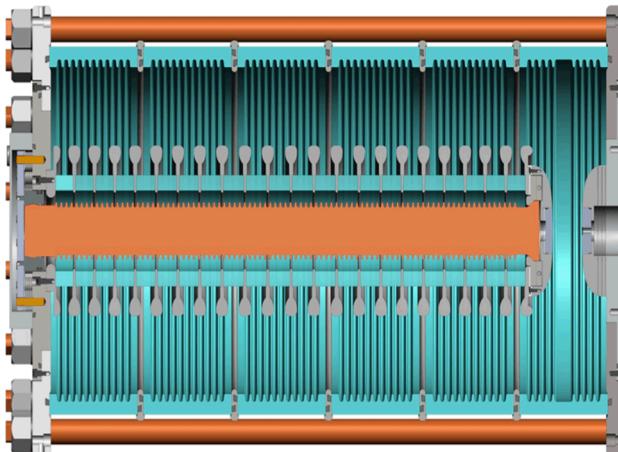


Figure 1. Cross sectional view of the C1.1 laser-triggered gas switch.

The unique features of the C1.1 LTGS are:

- Scalloped Torlon 4203 center rod,
- Torlon 4203 outer housing containment rods,
- Bellville washer tensioning mechanism,
- Tungsten alloy triggered electrode inserts,
- Varied cascade section electrode spacing for a uniform axial electric field,
- Elimination of the trigger plate to facilitate cascade section closure,

- Modified Harrison profile on the triggered electrodes, and
- Diagnostics.

These features will be discussed in the following paragraphs.

A. Cantilevered Section Support Rod and Outer Housing Containment Rods

One significant difference in the C1.1 LTGS from previous versions is that there is no trigger plate that is used for structural support of the cathode triggered electrode and cascade electrode assembly. Elimination of this trigger plate results in an enhanced overstressed electric field in the first cascade gap after the triggered gap closes. Since the total switch jitter is dominated by jitter in the cascade section and jitter in the first cascade gap accounts for a majority of the jitter in the cascade section of the switch, elimination of the trigger plate results in a lower overall jitter for the C1.1 LTGS.

The center support rod has demanding electrical and mechanical requirements placed on it. The support rod must withstand a significant amount of longitudinal and transverse mechanical stress without fracturing. It must also support ~85% of the voltage placed across the switch without flashover.

The material chosen for the center support rod is Torlon® 4203. From the manufacturer’s data sheet [4]:

“Torlon 4203 is an unreinforced, lubricated, pigmented grade of polyamide-imide (PAI) resin for extrusion. It has the best impact resistance and greatest elongation of all the Torlon grades. Torlon PAI has the highest strength and stiffness of any thermoplastic up to 275 °C (525 °F). It has outstanding resistance to wear, creep, and chemicals.

Torlon 4203 offers outstanding electrical properties, which makes it ideal for high performance parts such as connectors, switches and relays. In addition Torlon 4203 polyamide-imide can be used in applications such as thrust washers, spline liners, valve seats, bushings, bearings, wear rings, cams and other applications requiring strength at high temperature and resistance to wear.”

The mechanical and electrical properties of Torlon® can be found in the manufacturer’s data sheet. In our experience, the Torlon® components were easy to machine. However, the Torlon® rod stock as supplied from the manufacturer has a thin discolored outer region on it that we call a “bark” because it is similar to tree bark. Although there were claims made by the manufacturer that the bark has material properties similar to the bulk of the material, high voltage testing revealed otherwise. As such, we found that purchasing oversized stock and removal of the bark is necessary for achieving

the desired electrical performance from the finished components.

The outer surface of the center support rod was scalloped to mitigate electrical flashover at high voltage similarly to how high voltage power line insulators are scalloped in order to break up long stretches of high electric field tangential to the surface of the insulator.

The outer housing containment rods are also made of Torlon® 4203 due to its superior mechanical properties. Going to a higher switch hold off voltage requires a higher SF₆ pressure than currently being used. Analysis of the switch internal pressure during the firing pressure transient necessitated using a stronger material (over Nylon) to hold the switch together.

B. Center Support Rod Tensioning Mechanism

The center support rod is held in place at one end by a two-piece clamp. This clamp is in turn bolted to a plate that places the rod in tension using multiple stacks of Belleville washers between it and the end plate of the switch. A known amount of compression of the Belleville washers translates into a known amount of tension in the center support rod. Shims and the height of the Belleville washer stack are used to set the compression in each stack after hold down bolts are tightened. The number of Belleville washer stacks was maximized around the circumference of the tensioning plate and were placed at the maximum radius possible, given other physical constraints, in order to maximize the mechanical advantage of the clamping mechanism. In the first version of the C1 switch, metallic wear product debris generated in the tensioning mechanism infiltrated into the electrical portion of the switch presumably due to pressure gradients. The end clamp was modified to accommodate O-rings between it and the center rod and also between it and the pressure vessel end plate in order to mitigate any debris entry into the annular SF₆ filled region around the center rod.

The first version of the C1 LTGS suffered from a large deflection of the cascade section end and movement of components during the Z machine post firing shock profile. Since fixtures were already available for use, the cascade section was subjected to shock testing to determine how much of an improvement was made with the mechanical improvements to the clamping mechanism. The applied shock profile was based on g-logger measurements taken on Z. In addition to various accelerometers, a linear potentiometer was used to measure the deflection at the unsupported end of the cantilevered section. Shock testing revealed that the peak deflection of the cascade section end was reduced by more than a factor of two. Rotation of components (cascade pucks and electrodes) was also significantly reduced. The cascade section is shown supported by the test fixture and mounted to the shaker table in Figure 2. The measured end deflection after some number of hits is shown in Fig. 3. The shock testing was performed for 500

hits at the actual amplitude and 500 shots at an amplified amplitude of +3 dB (1.41x). No mechanical failures of any components was observed.

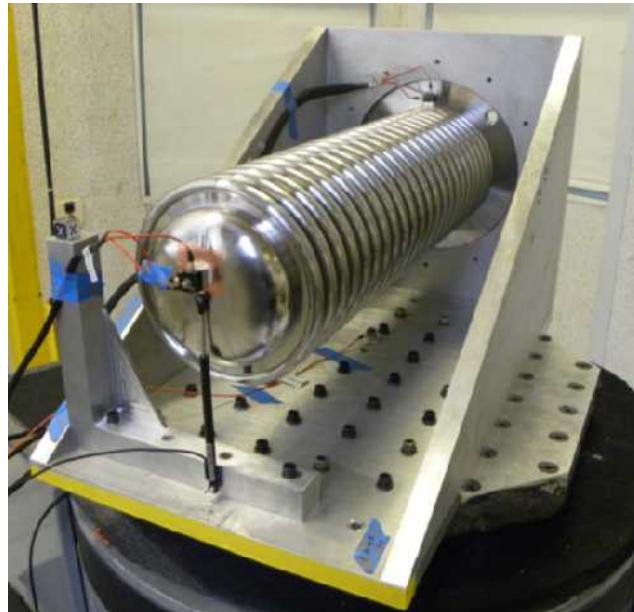


Figure 2. Cascade section of the C1.1 laser-triggered gas switch in a test fixture on the shaker table.

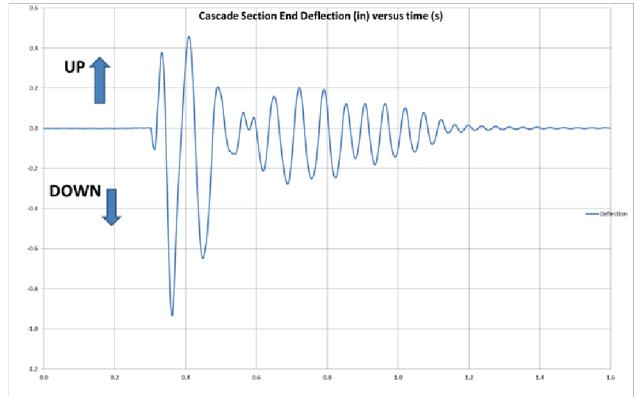


Figure 3. Measured cascade section end deflection during an actual Z machine shock profile applied on the shaker table.

C. Triggered Electrode Section

The unique features of the triggered section of the C1.1 LTGS are the removal of the trigger plate, the modified Harrison profile [1,3] on the triggered electrodes and the material used for the trigger electrode inserts.

Removal of the trigger plate used in previous versions of the switch allows for a larger electric field overstress in the first cascade gap after the triggered gap is closed. This overstress facilitates closure of the cascade portion of the switch. Since the runtime jitter of the switch is dominated by the cascade section, and the jitter of the cascade section is dominated by the first one or two cascade gaps, removal of the trigger plate should

significantly reduce the jitter of the C1.1 switch. This has been proven in electrical testing which shows that the runtime jitter of the C1.1 switch is more 2x less than the in the A5 switch that it will replace.

The modified Harrison profile is used for the triggered gap in order to create, as much as possible, a uniform electric field in this gap. The triggered electrode inserts are made from Elkonite 50W3 which is a 90% tungsten particulate, 10% infiltrated copper by weight manufactured by CMW, Inc. Weibull reliability statistics were applied to self-closure voltage data for various triggered gap profiles and electrode insert materials in order to determine what pressure is appropriate for a given voltage for some desired prefire rate.[1,3] The combination of modified Harrison electrode profile and Elkonite 50W3 insert material yielded the lowest prefire rate which is predicted to be 0.001% at an operating voltage of 6.7 MV.

D. Switch Diagnostics

The closure time, or *runtime*, of each of the 36 LTGSs on Z is monitored after every shot. A laser spark detector (LSD) is used in conjunction with each modules laser photodiode (PD) signal and pulse forming line (PFL) voltage probe diagnostic. The LSD basically consists of a lens that collects light from the expected location of the arc channel and couples this light into an optical fiber. The fiber then sends its light to a photomultiplier tube. The LSD is used prior to a shot during “light ups” to ensure proper optical alignment and plasma channel formation in the pressurized SF₆ and on-shot to monitor the arc channel formation during switching.

Use of the PD and PFL voltage diagnostics allows for determination of the total switch runtime. Use of the PD and on-shot LSD signal allows splitting the total switch runtime into its triggered and cascade section runtime components as follows. Look at the linear slope on the rising edge of the PD and LSD signals at half maximum and find their respective zero crossings. The time difference between these zero crossings is the triggered gap runtime. Look at the derivative of the PFL D-dot signal and find its peak. This is the closure time of the switch delayed ~13 ns by propagation through a transmission line. The time difference between the PD zero crossing and the peak of the derivative of the PFL D-dot is the total switch closure time.

III. SWITCH CLOSURE RUNTIME PERFORMANCE

For each switch closure on Z, runtime statistics are calculated in order to monitor switch performance and recommend runtime deviations which are input to the timing control system for the next planned shot to more precisely achieve the desired current profile.

As of writing this manuscript, the last Z shot number was 2520 and runtimes for all C1.1 switches have been

calculated up to and including this shot. The shots C1.1 switches were on Z included Marx charge voltages from 53 – 85 kV. Some shots were anomalous in that the pressure setpoint for the shot deviated from the desired value for the particular Marx charge voltage due to a machine problem. A histogram of the calculated runtime for all C1.1 switch closures is shown in Fig. 4. For the 377 C1.1 LTGS closures, the median runtime is 43.9 ns and the standard deviation, or jitter, is 5.4 ns.

C1.1 LTGS Runtime Distribution

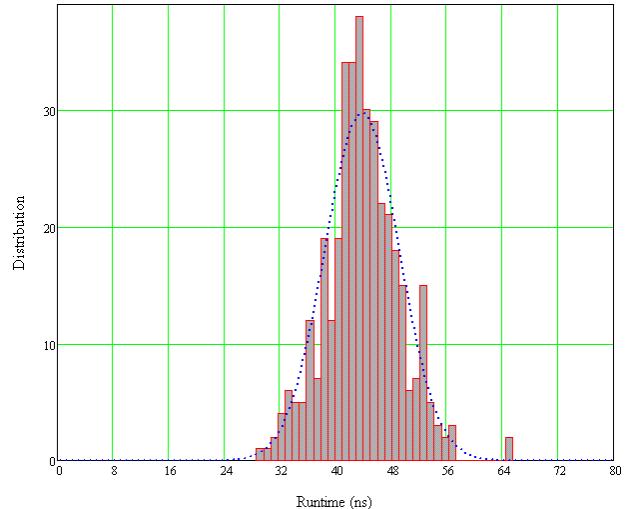


Figure 4. Histogram of the runtime for all C1.1 switch closures with a normal distribution overlaid.

IV. SUMMARY

We have described a laser-triggered gas switch that, when combined with other machine improvements, will allow the Z machine to routinely operate at 95 kV Marx charge voltages. The increased Marx charge voltage will allow Z machine to achieve record peak load currents which in turn will allow for increased material pressures and X-ray yields on targets of interest.

V. REFERENCES

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