

# THE PFL “SQUIGGLE:” AN INDEPENDENT MONITOR OF TRIGGER AND CASCADE SECTION RUNTIMES\*

D.E. Bliss<sup>‡</sup>, T.G. Avila, J.P. Corley, K.R. Lechien, S.D. Floor,  
J.E. Potter, M.E. Savage, J.J. Seamen, K.W. Struve, J.R. Woodworth,

Sandia National Laboratories, PO Box 5800, Mailstop 1193  
Albuquerque, NM 87185 USA

## Abstract

The refurbished Z pulsed power driver has been operational since October of 2007 delivering a peak current of  $\sim 26$  MA to the load. A critical component of the refurbished Z accelerator was the Laser Triggered Gas Switch (LTGS) with a maximum proven operating point of 6.5 MV, 820 kA and an overall  $1\text{-}\sigma$  timing jitter of  $\sim 6$  ns. We have identified a feature in the V-dot monitor on the Pulse Forming Line (PFL) downstream of the LTGS which is indicative of the closure of the trigger section of the switch. The PFL “squiggle” feature allows us to independently measure the runtime of the cascade and trigger sections and identify problems associated with the laser triggering of the switch, such as poor alignment or degrading transmission of the focusing lens. The squiggle also helps characterize the effect of changes in operating conditions and switch design. For the most recent design version of the LTGS, the trigger and cascade section runtimes with  $\pm 1\text{-}\sigma$  jitter are  $0.8 \pm 1.3$  ns and  $46 \pm 5.3$  ns respectively. The trigger and cascade section runtimes are not correlated suggesting that the trigger and cascade sections operate independently of each other.

## I. INTRODUCTION

### A. Background on LTGS Operation on Z

The Laser Triggered Gas Switch (LTGS) is arguably the most critical component for reliable timing and operation of a large multi-module pulsed power machine like Z. As the last actively controlled switch component, the LTGS has the most impact on timing jitter at the load and therefore determines an experimenter’s ability to synchronize triggered diagnostics such as the Z beamlet backlighter or gated diagnostics such as framing cameras or time resolved spectrometers. Also, for shock physics experiments, the precise shape of the current pulse at the load is controlled by the timing accuracy of independently triggering the gas switches. In May of this year, the highest flyer plate velocities to date,  $46 \text{ km s}^{-1}$  [1], were achieved on shock physics experiments utilizing the

increased current and pulse shaping capabilities provided by the Z refurbishment project.

The LTGS has been extensively tested and redesigned since originally becoming operational in October of 2007 [2]. Figure 1 shows a schematic diagram of the latest generation of LTGS which has a proven capability to routinely hold off 5.5 MV and has functioned properly on shots at peak voltages of 6.5 MV. When switched to the “On” state, a single LTGS can deliver peak currents of 820 kA. The original LTGS did not perform at such extreme operating conditions with high reliability. Modifications to the trigger electrodes, trigger gap, insulator housing, cascade electrodes, SF<sub>6</sub> operating pressure and grading rings has resulted in improved performance and reliability [2].

The gas switch is triggered by the Tempest Laser Trigger System (LTS) with 25 mJ, 3ns wide pulses of fourth harmonic Nd:YAG ( $\lambda=266\text{nm}$ ) focused in each

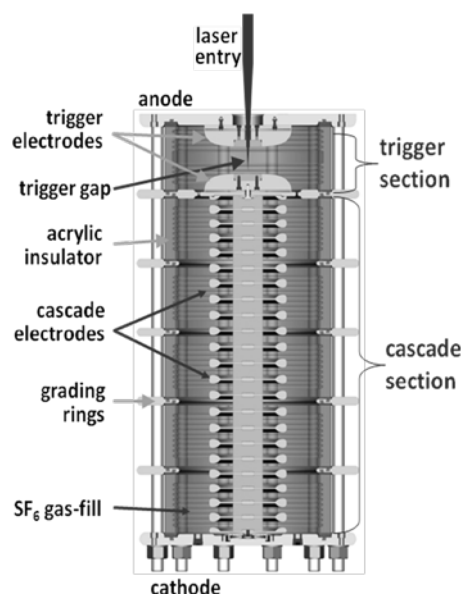


Figure 1. Schematic diagram of the laser triggered gas switch with a laser trigger and cascade self break sections.

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<sup>‡</sup> e-mail: [debliss@sandia.gov](mailto:debliss@sandia.gov)

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14. ABSTRACT <b>The refurbished Z pulsed power driver has been operational since October of 2007 delivering a peak current of ~26 MA to the load. A critical component of the refurbished Z accelerator was the Laser Triggered Gas Switch (LTGS) with a maximum proven operating point of 6.5 MV, 820 kA and an overall 1-ó timing jitter of ~6 ns. We have identified a feature in the V-dot monitor on the Pulse Forming Line (PFL) downstream of the LTGS which is indicative of the closure of the trigger section of the switch. The PFL squiggle feature allows us to independently measure the runtime of the cascade and trigger sections and identify problems associated with the laser triggering of the switch, such as poor alignment or degrading transmission of the focusing lens. The squiggle also helps characterize the effect of changes in operating conditions and switch design. For the most recent design version of the LTGS, the trigger and cascade section runtimes with ±1-ó jitter are 0.8 ±1.3 ns and 46 ± 5.3 ns respectively. The trigger and cascade section runtimes are not correlated suggesting that the trigger and cascade sections operate independently of each other.</b>			
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switch. Originally installed in 2003 into existing Z pulsed power components, the Tempest LTS was the first hardware upgrade of the ZR project [3]. Later, in October 2007, when the rest of the ZR project was brought online it became necessary to characterize the performance of the switch independently from the laser trigger system.

## II. RESULTS & DISCUSSION

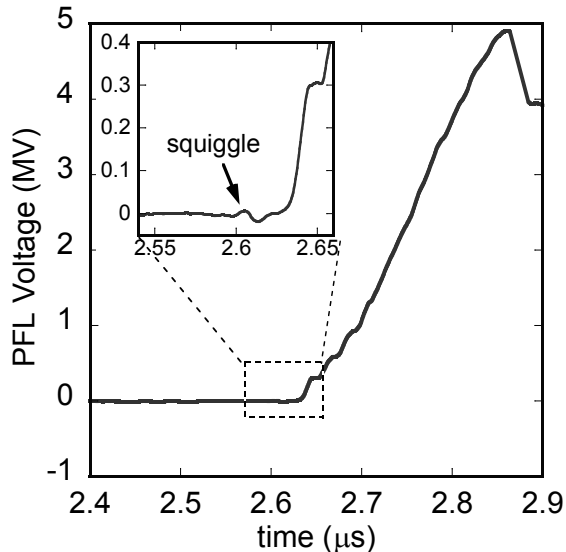
### B. Origin of the PFL Squiggle

Conceptually, the laser triggered gas switch can be considered to be two switches in series. The first switch is a single laser triggered gap and the second switch is a multi-gap, self breaking, cascade section as shown in Figure 1. Closure of the laser triggered gap increases the electrical field on the first few gaps in the cascade section initiating a self breakdown wave [4]. It takes approximately 40-50 ns for the breakdown wave to travel the length of the cascade section before electrical conduction of the LTGS begins. However, before electrical conduction happens, but after the trigger section is shorted by laser arc, the capacitive charge of the trigger gap is dumped into the PFL causing it to ring. Figure 2 shows a plot of the PFL Voltage on Z. Looking at the overall waveform, one might miss the small sinusoidal oscillation before the leading edge, but an expanded view clearly reveals the oscillations referred to as the PFL “Squiggle.” The period of the oscillation is 21 ns which corresponds to one half the PFL round trip time of 43 ns.

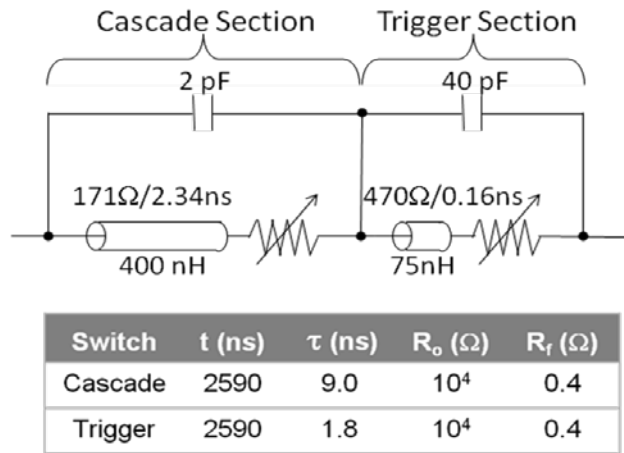
The squiggle is easiest to observe on un-integrated V-dot waveforms such as shown in Figures 5 and 8 for example. A similar feature was used to characterize runtimes of the triggered oil switches on Aurora [5].

### C. Circuit Modeling of the LTGS with BERTHA

Circuit modeling corroborates identification of the squiggle with the closure of the trigger section. A two



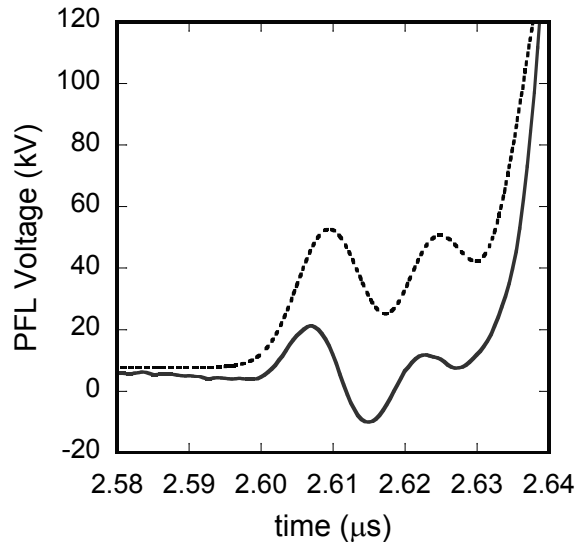
**Figure 2.** Plot of the PFL Voltage waveform for shot Z1923 line 09. The inset shows an expanded view with the PFL squiggle visible just before the primary switching.



**Figure 3.** Schematic diagram of the circuit model used in Bertha for the laser triggered gas switch. The exponential closing switch was used with the indicated parameters for each stage.

stage switch model was used with the circuit diagram and parameters shown in Figure 3. For each stage of the switch, the exponential switch model in BERTHA was used. The two stage switch was then inserted into a circuit for a single Z module which was terminated into an equivalent impedance at the stack.

The results of circuit modeling are compared to actual PFL voltages on the machine in Figure 4 for shot Z1862. The period, amplitude and timing of the squiggle on the leading edge of the PFL waveform are reproduced very well. There is a slight baseline offset between the two curves that is probably due to the exponential switch model not reproducing the time dependent resistivity change of the cascade section during the self breakdown period. Note, if a single stage switch is used for the LTGS, no squiggle is observed.



**Figure 4.** Plot comparing the measured PFL voltage waveform for shot Z1862 line 4 (—) with BERTHA circuit model (---) which used a two stage switch for the LTGS.

The amplitude and decay rate of the squiggle are sensitive to the rate of change of the resistivity at the time of switching in the circuit model. A careful parameter study could provide insight into the conductivity of the laser spark channel during this phase. Future investigation of circuit parameters is planned to understand this effect.

#### D. Picking the “Squiggle”

Breaking up the overall switch runtime into separate trigger and cascade section runtimes is a straightforward process with the squiggle. However, threshold levels for picking timing and propagation times between monitors should be treated carefully depending on how the runtime data is used. For instance, if switch performance is being monitored for Z operations, runtime definitions which include a constant offset or ignore propagation times pose no problem. The operator strives to correct for correlated changes in the switch runtimes in order to maintain constant timing at the load [6]. Thus any constant offset term drops out. The most important factor is to choose a consistent threshold that is insensitive to noise. On the other hand, if one has a more general interest in switch physics, or would like to compare switch performance between different machines, then a more precise definition is needed that eliminates any offset term.

Figure 5 shows a combined plot of the trigger laser photodiode (PD) signal and the PFL V-dot monitor waveform [7]. The time interval between the PD signal and the start of the squiggle is the trigger section runtime while the time interval between the start of the squiggle and the PFL voltage rise is the cascade section runtime as indicated in Figure 5.

The cascade section runtime is derived solely from the PFL waveform. Because of the relatively small amplitude of the squiggle, robust thresholds must be chosen that are not influenced by baseline noise. To pick the squiggle time, the un-integrated but filtered (1GHz low pass) V-dot

waveform is used. The first minimum in the squiggle was used as the reference point to pick the squiggle timing. This time is consistently 15 ns after the observed start of the squiggle as indicated at the bottom of Figure 5 and is subtracted to get the closure time of the trigger section. The time that the cascade section closes is measured at the 50% threshold of the first conduction oscillation as indicated on Figure 5. For a typical shot shown in Figure 5, the difference is 38 ns and corresponds to the cascade section runtime.

The trigger section runtime is defined as the time from the laser pulse to the start of the squiggle. Time shifts due to the laser path length from the photodiode to the trigger gap (31 ns) and the propagation time from the trigger gap to the position of the PFL V-dot monitor (29ns) [8] are added to the time scale for the photodiode trace. The most accurate laser timing is measured from the 50% threshold of the PD signal corresponding to the maximum rate of change. However, the full length (~1.5 cm) of the laser spark is not developed until peak laser intensity. Since both the trigger section closure time and the laser spark length depend on laser energy, one can infer that the streamer propagation time is greater than the time (~3ns) it takes to produce the full length laser spark. Therefore the time of laser initiation should be taken at the maximum of the photodiode when the laser spark is the longest.

Using this definition, the runtime of the trigger section in Figure 5 is -0.3 ns. Although the negative value would appear to be unphysical, it is within the accuracy that the timing of the various components can be characterized; laser path, detector response time, cable length, digitizer bandwidth and sample rate, etc. Therefore, for a properly functioning laser system as shown in Figure 5 the main conclusion would be that closure of the trigger section happens nearly instantaneously after creation of a full length laser spark. The next section presents results for a larger sample size as it considers every module over an 11 shot series.

#### E. Characterization of Switch Performance

The overall performance of the switches is characterized using the definitions for trigger and cascade runtimes from section D. Figure 6 plots the average trigger and cascade runtimes of each module for the shot range Z1860-1870. The error bars represent one standard deviation over the shot series. The average trigger and cascade runtimes for all the modules are  $0.8 \pm 1.3$  ns and  $46 \pm 5.3$  ns respectively as indicated by the dashed lines. For the case shown in Figure 5, or more generally, when LTS is functioning properly, closure of the trigger section is nearly instantaneous to within the timing accuracy and bandwidth limitation of the Z data acquisition system.

In Figure 6, the trigger runtimes for modules 9 and 31 are longer and have more jitter than the other modules which indicates low laser energy into those switches. Both of the final focusing lenses had been in place for over 60 shots and were due for replacement.

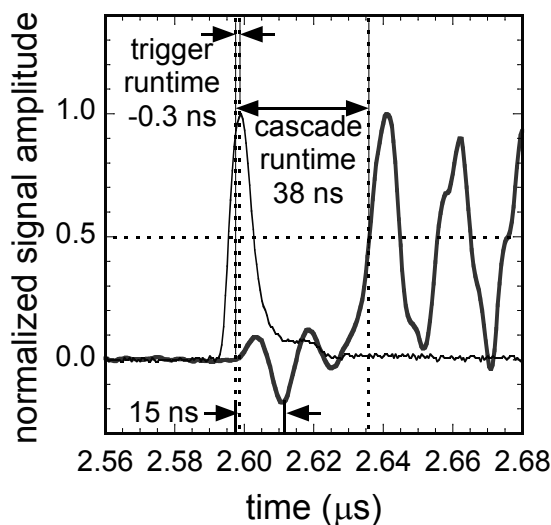
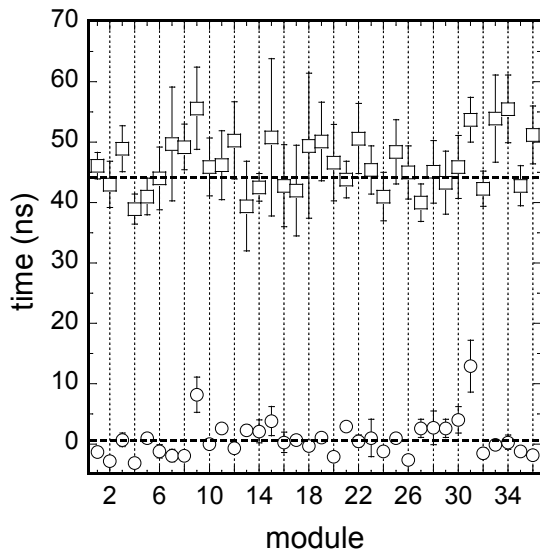


Figure 5. Plot of the normalized PFL V-dot (fat -) and trigger laser photodiode (thin -) signals for Z1862 line 4.

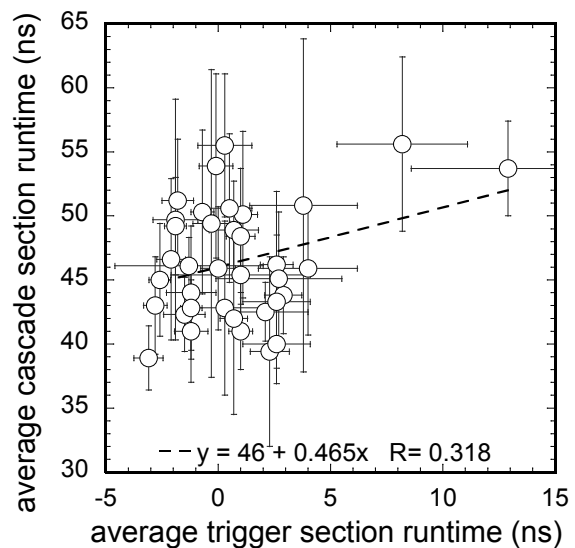


**Figure 6.** Plot of the average runtimes for the trigger (o) and cascade ( $\square$ ) sections for each of the modules for shots Z1860-Z1870. The error bars indicates one standard deviation for the shot series. Averaged across all the modules, the trigger and cascade runtimes are  $0.8 \pm 1.3$  ns and  $46 \pm 5.3$  ns respectively as indicated by the dashed lines.

Two processes reduce the laser transmission in the final focusing lens which is exposed to the electrical arc and switch environment: 1). Metal vapor and debris from the trigger electrodes eroding can coat the optic and 2) Fluorine radicals produced by  $\text{SF}_6$  breakdown can etch the lens. These chronic transmission losses occur on every shot and build-up over time. Typically the lenses require replacement every 50 shots. However, some lenses can degrade faster. Properly seated check valves and an immediate post-shot gas purge work effectively to limit back flow from the switch onto the lens and reduce the degradation rate. By using the squiggle to monitor the trigger runtime one can determine if a lens is degrading faster than normal. Acute, sudden losses in laser energy typically happen when an  $\text{SF}_6$  gas line becomes oil contaminated and transports oil onto an optic surface.

As expected, the jitter of the cascade section,  $1\sigma = 5.3$  ns, is significantly greater than the jitter of the trigger section,  $1\sigma = 1.3$  ns. If the runtime of the cascade section is independent of the trigger runtime (see Figure 7) then the total switch jitter can be added as the root mean square, RMS. Within the timing measurement accuracy at Z, all the LTGS jitter resides in the cascade section. Furthermore, past optical streak data indicates that most of the jitter resides in the time it takes to breakdown the first two cascade gaps [2]. Future design modifications to the switch are planned to reduce the breakdown time and therefore the jitter of the first two cascade gaps.

Closer inspection of Figure 7 which plots the average cascade runtime versus the average trigger runtime, reveals that a slight correlation possibly exists between the two runtimes. However, the correlation is due to the two outlier points on the right side of the plot, again



**Figure 7.** Plot of the average cascade versus trigger runtimes for shots Z1860-Z1870. Each point represents one module. A weak correlation is shown. When only properly running trigger sections are considered, no correlation exists.

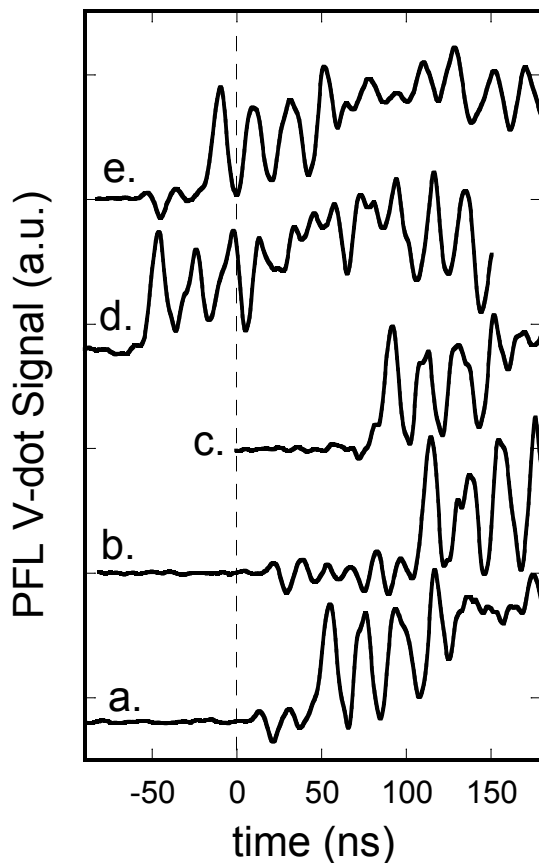
modules 9 and 31. These two modules were known to have low laser energy and longer trigger runtimes. The reason that the cascade section also runs longer is still uncertain. One explanation might be that slower trigger section closure rates reduce the inductive voltage on the cascade section. The magnitude of this effect is not proven. However, for the remaining 34 modules which have properly operating trigger sections, no correlation exists between the trigger and cascade section runtimes.

#### F. Determination of Switch failure mechanisms

When the LTGS does not operate properly, the squiggle can be a useful tool to help determine the origin of the failure. Failure mechanisms can be isolated within either the trigger or cascade section with two possible outcomes: an early pre-fire or a late/no fire. The presence of the squiggle indicates that the trigger section has closed before the cascade section. The lack of a squiggle indicates the cascade section closed first due to either a cascade pre-fire or an LTS malfunction.

By monitoring the trigger section runtime, any drop in laser energy which might cause the trigger section to run longer, can be tracked or identified.

Figure 8. illustrates four examples of problems with LTGS switching and also normal operation as a reference. Case a. shows normal operation. The squiggle is visible with normal runtimes for both the trigger and cascade sections. In case b. the squiggle is visible but the cascade runtime is long. For case, c. no squiggle is observed indicating the trigger section did not trigger. The cascade section did self break before the intermediate store could ring over. The pre-fire in case d. happened in the cascade section since no squiggle is observed. The pre-fire in case e. happened in the trigger section since the squiggle occurs before the arrival of the laser pulse.



**Figure 8.** Plot of various PFL V-dot waveforms illustrating timing problems with the LTGS. The waveforms have been time shifted relative to the laser PD time. From bottom to top, a. normal operation, Z1857M21, b. Late cascade section, Z1871M31, c. no trigger section, cascade self-break, Z1819M15, d. cascade section pre-fire, Z1877M13, e. trigger section pre-fire, Z1847M04.

For pulse shaped shots, such as for shock physics experiments, where the triggering of the gas switches is distributed over hundreds of nanoseconds, the squiggle is not a reliable tool for monitoring trigger section performance. The problem is that a module fired early can couple to neighboring modules creating an oscillation in the PFL voltage waveform similar to the squiggle. Approximately 200ns after an early module fires a squiggle-like feature can be induced on neighboring PFL waveforms due to a reverse charging wave traveling backwards from the water convolute, up the transmission line of the later module. The reverse wave obscures the real squiggle feature. Care must be taken when interpreting PFL waveforms on pulse shaped shots. For a later module that is indeed functioning properly, one might incorrectly conclude that the trigger section has pre-fired. Strangely, it would also incorrectly appear that the corresponding cascade section has compensated perfectly for the trigger pre-fire by running long for just the right amount of time!

### III. CONCLUSIONS

Important information about the performance of large pulsed power machines can be derived from small details in electrical diagnostic waveforms. In this paper, the PFL squiggle has been shown to be associated with closure of the laser trigger section and the resulting displacement of charge into the PFL. Under normal operation we find that the trigger and cascade section runtimes are independent with the cascade section being responsible for all the switch jitter. The ability to isolate trigger and cascade runtimes is an essential tool for evaluating switch failure mechanisms and characterizing the performance of next generation switches.

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- [7] As a historical note, higher bandwidth digitizers which could resolve the squiggle were installed for the PFL voltage monitors on Shot Z1817.
- [8] As a historical note, starting with shot Z1935 the PFL voltage monitors were moved to a new position 15 ns earlier up the PFL so the cables would no longer interfere with access to the maintenance ladders in the water tank.