# A NEW LASER TRIGGER SYSTEM FOR CURRENT PULSE SHAPING AND JITTER REDUCTION ON Z*


**D.E. Bliss[ξ], R.T. Collins, D.G. Dalton, E.J. Dawson Jr., R.L. Doty, T.L. Downey, H.C. Harjes, E.A. Illescas, M.D. Knudson, B.A. Lewis, J.A. Mills, S.D. Ploor, J.W. Podsednik, S.T. Rogowski, M.S. Shams and K.W. Struve**

*Sandia National Laboratories, PO Box 5800*
*Albuquerque, NM 87185 USA*



*Abstract*

A new laser trigger system (LTS) has been installed on Z that benefits the experimenter with reduced temporal jitter on the x-ray output, the confidence to use command triggers for time sensitive diagnostics and the ability to shape the current pulse at the load. This paper presents work on the pulse shaping aspects of the new LTS. Pulse shaping is possible because the trigger system is based on 36 individual lasers, one per each pulsed power module, instead of a single laser for the entire machine. The firing time of each module can be individually controlled to create an overall waveform that is the linear superposition of all 36 modules. In addition, each module can be set to a long- or short-pulse mode for added flexibility. The current waveform has been stretched from ~100 ns to ~250 ns. A circuit model has been developed with BERTHA Code, which contains the independent timing feature of the new LTS to predict and design pulse shapes. The ability to pulse-shape directly benefits isentropic compression experiments (ICE) and equation of state measurements (EOS) for the shock physics programs at Sandia National Laboratories. With the new LTS, the maximum isentropic loading applied to Cu samples 750 um thick has been doubled to 3.2 Mb without generating a shockwave. Macroscopically thick sample of Al, 1.5 mm, have been isentropically compressed to 1.7 Mb. Also, shockless Ti flyer-plates have been launched to 21 $km{\cdot}s^{-1}$, remaining in the solid state until impact.


## I. INTRODUCTION

### *A. ZR Requirements*

The new Tempest LTS is the first hardware upgrade to Z implemented as part of the ZR project [1]. The author list for this paper represents the dedicated crew that designed, built, installed and successfully brought up a fully operational LTS on Z without impacting a tight programmatic shot schedule. Three primary requirements of the Z Refurbishment (ZR) project have driven the need to install a new laser trigger system: 1. Increased reliability of a multi-user based facility with an increased shot schedule, 2. Jitter reduction for synchronization to diagnostics and a proposed petawatt fast-igniter, 3. Pulse shaping for shock physics experiments. The pulse-shaping requirement anchored the starting point of the LTS design. Pulse shaping is best accomplished by independently triggering each of the 36 pulse power modules with its own laser. The laser chosen to trigger the switches is a commercially available quadrupled YAG generating 30 mJ, 3 ns wide pulses at 266 nm [2]. Each laser has a dedicated photodiode (PD) and CCD camera to monitor energy output, timing and alignment. Alignment images utilize the leakage of the green second harmonic light as the illumination source. The alignment accuracy is improved because the images have greater clarity and contrast than the old LTS images. For a more complete description of the layout and operation of new Tempest LTS system see the paper by Podsednik [3].

The timing jitter of the new lasers is much less than for the old excimer laser, $1\sigma_{laser} = 0.2$ ns versus 2.7 ns. The pulse width is also narrower, 3 ns versus 20 ns for a corresponding faster trigger rise-time. With these enhancements in timing precision, the jitter of the peak x-ray emission has dramatically improved to $1\sigma_{x\text{-}ray} \cong 1.0$ ns versus 2.5 ns before. For a discussion of jitter on Z see the paper by Rogowski [4].

### *B. Shock (-less) Physics*

Two approaches to shock physics experiments have been undertaken on Z. One is to use the magnetic pressure to launch a flyer plate, which impacts a sample, generating a steady shock wave. Measurement of the resulting shock speed and mass velocity allows for the determination of the Hugoniot. The maximum flyer velocity has been attained on Z, $V_{max} = 28$ $km{\cdot}s^{-1}$ for a boiling Ti flyer plate. This type of measurement has successfully mapped the Hugoniot of $D_2$ to 0.7 Mb [5]. For 1% accuracy of the Hugoniot, a solid-state flyer is required. Using the new LTS on Z to generate a tapered current pulse, a shockless Ti flyer has been launched at 21 $km{\cdot}s^{-1}$ (see figure 1) in the solid phase.


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ξ e-mail: debliss@sandia.gov

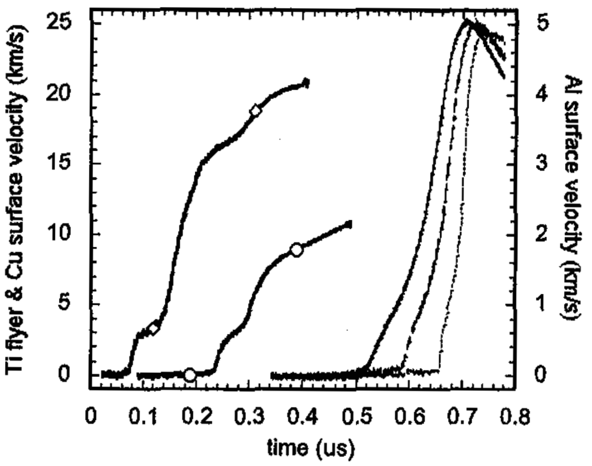


**Figure 1.** Shockless velocity profiles obtained on Z with Tempest LTS pulse shaping: (o) Cu ICE, 0.75 mm thick, Z1027. The peak velocity of 11 km·s-1 corresponds to 3.2 Mb. (◊) Shockless Ti composite flyer launched to 21 km·s-1 in the solid phase, Z1110. Al ICE, 1.55 mm thick sample is compressed to 1.7 Mb without generating a shock wave, shot Z1081. Sample thicknesses are (—) 0.75 mm (---) 1.15 mm and (···) 1.55 mm.

For many applications, the loading path lies much closer to the material isentrope. A second approach, ICE, has been developed to probe the material EOS along the isentrope [6] without generating a shock wave. A magnetic pressure ramp is applied to the sample directly without an intervening flyer plate. By careful control of the shape of the current pulse, the applied stress can be tailored to match the isentrope of the sample material. To study both soft and hard materials, the optimal current waveform is different. Waveforms must be tailored to suit the experiment. To date, the maximum isentropic loading applied directly to Cu samples 750 um thick is now 3.2 Mb. Macroscopically thick, 1.5 mm, samples of Al have been compressed to 1.7 Mb without a shock wave (see figure 1).

## II. SYSTEM PERFORMANCE

### *C. Pre-Installation Testing*

To test the concept of pulse shaping, nine Tempest lasers were originally installed on modules associated with the lower, D-level MITL of Z. The D-level lasers were typically fired 200 ns early, with the rest of the machine in high inductance mode. In high inductance mode, inductive springs are inserted in place of the water switch pins. Figure 2 shows the current at the load for a high inductance shot. Note that the peak current is down compared to a Tempest pulse-shaped shot and the rise-time cannot be controlled to match the desired isentrope. Also, damage occurred to the MITL's during some of the high inductance pre-pulse shots. This damage was thought to occur when an entire level is fired early because magnetic nulls exist near the inner MITL's, where the gaps are smaller and the electrical fields are higher.

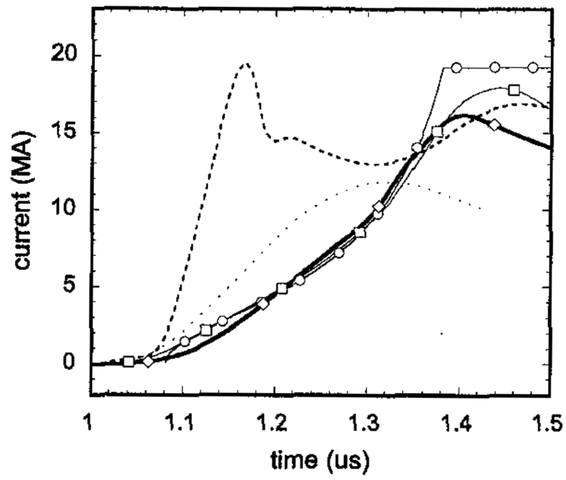


**Figure 2.** Plot of the various load current waveforms for Z1028: (o) desired, (□) predicted by BERTHA circuit model and (◊) measured. A (---) standard 90 kV shot, Z914, and an (···) 80 kV high inductance shot, Z788, are shown for comparison.

In order to minimize the duration of the magnetic nulls in the vacuum section, a three-point power feed symmetry was adopted. Three-point symmetry gives 12 timing groups of 3 modules. Furthermore, the average fire time for each of the 4 levels is balanced to minimize the migration of magnetic nulls to the post hole convolute region. Figure 3 shows a polar plot of the three-fold symmetry of the T1 target laser times. This approach allows nulls to form and move quickly out of the vacuum section into the water section before electric fields become sufficient to cause significant electron emission. Particle In a Cell (PIC) modeling of the magnetic nulls indicates this is a valid approach [7]. To test this approach before installing all the Tempest lasers, a short circuit dummy load was fired with only a single MITL, D level in place. Negative test results for damage confirmed the PIC modeling.

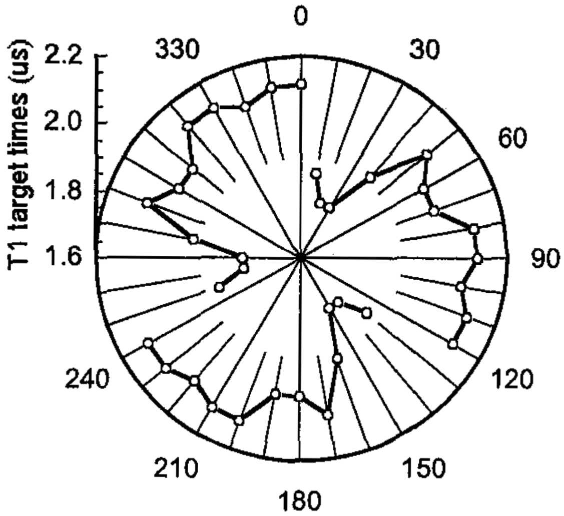


**Figure 3.** Polar plot of laser trigger target times, T1, versus module angle, Z1028. Note the three-fold symmetric power feed.

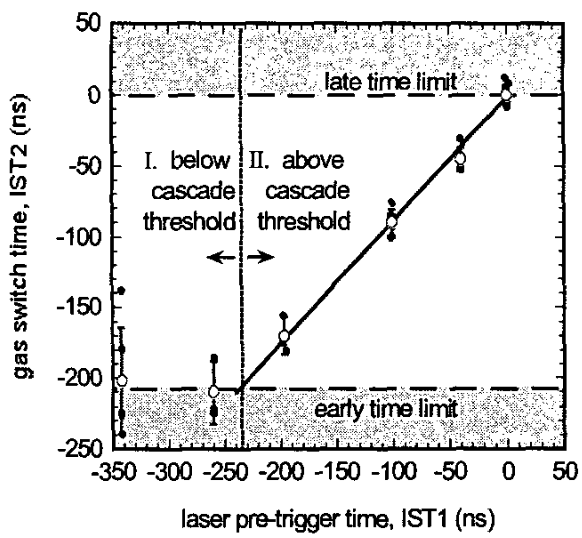


**Figure 4.** Plot of the change in gas switch electrical switching time (IST2) versus the change in laser trigger time (IST1) on shot Z1028: (•) switch times of individual modules, (o) average switching time of modules triggered at the same time, (I) error bar height is ±1σ of each timing group. The slope of the best-fit line through the first 4 points is 0.84.

### *D. Full LTS Operation, 36 Tempest Lasers*

Before a tailored pulse is fired on Z, a sequence of events must occur: 1.) The experimenter submits his desired waveform (see figure 2.). 2.) The circuit modeler adjusts the mode (short- or long-pulse) and switch time of the modules to best match the desired waveform. 3.) The experimenter reviews the predicted waveform to ensure that it meets his requirements. 4.) The electrical switching times, T2, are given to the LTS section to set the laser fire times, T1, based on the expected runtime of the switches. 5.) A text file containing the laser PD times is stored on the main control computer for Z. 6.) Timing shots are conducted prior to the down-line shot to verify the PD times. The header file, which contains the delay generator settings for the lasers, is edited so the measured PD times match the target times. 7.) After firing the shot, the measured and modeled currents are compared as well as the measured and target T1 and T2 times.

Accurate modeling of the load current pulse shape is limited by two primary factors: 1.) Knowing the gas switch runtime, i.e. the dependence of T2 on T1 and 2.) Predicting the waveform of an individual module correctly, particularly at times greater than 100 ns after the start of the current rise. Figure 4 plots the change in T2 versus the change in T1 for shot Z 1028. The late time limit, T1 > 0 is set by operations to prevent damage to the switch. If the fields are allowed to decome too high, the plastic supports inside the switch can track before the gas breaks down with catastrophic consequences.

Figure 4 shows for small amounts of pre-trigger, T2 changes linearly with T1 but not identically. The slope is 0.84 and not 1.0. As the laser is triggered earlier, the voltage on the intermediate store capacitor becomes less. The lower electric field across the gas switch results in a longer runtime as the streamer velocity is reduced. Therefore, a given change in the laser time results in an 84% change in the switching time until the early time limit is reached. For charging the intermediate store capacitor at an average rate of 5.5 kV/ns, 84% corresponds to a change in the runtime of 30 ns/MV.

Another complicating factor to accurately setting the T1 times is that the runtime of the gas switch depends on how the water switches are set, whether short- or long-pulse mode. For standard timing, with no pre-trigger, the gas switch runtime of a long-pulse module is 10 ns less than for short pulse mode. The difference in runtimes can be 30 ns for a pre-triggered module. It is suspected that capacitive coupling through the gas switch charges the transmission line just downline of the switch before it is triggered. Any charging reduces the field across the switch and increases the runtime. When the water switches are shorted for long pulse mode, the charge cannot build up on the transmission line down line of the switch. Therefore, the electric field across the switch is higher and the runtime is reduced. A 10 ns reduction in the runtime would correspond to ~300 kV of prepulse charging.

Attempts to trigger the switch with laser times earlier than 250 ns are ineffective, since the electrical switching time does not change below this limit. This behavior can be seen in Fig. 4. At this point the electric field is below the threshold for cascade operation of the switch. The field is sufficient to break down the laser enhanced triggered gap but successive gaps are still below the self-break threshold. Therefore, switching does not occur until the voltage on the intermediate store rises above the self-break threshold of the next gap. A significant increase in the variance of T2 from module-to-module is associated with operation below the cascade threshold as seen in figure 5. The rate of change of the standard deviation doubles below the cascade limit. Operation in this regime should be avoided since no further gains in

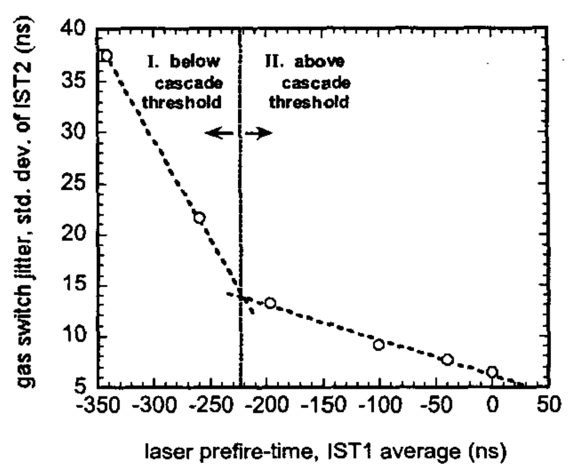


**Figure 5.** Plot of the standard deviation of the gas switch time versus laser trigger time for Z1028. The data represent the error bar heights in Figure 4.

pulse shaping can be made and the jitter of the machine becomes worse.

The best solution to overcoming limitations in pre-triggering the gas switches would be to implement independent triggers for the Marx banks. Then, the Marx trigger time would be set to follow any changes in the gas switch timing. This would accomplish several benefits. Runtimes would be nominally the same because the voltage on the intermediate store would be the same when the laser trigger enters the switch. The operator would only need to predict and compensate for trends due to aging and other correllated noise in the gas switch runtime [4].

Also, the amount of energy extracted from the intermediate store capacitors would be maximized. The extraction efficiency for shot Z1028 was calculated to be only 87% of a standard 90 kV wire array shot. This is based on the T2 timing of the modules; an average charge rate of 5.5 MV/us, a peak voltage of 4.7 MV and assuming the extracted energy is proportional to $V^2$. The V-dot monitors on the intermediate store can measure time more accurately than voltage since they are not calibrated on a regular basis. Pointon [7] and Lemke 8] calculate that 76% of the energy of a standard shot actually reaches the load. Therefore, other loss mechanisms in addition to the lower extraction efficiency must happen on pulse shaped shots. The loss mechanism is most likely due to down-line energy from the early modules, reaches the stack, and a fraction flows back up the late-time modules. That current is never recovered at the load.

The budget for the ZR project does not have funds for independent Marx bank triggers. However, ZR is being designed to not preclude independent Marx triggers, so they can be added in the future. A project is underway on Z to independently control the gas pressure on each of the modules and should be in place by August 2003. This will help extend the pulse-shaping window by lowering the selfbreak threshold of the switches fired early in time. Unfortunately, control of the gas pressure will not improve the energy extraction of the early modules.

Modelling of the current waveform is more complicated with pulse shaped shots than for standard wire array loads [9]. The two different modes, long- and short-pulse must be considered. Further complicating matters, the shape of the current waveform late in time is now important. In the past, modelling the current of a standard wire array 110ns after onset was unimportant since the implosion had already happened. Now, however, with the pulses stretched to > 250 ns, the late time current can contribute significantly to the shape of the overall load current. Unfortunately, the late time current can be non-deterministic. Often it is dominated by the unpredicticable nature of arcs in the water section. The main current pulse can reflect off the load, back reflect off a short in the water section and reverberate to the load. For long pulse modules, arcs at the prepulse shield around the water switches can truncate the tail end of the pulse. Inspection of waveform data from past shots indicates that the leading edge of the current pulse is very repeatable, but the trailing edge is very unpredictable.

## III. CONCLUSIONS

The range of possible pulse shapes for the load current on Z has been dramatically extended with the installation of the Tempest LTS. For the first time, the amplitude and rate of change of the current can be controlled as a function of time. The experimenter no longer needs to settle for whatever load current the machine produces, but rather can design the optimum pulse shape. Shock physics research has benefitted the most from pulse shaping, achieving the highest shockless velocities to date for both flyer plates and isentropic compression experiments. The Inertial Confinement Fusion program has also benefitted from the increased timing precision of the new LTS. Further improvements to Z triggering, such as independent control of gas pressure and Marx triggering will help the experimenter take full advantage of the new pulse shaping capabilities on Z in the future.

## IV. ACKNOWLEDGEMENTS

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