A STUDY OF TIMING JITTER IMPROVMENTS ON Z WITH A NEW LASER TRIGGERING SYSTEM *

Sonrisa T. Rogowski[ξ], David E. Bliss, Richard G. Adams, Kenneth W. Struve
Sandia National Laboratories, PO Box 5800
Albuquerque, NM 87185 USA

Abstract

A new, low jitter, laser trigger system (LTS) has been installed on the Z machine at Sandia National Laboratories. The installation of the new Tempest LTS has significantly reduced the jitter of the peak x-ray output. The most recent measurements of peak x-ray output show that the new LTS has reduced the jitter from $1\sigma \approx 2.5$ ns to $1\sigma < 1$ ns. In addition to having inherently less jitter than the old LTS, the independent precision triggering of the new LTS can compensate for timing errors due to drift and shot-to-shot correlations of other pulse power components further reducing the overall machine jitter. Specifically, the LTS compensates for trends in the gas switch runtime. By using a method based on linear prediction coefficients of previous shots, gas switch runtime noise can be further reduced by ~1 ns.

I. INTRODUCTION

The Z machine is the worlds largest x-ray generator. It has a cylindrically symmetric design that consists of thirty-six identical modules that converge to the center load. These modules are identical pulse forming transmission lines. The modules each contain five integral components; Marx bank, intermediate store capacitor, laser trigged gas switch, self-breaking water switch, and biplate transmission line. In this paper the timing jitter of the laser triggering system (LTS) and gas switches is examined.

The various components of the Z machine contribute to the jitter of the peak x-ray output. A study of these various sources is being performed to determine what their contributions to the overall jitter are, and what possibilities exist to reduce the jitter of these components. The motivations for reducing the jitter are to increase the reproducibility of experiments performed on Z, shape the load current pulses [1], synchronize diagnostics and a proposed petawatt laser for Fast Igniter experiments. Calculations show that subnanosecond synchronization is reguired between Z and the petawatt laser for fast igniter Inertial Confinement Fusion (ICF) experiments [2].

Components of the Z machine contribute jitter, which can be characterized as dependent or independent. The independent jitter affects each module randomly. The dependent jitter affects all the modules uniformly. Applying the Central Limit Theorem to the Z machine it is determined that the total jitter contributed by a component is reduced by $N^{1/2}$, the square root of the number of components.

$$\sigma_{total} = \frac{\sigma_n}{\sqrt{N}} \qquad (1)$$

The most effective way to reduce the jitter is to eliminate the largest dependent source, where N=1. The largest dependent source of jitter on Z was the LTS.

II. REDUCTION OF RANDOM JITTER

The original LTS laser, LTSA, was a single 4 J, 248 nm, KrF Excimer with a pulse width of 20 ns, and a one-sigma jitter of ~3 ns. LTSA served as the trigger for all thirty-six gas switches. Although LTSA worked reliably for seventeen years there were benefits to be gained by replacing it with the new low jitter system.

In December 2002 the new LTS was installed on the Z machine. The new LTS replaced the single KrF Excimer laser with thirty-six individual quadrupled YAG Tempest lasers [3]. The laser output at 266 nm is 35 mJ with a pulse width of 3ns. The measured one-sigma output jitter of a new trigger laser is 200 ps, which is a significant reduction from the KrF's approximate 3 ns one-sigma output jitter. The reduction of the trigger lasers' output jitter, and the individual laser for each switch, effectively eliminated the LTS jitter on Z, $\sigma_n \ll 1$ ns, N=36, therefore reducing the peak x-ray output jitter.

A statistical study of x-ray timing data on Z with LTSA as the trigger, yielded ~2.5 ns of jitter in the peak x-ray output. To determine the jitter, timing data was collected over several series of shots, each series with identical loads and machine configurations. The series were small data sets, containing at least two shots. In order to obtain the overall machine jitter with many small

---

* This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.
[ξ] email: strogow@sandia.gov

sets of data, a proper weight, which is the number of independent pairs of data, N-1, must be assigned to the variance of each shot series. The variance, V_n, of the peak x-ray time, t_i, of a shot series, n, is given as the sum over N_n shots

$$V_n = \frac{\sum_i (t_i - \bar{t})^2}{N_n - 1}. \quad (2)$$

The estimation of the total variance, V_{total}, of the parent distribution is the weighted sum over all n series,

$$V_{total} = \frac{\sum_n (N_n - 1) V_n}{\sum_n (N_n - 1)}. \quad (3)$$

This method of analysing the x-ray jitter, by using sets of shots with identical loads was then applied on shots triggerred by the Tempest lasers. The measured jitter from command fire to peak x-ray output is 1.0 ns. Table 1 summarizes the data and shot series used. The group variance for each shot series, the number of independent pairs and the weighted variance is shown.

The overall reduction of x-ray jitter has two origins. Obviously, reducing the laser jitter is one source. The second cause is the fact that the average runtime of the gas switches has also been reduced. The runtime of a gas switch is defined as the difference between the arrival time of the laser light in the switch and the onset of electrical conduction by the switch. The average runtime of the gas switches has dropped from ~75 ns to ~65 ns in operation with the new Tempest LTS. The reduction in the average runtime has two possible sources. The laser energy entering the modules is greater on average and also shows less variation from one module to another. By using beamsplitters to divide the energy of LTSA, some modules received upto 60 mJ of laser energy while other modules received less than 15 mJ. The modules receiving the lowest levels of laser energy had significantly greater runtimes. The Tempest LTS ensures that all the modules receive a similar amount of laser energy that is greater than ~24 mJ. The second possible source of runtime reduction is due to the smaller beam diameter the Tempest laser. The focussing optic in the switch is an f = 0.5 m lens. With a smaller beam diameter, the Rayleigh length of the focal spot is longer. A longer ionization needle in the triggered gap gives larger field enhancements, potentially reducing the gas switch runtime. If the average runtime is reduced, then it is readily apparent that the jitter in the runtime must also be reduced.

Table 1. Time of peak x-ray emission and the associated variance for shots triggered by the Tempest Lasers.

Shot	Load Type	Peak X-Ray, ns	Group variance	N-1	Weighted Variance
1038	Double Pinch	2556.5*			
1039	Double Pinch	2554.2*			
1041	Double Pinch	2555.9*			
1058	Double Pinch	2555.6*	0.95	3	2.85
1044	Fast Igniter	2541.0+			
1045	Fast Igniter	2543.9+			
1046	Fast Igniter	2541.9+			
1047	Fast Igniter	2543.9+			
1048	Fast Igniter	2543.6+	1.77	4	7.09
1059	LANL	2541.0#			
1060	LANL	2540.2#			
1061	LANL	2542.3#	1.12	2	2.25
1049	Pulse Shape	2527.9#			
1050	Pulse Shape	2528.7#			
1051	Pulse Shape	2527.9#			
1054	Pulse Shape	2528.8#	0.24	3	0.73
1042	Radjet	2525.4+			
1043	Radjet	2525.3+	0.00	1	0.00
Total weighted variance, ns				13	12.92
Variance, ns					**0.99**
Standard deviation, ns					**1.00**

X-ray detector used: *TGS-29, +TGS-17, #XRD

III. COMPENSATION FOR CORRELATED NOISE

Further reduction of the x-ray jitter can be accomplished by taking advantage of the independent triggering capability of the new LTS. The new LTS can actively compensate for the correlated noise in other pulsed power components; in particular the trends in the gas switch runtime. The gas switches on Z have an upper lifetime limit of 200 shots before mandatory replacement. However, the switches often do not survive the harsh environment on Z and must be replaced early because of damage.

The runtime of a gas switch on Z trends longer as the switch ages. The typical trend approximately 0.2 ns per shot increase over the lifetime of the switch. Along with the trend in the runtime, there is also noise as seen in Figure 1. With a method to predict the runtime of a switch, adjustments can be made to the laser fire time that will compensate for the predicted deviation in gas switch runtime. By reducing the correlated noise in components, the overall jitter of the peak x-ray emission is also reduced.

A study of the autocorrelation, R_{xx}, of the gas switch runtimes, x, was calculated by

$$R_{xx}(m) = \begin{cases} \sum_{n=0}^{N-m-1} x_{n+m} x^* & m \geq 0 \\ R_{xx}^*(m) & m \leq 0 \end{cases} \quad (4),$$

where n is the shot number and m is the shot lag. An examination of the autocorrelation of the runtime data indicates that the noise in the gas switch runtime is not entirely random. Using the correlation to previous shots, predictions can be made for the runtimes. This

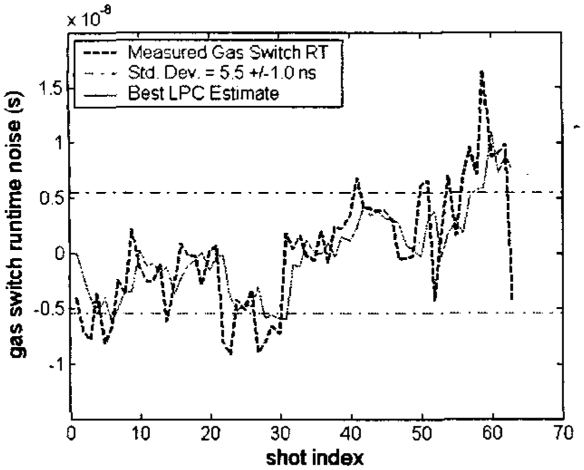

Figure 1. Gas switch runtime with best prediction from LPC. Module 19, Z shots 720 thru 833.

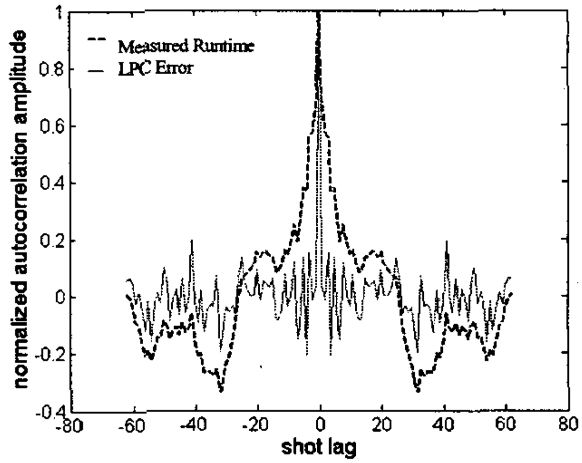

Figure 2. Autocorrelations of the gas switch runtime, and LPC prediction error. Module 19, Z shots 720 thru 833.

dependence on previous shots is indicated by the width of the autocorrelation spike in Figure 2. A truly random distribution of runtimes would give an autocorrelation as a delta function at zero shot lag.

Two methods were used to predict the gas switch runtimes. The first method is a running average of the runtimes of the preceding n shots, n = 3 yielded the smallest error for predicting the next runtime. For the shot series 720 to 833 on module 19 it was a noise reduction of ~1.6 ns. Applying this prediction method to previous Z runtime data, and then subtracting the predicted runtime from the measured runtime determined the error. Currently this is the method being implemented by the Z LTS operators.

The second method used as a runtime predictor is the Linear Prediction Coefficient (LPC). With LPC a linear combination of n previous runtimes is weighted with coefficients to predict the next runtime. The formula for LPC is

$$x(k) = -a(2)x(k-1) - a(3)x(k-2) - \ldots - a(n+1)x(k-n) \qquad (5)$$

Where x(k) is the predicted runtime for shot k, and the coefficients are held constant for each set of shots. The initial guesses for the coefficients are the autocorrelation coefficients. LPC then uses autoregressive modeling to determine coefficients that minimize the error. In this analysis n = 3, and the coefficients were as specified in Table 2.

Plotted in Figure 1 are the measured gas switch runtimes for shot series 720 to 833 on module 19, and the LPC predicted runtimes for that series, both subtracted from the mean runtime to show the noise. The LPC follows the measured runtime data closely. The noise in the runtime can be reduced by adjusting the laser fire time to compensate for the predicted runtime deviation, as determined by the LPC. The error is the difference between the measured runtime and the LPC predicted runtime. The ability of LPC to reduce the jitter is illustrated in Figure 3. A histogram of the runtimes and LPC error is plotted for module 19 shot series 720 to 833. The standard deviation of the measured runtime is 5.5 ns while the LPC error gives a standard deviation of 3.8 ns. LPC offers a reduction in runtime jitter of ~1.7 ns. The noise from the LPC runtime predictor is random, since the correlation is a delta function, Figure 2. Since the noise is now random, no further improvements can be made using this method.

With the Tempest system, the runtime predictors can be easily applied to take advantage of the noise reduction. With LTSA there was no effective method to deal with runtime noise. The operators were only able to

Table 2. LPC Coefficients, Module 19 Z shots 720-833

Coefficient, *a(n)*	Value
a(2)	-0.50
a(3)	-0.093
a(4)	-0.20

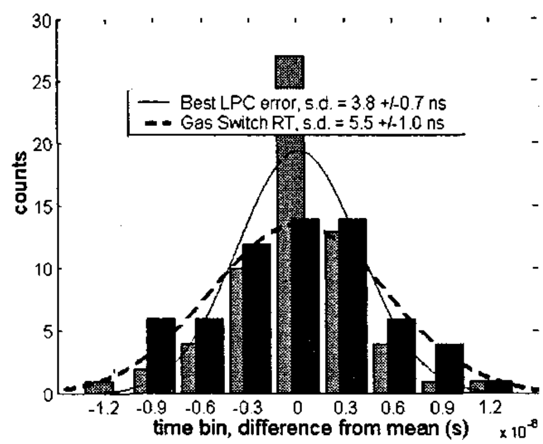

Figure 3. Histogram of the deviations of the runtime from the mean and the error of the LPC runtime predictor. Module 19, Z shots 720 thru 833.

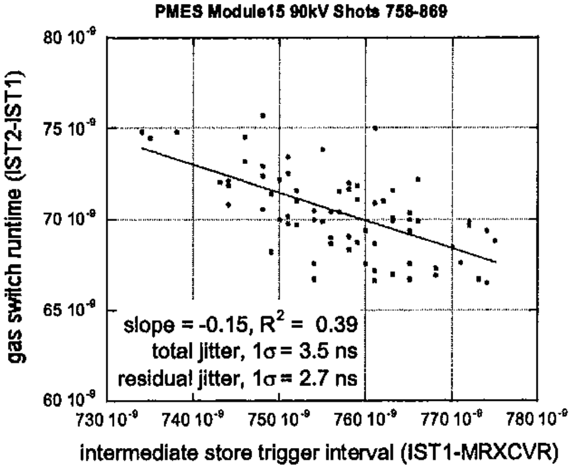

Figure 4. Dependence of the gas switch runtime on the charging interval of the intermediate store. Module 15 Z shot 758 thru 869, 90kV shots only.

compensate for the runtime trends of an aging switch by changing the optical path length between LTSA and the gas switch. This was done by translating a mirror and then realigning the beam path. This process was difficult and only performed when a gas switch runtime had increased enough to make that particular module run consistently more then 5 ns later then the rest of the modules. The triggering system for the Tempest system allows for individual changes to the laser fire time for each switch by entering a new fire time into the timing header file. When the LPC prediction method is automated on Z it will easily and effectively lessen the effects of the gas switch noise on current spread at the biplates, helping to maintain low peak x-ray jitter.

For the ZR project, an investigation was made of the dependence of the runtime jitter on the Marx firetime. The gas switch runtime is dependent on the voltage of the intermediate store capacitor which charges at rate of ~5 kV/ns. The charging interval is defined as the time between the electrical conductance of the Marx bank and the optical laser trigger of the gas switch. A change in the charging interval will result in a change in the gas switch runtime since the voltage at the switch will be changed. Figure 4 is a scatter plot of the gas switch runtime versus the intermediate store charging interval. Using the average charging rate of intermediate store, the observed change in gas switch runtime is 31 ns/MV. The slope of the best linear trend indicates that a change in the charge interval results in a 15% change of the gas switch runtime. The largest contributor to the charging interval noise is the Marx bank jitter, which is approximately 14 ns. Thus 15% of the Marx firetime jitter is imprinted on the runtime jitter. For operation of this particular switch, the total runtime jitter is 3.5 ns. However, by eliminating any Marx jitter, the residual jitter inherent in the gas switch is 2.7 ns. The usual assumption that the optical triggering of the gas switches isolates the load from jitter in the Marx firetime is therefore not entirely correct.

IV. SUMMARY

In summary, the installation of the new Tempest LTS has benefited the performance of Z both for pulse shaping applications and reduction of timing jitter. The new lasers have nearly zero jitter compared to the old trigger laser. The runtime jitter of the gas switches has also been reduced. With independent triggering of each module, drifts in the timing of other pulsed power components can be compensated. The net result is an overall reduction of the jitter of the peak x-ray emission to less than 1 ns. One advantage of reduced jitter is that diagnostics requiring critical timing, such as fast framing cameras can be operated from command triggers instead water triggers. This allows the diagnostics to be tested on pre-shot timing checks. Another advantage is that ZBL can be synchronized more precisely for ICF experiments, requiring fewer shots in an experimental run. Most importantly, statistically, it becomes feasible to consider fast igniter experiments on Z. The flexibility and timing precision offered by the new Tempest LTS will aid the experimenter with further breakthroughs and developments on Z and ZR.

V. REFERENCES

[1] D.E. Bliss, et.al. "A New Laser Trigger System for Current Pulse Shaping and Jitter Reduction on Z", in Proc. 14th International Pulsed Power Conference, 2003

[2] S.A. Slutz, M.C. Herrmann, "Radiation Driven Capsules for Fast Ignition Fusion," Phys. Plasmas, **10,** 234-240 (2003)

[3] J.W. Podsednik, et.al. "Operation of a Multiple Laser Trigger System on Z", ", in Proc. 14th International Pulsed Power Conference, 2003