Measurement of trigger and cascade section runtimes in 6 MV switches using fiber coupled photodetectors

Jens Schwarz, David Bliss, Joe Woodworth, Mark Savage, James Potter, Tom Avila, Stephen Floor, Patrick Rambo, and Briggs Atherton*

Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185-1193, USA

(Received 17 April 2012; published 18 July 2012)

Since October 2007 Sandia National Laboratories has operated the refurbished Z machine at an improved load current of 26 MA yielding 400 TW of x-ray power. The current pulse shape to the load is controlled by 36 independently timed laser triggered gas switches. As part of the refurbishment effort, a fiber coupled laser spark detector system has been installed which is able to detect the laser generated plasma *in situ* inside the trigger section of the high voltage switch. In this paper we describe how this detection system can be used to characterize the discharge dynamics of these 5.9 MV, 820 kA switches.

DOI: [10.1103/PhysRevSTAB.15.072802](https://doi.org/10.1103/PhysRevSTAB.15.072802)

PACS numbers: 84.32.Dd

I. INTRODUCTION

The Z accelerator [1] is a pulsed power driver that can deliver peak currents of 26 MA to a central load. It is based on 36 pulse forming line modules (stacked 2 high) built in a circular configuration. Figure 1 shows one of these 18 pulse forming pairs as well as a timeline of the temporal pulse compression of the electrical pulse traveling to the load. With ± 85 kV DC charge, the Marx generators can store up to 21 MJ of energy which is switched with a total jitter of less than 10 ns. Over the next 1.4 μ s, the intermediate store capacitors are charged to 5.9 MV. Successive pulse forming capacitors are charged in 150 ns to about 5 MV and two sets of self-closing water switches sharpen the output pulse further. The 10%–90% rise time of the load current is typically 85 ns, depending on the exact load configuration. The vacuum power flow region receives 9 MJ within the first 100 ns and radiating loads can produce up to 400 TW of nearly blackbody x rays.

As one can see, the laser triggered gas switch (LTGS) is the last actively controlled element in the pulse forming line. The current at the central load is directly controlled by the timing accuracy of the switches. Figure 2 shows the LTGS in more detail. A 25 mJ, 3 ns FWHM, 266 nm UV laser beam enters the laser can through a laser crossover tube and is focused by a 50 cm focal length lens into the LTGS. Precise beam alignment is achieved remotely via piezoelectric controlled mirror mounts and an elaborate beam imaging system. Proper alignment of the laser into the trigger section of the switch [2] (see Fig. 3) is ultimately verified by directly looking at a bright plasma spark in the center of the trigger gap. However, in shot

configuration, the LTGS is immersed in oil and a plasma spark can no longer be observed directly. As the Z accelerator is filled with oil, components can shift and proper laser alignment into the trigger section can no longer be guaranteed. Hence, a remote fiber coupled laser spark detector system was developed to ensure correct alignment and therefore optimal machine performance.

II. THE LASER SPARK DETECTION SYSTEM (LSD)

The laser spark detector (LSD) is located 1 m away from the switch and images the trigger gap via a custom collimator onto a 400 μ m diameter multimode fiber (see Fig. 4). Photomultiplier tubes (PMT) in the control room can detect the faint plasma spark which allows one to optimize laser beam alignment into the trigger gap. Figure 5 shows a typical PMT signature of a laser generated plasma spark in SF₆.

III. USING LSD TO ROBUSTLY MEASURE TRIGGER AND CASCADE SECTION RUNTIME

Trigger and cascade section runtimes are the primary data that characterize the performance of the laser trigger as well as the switch, e.g. for a given pressure, a longer than usual trigger runtime signifies diminished laser energy whereas an extremely fast runtime in the cascade section may indicate tracking at the inside of the switch housing. To ensure optimal machine performance, trigger and cascade runtimes are measured after each shot. To that extent, an elaborate technique was devised that allows one to interpret subtle features (see Fig. 6) in the PFL signals as a measure of trigger runtime [3]. This subtle PFL signature is generated due to displacement currents as a result of the total capacitance change in the LTGS. Its amplitude is quite low as compared to the main PFL signal, and is therefore difficult to resolve; in part due to limited oscilloscope dynamic range, and in part due to electromagnetic

*jschwar@sandia.gov

Published by the American Physical Society under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

FIG. 1. Cutaway view of the pulse forming line in the Z accelerator. Capacitors, transmission lines, and switches are used to achieve a 1000:1 temporal pulse compression as the 26 MJ of stored energy are passed to the load.

noise issues on parts of the diagnostic cabling plant. Until recently, this subtle feature was the only method of measuring trigger runtimes. Because the signal is so low it is subject to interpretation and different observers may reach different conclusions. For special types of pulse-shaping shots, one can receive substantial return currents on the PFL signal which make it impossible to identify a displacement current.

Recently, we have started to acquire LSD signals during Z shots in hopes of finding a more robust way of measuring

FIG. 2. View of the laser triggered gas switch. A UV beam is used to generate a plasma spark in the switch trigger section which will trigger the switch and conduct the current from the intermediate store (I-store) to the pulse forming line (PFL).

FIG. 3. The laser triggered gas switch in the Z accelerator is filled with 70 psia of SF₆ and consists of a laser “trigger section” and a “cascade section.” The laser induced breakdown of the trigger section causes an overvoltage on the cascade section and starts the self-breakdown process along the cascade electrodes which takes about 40–50 ns to complete.

FIG. 4. (a) Location of the LSD collimator with respect to the trigger gap. One can see that only the trigger section is within the field of view of the collimator. The “collimator field of view” in the figure represents the solid angle that the fiber collimator can “see.” (b) Optical collimator assembly: The 30 mm diameter, 35 mm focal length lens is located in an air filled chamber that is sealed with a window on each side (40 and 19 mm diameter). The fiber tip itself is located in an oil filled chamber.

trigger and cascade runtimes. In order to prevent damage to the PMT, we lowered the bias voltage and thereby reduced the sensitivity by a factor 10^4 . Figure 6 shows a representative data set of a normalized LSD signal acquired during a Z shot in relation to the UV laser temporal photodiode trace and the downline PFL signal. In order to get a meaningful physical interpretation of the signals they had to be time corrected as follows.

(i) A photodiode trace (silicon detector with 1 ns rise time) is recorded immediately after the output of each of the 36 lasers in order to verify their proper timing with respect to the desired trigger time. The temporal path difference Δt from the photodiode location to the center of the switch trigger section can be easily measured and is well known. This temporal delay Δt is then added to the recorded on-shot photodiode trace to yield a pulse arrival time equivalent to the center of the trigger section.

FIG. 5. Normalized LSD signal of the UV laser generated plasma spark in SF₆. The 266 nm, 3 ns FWHM laser pulse had an energy of about 25 mJ. The pulse rise time is slightly longer than the expected 1.5 ns which is due to the response time limitation of the PMT and the digitizer. Likewise, the fluorescence lifetime of 10 ns is also slightly prolonged by the same limitations.

(ii) The on-shot LSD signal is corrected as follows: A calibration shot is performed on each line at which the photodiode trace and the LSD trace are recorded on the same digitizer. The measured time delay $\Delta \tau$ and the known delay of the photodiode Δt are added to give a time corrected signal that corresponds to the plasma emission from the center of the trigger section.

FIG. 6. Plot of the laser photodiode trace (black), the PFL signal voltage (red), and the on-shot LSD signal (blue). All signals have been normalized and are time corrected as explained in the text. The first derivative of the LSD signal (green) is shown as well. Note: The trigger (7.7 ns) and cascade (130 ns) runtimes shown in this figure are unusually long. This was done in order to see details in the LSD signal more easily.

(iii) The PFL voltage signal is recorded downline from the high voltage switch and has a known electrical time delay with respect to the switch trigger section. This delay is simply subtracted to yield the correct timing.

A. How to measure trigger runtime

Looking at the LSD signal in Fig. 6, one can see a slight rise in amplitude over the rise time of the photodiode trace. The first derivative shows this even more clearly. As indicated in the figure, this very early part of the LSD signal is due to the closure of the trigger section and it corresponds nicely to the occurrence of the first displacement current signature in the PFL signal. For this particular example, one could directly measure the true trigger runtime from the LSD signal. However, most traces show a significant shorter trigger runtime and the sampling rate of our digitizer is not high enough to display enough data points over the relevant time span. Furthermore, one needs to keep in mind that the data acquisition will be automated and that one needs to identify robust signals for this purpose. We have therefore decided to define the trigger runtime as the difference between the rising edge of the photodiode trace (calculated by finding the intersection of the linear rising slope with the photodiode trace baseline) and the rising edge of the LSD signal trace (calculated by finding the intersection of the linear rising slope with the LSD trace baseline). It turns out that this method is very robust, because it takes advantage of many more data points and it also corresponds very well with the true physical runtime of the trigger section.

B. How to measure cascade runtime

One should note that the LSD's collimator field of view only includes the space between the trigger electrodes [see Fig. 4(a)]. Therefore one can only indirectly observe the behavior of the cascade section as it affects the current channel in the trigger section. The start of the cascade section can easily be identified by the steep rise of the LSD signal. Initially, the current channel in the trigger section is relatively cold and its associated large resistivity leads to strong Ohmic heating during the first few ns of the cascade section discharge process. As more current gets conducted down the switch, the trigger channel still increases in brightness. However, its rate of brightness increase is lowered by the decreased resistivity of the now hot plasma channel. Comparing the LSD signal with the PFL signal in Fig. 6, one can see that a distinct rise in LSD signal amplitude late in time corresponds well with the switch closure indicated by the PFL signal. This rise in LSD signal amplitude is due to increased current flow throughout the whole switch as a result of complete switch

closure. The first derivative of the LSD signal shows a distinct maximum as a result of the increased LSD signal slope. The cascade runtime is then defined by the time difference between the rising edge of the LSD signal (calculated by finding the intersection of the linear rising slope with the LSD trace baseline) and the second, smaller maximum of the first derivative of the LSD signal trace. This definition is also computationally robust since it relies on prominent, repeatable features.

IV. CONCLUSION

A laser spark detection system has been implemented in order to verify laser beam alignment into the trigger section of a 6 MV class switch while it is immersed in oil. This initial concept was taken further by collecting LSD signals during an actual switch discharge. This additional piece of data has been analyzed and its results agree well with the known discharge dynamics of MV class switches. The "on-shot" LSD signal is very repeatable over many shots and across various switches and shows distinct features that allow one to robustly measure trigger and cascade runtimes.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

-
- [1] M.K. Matzen, B.W. Atherton, M.E. Cuneo, G.L. Donovan, C.A. Hall, M. Herrmann, M.L. Kiefer, R.J. Leeper, G.T. Leifeste, F.W. Long, G.R. McKee, T.A. Mehlhorn, J.L. Porter, L.X. Schneider, K.W. Struve, W.A. Stygar, and E.A. Weinbrecht, *Acta Phys. Pol. A* **115**, 956 (2009).
 - [2] K.R. LeChien, W.A. Stygar, M.E. Savage, P.E. Wakeland, V. Anaya, D.S. Artery, M.J. Baremore, D.E. Bliss, R. Chavez, G.D. Coombs, J.P. Corley, P.A. Jones, A.K. Kipp, B.A. Lewis, J.A. Lott, J.J. Lynch, G.R. McKee, S.D. Ploor, K.R. Prestwich, S.A. Roznowski, D.C. Spencer, S.D. White, and J.R. Woodworth, *Phys. Rev. ST Accel. Beams* **13**, 030401 (2010).
 - [3] D.E. Bliss, T.G. Avila, J.P. Corley, K.R. LeChien, S.D. Ploor, J.E. Potter, M.E. Savage, J.J. Seamen, K.W. Struve, and J.R. Woodworth, in *2009 IEEE Pulsed Power Conference, Vols. 1 and 2* (IEEE, New York, 2009), pp. 680–684.