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

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Abstract

Since October 2007 Sandia National Laboratories operates 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 (LTGS). As part of the refurbishment effort, a fiber coupled laser spark detector (LSD) system has been installed which is able to detect the laser generated plasma in situ inside the trigger section of the HV 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.

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Nomenclature

DC Direct Current

FWHM Full Width at Half Maximum

I-store Intermediate-Store

LSD Laser Spark Detector

LTGS laser-triggered Gas Switches

PFL Pulse Forming Line

PMT Photo Multiplier Tube

psia pounds per square inch absolute

UV ultraviolet (light)

1 Introduction

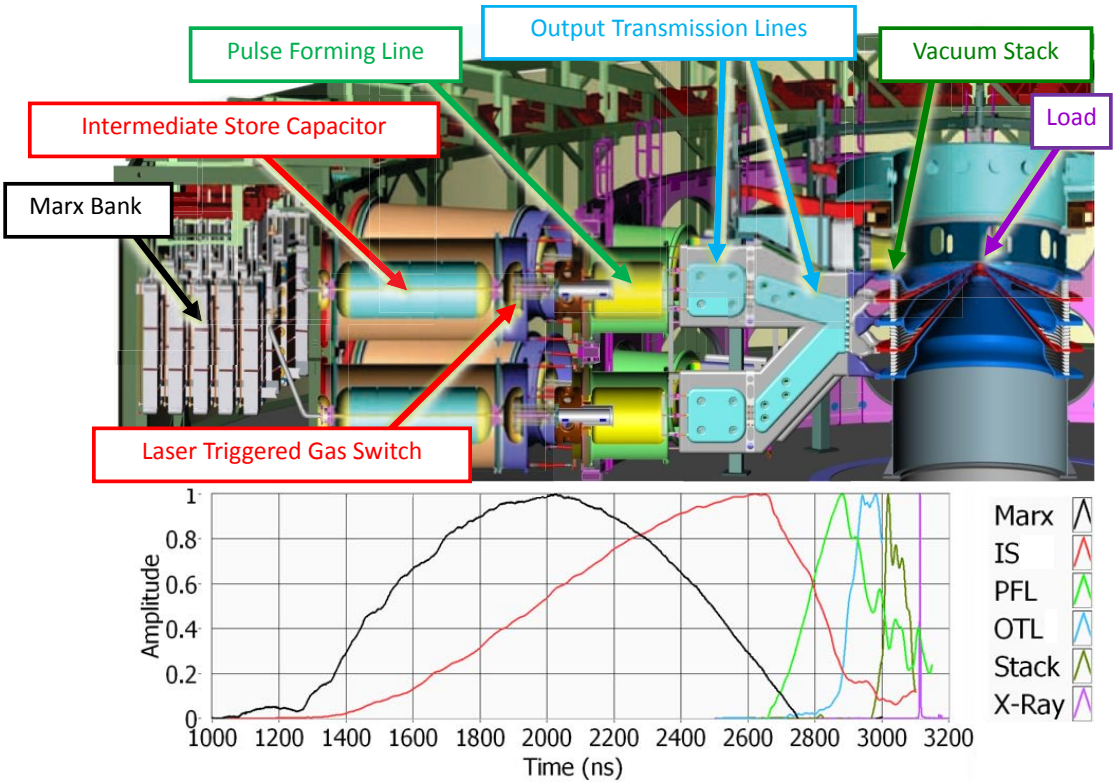

Figure 1. Cutaway view of the pulse forming line in the Z-Accelerator. Capacitors, transmission lines and switches are used to achieve a 1000:1 temporal pulse compression as the 26 MJ of stored energy are passed to the load.

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 μs, 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 black-body 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

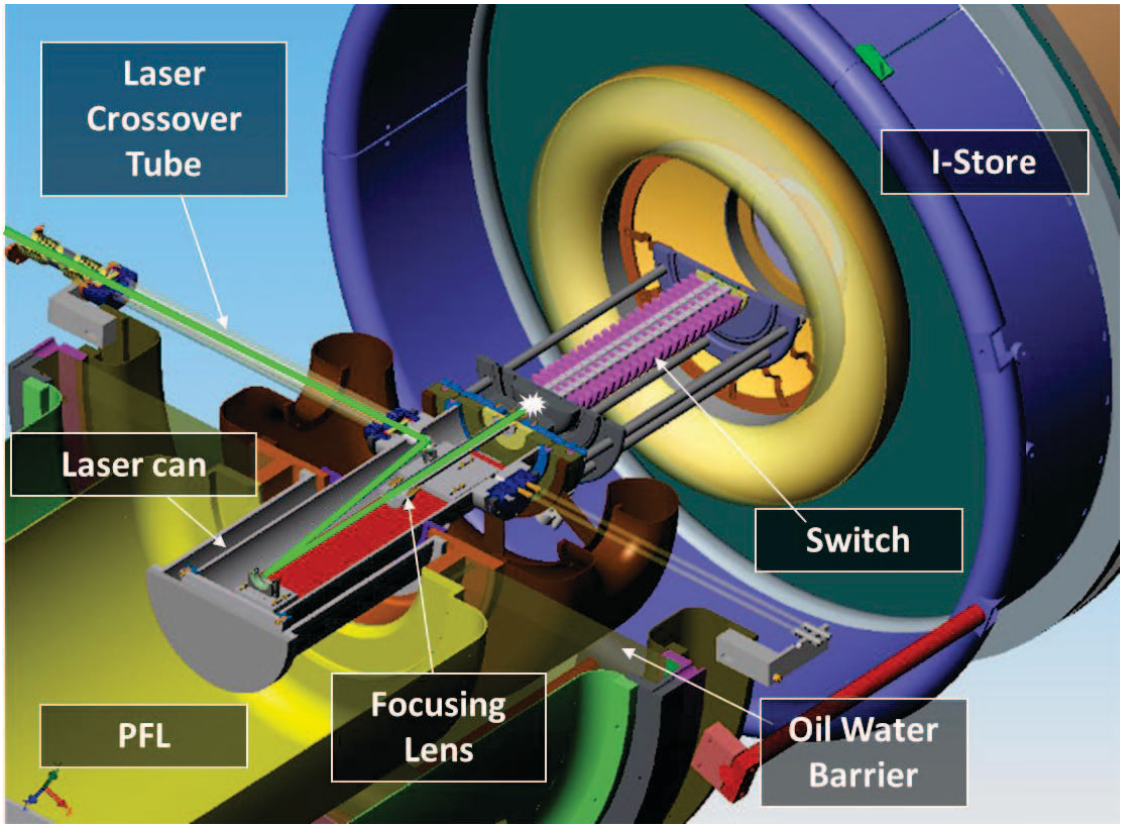

Figure 2. View of the laser-triggered gas switch. A UV beam is used to generate a plasma spark in the switch trigger section which will trigger the switch and conduct the current from the intermediate store (I-store) the the pulse forming line (PFL).

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.

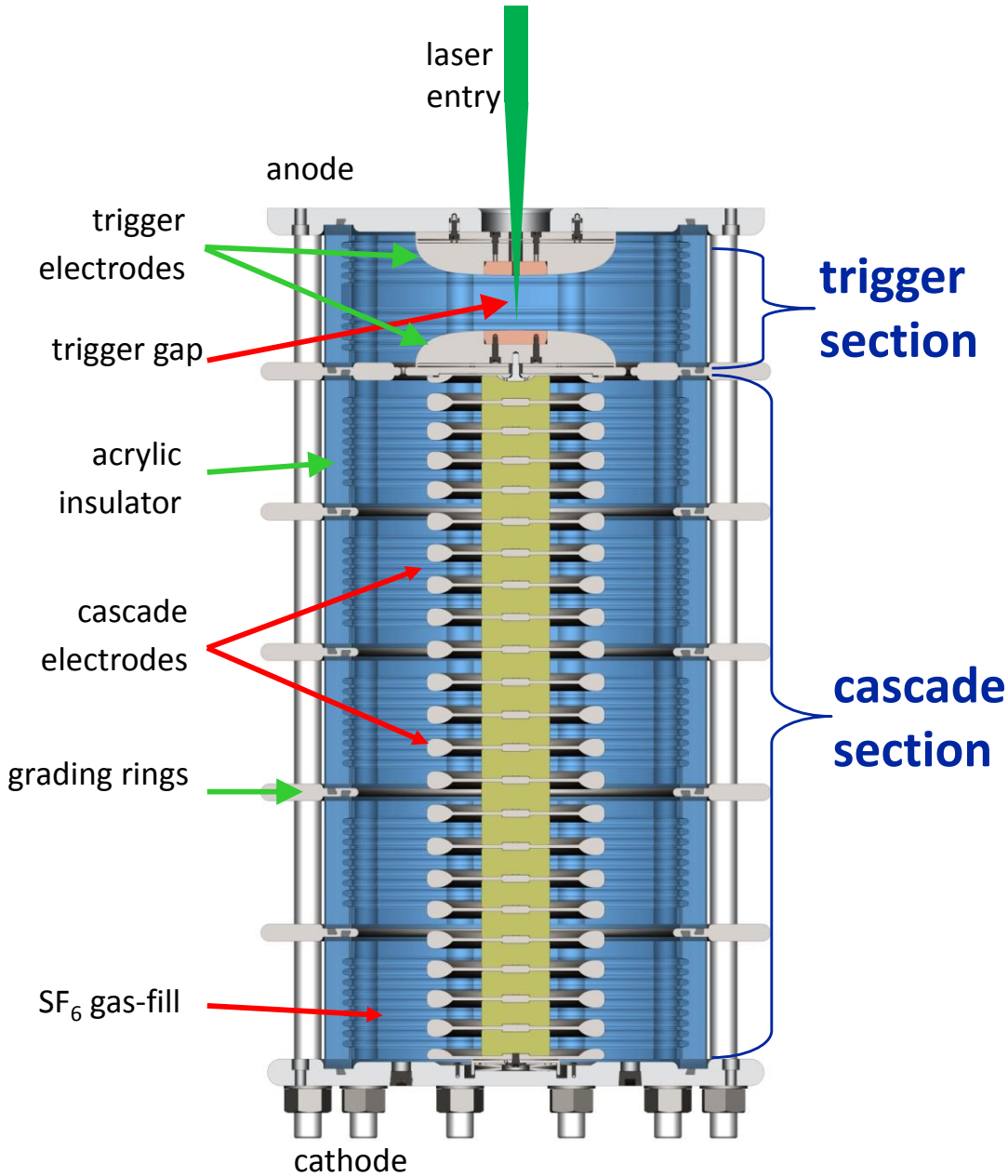

Figure 3. The laser-triggered gas switch in the Z-Accelerator is filled with 70 psia of SF_6 and consists of a laser "trigger section" and a "cascade section". The laser induced breakdown of the trigger section causes an over-voltage on the cascade section and starts the self-breakdown process along the cascade electrodes. The process takes about 40-50 ns to complete.

2 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 μm diameter multimode fiber (see Fig. 4). Photo multiplier tubes (PMT) in the control room receive the fiber output. These PMT's 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 SF_6.

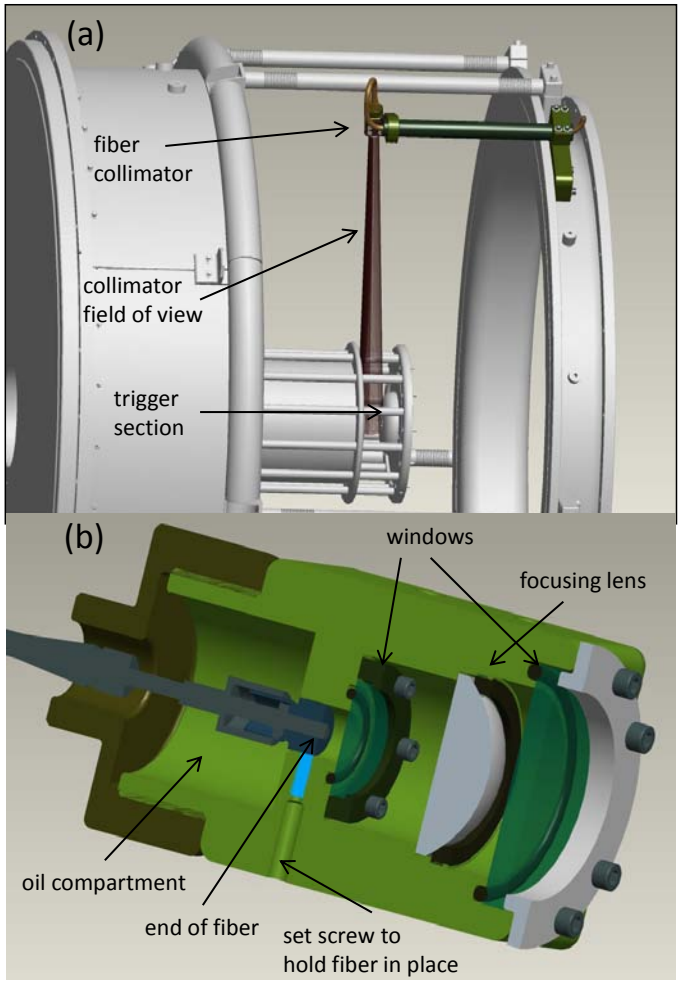

Figure 4. (a) Location of the LSD collimator with respect to the trigger gap. One can see that only the trigger section is within the field of view of the collimator. The "collimator field of view" in the figure represents the solid angle that the fiber collimator can "see". (b) Optical collimator assembly: 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 mm and 19 mm diameter). The fiber tip itself is located in an oil filled chamber.

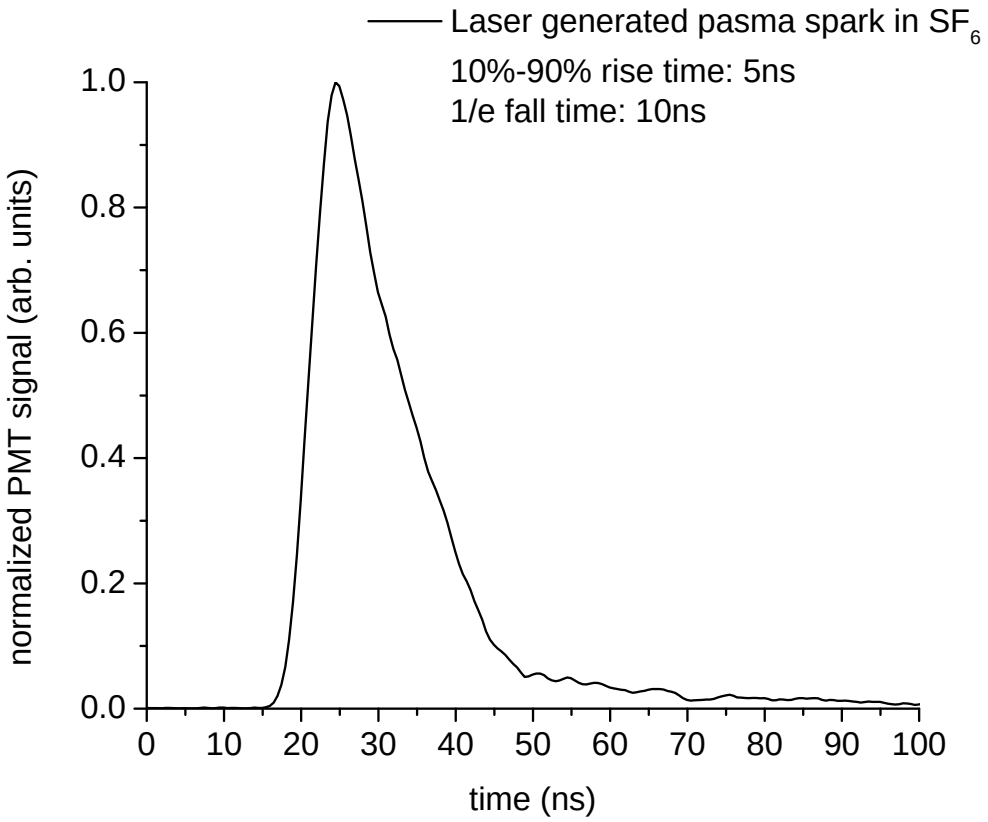

Figure 5. Normalized LSD signal of the UV laser generated plasma spark in SF_6. The 266 nm, 3 ns FWHM laser pulse had an energy of about 25 mJ. The pulse rise time is slightly longer than the expected 1.5 ns which is due to the response time limitation of the PMT and the digitizer. Likewise, the fluorescence lifetime of 10 ns is also slightly prolonged by the same limitations.

3 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. 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 with 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 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. Furthermore, 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 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 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:

- 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.

- 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.

- The PFL voltage signal is recorded downline from the HV 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.

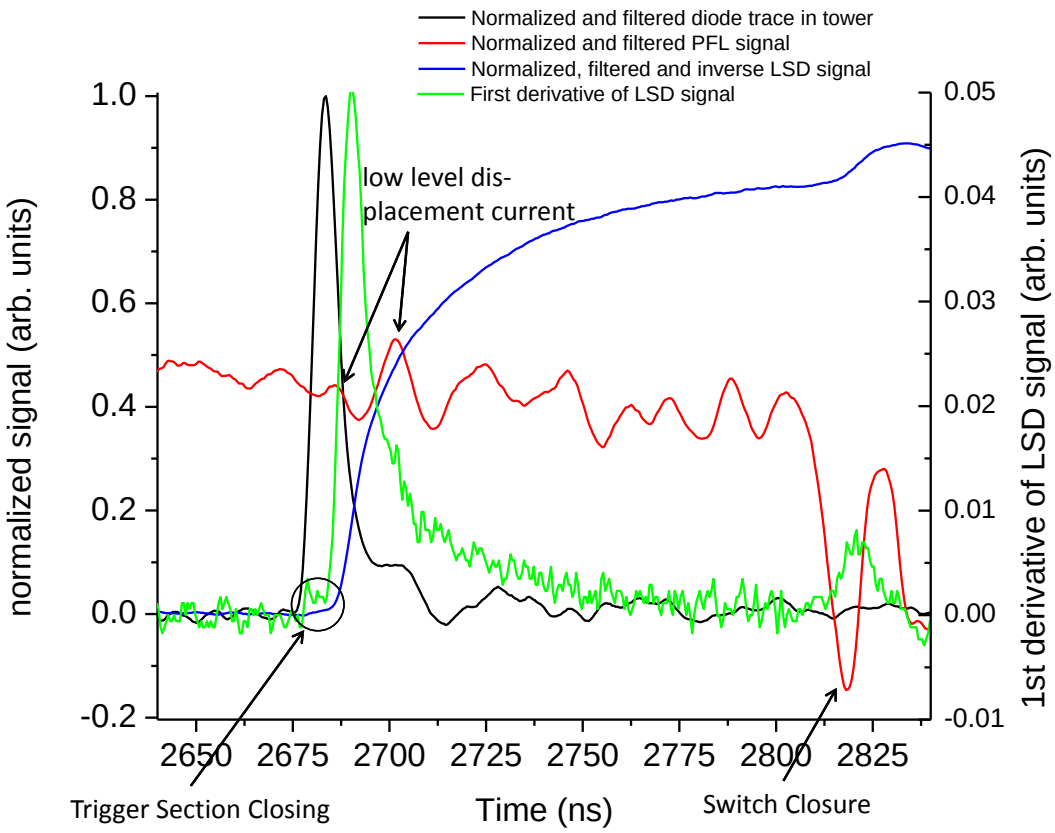

Figure 6. Plot of the laser photodiode trace (black), the PFL signal voltage (red), and the on-shot LSD signal (blue). All signals have been normalized and are time corrected as explained in the text. The first derivative of the LSD signal (green) is shown as well. Note: The trigger (7.7 ns) and cascade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

3.1 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 significantly 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.

3.2 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.

4 Examples

In this section, we present and analyze three example measurements of LSD data that yielded valuable insight that would not have been possible using PFL signals alone.

4.1 Detect faulty PFL signals

So far PFL detectors have been the only way to measure trigger and cascade runtimes in our HV switches. It was therefore rather difficult to identify faulty PFL lines. Figure 7 depicts a good example where a "normal" looking PFL signal would have given significantly wrong results if no LSD signal would have been present.

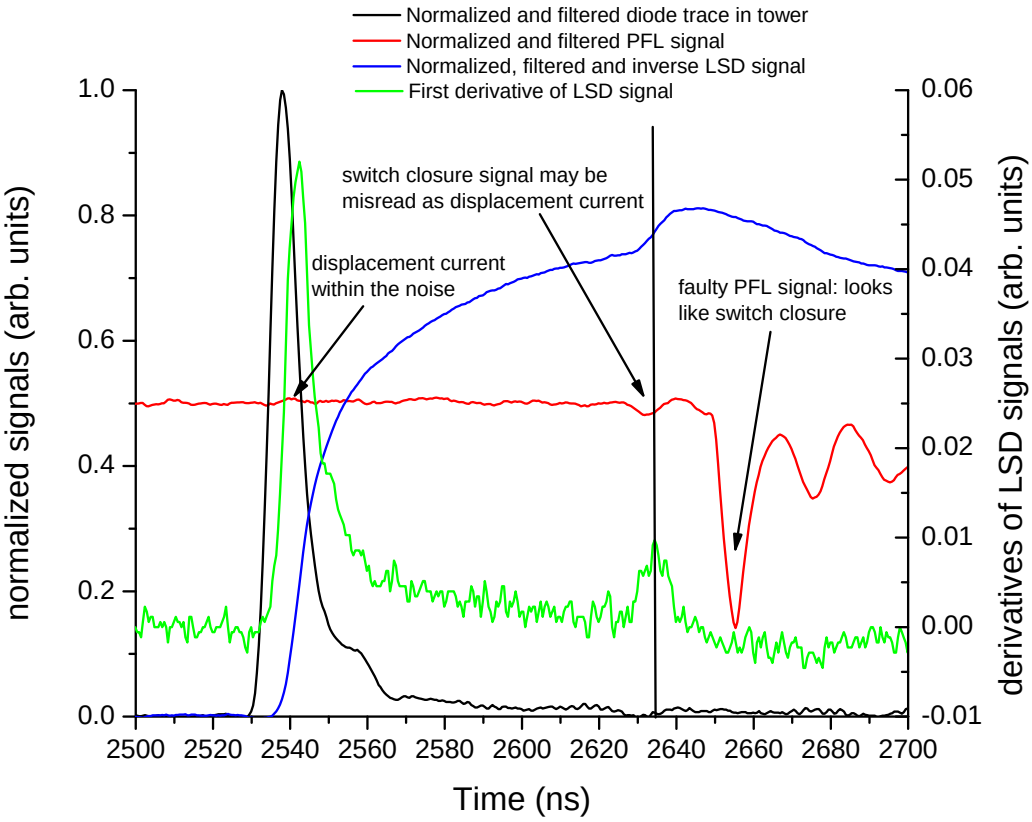

Figure 7. Plot of the normalized filtered diode trace (black) and the normalized filtered PFL signal (red). The blue line shows the on-shot LSD signal while the green line represents the first derivative of this LSD signal. The straight black line indicates the switch closure event based on a reliable LSD signal (see switch closure definition in previous sections).

One can see that the displacement current on the PFL signal is within the noise and that the actual switch closure signal could be easily misinterpreted as a displacement current. Furthermore,

the PFL signal shows a signature that looks like switch closure but has in fact no correlation to switch closure. Only with the LSD signal in place one can unambigiously point out the faulty PFL signal and avoid measurement errors of almost 100 ns.

4.2 Characterize switch failure

The LSD detectors can be a powerful tool when investigating on-shot switch failures. As a reminder, for a typical switch closure (see Fig. 8a), the laser pulse arrives first in the trigger section (black curve) at which point trigger section closure starts. With the PMT voltage lowered for Z shots, the LSD cannot pick up the laser plasma spark because it is too weak compared to the discharge arc. The rising edge of the LSD signal (blue curve) and the displacement current on the PFL both indicate trigger section closure. Complete switch closure is indicated by the PFL signal as well as distinct features in the LSD trace.

In the case of the pre-fire (see Fig. 8b) one can see that the PFL displacement current registers first, even before the LSD signal. This means that the self-breakdown that caused the pre-fire originated in the cascade section and not in the trigger section; otherwise the LSD signal would have registered before the PFL displacement current. This has been corroborated by close switch inspection which showed that an insulator ring between the cascade electrodes failed.

This means that the LSD signal is not only an additional indicator of pre-fire, but can also serve, in conjunction with the PFL, as a diagnostic of where the pre-fire occurred.

4.3 Verify unexpected PFL data

Since the displacement current signal on the PFL lines is difficult to interpret, one has to be cautious when such a signal based measurement yields data that is far outside the expected range. Figure 9a shows photodiode, LSD, and PFL traces for Z shot Z2367 on line 16 for an A5+ style LTGS. Based on the displacement current signal on the PFL line one measures about 30 ns for the trigger section discharge time. This is twice as long as the routinely measured trigger closing time of 15 ns. In such a case, the LSD signal can help gaining confidence in this measurement by corroborating the finding (as seen in Fig. 9a). Having high cofidence that the long trigger section runtime is indeed "real", one can then take corrective action. In this case, the beam expander at the exit of the Tempest laser was changed from 3× to 2× which increased the f/# of the focusing optic into the switch by 50% which in turn increases the plasma length by roughly a factor of 2. This modification led to reduction of trigger closing time back down to 15 ns (see Fig. 9b). Note: It is not clear why the trigger closing time was so long in the first place. We believe that it has something to do with the geometry of the trigger section itself and not the fact that it was an A5+ switch. Other A5+ switches in the system ran quite normal, even with the 3× beam expander.

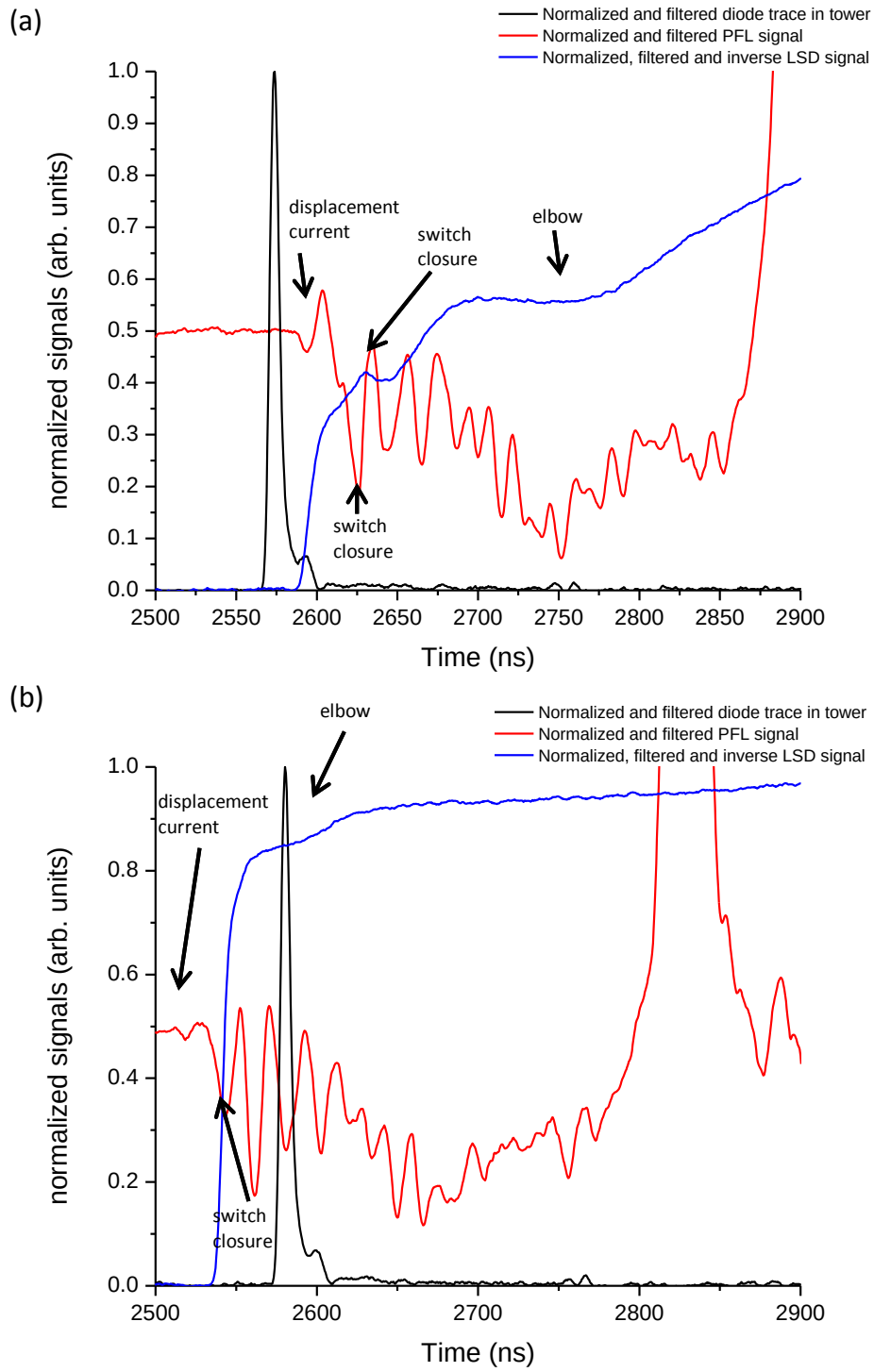

Figure 8. Comparison between a typical switch closure (a) and a pre-fire (b). Please keep in mind that the LSD can only detect signals/light originating from the trigger section.

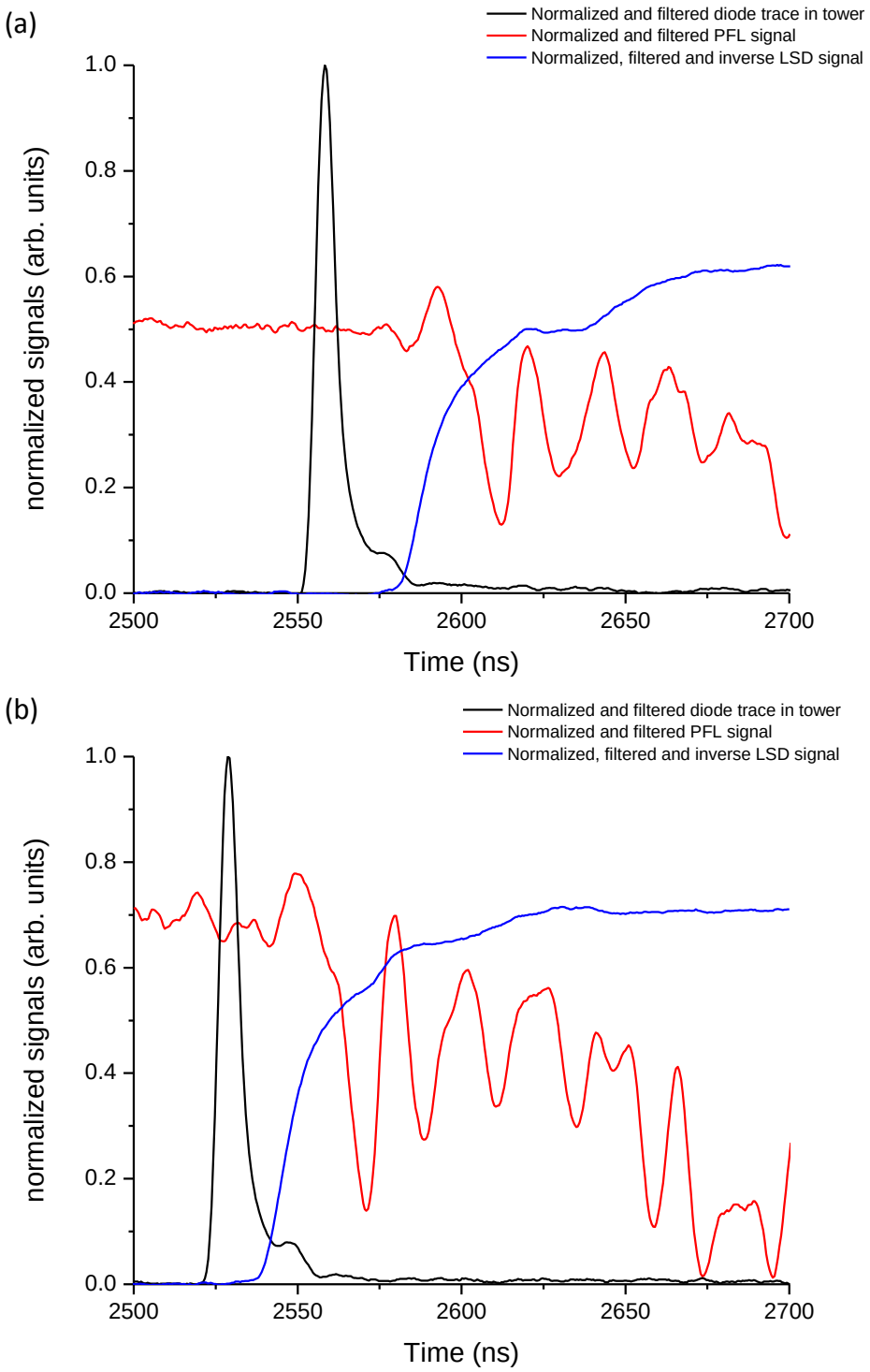

Figure 9. Comparison between an unsusally long trigger closing time (a) and the corrected trigger closing time after modification of the Tempest beam expander (b).

5 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. Furthermore, this diagnostic has been proven to be a vital tool in diagnosing PFL and switch failures.

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