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ANALYSIS OF A LASER INDUCED PLASMA IN HIGH PRESSURE SF_6 GAS*

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Abstract

The Laser Triggered Switch Program at Sandia National Laboratories is an intensive development study to understand and optimize the laser triggered gas switch (LTGS) for the Z-Refurbishment (ZR) project. The laser triggered gas switch is the final command-triggered switch in the machine. Reliability and performance of the switch is crucial.

A modified LTGS trigger section with optical viewing windows perpendicular to laser propagation is used to analyze a laser induced plasma spark in sulfur hexafluoride (SF_6) gas in order to quantify parameters such as spark length and plasma temperature. The laser spark is created through a focusing lens by the fourth-harmonic (266nm) of a 5ns FWHM pulsed Nd: YAG laser with 30mJ maximum energy output.

Several diagnostic methods are used to analyze the laser spark. Visible spark length measurements are made using a CCD camera at gas pressures ranging from sub-atmosphere to 4 atmospheres. Differing focal length lenses are compared to determine optimal visible spark length for a given gas pressure. Spark length is used as an indicator of the ability of a switch to trigger at a given gas pressure and charge voltage. Typically, the visible spark length must be 10-30% of the electrode gap spacing to produce acceptable switch run-time and jitter. In addition, spark lengths were found using laser schlieren and by a capacitive diagnostic.

I. INTRODUCTION

Sandia National Laboratories Laser Triggered Gas Switch (LTGS) program has identified several subsets of switch failures in a single ZR module (1/36 of the full machine) switch test bed known as Z_{20}. These failures include: surface breakdown of the gas-plastic interface, reduction in laser trigger optical energy due to debris coating of optical elements and run-time and jitter of the switch after triggering. Excessive jitter in the closing time of the switch has been determined to be a critical issue, resulting in the construction of a laboratory apparatus (gas cell) used to analyze the laser generated plasma sparks in high-pressure SF_6 gas [1].

II. DESIGN

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A. Gas Cell

The gas cell consists of two hemispherical electrodes, one with a centered, 6.4mm hole for admittance of the trigger laser. The switch housing is two acrylic envelopes separated by a trigger plate which supports the cathode electrode, enclosing a common gas volume. The apparatus is compressively held together by aluminum end plates and 10-25.4cm diameter nylon rods.

For optical diagnostics of the laser induced plasma, an acrylic envelope for the trigger section (from one end plate to the trigger plate, encompassing both electrodes) was designed to include two 76.2mm optical diagnostic windows perpendicular to laser propagation.

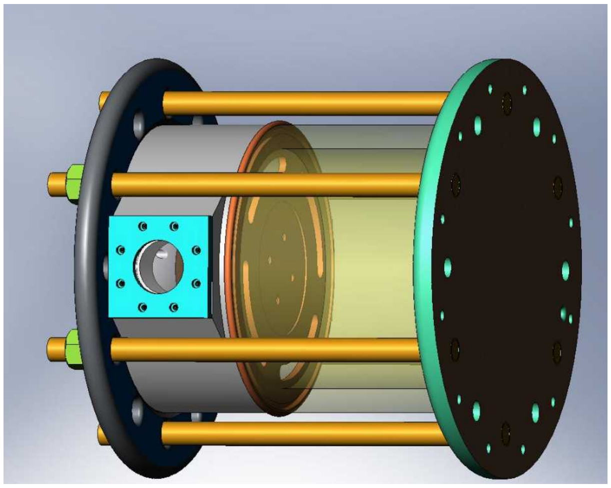

Figure 1. Laboratory apparatus (gas cell) showing optical viewing windows of the trigger section. Plasma inducing laser is incident from left.

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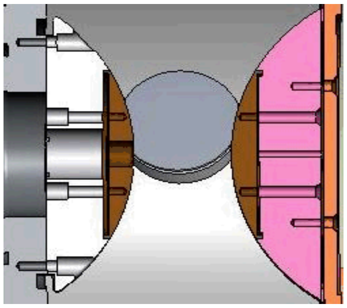

Figure 2. Cross sectional view of hemispherical electrodes and optical diagnostic window of gas cell trigger section. Electrode gap distance is 4.6cm. Laser is incident from the left.

B. Lasers

Two New Wave Research Tempest-10 lasers were used in tandem to create and analyze the laser induced plasma.

The first, used to create the plasma spark, is a Q-switched, Nd:YAG, near infrared (1064nm fundamental) laser operated in the fourth-harmonic (266nm) with 30mJ of maximum output energy. Laser pulse width is 5ns FWHM. The laser beam output diameter (following a 2X beam expander) is ~12mm. Varying focal length lenses were used to focus the output beam into the region of the gas cell between the electrodes where laser breakdown of the SF6 gas takes place given sufficient laser energy.

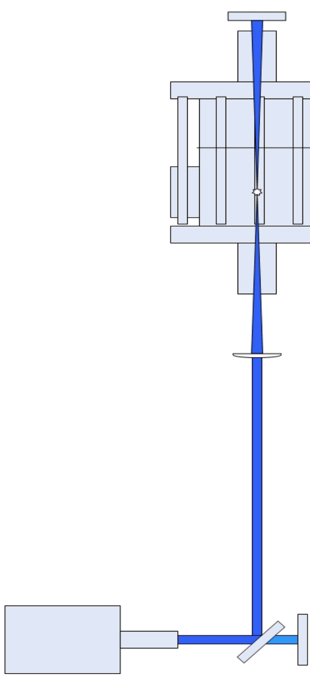

Figure 3. Schematic of the laboratory setup showing the laser plasma spark generating components including laser, turning mirror, energy meter, focusing lens and gas cell with diagnostic windows.

The probe laser used for schlieren imaging is operated in the visible (532nm, second harmonic) with the same functional characteristics as the plasma spark generating laser.

III. RESULTS

Laser plasma spark images were acquired and analyzed for the parameters listed in table 1 by means of several diagnostic methods. These include visible imaging, schlieren imaging and a capacitive diagnostic rendering electrical spark length.

Effective spark length is defined as the laser plasma spark length required to initiate electrical closure of the spark gap with a desired run-time. Experimental results dictate that the visible laser plasma spark length be at least 25% of the spark gap to achieve acceptable run-times [1]. The laser plasma spark length is studied with respect to the variable parameters of SF6 gas pressure, lens focal length and available laser energy.

Table 1.

SF6 Gas Pressure (PSIG)	Lens Focal Length (mm)	Laser Energy (mJ)
10-60	500	.25-26
10-60	750	.25-26
10-60	1000	.25-26

A. Visible Imaging

Visible laser plasma spark images captured with a thermoelectrically cooled CCD camera were analyzed with a Matlab program written to read in the TIFF image and return spark length. Figure 3 shows visible spark length comparisons for the three focal length lenses through the range of laser energy from minimum required for a visible spark to maximum laser energy available. The plots are averaged over the SF_6 pressure range of 10-60psig.

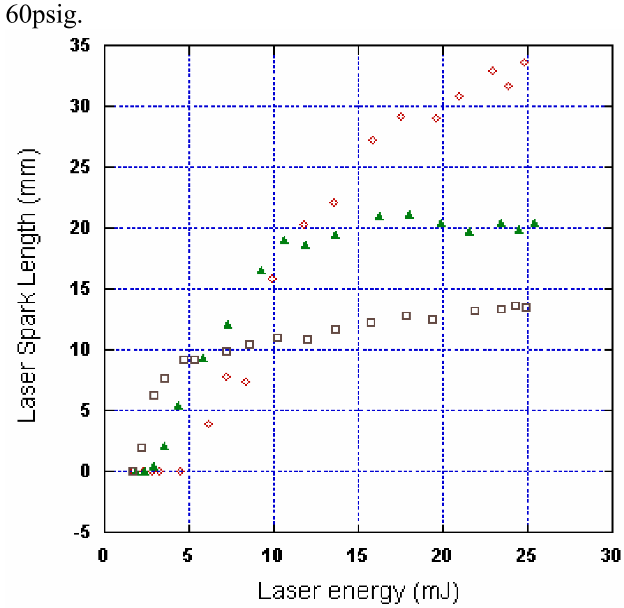

Figure 4. Plot of laser energy versus visible spark length for three focal length lenses (□ = 500mm, ▲=750mm, ◊ = 1000mm).

As can be seen in fig. 3, each of the three lenses exhibit a "roll-off" point at which the spark length slope changes dramatically. It can be seen that spark lengths below (lower laser energy) this roll off point are much more sensitive to changes in laser energy than are those above. The number of shots in the switch that can be achieved before this roll-off point is reached can be characterized as the switch life time; the time in service before a switch rebuild (replace or clean optics, etc.) is required.

However, it has been seen in several low laser energy shots in the Z_{20} full switch test bed that trigger-ability is achievable at laser energies below that required to create a visible plasma spark. These low laser energy triggered shots do have exceedingly long trigger section run-times (~55ns) and high jitter.

B. Electrical Length

Electrical length of the laser plasma spark is found using a capacitive diagnostic measuring displacement current caused by the altered coupling capacitance from the rapidly created conducting plasma. It can be seen in fig. 5 that electrical spark lengths are greater for a given laser energy as compared with the visible spark lengths for a given focal length lens.

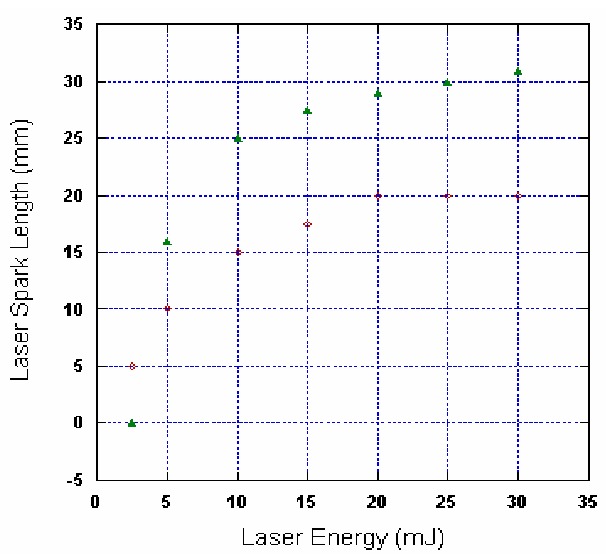

Figure 5. Plot of laser energy versus spark electrical length for two focal length lenses (▲= 750mm, ◊ = 500mm).

C. Schlieren Imaging

Schlieren imaging is used as an additional laser plasma spark length diagnostic by measuring the refractive index gradients along the axis of laser propagation. Schlieren images were obtained and analyzed using the aforementioned Matlab code used for visible spark lengths.

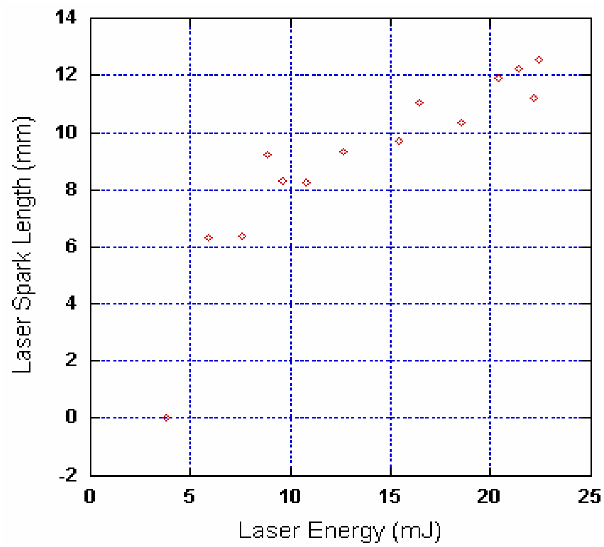

Figure 6. Plot of laser energy versus schlieren spark length for one focal length lens (◊ = 500mm).

Laser spark lengths obtained through schlieren imaging have proven to be the least sensitive spark length diagnostic used in this study.

IV. SUMMARY

Several diagnostic techniques are utilized to study and analyze laser induced plasma in SF_6 gas. All diagnostics show the same length versus energy structure, with a "roll-off" located at a specific laser energy and spark length, while the differences are attributed to the sensitivity of each of the diagnostics.

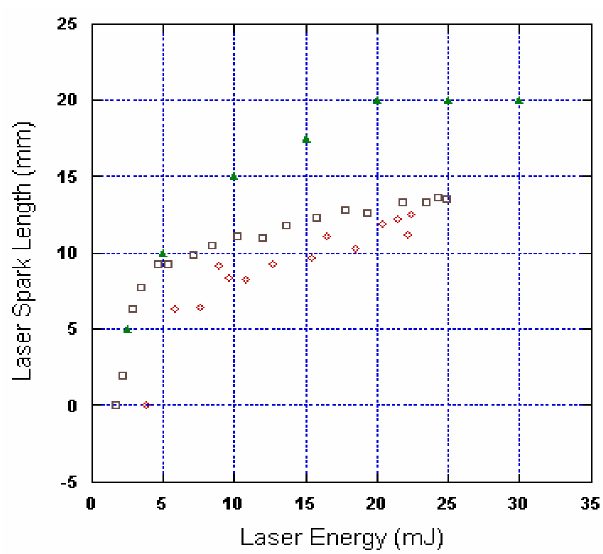

Figure 7. Comparison plot of diagnostics (500mm focal length lens: ◊ = schlieren diagnostic, □ = visible technique, ▲ = capacitive diagnostic).

This study's results pertain to the switch failure mode of optics degradation. Optics degradation results in decreased laser energy available for SF6 breakdown. Bearing in mind the empirical length parameter of 25% gap coverage (45.7mm gap: ~11.4mm spark) by the laser induced plasma spark, it is concluded that the 500mm focal length lens would provide the optimal combination of spark length at the greatest energy range. Barring other modes of failure, the 500mm focal length lens' spark length-energy range is indicative of longer switch lifetimes and acceptable trigger section run-times.

V. REFERENCES

[1] W.T. Clark, M.S. Thesis, "Analysis of a laser induced plasma in high pressure SF_6 for high-voltage, high-current switching", University of New Mexico, (2007).

[2] K. LeChien, M.E. Savage, "ZR Laser Triggered Gas Switch Requirements and Performance," presented at 16th IEEE International Pulsed Power Conference, Albuquerque, NM, 2007.