Chapter 11

Laser Triggered Spark Gaps Switches

––Ritu Agarwal

In Pulsed Power technologies, Triggered spark gap (SG) switches are one of the most essential components. The synchronized triggering of two or more spark gap switches, capable of switching large currents and handling high voltages (few kV's to 100's of kV) is required for high performance of Pulse power system. Laser triggering technique using optical fibres is developed for the triggering of spark gaps and their synchronization. The Nd:YAG laser of wavelength 1064 nm and 360 mJ of energy, which is converted into second harmonic of 532 nm carrying energy of 180 mJ is used. The Laser system (532 nm, 7 ns pulse) is provided with nineteen fiber optic beam delivery system each having less than 1 mJ of energy.

11.1. Spark Gap Switches

The spark gap switches are most commonly used in pulse power systems due to its advantages of high hold-off voltage, large conducting current, high energy efficiency and low cost. They are robust and relatively simple in design perspective. A spark gap (SG) switch is formed when two electrodes are separated by a dielectric medium. Figure 11.1 shows the equivalent circuit of spark gap consists of self-capacitance (C) in parallel with a series combination of spark channel resistance (R) and spark channel inductance (L). R and L are time dependent and hence switch acts as capacitor when it is open whereas when it is open it acts as a series combination of R-L.

$$C = \frac{\epsilon_0 \epsilon_r A}{d} F \qquad R = \frac{k\,l}{Q}\,\Omega\ ,\ L = 0.002 * l * \left[l_n * \frac{2l}{\rho} - \frac{3}{4}\right] \mu\text{H} \qquad (11.1)$$

Where,

ϵ_0- Relative Permittivity of free space

ϵ_r- Relative Permittivity of dielectric medium

A – Area of electrode in meter^2

d – Gap spacing in meters

K – Toepler constant (0.8e^{-3} for air)

l – Length of the spark in cms

Q – Charge transferred through spark gap (Asec)

ρ– Radius of spark channel (cm)

11.2. Laser Beam Triggering

In Laser Triggered spark gap switch, Laser can be focused using lens, on-axis or mid-plane point between the electrodes. Figure 11.2, shows the schematic of laser triggered SG switch having Laser focussed on-axis. When the laser beam is directed at the surface of cathode of SG where the energy from laser causes thermo emission of electrons, and even an explosion of the cathode metal at the surface. In the presence of an electric field, the process develops in the same manner as in the presence of initiating plasma. It is interesting that the delay time of the discharge in the switch practically does not depend on which anode or cathode surface plasma is generated.

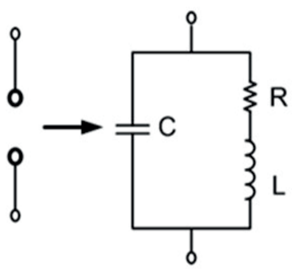


Figure 11.1 Equivalent circuit of Spark gap.

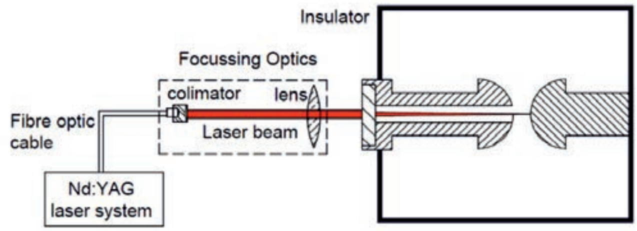


Figure 11.2. Schematic of Laser Triggered Sparkgap Switch.

11.3. Laser Induced Breakdown

Figure 11.3 shows Visualization of laser induced breakdown. The optical breakdown of gases follows essentially a three-step process: (1) Multi-photon ionization of impurity molecules with low ionization potentials would easily provide a few free electrons with low initial kinetic energy in the focal volume at the front part of the pulse; (2) The free electrons in the strong laser field could absorb n photons (n = 0, 1, 2, 3 ...) while colliding (scattering) with a much heavier particle (atom, molecule or ion). The heavy particle is to conserve momentum during the interaction. This process is called inverse Bremsstrahlung or free–free transition; (3) After one or more inverse Bremsstrahlung processes, the free electron would acquire a kinetic energy E_e higher than the ionization potential of the gas molecule /atom. Subsequent collision would give rise to the ejection of an extra electron from the molecule/atom. This would result in two low energy electrons. They would undergo the same processes as before each giving rise to two electrons, and so on until the gas is fully ionized. This is called cascade or avalanche ionization. Relation between Intensity of laser pulse and electric field produced by it is given by $I = \frac{1}{2}\varepsilon_0 c E^2$. (Where c is velocity of light and ϵ_0 is permittivity)

11.3.1. Fiber Coupling and Minimum Spot Size

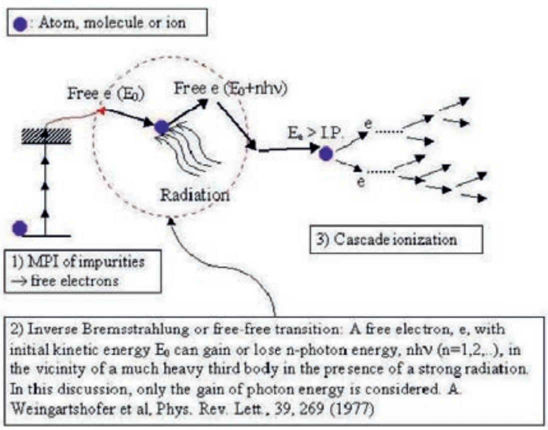


Figure 11.3. Visualization of Laser Induced Breakdown [Weingartshofer et al. *Physical Review Letter,* 39, 269 (1977)].

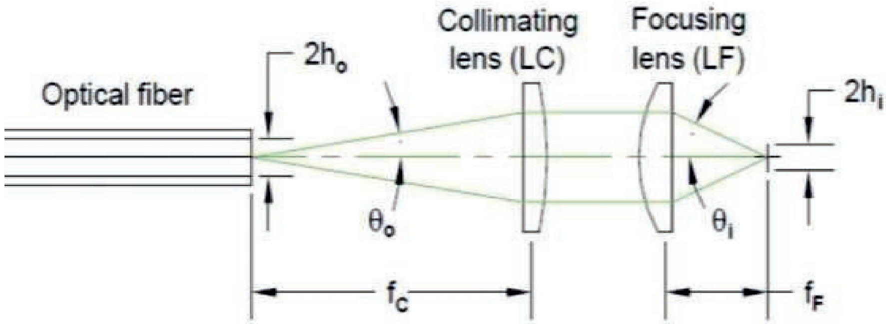


Figure 11.4. Schematic of laser focusing.

Image magnification is given by,

$$h_i = h_0 \frac{f_F}{f_C} \tag{11.2}$$

Minimum spot size,

$$d_m = \frac{4M^2 f_F \lambda}{\pi d_L} \tag{11.3}$$

Where M^2 is beam quality from fiber.(For beam from laser to fiber coupling, assume $M^2 \cong 1.2$)

Peak Irradiance (W/cm^2)

$$I = \frac{E_{Pulse}}{t_{Pulse} \times \pi \left(\frac{d}{2}\right)^2} \tag{11.4}$$

11.3.2. Focusing Optics for Laser Beam

The laser beam is transmitted through a multimode 200 µm fiber with N. A. = 0.26, therefore gets diverged by an angle of 30 deg. A collimator setup has been designed containing a convex lens of f = 50 mm such that it made the diverging beam into a parallel beam. Further, the parallel LASER beam was focused at the surface of cathode by a converging lens of f = 50 mm. Figure 11.5 depicts a typical collimator setup where a laser beam coming out from optical fibre and gets diverged in the air medium by around 30 deg. The collimator converges the beam into a parallel beam. As the parallel beam passes through convex lens with focal length f_2, it gets converged at the surface of the cathode of the spark gap. This results in excitation of ions at cathode surface along with the ionisation of gas medium.

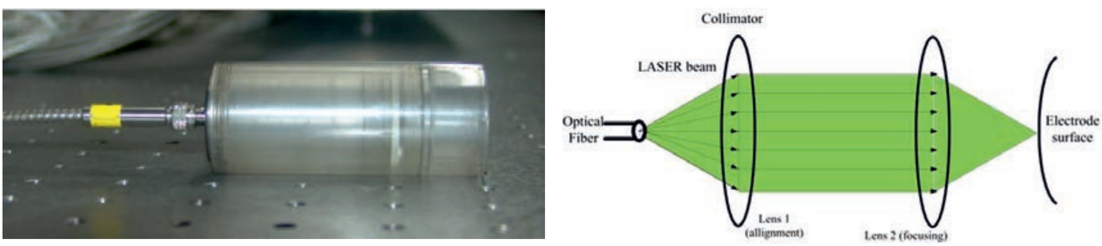


Figure 11.5. Focusing Optics for LASER beam.

11.3.3. Design and Simulation of LASER triggered spark gap switch.

The Figure 11.6 displays CST EM STUDIO simulation of a laser triggered SG to obtain electric field distribution along cross section of the SG switch. For electrode separation of 4 mm at a potential of 15 kV with air medium, maximum field obtained is 38.87 kV/cm and field at the centre of bottom electrode is 22.79 kV/cm.

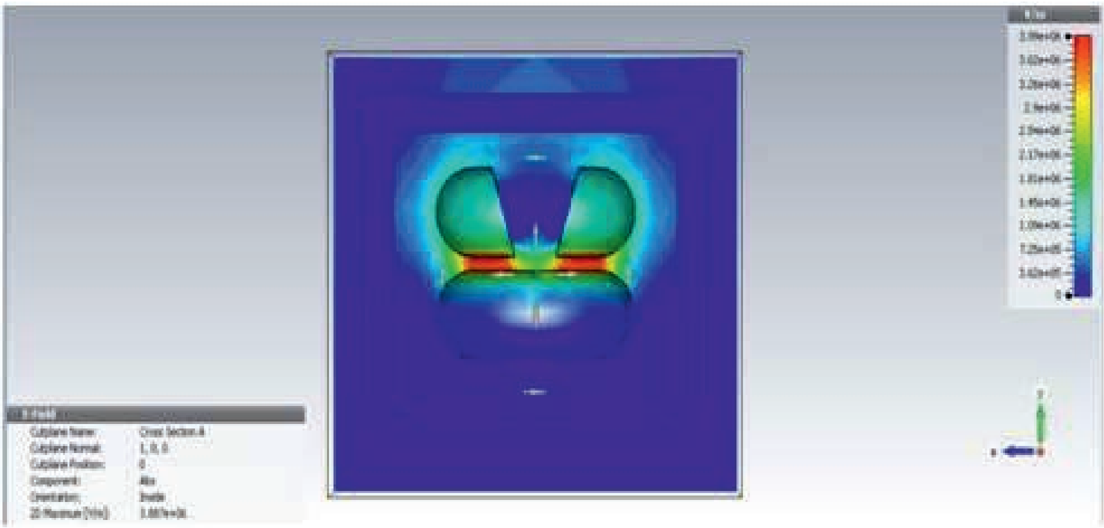


Figure 11.6. CST simulation of Laser Triggered Sparkgap Assembly.

11.4. Laser Triggering of Spark-Gap

A laser triggered SG system has been developed using Nd-YAG laser (532 nm) of 6-7 ns pulse duration with 19 fiber optic beam delivery system having less than 1 mJ of energy from each fiber. The optical fibre reduces the complex system of mirrors used to transport the laser beam to the spark gap switches. In order to pressurize the SG, a feed through window was required between focusing arrangement and SG assembly. For that study of percentage absorption of laser energy when passing through different materials (fused silica, glass and perspex) was carried out. It was observed that perspex scatters the laser light, glass absorbs more energy as compared to fused silica for the same thickness. Due to the absorption, the Laser energy further reduces. Hence, focussing lens itself is used as a feed-through in the above experiments. The power density of laser beam when it hits the electrode is 0.40 GW/cm^2. Figure 11.7(a) displays the Laser system and Figure 11.7(b) shows spark gap switch with focussing optics being pressurized by N_2 gas. For the experimental setup, energy storage capacitors of 0.15 µF/ 50 kV has been discharged through laser triggered SG across non inductive load of 10 Ω. In order to increase the SBV of spark gaps, they were filled with N_2 gas at a pressure of 0.2 kg/cm^2. The pressurized gases follow Streamer theory and Paschen's law where the breakdown occurs at range of nano seconds.

Figure 11.7(a). Innolas Spit Light 400 LASER setup.

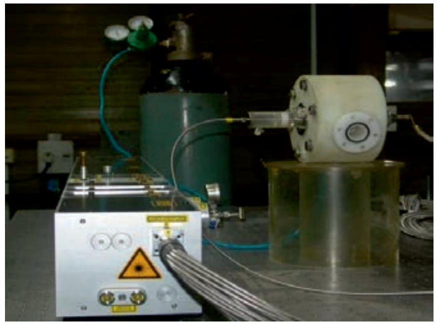
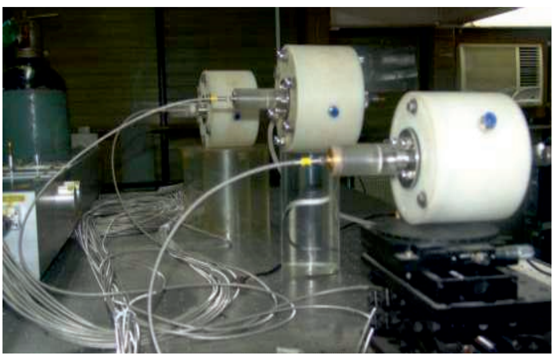


Figure 11.7(b). N_2 gas pressurized SG switch.

11.5. Synchronisation of Two Spark gap Switches using Optical Laser

Figure 11.8 shows the triggering and synchronisation of two spark gaps simultaneously. The gap spacing between the two electrodes was adjusted to 4 mm in each of the sparkgaps, having SBV obtained was 18.4 kV and 18.6 kV respectively. The collimator and lens assembly was same for both the sparkgaps with lenses having focal length of 5 cm. The output waveform showsthe synchronization of two SG with jitter <5 ns at a charging voltage of 17.5 kV. Further experiments demonstrate that for electrode gap of 5 mm and SBV of 16.5 kV, switching range of 16% was obtained for Laser Pulse energy of 900 µJ. While for SBV of 20 kV, switching range of 12% was obtained at Laser energy of 800 µJ. It was observed that for lower Laser energy, switching range reduces drastically. The SG has been tested upto of SBV of 32 kV under pressurized condition.



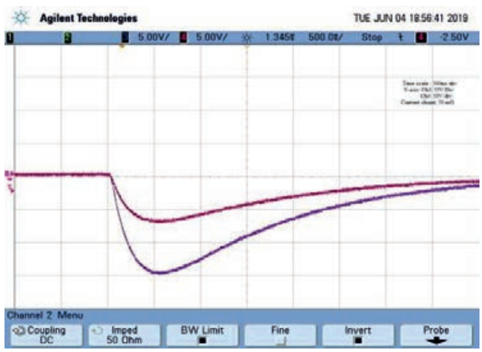


Figure 11.8(a). Photograph of sparkgaps assembly with focusing optics and (b). The output waveform of two switches showing jitter <5 ns.

11.6. Synchronisation of Two Sparkgaps using Mirror, Beam Splitter and Lens for Focussing

Figure 11.9 shows the experimental results using Nd-YAG laser (532 nm) of 10 ns pulse duration and 80 mJ energy per pulse. In this experiment, Laser was focusssed using mirror, beam splitter and Lens. The 50/50 beam splitter was used. So Laser energy at each sparkgap is 40 mJ. Gap spacing between the two electrodes of sparkgap is 4 mm. The self-breakdown voltage was 12.4/12.5 kV. Using this method, synchronization of two spark gaps was observed above 11 kV with jitter of 120 ns and at 12.3 kV jitter of 2 ns was observed.

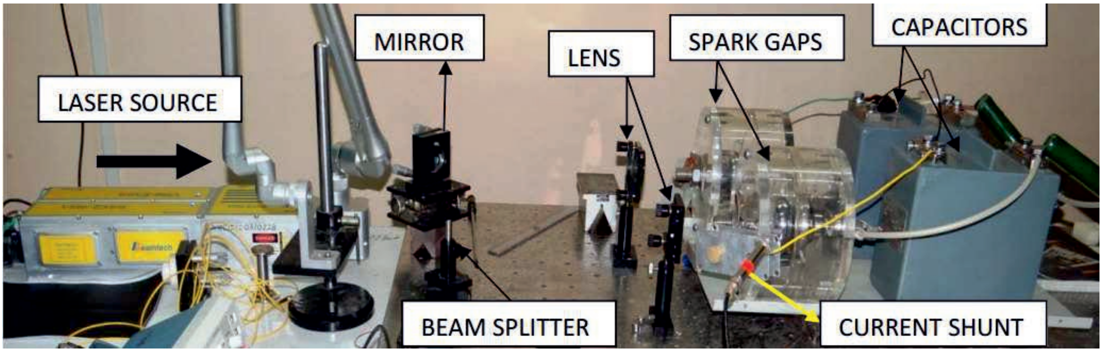


Figure 11.9. Synchronisation of two sparkgaps using mirror, beam-splitter and lens.

11.7. Summary

The synchronization of two SGs using fiber-delivered Nd-YAG laser at lower voltages with jitter < 5 ns has been achieved at laser energy < 1 mJ. Triggering of sparkgaps using Laser is the fastest way of triggering as compared to other triggering methods. It provides excellent solution to trigger the spark gap with less energy transportable through an optical fibre which can either ionize the insulating gas or create plasma by focusing the beam on targeting electrode. The main characteristics inherent to the laser–triggered spark gap are electrical decoupling, remote operation, short and variable delay with low jitter, simple structure, reproducible, reliable, low maintenance, suitable for repetitive operation, low voltage triggering of long gaps and suitability for all types of dielectric media. One drawback of the current laser triggering technology compared with other triggering techniques is that laser systems are more complex and prone to electromagnetic interference. However, the laser offers an alternative triggering device which is basically safer and simpler to use as it is isolated electrically from the sparkgap.

References

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