Preliminary investigation into the simulation of a laser-induced plasma by means of a floating object in a spark gap

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Abstract: In this research, an orthogonally laser-triggered spark gap is investigated. The laser beam is directed in the region of a 30 mm spark gap at 90 degrees to the gap and focused on the axis. The influence of plasma position within the spark gap on breakdown strength was investigated.. The experiments showed that the laser induced plasma was able to successfully trigger the gap, with the breakdown voltage a function of plasma position. At the optimal position, the minimum breakdown voltage was 16.7 kV,. This represents 21% of the maximum withstand voltage of the gap. It was shown that the laser-induced plasma had a greater effect on the breakdown voltage of the spark gap in question than a single floating object of similar dimensions.

1 INTRODUCTION

It is well known that the presence of a floating object in a spark gap under impulse conditions reduces the breakdown strength of the gap. Rizk and Hutzler applied this principle in order to investigate the effect of a conducting object in the case of switching impulses [1], [2]. In the mid-1960s, it was noted that a focused laser beam was able to generate a plasma in air [3]. This discovery lead to a number of subsequent experiments involving triggering of spark gaps for various applications [4], [5]. In all cases, the laser beam was directed along the axis of the spark gap. This allowed the entire gap to be irradiated by the laser beam.

There are two main geometries that one can use in the case of laser-triggered spark gaps. The laser beam can be directed along the gap axis (coaxial geometry). The beam can also be focused perpendicular to the gap axis (orthogonal geometry). The experiments in this paper will be restricted to orthogonal gap arrangements.

Breakdown in the case of an orthogonal laser-spark gap arrangement can be thought of as a result of a strong modification of the electric field of the gap. The power density at the focal point of the beam causes air to ionise and laser-induced plasma is generated. This disturbance in the electric field of the gap is responsible for the reduced breakdown strength observed. The question posed in this paper is whether one could think of the laser-induced plasma as a floating object in the gap and whether the presence of more than one pocket of laser-induced ionisation would result in a further reduction of the breakdown strength of the gap.

The orthogonal approach was favoured over the coaxial one for a number of reasons: (i) An orthogonally triggered spark gap is a more practical arrangement. (ii) One does not have to guide the laser beam in the region of the gap (in most cases through a hole in one of the electrodes). (iii) Orthogonally laser-triggered spark gaps also provide great research interest since they have not been studied extensively.

In this paper, the background of the work is presented followed by the experimental setup, the results obtained and a discussion section.

2 BACKGROUND

Previous experiments showed that one of the most important parameters that govern the formation of a laser-induced plasma is the intensity of the laser beam.

A focused laser beam will generate a spark in air at the focal point of the lens provided that the peak intensity is within a specific threshold [6]. The peak laser beam intensity is given by the following equations:

$$I_0 = \frac{2E_T}{\pi\omega_f^2\tau} \tag{1}$$

$$\omega_f = \frac{M^2\lambda f}{\pi\omega_0} \tag{2}$$

where I_0 is the peak laser beam intensity, E_T is the total energy, ω_f is the beam radius at the focal point, ω_0 is the beam radius incident on the lens and τ is the FWHM laser time pulse. For Gaussian beams the beam quality factor, M^2, is equal to 1, and greater than 1 for all other intensity profiles.

The wavelength of the laser light plays an important role. Shorter wavelengths result in photons of higher energy, and the minimum focal spot decreases linearly with decreasing wavelength as can be seen in (2). The effect of the wavelength though was found to affect the formation of the laser-induced plasma to a lesser extent than the other laser parameters, such as pulse energy, pulse width and spot size due to focal lens choice [7].

When using a laser to trigger a spark gap, the orientation of the laser beam with respect to the gap axis pays a significant role. Experiments were carried out with short gaps (5-10 mm) and the laser beam entering the gap in coaxial and orthogonal geometries [6] as can be seen in Fig. 1. These experiments showed that orthogonal laser-spark gap geometries produced the best results.

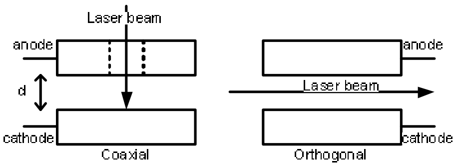

Fig. 1: Coaxial and orthogonal laser-spark gap geometries (electrodes have Rogowski profiles to provide a uniform electric field)

3 EXPERIMENTAL SETUP

The experimental system for delivery of the laser beam is shown in Fig. 3. A Q-switched, flash-lamped pumped Nd:YAG laser (Continuum, Powerlite) operating at the fundamental frequency of 1 064 nm was used. The linearly polarised output beam could be varied in both energy and pulse width through adjustment of the Q-switch delay. The repetition rate of the laser was set at a fixed 10 Hz throughout the experiments. A visible Helium Neon laser was aligned collinear to the Nd:YAG laser for ease of optical alignment. The laser beam passed through two Brewster windows which could be rotated, thus allowing energy attenuation external to the laser cavity. A pop-up mirror allowed for the laser beam to be directed to laser diagnostics: laser pulse duration was measured with a fast Si photodiode (ThorLabs, model DET210) and an energy meter (Gentec, model ED200) was used to determined the total pulse energy.

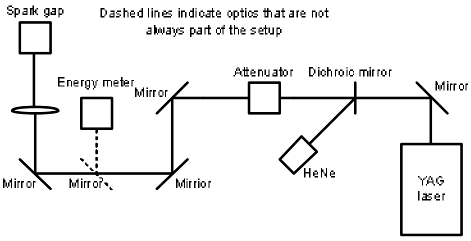

Fig. 3: Laser, optics and spark gap setup

With the pop-up mirror in the down position, the laser beam was delivered to a final focussing lens (uncoated quartz, plano-convex) for plasma generation. The spot size at the focus could be changed by changing the focal length of the lens.

The electrodes of the spark gap had a Rogowski profile and were arranged in such a way so as to allow the laser beam to intersect the gap axis at right angles. Rogowski profiles were used in order to create as uniform a field as possible in the spark gap. The vertical position of the focal point in the gap was varied by adjusting the height of the spark gap off the laser table, at a fixed gap length of 30 mm.

The spark gap was fed by means of a simple 30 kV DC source, as shown in Fig. 4.

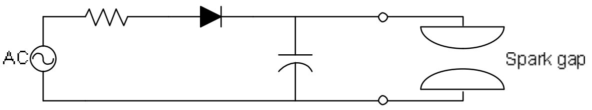

Fig. 4: High voltage supply circuit.

The AC source in Fig. 4 was a variac-controlled high voltage transformer. The DC voltage was monitored by means of a Fluke 80K-40 high voltage probe.

The time evolution of the laser-induced plasma was monitored with a gated camera (Xybion, model ISG-250) aligned to face along the laser beam axis, for "head-on" plasma recording, or perpendicular to the laser beam axis, for a "side view" of the plasma. The gate time of the camera was set to 50 ns, and delayed relative to the laser pulse by means of a Stanford Delay Generator (model DG-535). A block diagram and a time line for the system can be seen in Fig. 5.

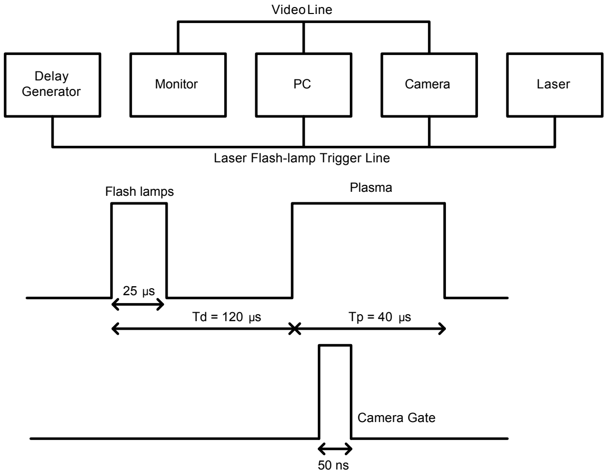

Fig. 5: Camera, laser and delay generator set up

In order to ensure that the camera did not saturate, the following procedure was performed: The brightest image of the plasma formation was determined and the camera gain reduced until the saturation was minimised. All further images were recorded at this gain setting.

4 RESULTS

4.1. Laser Beam Characterisation

Experiments were performed in order to determine the various laser beam parameters that are important for the experiments to follow. In this work we concentrated on pulse energy and pulse duration.

The laser energy and pulse width were measured at various Q-switch values ranging from 90 to 270 µs. The aim was to identify the Q-switch values for which the laser operated at an optimum level. It was found that the laser was not able to generate a plasma for Q-switch values less than 90 µs and greater than 260 µs. This range is represented by the shaded regions in Fig. 6.

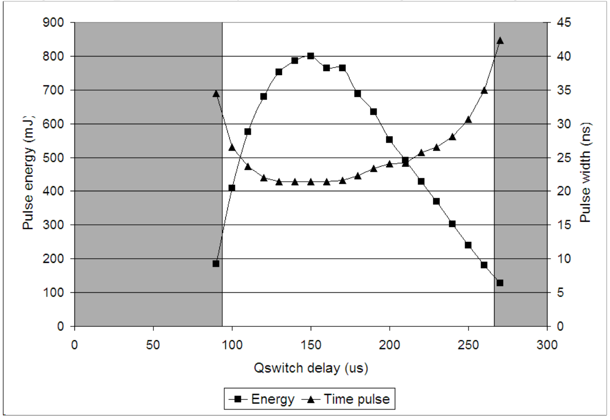

Fig. 6: Energy and pulse width variation with Q-switch delay

An example of a normalised pulse, representing one of the data points in Fig. 6, can be seen in Fig. 7. The FWHM pulse width was found to be approximately 15 ns at the optimum Q-switch delay.

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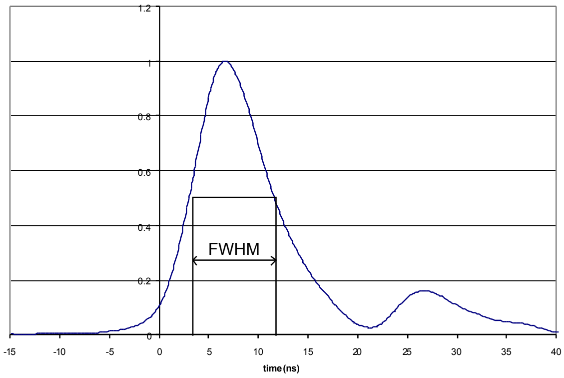

Fig. 7: Example time pulse of the Continuum Nd:YAG laser

Finally, time-evolution images of the plasma were taken using the gated camera. It was found that the plasma life-time T_p was 40 µs. The plasma started forming at $T_d = 134$ µs and died away at $T_d = 174$ µs. Head-on and side view images of the laser-induced plasma can be seen in Figs. 8a and 8b.

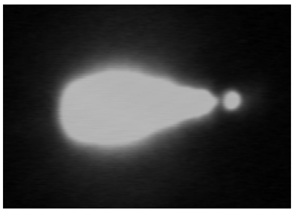

Fig. 8a: Side-view of plasma

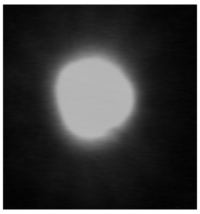

Fig:8b: Head-on view of plasma

From these images, the diameter and length of the laser-induced plasma was measured and found to be 3.14 mm and 7.14 mm respectively. In previous research by the authors, it was found that the electron density was about 7×10^{17} cm^{-3} for an energy of about 175 mJ. The refractive index was also found to follow a convex parabolic trend [8].

The camera was also able to capture the gap breaking down as a result of the plasma (Fig. 9). In the image obtained, one can clearly see the laser-induced plasma and the subsequent arc that was formed.

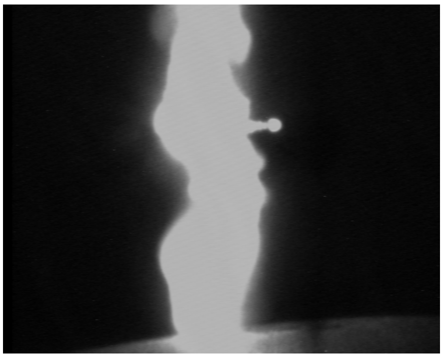

Fig. 9: Side view of the gap breaking down. Notice the plasma plume in the top 1/3 part of the image

Using equations 1 and 2, the beam radii and the peak beam intensities for three different local length lenses (150, 200 and 250 mm) were calculated. The value of the intensity and radius for the 150 mm lens was taken as 1. The results can be seen in Tab. 1.

Tab. 1: Variation of beam radius at peak intensity at focal plane

Focal length f (mm)	Beam radius ω_f	Peak intensity I_0
150	1	1
200	1.33	0.56
250	1.67	0.36

From Tab. 1 it can be seen that the shape of the plasma plume is dependant on the lens used since the lens affects the laser beam intensity at the focal point. A shorter lens increases the beam intensity. A longer lens has the opposite effect. This is due to the fact that the laser beam intensity as can be seen from (1) is dependant on the beam radius ω_f which in turn is dependant on the focal length of the lens used.

4.2. Voltage Breakdown Levels

Initially, the Q-switch delay was varied and the breakdown voltages obtained for each delay were recorded. These results can be seen in Fig. 10.

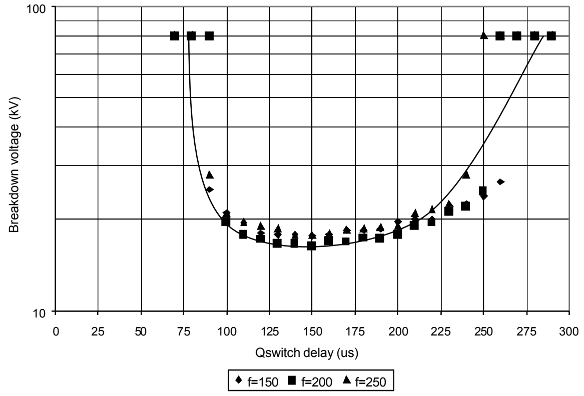

Fig. 10: Variation of breakdown voltage with Q-switch

From Fig. 10, it can be seen that the lowest breakdown results were obtained for the range of Q-switch values between 130 and 180 µs. It is interesting to notice that the shape of this plot is very similar to the plots obtained for the energy and pulse width of the laser (Fig. 6). In both graphs one notices a very similar steep gradient from 90 to 150 µs and a similar slow rate of change from 150 to 270 µs. In other words, the parabolic-like curve is asymmetrical. This asymmetry manifests itself in a similar asymmetry in the breakdown voltage as a function of Q-switch delay.

The main body of the experiments involved finding the minimum voltage range the laser was able to trigger. This range ΔV is defined as the difference between the maximum voltage the gap is able to withstand ($V_{\max}$) and the minimum voltage the laser was able to trigger ($V_{\min}$).

$$\Delta V = V_{\max} - V_{\min} \qquad (3)$$

At the same time, the effects of the position of the plasma plume in the gap and the focal length of the lens on the breakdown voltage was investigated. In these experiments the laser operated at maximum energy (800 mJ) and at a repetition rate of 10 Hz.

These experiments were performed as follows: The voltage was applied to the gap and the laser was fired. If breakdown did not occur then the voltage was reduced and the laser fired again. If the gap fired, then the voltage was increased and the experiment repeated. This was done until the minimum voltage level was found. The experiment was then repeated using a lens of different focal length. In all cases the plasma was generated in the midpoint of the gap. The results showed that the laser was able to successfully trigger the gap at low voltages. The results can be summarised in Tab. 2.

Tab.2: Minimum breakdown voltages for three different focal lengths.

Focal length (mm)	Breakdown voltage (kV)
150	17 ± 1kV
200	16 ± 1kV
250	17 ± 1kV

From the above table, it can be seen that the average breakdown voltage is 16.7 kV. Under standard conditions, the 30 mm gap used typically breaks down at about 80 kV. Therefore the minimum voltage found represents 21% of the maximum withstand voltage. In other words the breakdown range is approximately 63 kV. This breakdown range is significantly larger than that obtained in [7].

As mentioned, the next step was to vary the position of the laser-generated plasma in the gap. This was done by raising or lowering the entire spark gap system while keeping the laser beam position fixed. A height - adjustable platform (lab-jack) was used. The plasma position was varied with millimetre accuracy from -15 mm to 15 mm. For each position, the procedure described above was performed in order to find the minimum breakdown voltage. The experiments were repeated for 150, 200 and 250 mm focal length lenses.

The results from these experiments can be seen in Fig. 11.

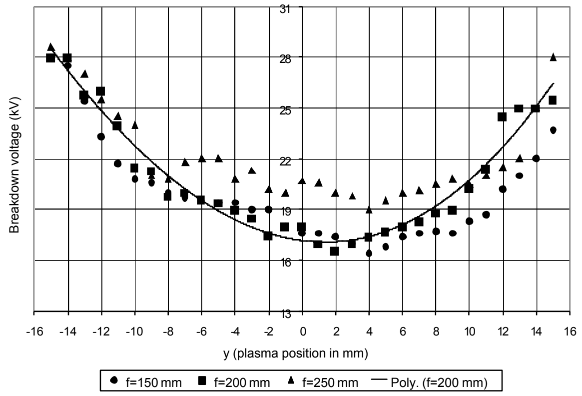

Fig. 11: Breakdown values for various position of the laser beam and for three different focal lengths (150, 200 and 250 mm)

The gap geometry is illustrated in Fig. 12. From Fig. 11 it can be seen that a general trend exists: The breakdown voltage with the beam on the surface of the cathode is a lot higher than when it is located on the surface of the anode. Since the laser-induced plasma provides an abundance of free electrons very close to the cathode, the electric field does not allow these negative charges to progress along the gap and cause breakdown. However, if the plasma is located close to the surface of the anode, then the electron avalanche is more likely to start and create breakdown the gap. It can also be noted that all three plots follow a roughly parabolic trend.

It is interesting to notice that the lowest breakdown voltage in all three cases occurs when the laser beam is focused just below the mid-point of the gap (about 5 mm below the centre). Since the length of the gap is $L = 30$ mm, it transpires that minimum breakdown voltage occurs in the region between $\frac{1}{3}L$ from the cathode and $\frac{1}{2}L$. These regions can be seen clearly in Fig. 12.

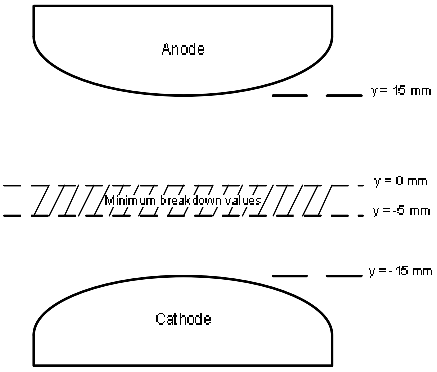

Fig. 12: Region of the spark gap where minimum breakdown values were observed.

When the 250 mm lens was used, it was noted that the breakdown voltage values that were obtained followed the general parabolic-like trend. The voltage levels obtained were slightly higher and more random than when a 150 and 200 mm lens was used. This could be due to the fact that the peak laser beam intensity in the case of a 250 mm lens is almost 3 less than that of a 150 mm lens. However, from Fig 5, one can see that the difference between the three plots is only slight which means that the reduction of the beam intensity by a factor of 3 did not really affect the results. A far more severe increase in focal length would be needed in order to have a significant effect on the voltage breakdown levels.

Finally, cylindrical metal floating objects were suspended in the spark gap. This was done in order to quantify their effect on the breakdown voltage of the gap. These objects had a length of 10 mm and a diameter of 5 mm (dimensions similar to those of the laser-induced plasma). However, it was found that there was not enough voltage to test electrical breakdown with one floating object suspended in the centre of the gap. When two floating objects were suspended (one at 5 mm and the other ay 10 mm above the cathode) breakdown was observed at 29 kV. This represents 38% of the maximum gap breakdown voltage (80 kV). This percentage is higher than that obtained when that laser-induced plasma was present in the gap. This shows the dramatic effect the presence of the plasma has on the breakdown strength of the gap.

5 DISCUSSION

This paper involves experiments that are being performed in order to investigate the effect of different focusing strategies on the breakdown behaviour of a spark gap (short gap). One of the goals of the current research is to try and draw parallels between laser-induced plasmas and conductive floating object suspended in a spark gap. Thus far floating object research has been mainly performed for long gap breakdown and the balance between the formation of streamers and leaders [1], [2] in a long gap.

A laser-induced plasma can be thought of as a floating conducive object. However it has a transient behaviour unlike a conventional floating object. Its presence in the gap is dependent on the plasma lifetime which in turn depends on the type of laser used. One could think of a laser-induced plasma as a “dynamic” floating body.

The preliminary results of this paper confirm that a laser beam focused on the axis of a spark gap and at right angles to it is able to dramatically reduce the breakdown strength of a spark gap, but introduces a new finding that careful consideration must be given to the position of the focussed laser beam in the gap, perhaps even more so than the actual parameters of the laser used.

6 CONCLUSION

The research presented in this paper involves investigating the behaviour of a laser-triggered spark gap in the special case of the laser beam being perpendicular to the axis of the gap (orthogonal arrangement). An Nd:YAG laser was used in the experiments. The results thus far show that the breakdown strength of the gap is reduced considerably when the laser beam is focused 5 mm above the cathode (1/3rd of the length of the gap). In the case of a 30 mm gap, the laser is able to trigger a voltage of 16.7 kV. This represents roughly 21% of the gap withstand voltage. It was noted that the variation of laser energy and time-pulse with Q-switch delay was mirrored in the variation of the breakdown voltage with the laser Q-switch delay. They both produced the same asymmetrical parabolic-like curves. The laser-induced plasma was able to reduce the breakdown strength of the gap far more than a single floating object would. This can be attributed to the strong transient nature of the plasma.

7 ACKNOWLEDGMENT

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