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Preliminary investigation into laser-high voltage interaction in the case of the streamer-to-leader process using a high power CO_2 laser

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Abstract – **This paper describes the preliminary small-scale experiments conducted in order to investigate the influence of intensely focused laser light produced by a CO_2 laser on high voltage fields. The laser used operated at a maximum energy of 430 mJ per pulse and emitted in the far infrared region (10.6 μm). The pulse had a FWHM of 80 ns and a tail of 1 μs. Experiments were performed in order to obtain the minimum laser-induced break down voltage voltage for specific spark gap arrangements (namely a coaxial and orthogonal gap of varying gap length. The results show that the orthogonal gap performed much better than the coaxial one. The minimum breakdown voltage that was obtained was for a 10 mm orthogonally orientated gap. For this case laser-induced breakdown strength was found to be 3 kV (11% of 27 kV).**

Index Terms – **CO_2 laser, laser-induced breakdown, Streamer-to-leader**

I. INTRODUCTION

The two main mechanisms that are used to describe high voltage breakdown are the streamer and leader processes. The former is used to describe processes that happen in short gaps. The latter refers to long gaps. A good example of the leader process is the formation and propagation of lightning. Upward streamers that are generated in the presence of a downward moving leader can be converted to upward leaders under the correct conditions. The conditions that lead to a streamer-to-leader transition are dependent on many parameters such as the electric field and the height of the object above ground (in the case of lighting).

Since the mid 1960s, it has been known that intensely focused laser light is able to cause local breakdown in air. This knowledge was used to research the possibility of using laser light as a method of triggering high voltages [1][2][3]. The fact that a laser can produce very

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high electric fields and power densities in air has led researchers to investigate the possibility of laser beams used in lightning attachment experiments.

The main aim of this work is to compare the traditional coaxial geometry used in the case of lightning attachment with an orthogonal approach. In other words, focusing a laser beam at 90 degrees to the axis of the spark gap. Multiple focal points can also be used to further modify the electric field. This is done in order to facilitate the transition of an upward streamer to an upward moving leader. In this paper, preliminary small-scale experiments are presented. The experimental setup is presented followed by discussion of the preliminary results.

II. BACKGROUND

Laser-induced breakdown of air was first observed in 1963 [1]. In order to generate a spark in air using a focused laser beam, a peak laser beam intensity of about 10 GW/cm^2 is required. This can be easily obtained using a 100 mm lens and a laser energy of about 100-200 mJ per pulse with a 10 ns pulse [4]. The peak laser beam intensity is given by the raltionship:

$$I_0 = \frac{2E_T}{\pi \omega^2 \tau} \qquad (1)$$

Where:
I_0 = the peak laser beam intensity (W/cm^2)
E_T = Total energy (J)
ω = beam radius (for gaussian beams)
τ = laser time pulse (FWHM)

The average peak intensity for a gaussian beam is given by:

$$I_0 = 2\bar{I} \qquad (2)$$

The factor of 2 will change according to the spacial properties of the laser beam. For example, in the case of a flat-top beam, the coefficient is 1.

Laser-triggering of long gaps (and ultimately lightning) has been investigated by many researchers [5][6]. Research has shown that a high power laser can be used successfully to trigger long gaps. In most cases a CO_2 laser was used with energies of about 100 J.

In previous experiments [7] using various wavelengths it was shown that the most important parameter that influences the ability of a laser beam to trigger a spark gap is the power density of the focused beam (laser beam intensity I). The higher the power density, the easier breakdown occurred. The process was affected by the wavelength (shorter wavelength proved more effective due to higher energy per photon). The effect of wavelength though was not as great as that of power density. In the experiments presented in [7], for a 5 mm gap and a Nd:YAG laser operating at 170 mJ per pulse ($\lambda = 1\ 064$ nm), with a spot size of 400 μm and a time pulse of 8 ns, the breakdown voltage was reduced to 600 V from 13 kV (representing about 4.6 % of maximum voltage).

This paper is an investigation of the interaction of intense laser light with high voltage fields. The aim of the research is to understand this interaction in terms of the trying to generate the correct conditions for a streamer-to-leader transition.

III. THE LASER AND EXPERIMENTAL SETUP

The purpose of these preliminary experiments is to lay down the ground work for the investigation of long gap laser-induced breakdown. In the small-scale experiments that were performed, a TEA CO_2 laser (EMG103 MSC) was used . The laser had an energy of 430 mJ per pulse. The pulse width has a FWHM of 80 ns and a tail of about 1 μs. The wavelength of the laser was measured and found to be λ=10.6 μm. The percentage energy contained in the spike and the tail of the time pulse was calculated numerically. It was found that the energy in the spike comprised 53.38 % of the total energy. The remaining 46.62 % was found in the tail. The time pulse of the laser is shown in Fig. 1.
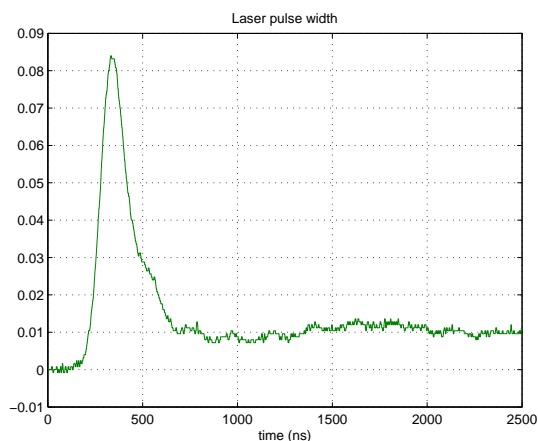

Fig. 1.　: CO_2 laser pulse width

The measurements were taking using a Tektronix

handheld oscilloscope (THS720P). The waveforms were captured using the Tektronix WaveStar software package. A Lambda Physik 3.5 V/J energy meter and a Boston Instruments PEM detector was used to measure the energy and time pulse respectively. The laser was operating at a maximum repetition rate of 20 Hz in these experiments.

A simple single stage voltage impulse generator was used to apply a maximum voltage of 30 kV across the test spark gap.The optical setup used in the experiment can be seen in Fig. 2. The spark gap arrangements can be seen in Fig. 3.
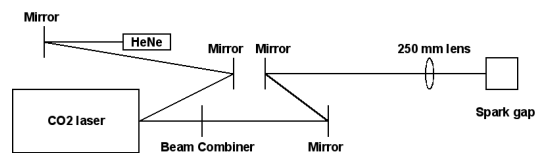

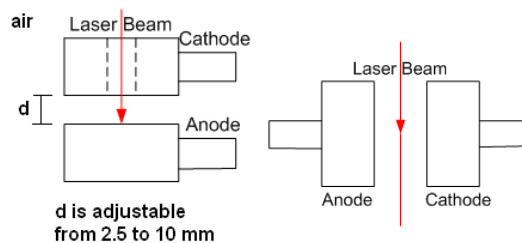Fig. 2.　: Optics and laser setup

Fig. 3.　: The spark gap used in the experiments (coaxial geometry and orthogonal geometry)

The spark gap was made of brass. The diameter of each electrode was 15 mm and the cathode had a 5 mm hole in it allowing the laser beam to penetrate through the gap to the anode in the case of a coaxial geometry (Fig. 3). In the case of an orthogonal geometry, the laser beam was focused in between the two electrodes of the spark gap. The laser beam was focused by means of a 250 mm focal length lens. All the high voltage measurements were taken using a Tektronix wide bandwidth 1000:1 high voltage probe (P6015A). The probe was connected to the output of the impulse generator. The laser was used to trigger the switching spark gap of the impulse generator.

A number of experiments were performed at the CSIR - NLC (National Laser Centre). These experiments were conducted in order to find the radial variation of an laser-induced air plasma. In these experiments an Nd:YAG laser (Continuum Powerlite, PL9010) was used. An Ocean Optics spectrometer (LIBS2000+) was used to detect the intensity of the generated plasma. The results of this research are presented in [8].

Table. I. Minimum breakdown voltages for 5 and 10 mm coaxial gap - 10 Hz

5 mm V_{max}=15 kV		10 mm V_{max}=27 kV	
V [kV]	% V_{max}	V [kV]	% V_{max}
1.8	12.5	6.0	22.0

Table. II. Minimum breakdown voltages for 5 and 10 mm orthogonal gap - 10 Hz

5 mm (10 Hz)		10 mm (10 Hz)	
V [kV]	% V_{max}	V [kV]	% V_{max}
0.25	1.67	4.0	14.8

Fig. 4. : Laser-triggered impulse waveform with maximum voltage of 1.8 kV

Fig. 5. : Laser-triggered impulse waveform with maximum voltage of 6 kV

IV. RESULTS

Two main experiments were conducted. The aim of both experiments was to find the minimum voltage the laser can trigger compared to the maximum voltage the gap can withstand. In other words, the voltage range $\Delta V = \Delta V_{max} - \Delta V_{min}$, where ΔV_{max} is the maximum voltage the gap can withstand and ΔV_{min} is the minimum voltage the laser can trigger. All experiments were conducted in air. Two cases were considered thus far: A gap spacing of 5 mm and a gap spacing of 10 mm for both a coaxial and orthogonal geometry. The laser in both experiments operated at maximum energy and at a maximum repetition rate of 20 Hz. The results are summarised in Table I and II.

A Spark gap with coaxial geometry

In this case, the laser was directed in such a way that the focal point was half way between the two electrodes. From these experiments it was noted that the laser was able to drop the breakdown strength of the 5 mm gap to 1.8 kV (representing 12.5 % of the maximum withstand voltage which was measured to be about 15 kV). The waveform obtained for this case can be seen in Fig. 4. In the case of the 10 mm gap, the breakdown strength was reduced to 6 kV or 22 % of the maximum voltage (27 kV). The reduction in this case is smaller due to the larger gap. The corresponding waveform can be seen in Fig. 5. These results are in line with those obtained in [7]. The laser-induced breakdown voltage in this case is lower than the ones previously obtained (using a KrF laser at 248 nm). This is due to the higher energy: 430 mJ of the CO_2 vs, 200 mJ for the KrF laser.

B Spark gap with orthogonal geometry

In this case, the laser was once again focused between the two electrodes, however, the beam is set to be perpendicular to the axis of the gap. The experiments were performed for a 5 mm and a 10 mm gap spacing. The experiments showed that the laser was able to trigger a minimum of 250 V for the 5 mm gap (1.67 % of 15 kV) and 4 kV in the case of the 10 mm gap (14.8 % of 27 kV). The laser was then set to run at a maximum of 20 Hz. Under these conditions, the 10 mm gap broke down at 3 kV (11 % of 27 kV).
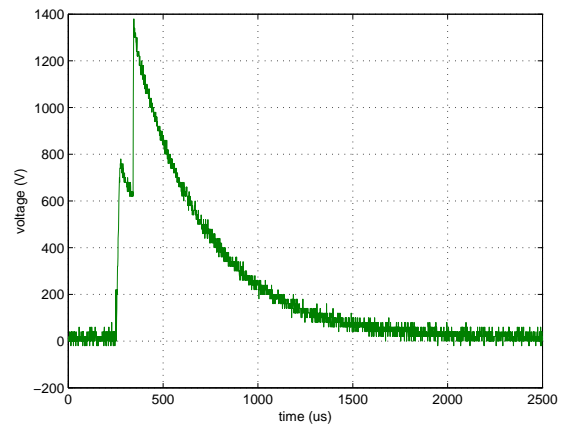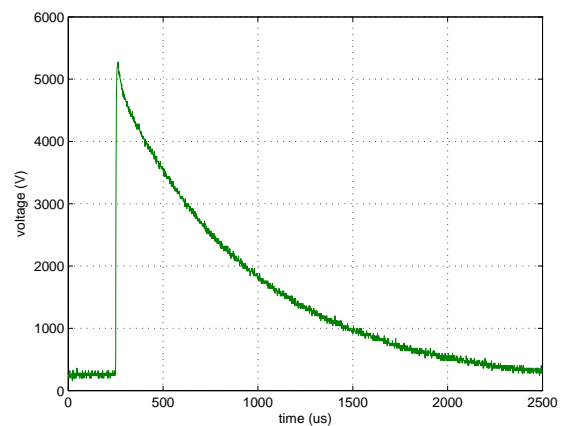
The breakdown strength of the 5 mm gap was found to be so low, due to the fact that the size of the laser-induced plasma bead was about 4 mm in diameter. This means that the plasma was effectively bridging the gap. These results show once more that the wavelength of the laser is important, but not as important as the power density of the focused beam. In these experiments, the photon energy was considerable less (about 112 meV for 10.6 μm) than say a KrF laser (4.6 eV for 248 nm)

C Pre-breakdown phenomena

When the spark gap was charged to a lower voltage than the threshold value and the laser was fired (either in a coaxial or orthogonal geometry) small amplitude impulses were measured on the output of the generator. The peaks of these impulses varied from 5 to 150 V. A typical impulse of this type can be seen in Fig. 6.

The appearance of such small impulses on the output of the generator can be attributed to the formation of charge carriers that are re-absorbed into the impulse generator circuit and appear at the output as a voltage
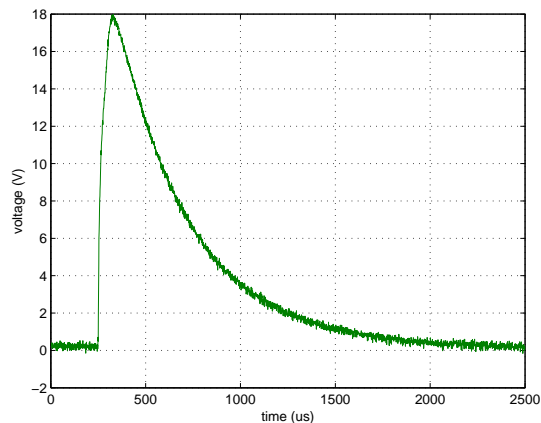
Fig. 6. : Typical pre-breakdown impulse waveform (V_{charge}=5.5 kV)

Parameter	Orthogonal	Coaxial
% Max non-linearity	35.2	22.6
Correlation coefficient (R)	0.961	0.959

breakdown.

When the orthogonally orientated gap was used, the results proved to have a linear trend, but the values tended to be more random. This can be explained by considering that the focused laser beam does not strike any part of the gap. The process relies on the laser-induced breakdown of air and the formation of space charge in the region between the two electrodes. The percentage maximum non-linearity and the correlation coefficient R in both cases (coaxial and orthogonal) were calculated. These parameters can be seen in Table III.

V.   PROPOSED FUTURE WORK

As mentioned, the aim of this present work is to lay down the foundations for further investigation of the streamer-to-leader transition in the case of laser-induced breakdown. In other words, it is important to become aware of the parameters that surround the inception of an upward leader such as the critical electric field or the hight and geometry of a structure [9] and relate them to the electric field modification induced by an intensely focused laser beam.

Further experiments will be conducted using longer gaps. The main gap geometry that will be used is a rod-to-plane as can be seen in Fig 8. In the experiments, measurements will be made concerning the electric field generated in relation to the radius of the tip and the height of rod. The laser beam will be set up to interact with the gap at various angles (orthogonally, coaxially and at an angle to the rod other than 90 degrees).

At a later stage, the experiments will be repeated using a high power KrF excimer laser. This will be done in order to investigate the effect of UV light on the system and compare it will the far IR case just presented (10.6 μm). In this case, the effect of the wavelength on the breakdown process can be investigated. In these experiments, the voltage will also be increased to about 60 kV.

impulse of reduced amplitude.

A number of experiments were performed on a 10 mm gap in both the orthogonal and coaxial arrangement. This was done in order to try and find whether or not a trend exists in the values of the generated impulses for various charging voltages. The laser operated at 10 Hz with an energy of 386 mJ. The gap was subjected to 5 seconds of laser radiation (approximately 50 pulses). The results show that the impulse maximums follow a roughly linear trend. The results obtained from the coaxial geometry were found to be more linear than those obtained in the case of the orthogonal gap arrangement. This can be seen in Fig. 7.
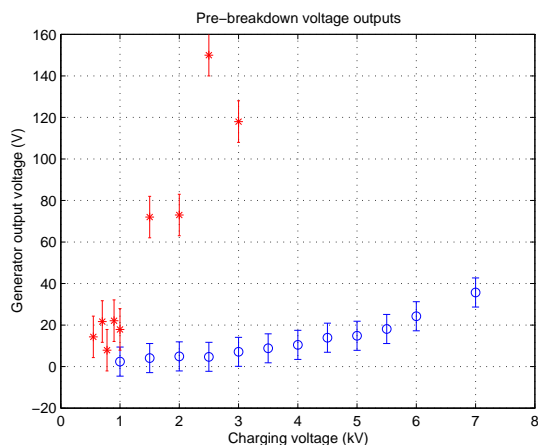

Fig. 7. : Plot of the impulse peaks obtained for various charging voltages in the case of a coaxial and orthogonal gap geometry

From Fig. 7, it can be seen that in the case of the coaxial geometry, the progression is fairly linear. This can be attributed to the fact that the laser beam enters through a hole in the one electrode and always strikes the surface of the other. This leads to ablation and emission of secondary electrons that get re-absorbed in the circuit. The presence of these electrons is always there until the voltage applied is enough for the gap to
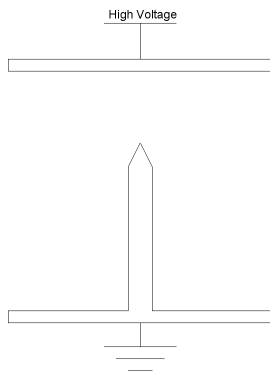
High Voltage

Fig. 8. : Rod-plane spark gap arrangement

VI. Conclusion

This paper describes the preliminary investigations relating to the interaction of intense laser light with high voltage electric fields. In the preliminary experiments that were conducted, a CO_2 operating at a maximum repetition rate of 20 Hz and an energy of 430 mJ per pulse laser was used. Two gap lengths and orientations were used in the experiments: a 5 mm and 10 mm gap in a coaxial and orthogonal arrangement.

In the case of the 5 mm gap, its breakdown strength (15 kV) was reduced to 1.8 kV (coaxial arrangement) and 250 V for the orthogonal case. The latter reduction was due to the size of the plasma plume generated by the laser. In the case of the 10 mm gap, the breakdown strength (27 kV) was reduced by 78% to 6 kV for the coaxial gap and 3 kV in the case of the orthogonal spark gap arrangement.

VIII. References

[1] P. D. Maker, R. W. Terhume, and C. Savage. Optical third harmonic generation. Proceedings of the 3rd IEEE international conference on quantum electronics, Paris, 1964.

[2] A. H. Guenther and J. R. Bettis. Laser-triggered magavolt switching. *IEEE Journal of Quantum Electronics*, vol. 3, no. 11, pp. 581–588, November 1967.

[3] T. X. Phuoc. An experimental and numberical study of laser-induced spark in air. *Optic and Lasers in engineering*, vol. 43, pp. 113–129, 2005.

[4] N. J. West and I. R. Jandrell. Investigation into ultraviolet laser triggering of spark gaps in air and sulphur hexafluoride. South African Universities Power Engineering Conference, 2005.

[5] D. Wang, Z.-I. Kawasaki, K. Matsuura, Y. Shimada, S. Uchida, C. Yamanaka, E. Fujiwara, Y. Izawa, N. Simokura, and Y. Sonoi. A preliminary study on laser-triggered lightning. *Journal of Geophysics Research*, vol. 99, no. D8, 1994.

[6] M. Megumu, A. Wada, and T. Shindo. Characteristics of upward leaders triggered by CO_2 laser. International Conference on Lightning Protection, September 2004.

[7] N. J. West and I. R. Jandrell. Laser-induced breakdown at 248, 532 and 1 064 nm for use in high voltage switching applications in air and sulphur hexafluoride. 28th International Symposium on High Voltage, 2005.

[8] M. Mathuthu, R. M. Raseka, H. G. C. Human, N. West, and A. Forbes. Radial variation of air plasma parameters. Submitted to IEEE Transactions on Plasma Science.

[9] F. A. M. Rizk. Modeling lightning incidence to tall structures. *IEEE Transactions on Power Delivery*, vol. 9, 1994.