Insights into the peculiar field structure of a recent diffuse discharge under extreme voltage conditions by electric field induced second harmonic generation and optical emission spectroscopy

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Abstract: The axial temporal evolution of the electric field of a diffuse nanosecond air discharge is measured with high resolution (<100 ps). This discharge is generated at atmospheric pressure in a pin-to-plane configuration for voltages ranging from 20 to 85 kV The electric field is derived by field induced second harmonic generation. It is shown that for peak voltages above 56 kV, the electric field behind the field front increases with voltage and exceeds the ionization threshold at 85 kV. Results are compared to recent measurements [1].

Keywords: Nanosecond diffuse atmospheric plasma, electric field induced second harmonic

1. Introduction

A diffuse nanosecond discharge in atmospheric air was recently obtained under very high electric fields [2]. It is of great interest regarding flow control, air depollution and plasma assisted combustion [3]. It is generated in a pin-to-plane geometry by a 10ns pulse with overvoltages as high as 800 % from static breakdown voltage. In such conditions, discharge properties are deeply modified. Specifically, previous electric field measurements by optical emission spectroscopy (OES) showed that high field strengths could be sustained over long distances during the propagation of the discharge and along the conduction stage [1]. However, OES measurements are subjected to some limits such as the accuracy of the kinetic model to be used and eventually to the limitation of the spatio-temporal resolution. A ps laser technique, electric field induced second harmonic (E-FISH), recently applied for air plasma diagnostic [4], is used in this work to improve the knowledge of the peculiar field distribution of this very transient discharge.

The main aims of the present study are to evaluate with high spatio-temporal resolution how extreme voltage pulses affect the field structuration of the discharge and to explore the ability of the method to be applied to a very transient discharge.

2. Experimental methods

The discharge is created in a pin-to-plane configuration of 16 mm gap in dry air. The tungsten pin is 100 µm curvature radius and the copper plane is 5 cm radius. The positive high voltage, applied to the pin, is a nanosecond pulse generated by a FID-type technology power supply. It is run at 10 Hz to limit memory effects. The plane is connected to the ground through a high bandwidth resistive shunt. Typical electrical signals at 85 kV are presented in figure 1. The voltage rise time is as fast as 2 ns. A complete description of the device is presented in [2]. During the experiments, the voltage amplitude was increased from 20 to 85 kV at 3 mm from the pin. At 85 kV additional measurements at 6 mm and 9 mm from the pin were made.

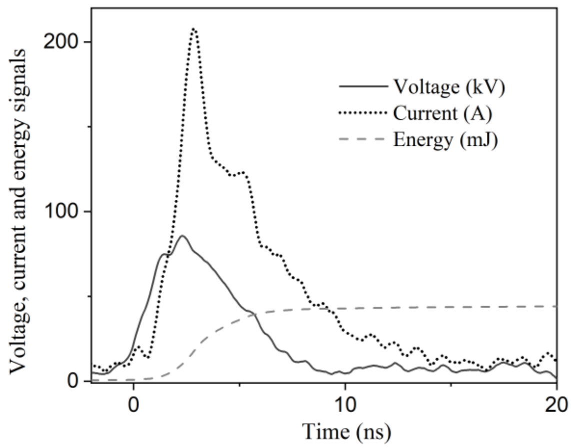

Fig. 1. Voltage, current and energy signals for a typical 85kV peak voltage pulse.

The experimental setup is presented in figure 2. A 1064 nm mode-locked Nd:YAG laser of 30 ps pulse width is used. In order to avoid laser induced breakdown events, the beam energy is limited to 1.8 mJ and the confocal beam parameter is 2.4 mm. This last parameter defines the FWHM of the spatial extent along the laser beam that leads to a significant E-FISH signal [4]. It is centred around the beam waist location and corresponds to twice the Rayleigh range as demonstrated in [4] for a Gaussian-like beam. The beam width is 40 µm. The laser first crosses a half-wave plate in order to ensure the vertical polarization of the laser. A plano-convex lens focuses the beam on the probed volume. To assure that no second harmonic light has been generated on the previous optics and laser path, a long pass filter is inserted just ahead of the discharge. A dispersive prism separates the initial 1064 nm beam and the discharge induced 532 nm second harmonic beam. The infrared signal is recorded by the photodiode (PD) while the visible signal, proportional to the square of the electric field, is focused on a photomultiplier (PMT) equipped with a 532 nm polarizer.

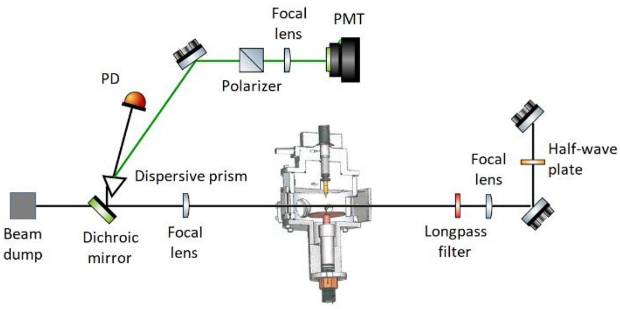

Fig. 2. Electric field induced second harmonic setup.

3. Electric field calibration

The square root of the integrated PMT signal is divided by the integrated photodiode signal in order to correct for laser power variations from shot to shot. For each set up condition (voltage pulse, spatial position), the time evolution of the electric field is described by at least one thousand shots.

The calibration of the electric field is done at 20 kV peak-voltage condition at 3 mm from the pin and restricted to the early stage of the voltage rise. The ignition of a discharge at the pin starts to be visible at about 24kV, corresponding to a Laplacian field of 14 kV/cm at 3mm. The limitation of the calibration voltage range to 14 kV avoids any field disturbance at 3mm. During the voltage rise, the electric field is assumed to be Laplacian and proportional to the voltage applied to the pin. The coefficient of proportionality was determined at 14 kV using a COMSOL electrostatic simulation taking into account the complete reactor geometry. The field is integrated over 2.4 mm to take into account the E-FISH signal contribution along the complete interaction length of the laser. The calibration curve is presented in figure 3.

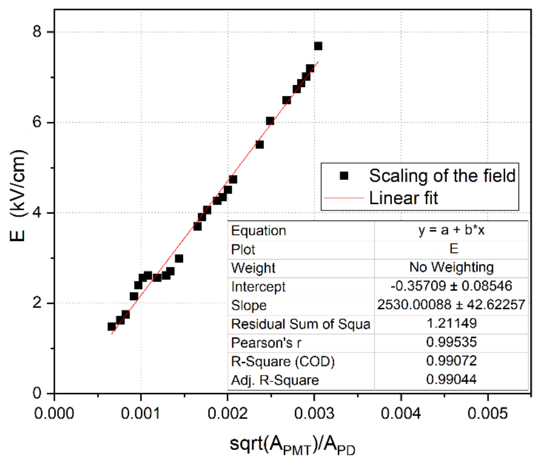

Fig. 3. Electric field calibration curve between 2 and 14 kV. A_{PMT} and A_{PD} are the areas of the PMT and PD signals respectively.

4. Results

Temporally resolved electric field measurements at 40, 56, 68 and 85 kV at 3 mm from the pin are presented in figure 4. Each curve shows the temporal evolution of the axial component of the field. All field distributions are made up of two contributions: a 10 ns component strongly related to the voltage time evolution and a very transient contribution representative of the peaked space charge field. Then, dependent on whether the discharge reaches or not the plane, additional structures can be observed.

At 40 kV and 3 mm, the E-FISH signal deviates from the Laplacian field from the very beginning of the voltage rise under the influence of the discharge ignition. Then, the crossing of the laser beam by the peaked space charge is observed and affects the E-FISH signal for about 1.4 ns. This is quite long compared to the initial discharge propagation speed of 3 mm/ns [2]. Based on this speed and assuming that the high field space charge is localised in space, its influence on the E-FISH signal should be much shorter. This discrepancy probably comes from the fact that the discharge does not reach the plane but progressively stops to propagate at a distance close to the probed region. Then, it vanishes in the gap as the voltage falls. At 40 kV, the light front extinguishes at about 5 mm from the pin and the long duration of the space charge influence on the E-FISH measurements simply comes from the slow propagation and speed reduction of the discharge at low fields.

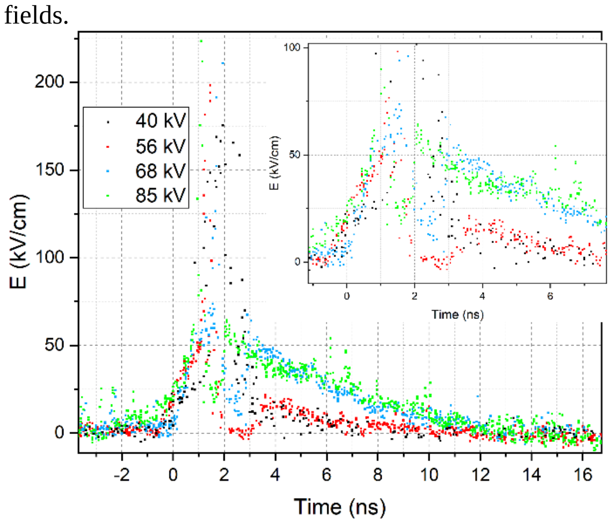

Fig. 4. Electric field measurements in time at 3 mm from the pin at 40, 56, 68 and 85 kV. Time zero corresponds to the discharge ignition.

On the contrary, at higher voltages, the discharge has propagated far enough in the gap to be strongly accelerated under the influence of the cathode plane [2]. At 56 kV, the discharge crosses the gap. New discharge development steps are now clearly visible. At some point of the voltage rise (when the field reaches around 14 kV/cm) the discharge ignites and the very high field discharge front starts to propagate with some delay compared to the propagation of the light emission front as observed in [1]. Behind the passage of the front, the field drops very abruptly to almost zero. This is characteristic of a streamer development. It reaches the plane in 3 ns. When the junction at the plane is made, the excess of remaining positive ions in the gap are neutralized (return stroke) in less than one nanosecond. The field is rebalanced in space and decreases with the applied voltage.

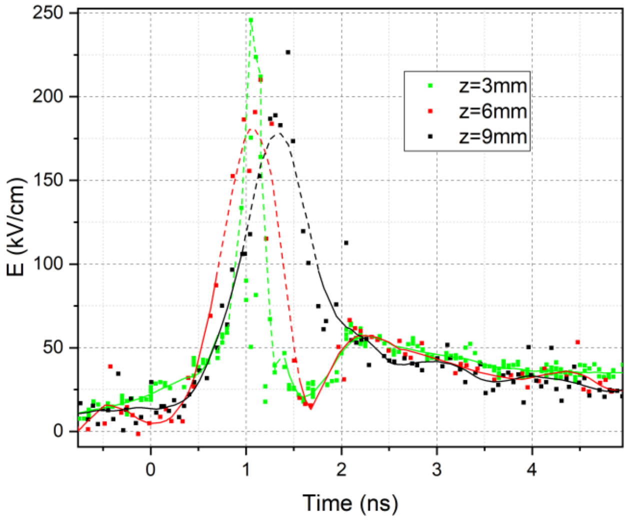

Fig. 5. a) Electric field measurements in time at 3, 6 and 9 mm from the pin at 85 kV. b) Zoom of a) with data smoothing. The dashed parts of the smoothing represent the parts where field variations are too strong to be accurately described by the smoothing.

As the maximum voltage amplitude increases, the discharge propagates faster and as the field extends in space, the concept of plasma channel is modified and high fields are sustained after the discharge front [1,2].

As the propagation speed increases, the time width of the very high field component gets narrower: 300 ps at 56 kV, 200 ps ± 50 ps at 68 kV and 100 ps ± 50 ps at 85 kV. Also, the junction at the plane happens faster and it takes 2.5 ns at 68 kV and 1.5 ns at 85 kV. It occurs less than one nanosecond after the passage of the high field front. As soon as the discharge reaches the plane, the return stroke sets back a field more or less proportional to the applied voltage. Therefore, a low field channel does not have the time to build up and high fields are sustained in the gap. At 68 kV, the field front passes at 3 mm after 1.5 ns and reaches the plane after 2.5 ns. Between 1.5 and 2.5 ns, the field varies from 200 to 20kV/cm. This is coherent with electric field measurements obtained by OES in [1].

The increase of the electric field behind the field front as the peak voltage increases is not observed and is not described in the classical streamer theory. For streamers, the field in the channel is governed by attachment processes and stays below the ionisation threshold which is about 100 Td. It seems to still be the case at 56 kV since the field is below the detection limit. In [2], it was shown that emission profiles could be either described by a monotonically decreasing (or at least continuous) pattern from the pin to the plane or a bimodal pattern according to electrical and geometrical conditions (gap distance). In the bimodal pattern, the light emission stays high at the pin but as the discharge propagates, a luminous structure detaches from the pin and no emission is observed in-between. This last feature is much more similar to classical streamer theory. At 68 kV, the axial light emission profile proved to be rather monotonous during the propagation. This can be seen as an indication of the continued existence of relatively high fields in the channel. As shown in [1], light emission patterns may be misleading, though. This is due to the delay in emission of excited species. The E-FISH method is not subjected to this effect and the accurate field measured behind the field front at 68 kV has risen up to around 20 kVcm^{-1} (77 Td.) At such fields, the activity of the plasma channel may become important. At 85 kV, it has reached about 28 kV.cm^{-1} (114 Td) for which the activity of the plasma channel is significant by triggering dissociative and ionisation processes.

The measured electric field in the discharge front is between 175 and 225 kV.cm^{-1} (715 to 900 Td) for any voltage condition. For comparison, the typical electric field in the discharge front of a classical streamer is about 800 Td. However, due to the high propagation speed, very few data are statistically obtained at the discharge front unless a very long measurement is done. Therefore, it is possible that the maximum electric field of the discharge front is missed. Moreover, the electric field calibration was done up to 8kV/cm in order to avoid any disturbance from a discharge ignition event. The validity of this calibration at fields twenty times higher remains questionable.

In order to evidence the propagation of the high field discharge front by E-FISH, additional measurements were made at 85 kV at 6 mm and 9 mm from the pin. They are shown in figure 5.

Several elements can be discussed. Firstly, it can be seen from those figures that the high field peak left by the passage of the discharge front is delayed from 3 mm to 9 mm, as excepted. The propagation speed obtained from this delay is half higher than the real speed of the discharge obtained from the light emission of the discharge, though. However, it is shown that the propagation of the field front is delayed compared to the light emission at very high voltage and the propagation speeds are not easily comparable. No real propagation can be measured between 3 and 6 mm and this can be explained by the very good but nevertheless limited temporal resolution of the measurements compared to the discharge dynamics and the limited statistics used to describe such highly transient events.

Finally, at 9 mm, the low field channel structure is not observed anymore. This could have at least two explanations. It could be that the temporal resolution is not enough to describe the quasi-instantaneous junction of the discharge at the plane. It could also come from other mechanisms such as electron emission from the plane which maintain high fields at 9 mm which is in line with the high field peak broadening in time. This question remains open.

In [1], electric field measurements were done along the axis of the discharge at 0.5, 1, 2, 3, 4 and 6ns by means of OES (c.f. figure 6.). This method is based on the analysis of the intensity ratio of two transitions of nitrogen. Measures were integrated over 500 ps with about 450 µm spatial resolution along the axial direction. Despite the relatively low temporal resolution of the measurements done by OES, field matching with E-FISH measurements is good within uncertainty limits. At 1 ns, both methods have measured a field of about 900 Td at 3 mm, about 620 Td at 6 mm and about 430 Td at 9 mm. The same comparisons can be made at later times.

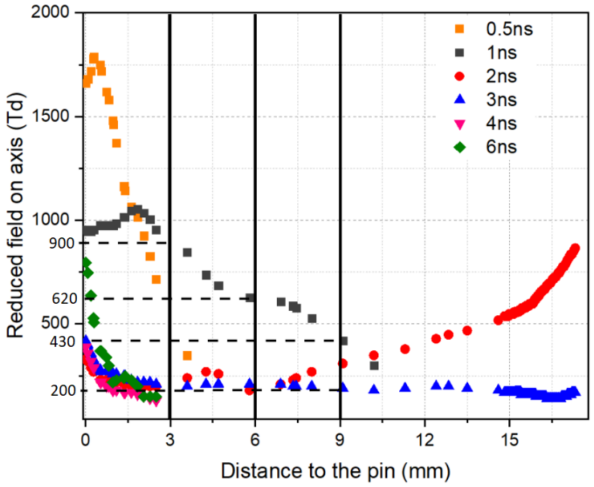

Fig. 6. Electric field measurements by OES on the pin-to plane axis at different times after the discharge starts in the same conditions as in [1] (85kV peak voltage, 18mm gap).

5. Conclusion

The E-FISH technique, recently reused for non-thermal plasmas diagnostics, is applied in this work to a diffuse nanosecond discharge generated in atmospheric air under extreme voltage conditions. The different discharge development steps are described (Laplacian voltage rise, discharge ignition and front propagation, return stroke and conduction phase) according to voltage amplitude and position in the gap. It is shown that as the peak voltage increases, the discharge propagates faster and the field behind the front increases up to the ionisation threshold at 85 kV contrary to classical streamers. Absolute values of reduced electric fields are in good agreement with values recently obtained by means of OES which supports the use of this technique at very high and transient electric fields.

6. Acknowledgment

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7. References

[1] A. Brisset, K. Gazeli, L. Magne, S. Pasquiers, P. Jeanney, E. Marode, P. Tardiveau, Plasma Sources Sci. Technol., Submitted, (2018).

[2] P. Tardiveau, L. Magne, E. Marode, K. Ouaras, P. Jeanney, et B. Bournonville, Plasma Sources Sci. Technol., **25**, 054005 (2016).

[3] A. Lo, G. Cléon, P. Vervisch, et A. Cessou, Appl. Phys. B, **107**, 229-242 (2012).

[4] A. Dogariu, B. M. Goldberg, S. O'Byrne, et R. B. Miles, Phys. Rev. Applied, **7**, 024024, (2017).