Sliding Discharge Optical Emission Characteristics

V. Lago, D. Grondona, H. Kelly, R. Sosa, A. Marquez, G. Artana

***Abstract*— In this work, several optical studies have been performed in an atmospheric pressure sliding discharge (plasma sheet). This discharge is generated using two electrodes flush mounted on an insulating flat plate (upper electrodes), and a third electrode flush placed on the opposite side of the plate facing the upper inter electrode space (lower electrode). A DC negative voltage is applied to one of the two upper electrodes and to the lower electrode, while the other upper electrode is biased with an AC voltage. In this configuration a sliding discharge is produced on the flat plate within the upper electrode's gap.**

The plasma sheet optical emission of the spectral bands corresponding to the 0-0 transition of the second positive system of N_2 (λ=337.1 nm) and the first negative system of N_2^+ (λ = 391.4 nm) have been measured. The reduced electric field in the plasma sheet has been derived from the measurement of the intensity ratio of these lines. This study has been realized varying the amplitude of the DC voltage and the amplitude and the frequency of the AC voltage. The reduced electric field strength is found to be almost constant for all the experimental conditions, with a value of 500 Td.

Also the light spatial distribution in the plasma sheet has been study using a CCD camera coupled to interferential filters corresponding to the wavelengths investigated.

I. INTRODUCTION

The sliding discharge or plasma sheet has been developed in a joint effort between the groups of the University of Buenos Aires and the University of Poitiers. The sliding discharge is very efficient for ion wind generation, so this characteristic makes it an excellent candidate for boundary layer control of moving objects. Several electric and fluid-dynamics techniques were employed to characterize the plasma sheet [1]-[3]

In this work, the plasma sheet is generated using two electrodes (1 and 2) flush mounted on an insulating flat plate, and a third electrode (3) flush placed on the opposite side of the plate facing the upper inter electrode space. A DC negative voltage (V_{dc}) is applied to electrodes 1 and 3, while 2 is AC biased (V_{ac}). In this configuration a sliding discharge is produced on the flat plate within the upper electrode's gap (between electrodes 1 and 2).

In the present paper, a spectroscopic diagnostic of the plasma sheet generated in air at atmospheric pressure is presented. The intensities of the spectral bands corresponding to the 0-0 transition of the second positive system (SPS) of neutral nitrogen molecule N_2 (band heads wavelength λ=337.1 nm) and the first negative system (FNS) of ionized molecule N_2^+ (band head wavelength λ = 391.4 nm) are experimentally determined varying the amplitude of V_{dc} and the amplitude and frequency of V_{ac}. The ratio of the intensities of FNS and SPS band head is used to determine the average value of the reduce electric field [4]-[6].

Also optical images of the plasma sheet have been obtained using a CCD camera coupled to interferential filters corresponding to the FNS and SPS wavelengths.

II. EXPERIMENTAL SET-UP

The electrode arrangement of our experiment consist in two flat aluminium foil electrodes flush mounted on the dielectric surface (1 and 2) and a third one flush mounted on the opposite side (electrode 3) of the plate facing the upper inter electrode space. The flat plate is made of PMMA with a thickness of 4 mm. The electrodes are aluminium bands of 50 μm thickness with a length of 150 mm and wides of 40 mm (electrodes 1 and 2), and 30 mm (electrode 3).

A DC FUG power supply (35 kV, 4 mA) biases electrodes 1 and 3, and a function generator plus a TRECK amplifier (400 mA, 20 kHz) supplies an AC sine voltage (from 0 to 20 kV) to electrode 2. The electrode arrangement is placed inside an insulating vacuum chamber.

First, a dielectric barrier discharge (DBD) is established by increasing the amplitude and frequency of V_{ac}. Then V_{dc} is turned on and increased until the plasma sheet appears at the inter electrode space on the upper side of the plate. The DC voltage is ranged between –14 kV to –20 kV. The AC

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voltage is ranged between 13 kV to 20 kV (peak to peak), while its frequency (f) is varied between 3 to 11 kHz. Note that within the quoted range of values for the power sources, electrodes 1 and 3 are always negative with respect to electrode 2. Measurements of the DC current component of the discharge are registered using a current monitor included in the FUG power supply.

Light emitted from the plasma sheet is detected by a monochromator SOPRA F1500 of the Ebert-Fastie-type with a focal length of 1500 mm and a diffraction grating of 1800 grooves/mm. The plasma is imaged onto the monochromator by two plane-convex lenses coupled to the monochromator entrance slit by a quartz optical fiber. The detector is an intensified OMA (Princeton Instruments IRY 1024) that allows registering an optical window of 8.5 nm.

A CCD Princeton PI-MAX camera coupled to 337 and 391.4 nm interferential filters is employed to image the discharge at a wavelength corresponding to intense emission of the excited species present in the plasma. The camera is focused in such a way that both electrodes edges and the interelectrode gap are within the picture frame.

The scheme of the experimental set up is shown in figure 1.

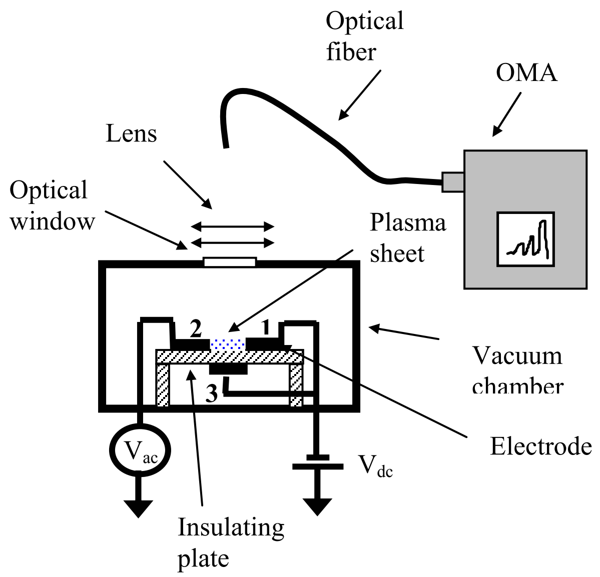

Figure 1: Experimental set-up

III. Experimental Results

Typical spectra corresponding to the FNS system and to the SPS system are presented in figure 2. The acquisition time of the OMA is 2 s.

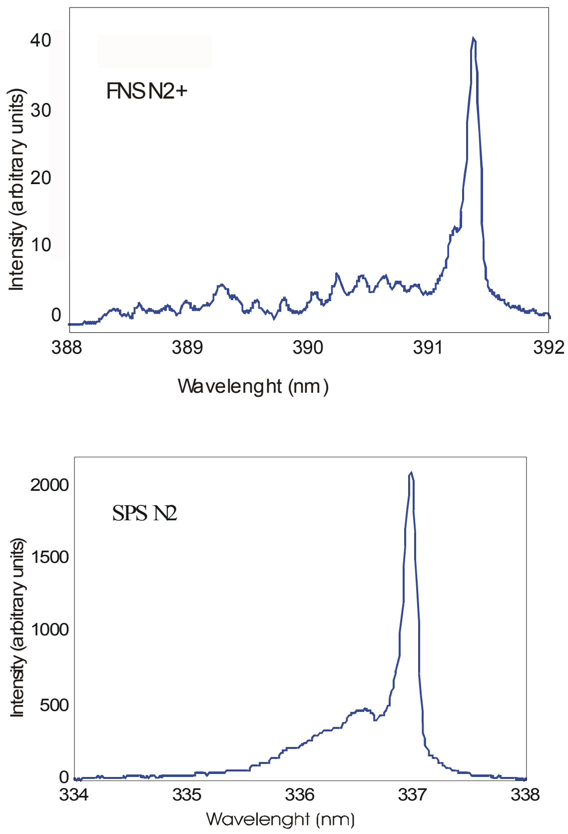

Figure 2: Typical nitrogen spectra for air plasma sheet.

For each band, the intensity as a function of V_{ac}, V_{dc} and f is measured. This intensity corresponds to the maximum of the vibrational band head (0-0). It should be noted that wavelength differences in the sensibility of the optical system are taken into account by normalizing the detector count number to the SPS line (in practice, this means that the count number corresponding to the FNS line is reduced by a factor of 8).

In the figures 3 and 4 the intensity as a function of V_{ac} for f = 7 kHz and V_{dc} = - 14.5 kV for both spectral lines are presented. It can be seen that in both cases the intensity increases smoothly with V_{ac}.

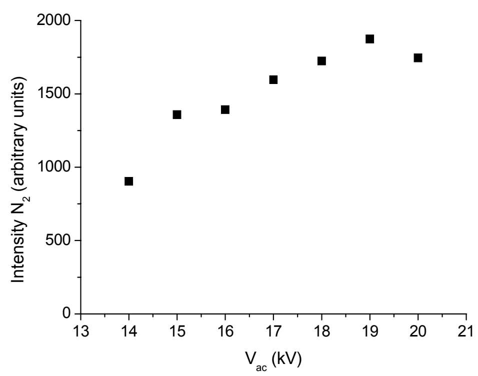

Figure 3: SPS intensity vs. V_{ac}
f = 7 kHz, V_{dc} = - 14.5 kV

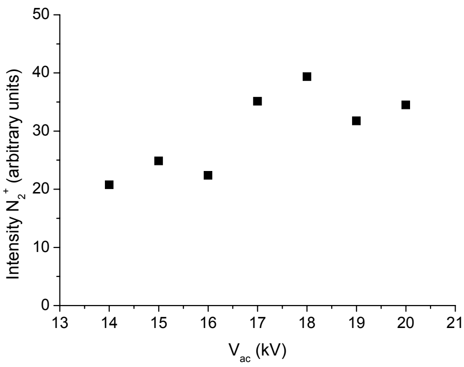

Figure 4: FNS intensity vs. V_{ac}.
f = 7 kHz, V_{dc} = - 14.5 kV

In the figures 5 and 6 the intensities for both spectral lines as functions of V_{dc} for V_{ac}=15 kV and f = 7 kHz, are presented.

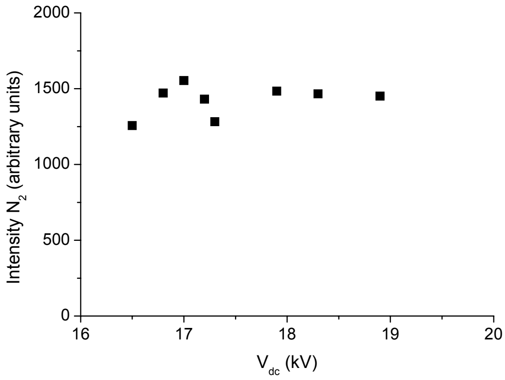

Figure 5: SPS intensity vs. V_{dc}
f = 7 kHz, V_{ac} = 15 kV

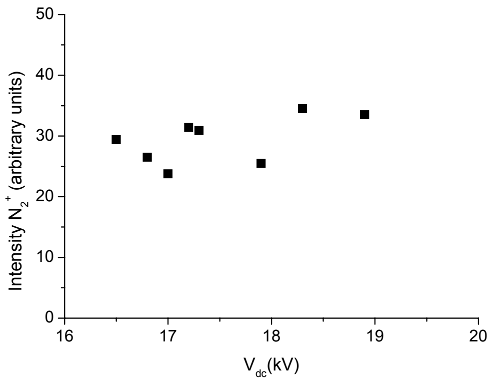

Figure 6: FNS intensity vs. V_{dc}
f = 7 kHz, V_{ac} = 15 kV

From figure 5 and 6 it can be noticed that the intensity remains approximately constant in the whole range of V_{dc} values.

Also, intensity measurements of the lines are performed varying the AC voltage frequency in the range of 3 - 11 kHz. Once more, for the whole range, the lines intensities remain almost constant.

From the images obtained with the CCD camera, it can be observed that the plasma sheet consists in an arrangement of branched streamers that bridge the discharge gap (figure 7). The SPS intensity (figure 8) is higher than the FNS intensity (figure 9), and for both lines the intensity is higher near the electrode 2 where the DBD discharge is initiated.

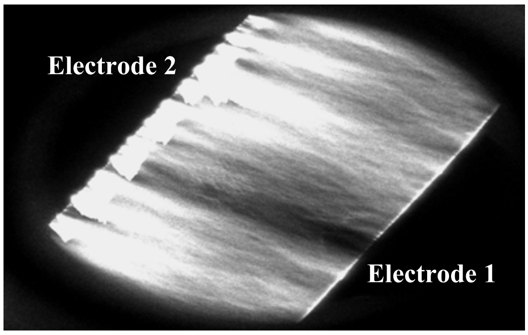

Figure 7: CCD image for an air plasma sheet without interferential filters.

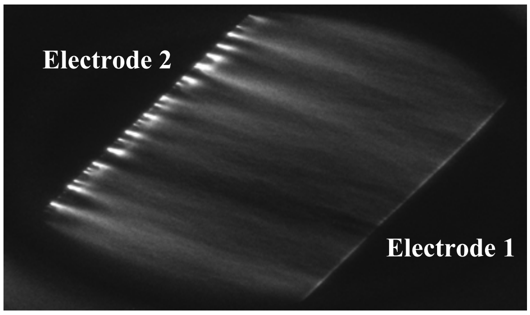

Figure 8: CCD image for an air plasma sheet filtered with a 337 nm interferential filter

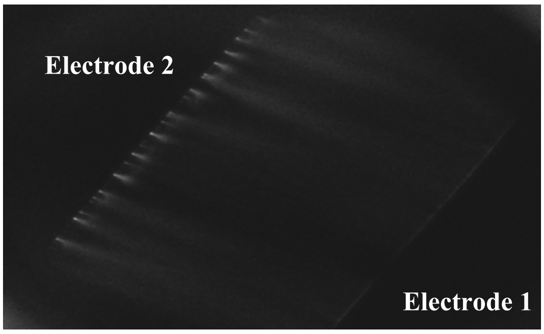

Figure 9 CCD image for an air plasma sheet filtered with a 391.4 nm inferential filter.

IV. ANALIYSIS OF THE EXPERIMENTAL DATA

The origin of the light emission within the plasma sheet is the process:

$$
\begin{aligned}
& e + N_2\left(X^1\Sigma_g^+\right)_{v=0} \rightarrow N_2\left(C^3\Pi_u\right)_{v'=0} + e \\
& \Delta E = 11 eV \\
& N_2\left(C^3\Pi_u\right)_{v'=0} \rightarrow N_2\left(B^3\Pi_u\right)_{v''=0} + h\nu \\
& \lambda = 337.1\, nm, \quad \tau = 40\, ns
\end{aligned}
\qquad (1)
$$

for the SPS spectral band head (0,0), and

$$
\begin{aligned}
& e+N_2\left(X^1\Sigma_g^+\right)_{v=0} \rightarrow N_2^+\ \left(B^2\Sigma_u^+\right)_{v'=0}+2e \\
& \Delta E = 18.7\ eV \\
& N_2^+\ \left(B^2\Sigma_u^+\right)_{v'=0} \rightarrow N^+{}_2\left(\mathrm{X}^2\Sigma_u^+\right)_{v''=0}+h\nu \\
& \lambda = 391.5\ nm, \quad \tau = 60\ ns
\end{aligned} \tag{2}
$$

for the FNS spectral band head (0,0)

In air, at atmospheric pressure, the excitation processes only comes from direct electron impact. Then, the reactions rates are directly proportional to the electron density, while the rates constants are strongly depended on the electric field.

The local continuity equations for the excitation of the FNS and SPS by direct electron impact and their successive collisional quenching in a steady-state approximation can be written as follows [7]:

$$k_{x\rightarrow c}\, n_e\, \left[N_2\right] = \nu_C^q\, \left[N_2(C)\right] \tag{3}$$

$$k_{x\rightarrow B}\, n_e\, \left[N_2\right] = \nu_B^q\, \left[N_2^+(B)\right] \tag{4}$$

where $\left[N_2\right]$ is the nitrogen population number density, $\left[N_2(C)\right]$ and $\left[N_2^+(B)\right]$ are the population number densities of SPS and FNS respectively (in cm^{-3}), n_e is the electron density (in cm^{-3}), $k_{x\rightarrow c}, k_{x\rightarrow B}$ are the rates constants of the excitation processes (in cm^3 s^{-1}) and ν_C^q, ν_B^q are the quenching rates in (s^{-1}). For atmospheric air density, the quenching rates are [7]:

$$
\begin{aligned}
\nu_C^q &= 1.84\ \ 10^9\ s^{-1} \\
\nu_B^q &= 1.74\ \ 10^{10}\, s^{-1}
\end{aligned} \tag{5}
$$

and the rates constants are [6]:

$$
\begin{aligned}
\log k_{x\rightarrow C} &= -8.87 - 228/\theta \\
\log k_{x\rightarrow B} &= -9.03 - 509/\theta
\end{aligned} \tag{6}
$$

where θ is the reduced electric field $\dfrac{E}{N}$ in Td (1 Td = 1 10^{-17} V cm^2), with E the absolute electric field and N the total number density of air molecules. From (3) and (4) the intensity ratio under stationary conditions is,

$$\frac{\left[N_2^+(B)\right]}{\left[N_2(C)\right]} = \frac{k_{x\rightarrow B}}{k_{x\rightarrow c}}\frac{\nu_C^q}{\nu_B^q} \tag{7}$$

From this ratio the value of θ can be derived. For all the experimental conditions studied in this work, the value of the line intensity ratio is almost constant, equal to 0.02 and the value of θ obtained from (7) is 501 Td.

V. Final Remarks

A useful method of diagnostics for weakly ionized plasma has been employed to determine the reduced electric field in a sliding discharge. The reduced electric field obtained, averaged in space and time, corresponds to the value of the reduced electric field present in a streamer head. The detected light comes from the streamer head where intense vibrational excitation of the molecules occurs. This result, together with the visual inspection of the plasma sheet that looks like a diverging plume of several filaments with its vertex on the anode, indicates that the plasma sheet is composed by positive streamers (cathode directed) that bridge the interelectrode gap. When the external field exceeds the value required to sustain the streamer, a self-propagating head with a local electric field depending very little on the external field, bridges the gap, producing and absorbing avalanches by its own.

Our experimental results indicate that the plasma light intensity depends slightly on V_{ac} but is almost independent on V_{dc} and f. Although we have not explanation for these findings, the behaviour with V_{ac} seems to be related to a more uniform light distribution in the gap, which in turn can be related to an increasing number of filaments of the DBD discharges when V_{ac} increases. This last discharge charge the insulator´s surface generating a local enhancement of the electric field near the anode thus favoring the streamers formation and propagation across the interelectrode gap when V_{dc} is applied.

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References

[1] Chistophe Louste, Guillermo Artana, Eric Moreau, Gérard Touchard "Sliding discharge in air at atmospheric pressure: electrical properties," *Journal of Electrostatic*,. Vol. 63, 2005, pp. 615-620.

[2] C. Louste, E. Moreau et G. Touchard, " Etude du vent ionique et du comportement électrique d´une décharge rampante" *5éme Conference de la Societé Francaise d¨Electrostatique* ", Grenoble, France, 2006, pp. 57–62.

[3] R. Sosa, E. Arnaud, G. Artana, Study of the Flow Induced by a Sliding Discharge, International Simposium on Electrohydrodonamics (ISEHD), 4-6 december, 2006, Buenos Aires, Argentina.

[4] Yuri V. Shcherbakov and Reidar S. Sigmond," Novel high-resolved experimental results by subnanosecond diagnostics of streamer discharge", *37th AIAA Plasmadynamics and Lasers Conference*, San Francisco, California, USA, 2006.

[5] P. Paris, M. Aints, M. Laan and F. Valk, "Measurement of the intensity ratio of nitrogen bands as a function of field strength", J.Phys. D: Appl. Phys., Vol 37, 2004, pp. 1179-1184.

[6] P. Paris, M. Aints, F. Valk, T. Plank, A.Haljaste, K.V. Kozlov and H. E. Wagner, "Intensity ratio of spectral bands of nitrogen as a measured of electric field strength in plasma", J.Phys. D: Appl. Phys., Vol 38, 2005, pp. 3894-3899.

[7] Yu. V. Shcherbakov and L.I.Nekhamkim, "Accurate Specroscoìc Studies of Streamers Discahrge, 2. Theoretical Background ans Analysis" Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2005, pp. 593-596.