Plasma-substrate interaction in a dual frequency APPJ

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Abstract: The Argon plasma produced in a coaxial jet by a pair of high frequency (HF 17 kHz) electrodes and a downstream ring radiofrequency electrode (RF 27.12 MHz) were investigated by means of 2D simulations and electrical and optical characterizations. As ignited, the plasma spreads to the facing surfaces and couples the HF and RF electrodes, even if positioned a few cm apart from each other. As a result, the HF to drive ions to the substrate while the RF allows to sustain the plasma while limiting the current density.

Keywords: APPJ, dual frequency, simulation, dielectric barrier discharge (DBD), dual frequency, ion bombardment, diffuse DBD.

1. Introduction

Atmospheric pressure DBDs driven by dual frequency waveforms combining kHz (HF) and MHz (RF) excitations have shown to improve the discharge homogeneity for facing plates configurations [1]. At the same time, the dual excitation with similar frequencies have allowed to increase the electron temperature and the ionisation degree [2]. This coupling of the RF and HF frequencies in a parallel plates configuration have been investigated both experimentally and by 1D simulations [3-5]. As a result of the coupling, the RF plasma exhibits a hybrid mode with a transition from α to γ depending on the relative polarization of the electrodes. The HF electrode acts as a drag for ions, alternatively supplying or subtracting them from the RF discharge. Therefore, there is a competition between RF parameters, which control the plasma creation in the discharge bulk, and the HF voltage, which controls the ions flux, i.e., their losses [5].

RF-HF dual frequencies have been considered also to produce plasma jets [6,7]. In this configuration, the two waveforms are applied in different regions of the jet and it can be supposed that two spatially separated discharges are generated [5]. However, in this work we will show that also in the coaxial geometry of an atmospheric pressure plasma jet (APPJ), the simultaneous excitation with different electrodes supplied with different frequencies generates a single plasma volume, which, in turn, couples the electrodes. In order to provide such information a 2D simulation of a coaxial APPJ with a distance between the electrode of more than 1 cm was set up. Electrical and optical characterisation was performed close to the substrate at the outlet of the jet to verify the simulation suggestions and to better highlight the behaviour of the discharge.

2. Experimental

The simulated and experimentally measured device is an APPJ based on Plasma Stylus Noble (Nadir srl). The device has a coaxial design, with two excitation ring electrodes positioned outside of an alumina tube. The tube has a 9 mm diameter and has a thickness of 0.5 mm (Fig. 1). The spacing between the upstream HF (17 kHz) electrodes is 2 mm, with the downstream one grounded. A RF (27.12 MHz) electrode is positioned 13 mm downstream, 3 mm from the outlet of the jet. The argon flux in the tube was kept at 5.0 slm. A glass substrate, with a grounded electrode below, is positioned at 5 mm from the jet outlet.

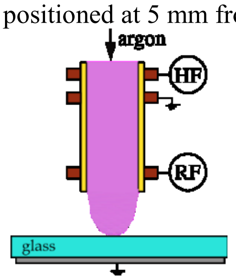

Fig. 1. Scheme of the dual frequency APPJ.

The electrical characterisation was performed using a capacitive divider and Tek PPE 4 kV voltage probe for the HF and a frequency calibrated resistive divider for the RF voltage. Charge on the HF ground and on the ground below the sample was recorded by voltage measurements across a series capacitor. The photon emission was collected by a PMT (Hamamatsu H11901-20) through a two lenses optical system with a focus of 200 μm at about 1 mm above the glass surface. Plasma time resolved images were recorded by a gated camera (PSEL ICMOS Photonic Science), while averaged optical emission was obtained by a multiple CCDs spectrometer (Avantes AvaSpec, 6 modules, 300-950 nm).

The simulations were carried out using the COMSOL 6.0 Plasma module in the time domain, considering $Ar_2(1\Sigma_u^+)$ and $Ar_2(3\Sigma_u^+)$ excimers [8]. Before running the plasma simulation, the mass-averaged Ar flow velocity of the gas was determined in the hypothesis of laminar flow. The plasma simulation is solved under the local mean energy approximation by specifying rate constants for the elementary processes. Those constants were obtained by preliminary evaluating the electron energy distribution function (EEDF) via a two-term 0D approximation of the electron Boltzmann equation. The EEDF was parametrised to ionisation degree, keeping Ar metastable and excimers species in a fixed ratio to the ionisation degree (respectively $Ar^* = 10^2$ n_e, $Ar_2(1\Sigma_u^+) = 12.5$ n_e, $Ar_2(3\Sigma_u^+) = 10^3$ n_e). The fixed ratio values were determined by running a series of simulations of the full problem by assuming a Maxwellian EEDF. The simulation in the time domain was started with a seed charge close to the RF electrode. After more than 1000 cycles the RF discharge was stabilised and the HF voltage was applied.

3. Results and discussion

The simulation shows the existence of two separate discharges at the HF discharge onset. As the HF section is switched on at 41.5 µs in Fig. 2, electrons are accelerated to the ground electrode and from space charge separation a positive streamer head propagates to the upstream negative voltage. As the whole surface facing the electrodes is covered at 48 µs, the streamer propagation slows down and the electrons start to respond to the RF pulsing field. A bulk ionisation of the argon in the region in between slowly starts with the formation of a high-density channel, which after 10 µs connects the HF and RF electrodes. The time needed for the channel formation as its thickness, together with the wide ionisation area confirm the RF origin of the electrodes coupling. The presence of the HF voltage pushes the electrons even further the RF electrode leading, at a later time, to a plasma plume close to the substrate with densities higher than 10^{16} m^{-3}. At about 70 µs, the HF voltage is close to the polarity change and the RF continuously induces a space charge separation at the plume tip. When this space charge creates a field strong enough an RF modulated positive streamer originates, then reaches the substrate surface and after propagates on the dielectrics. Therefore, the substrate is negatively charged at the beginning of the simulation due to the higher electron mobility, up to 70 µs when the streamer reaches the substrate. However, the glass surface charging, as shown in Fig. 2, appears continuous and RF modulated.

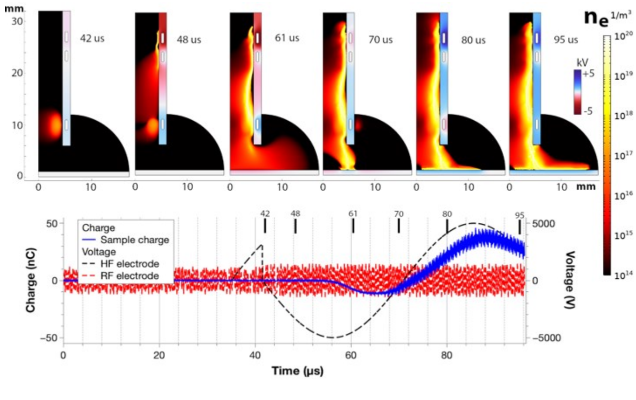

Fig. 2. Simulation of the dual frequency discharge propagation on a glass substrate. On the top the electron density and the electric potential 2D maps, on the bottom the RF and HF voltage as a function of time and of the total charge on the glass surface.

The predicted behaviour is consistent with the experimental observations. The electrical measurement of the same quantities plotted in Fig. 2, with the addition of photons emission are presented in Fig. 3. The RF power is kept constant while the HF voltage is changed from 1 kV up to 4 kV, always higher than the RF voltage. At lowest HF voltage, the plasma plume is not interacting with the substrate, leading to a capacitive coupling of the substrate. Increasing the voltage, the ion flux on the surface increases as well and in correspondence to small steps in the positive charging phase a photon emission intensification can be detected. This can be due to small streamers reaching the surface, such as the one shown in the simulation. Their duration is always in the microsecond scale and the charge per streamer collected on the surface is limited. This mixed propagation behaviour is also highlighted by the pulsed nature of the photon emission with RF frequency also during the step phase.

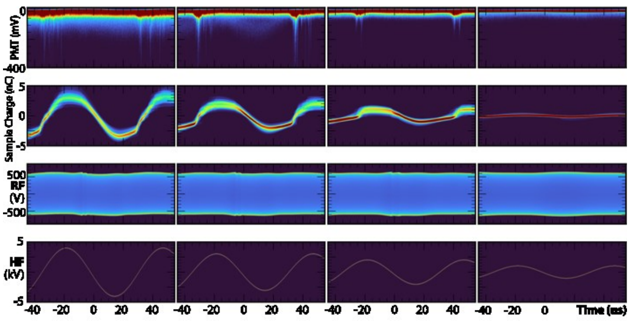

Fig. 3. Measurement of the electrode voltages, total charge on the glass substrate and photons emission close to the substrate as a function of time and of the HF electrode voltage.

4. Conclusions

The results presented show the existence of a single discharge even in the dual frequency APPJ configuration. In addition, they highlight the mixed propagation of streamers controlled by RF bulk ionisation in proximity of the substrates and the link between the HF voltage and the ion flux to the substrate.

5. References

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