Generation, annihilation and motion of self-organized filaments in dielectric barrier discharges

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A planar dielectric barrier discharge (DBD) is an excellent tool for studying self-organization of filaments. A large variety of structures can be easily obtained by tuning the discharge parameters, voltage amplitude, frequency, pressure, nature of the gas or gas mixture. In this lecture we use a 2D fluid model in association with experiments to discuss the potential effect of an unexpected optically invisible "side" discharges, immediately beyond the inhibition zone around each filament. These discharges are essential to soliton generation and traveling but also responsible for most observed spatio-temporal filament dynamics, including the recently discovered half-period alternate quincunx structures.

1. Introduction

Dielectric barrier discharges are widely used in industrial application due to their ability to produce large volume non-equilibrium plasmas at high pressure. Plasma display panels, ozone generation or surface treatment are a few examples among many others. As a rule, when the radial diffusion length of one electron during its transit from cathode to anode become small with respect to the transverse dimension of the discharge one can expect that a large volume non-thermal plasma will exhibit strong radial non-uniformities. This is certainly a drawback for applications such as surface treatment where uniformity is often required, but the structures that can be observed in DBDs make them a fascinating tool for the study of morphogenesis phenomena. A wide range of morphogenesis features can be obtained, from complex stationary patterns, to the generation, annihilation and traveling of dissipative solitons and pseudo-molecules [1-3]. Some typical examples are reported in figure 1 for a 2D geometry.

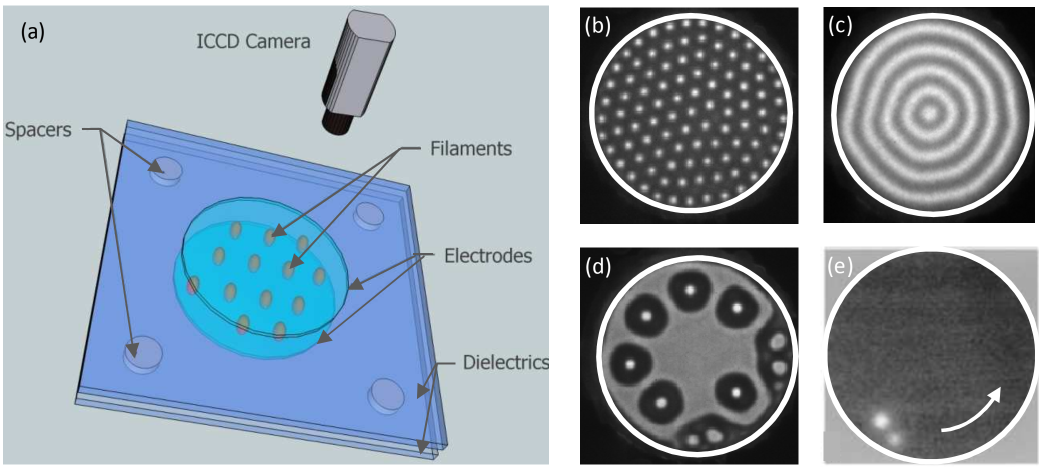

Fig. 1: 2D self-organized patterns of filaments. (a) Skecth of the 2D geometry, filament patterns are observed through a transparent electrode; (b) hexagonal; (c) target; (d) hybrid; (e) pair of filament in motion (from Ref. [4]). The conditions are: 2 mm gas gap filled with neon at pressure around 0.1 atm, between two 2mm glass dielectric layers covered with circular electrodes of 55.4 mm diameter and powered with sinusoidal voltage of 500-1000 V amplitude at frequency in the 10 kHz range.

In this paper we discuss the importance of phenomena occurring spatially and temporarily between the filaments. We show that the filamentary discharge may be associated in some cases during the same half-period of voltage signal, with a Townsend dark discharge or even in other cases by a second filamentary discharge. There is evidence from models and experiments that these additional discharges are the source of many observed phenomena such as merging [2], separation [2], travelling of filaments [5], or the formation of special structures such as quincunx [6].

2. Experimental set-up and 2D fluid model

We used two different systems, a two dimensional geometry shown in figure 1a and a one dimensional geometry, displayed in figure 2a. Our 1D geometry, is similar to that of Guikema et al. [7], and allows a fast optical diagnosis, both along the direction of pattern formation *y* and along the discharge axis *x* (see Fig. 2). Part of the complexity and variety of 2D patterns is lost, but valuable information is gained about the depth distribution of photon emission (directly related to electron density) and we preserve the main ingredients of self-organised pattern formation. Another advantage is that experimental results can be easily compared with results from a 2D discharge model. In the 1D device, two glass plates of 2 mm thick act as dielectrics. The electrodes of 7 cm long are 5 mm wide. One of them consists of a metal grid with a mesh size that allows to view through.

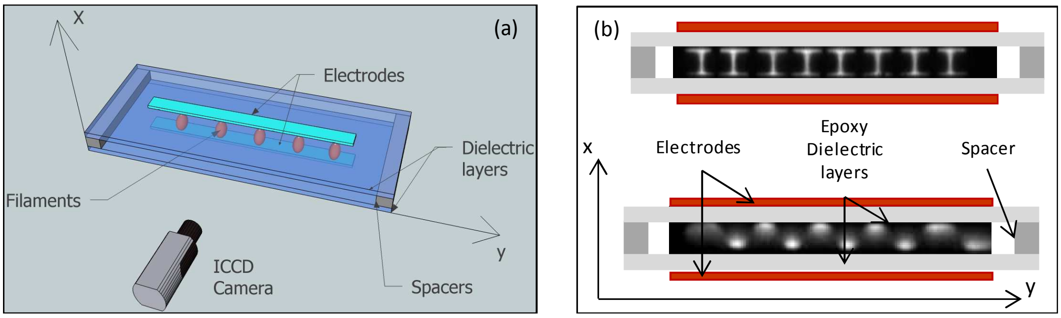

Fig. 2: 1D self-organized patterns of filaments. (a) Skecth of the 1D geometry, filament patterns are observed through a transparent electrode along the discharge axis *x* or along the direction of pattern formation *y*; (b) on top the classical filamentary discharge and on bottom the quincunx structure (Neon gaz at 50 torr, V_m = 524 V, f = 30 kHz).

The model used in this paper is a 2D cartesian (in the [x,y] plane of Fig. 2) self-consistent fluid discharge model [8] where electron and ion continuity and drift-diffusion momentum transfer equations are solved together with Poisson’s equation in pure neon. Only direct ionization (in the local field approximation) and atomic ions are considered. A constant secondary emission by ion impact on the dielectric is assumed (with a value γ=0.3) and the charging of the dielectric surface is taken into account self-consistently. Pattern formation in DBDs has been successfully reproduced in previous papers with similar 2D and 3D fluid models [9-10].

3. Classical filamentary discharge

We first discuss a typical filamentary discharge regime and its stability. Such regime generally corresponds to the 2D hexagonal structure (see figure 1b) and the 1D arrangement shown on the top of figure 2b. The electron density integrated over one period of the signal predicted by the 2D fluid model in the case of a classical filamentary structure is shown in figure 3a. The filaments, four in these conditions, are uniformly distributed along the 2 cm long electrode (symmetric boundaries conditions are assumed). Just before a new breakdown, the surface charges distribution (see figure 3b) is non-uniform with maximum at each filament location. The applied voltage adds to the memory voltage, so the voltage is higher where previous filaments occurred than in the space between filaments (see figure 3c at t = 490 µs forr example). The new breakdowns will start therefore at the location of the previous filaments at time t ~ 503 microseconds in combination with a sharp drop in potential in these regions. The initial voltage between filaments is smaller than in the axis, it increases as the applied voltage and when the current pulse occurs, it also decreases due to spreading of charges generated by the filament. The presence of the filament limits the possibility of breakdown between filaments. In terms of morphogenesis phenomena we have an inhibition mechanism (the spreading of the charges along the dielectric surface induces a voltage drop that prevents the plasma to form in the vicinity), associated with an activation mechanism (the formation of the filament due to the applied voltage associated with surface and volume charges). It should be noted that a condition for pattern formation in a reaction-diffusion system is that the inhibitor diffuses faster than the activator, which is the case here. The structure is stable.

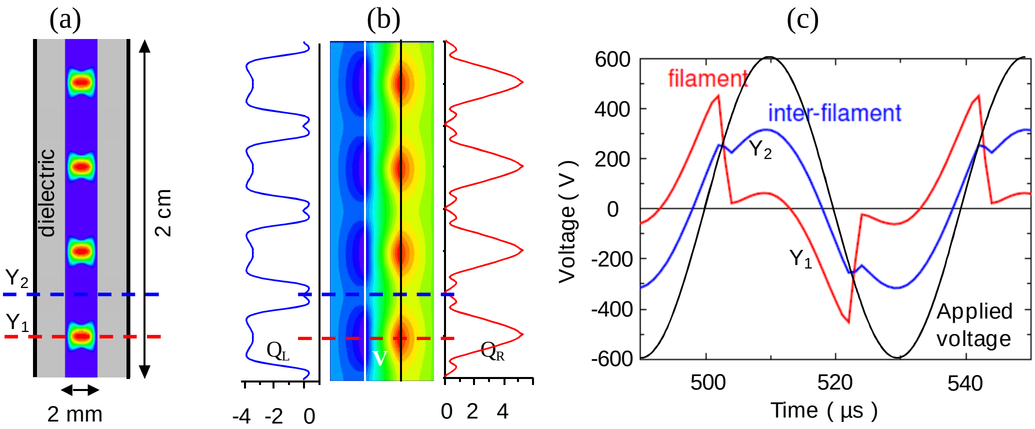

Fig. 3: Classical filamentary pattern predicted by the model. (a) Electron density integrated over one period (log scale on two decades with max = 7.5 10^9 cm^{-3}) ; (b) distribution of surface charges on left and right dielectrics and potential distribution just before a current pulse (max in red = 325 V and min in purple = -112 V) ; (c) gas and applied voltages. Conditions are : Neon gaz at 50 torr, V_m = 600 V, f = 25 kHz.

4. Non-classical pattern

In this section we discuss a singular case, the quincunx structure (see figure 2b on bottom) for which phenomena occuring between filaments can strongly modify the pattern formation. This regime is non-intuitive because discharge filaments at successive half cycles do not occur at the same location but are shifted by half a spatial period. As for the classical filament regime, we find the quincunx structure using the model. The electron density averaged over one period of the signal voltage is shown in figure 4a. We notice that for conditions close to the classical filamentary regime described in the previous section, the number of filaments has doubled since there are eight (4 for the positive half cycle and 4 for the negative half cycle).

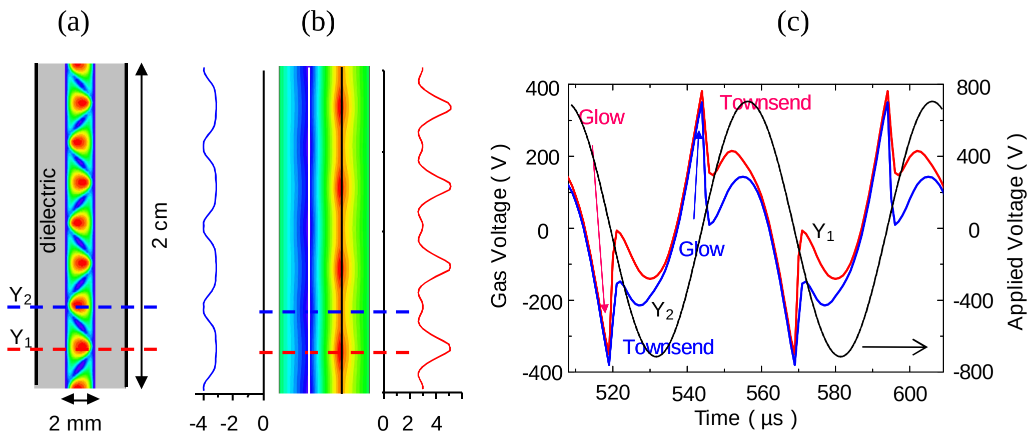

Fig. 4: Quincunx structure predicted by the model. (a) Electron density integrated over one period (log scale on two decades with max = 4 10^9 cm^{-3}) ; (b) distribution of surface charges on left and right dielectrics and potential distribution just before a current pulse (max in red = 212 V and min in purple = -182 V) ; (c) gas and applied voltages. Conditions are : Neon gaz at 50 torr, V_m = 700 V, f = 20 kHz.

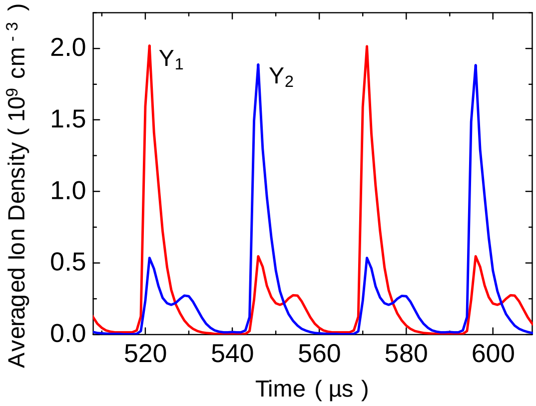

Fig. 5: Averaged ion density along *x* axis as a function of time for two *y* positions. Y_1 in red corresponds to the bottom position in Fig. 4a and Y_2 in blue to the top one. Conditions are the same as in Fig. 4.

We observe figure 4b that the surface charges distributions on both dielectric sides are distributed much more uniformly compared to the classical structure. The memory effect of surface charges will be less likely to promote the breakdown at a specific location. Another parameter will then compete with surface memory charges, it is the volume memory charges (i.e. the ion density inside the gas gap). Under some conditions, once the filamentary regime ended or during its extinction, the voltage across the gas between two filaments is large enough (see figure 4c at t = 530 µs) to generate a Townsend type discharge. This will maintain an ionization source term in volume which will result in a final average ion density much larger between the filaments than along the filament axis (see Fig. 5). In this situation, at the next half cycle, even if the voltage across the gas is slightly greater on the filaments axis (red curve of figure 4c at t = 543 microseconds) than between two filaments (blue curve at the same time) the new glow discharges will take place between previous filaments because the overall charges (surface + volume) are much greater in these regions.

Pattern formation is not only governed by surface charges. Charges remaining in the volume from previous discharges also play an important role in discharges breakdown and their organization. Townsend discharge that occurs during the same half period that glow discharge is not necessarily visible (optically or electrically) but plays a leading part not only in the generation of quincunx regime but also in the dynamics of filaments such merging or separation.

5. Conclusion

The large variety of pattern filaments that can be observed in DBDs is the result of strongly non-linear activator-inhibitor mechanisms and it is difficult to present a simple theory that can predict this variety. Nevertheless we have highlighted the competition between surface charges and volume charges to decide the location of breakdown. Volume charges just before breakdown and distribution of surface charges are strongly related to the presence of a secondary Townsend discharge occurring during the same half-period that the glow discharge. The occurence of this discharge is also responsible for soliton dynamics and can generate merging or separation of filaments.

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