Self-organization in DC glow microdischarges: bringing the modelling closer to the experiment

P. G. C. Almeida[1,2], M. S. Benilov[1,2], and D. F. N. Santos[1]

[1]*Departamento de Física, CCCEE, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal*
[2]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

New steady-state 3D modes of self-organization in DC glow discharges are computed in the framework of the simplest self-consistent model of glow discharge. Patterns associated with the modes computed are similar to those observed in the experiment. In particular, computed bifurcations of modes with 3D spots and the axially symmetric fundamental and ring modes reproduce the corresponding transitions observed in the experiment. This agreement is a strong indication that bifurcations can be directly observed in the experiment, thus supporting the hypothesis that self-organization in DC glow microdischarges is adequately described in terms of multiple steady-state solutions and their bifurcations.

1. Introduction

Self-organized patterns of cathodic spots in DC glow microdischarges have been observed for the first time a decade ago [1] and represent a very interesting and potentially important phenomenon. Since then, a number of experimental reports on this phenomenon have been published, see review [2] for references, and a theoretical interpretation in terms of multiple solutions existing in the theory of glow discharge for the same value of discharge current has been given [2]. The cornerstone of the theory is the existence of bifurcations of steady-state solutions. These solutions represent modes which are associated with different spot patterns. A quasi-stationary, continuous and reversible transition between the diffuse 2D (axially symmetric) mode and the 3D mode with four spots has been observed in the experiment [3]. These observations represent a direct proof of the existence of bifurcations of steady-state solutions. Also observed in [3] was a transition from the 2D mode with a ring spot to the 3D mode with five spots. Although this transition was not reversible, it nevertheless suggests the existence of the corresponding bifurcation. These transitions have not been computed before, and neither have some of the modes reported in experiments, namely modes associated with two to six spots observed, e.g., in [3,4]. In the present work these transitions and modes are computed and compared with their experimental counterparts.

2. Model

In this work the simplest self-consistent model of glow discharge is employed. It comprises equations of conservation of a single ion species (molecular ions) and the electrons, transport equations for the ions and the electrons written in the drift-diffusion local-field approximation, and the Poisson equation.

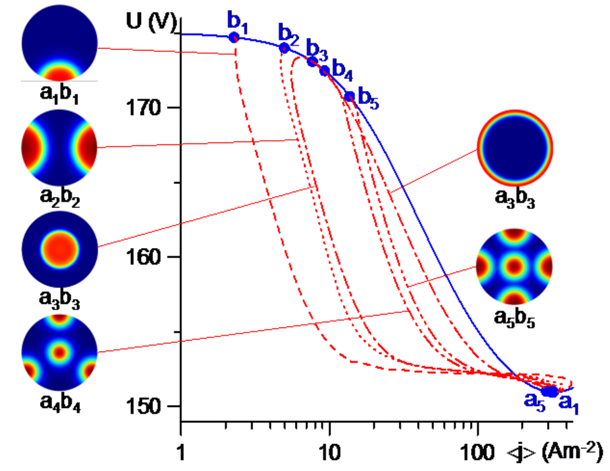
The discharge configuration is the classical case of a cylindrical vessel with plane parallel electrodes. Boundary conditions at the cathode and anode are in the conventional form. On the electrodes, diffusion fluxes of the attracted particles are neglected as compared with drift; the normal flux of the electrons emitted by the cathode is related to the flux of incident ions in terms of the effective secondary emission coefficient; density of ions vanishes at the anode; electrostatic potentials of both electrodes are given. One boundary condition at the wall of the discharge vessel is the conventional condition of zero electric current density. Two boundary conditions are used alternatively for the charged species at the wall, corresponding to the cases (i) where the wall is reflecting, and (ii) where the wall is absorbing.

Modelling is performed for a cylindrical discharge between parallel-plane electrodes for xenon at 30Torr; the interelectrode gap and radius of the discharge vessel are both 0.5mm. A full list of equations, boundary conditions, and transport and kinetic coefficients can be found in [5]

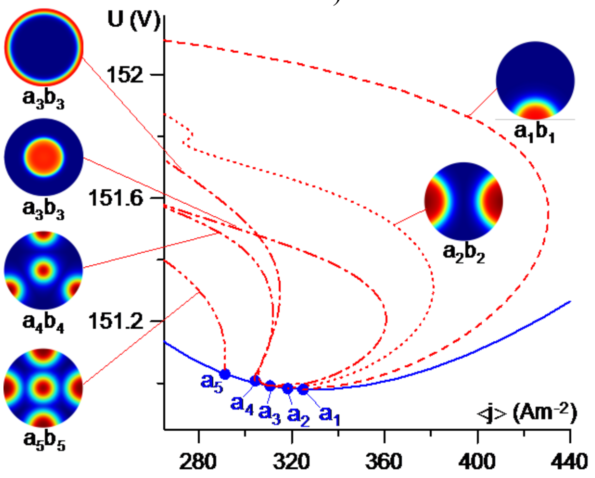
Numerical results reported in this work have been calculated with the use of a steady-state solver of the commercial finite element software COMSOL Multiphysics.

3. Results

Figure 1 depicts the CVC of the 1D mode and of the first five multimensional modes. (Here $\langle j \rangle$ is the average current density evaluated over a cross section of the discharge vessel.) The schematics in



a)



b)

Figure 1: CVCs. Solid: the 1D mode. Dashed-dotted: 2D mode a_3b_3. Other lines: different 3D modes. Circles: bifurcation points. a): General view. b): Details near the point of minimum of the CVC of the 1D mode.

this figure illustrate distributions of current density on the cathode surface associated with each mode. a_i and b_i designate bifurcation points where the corresponding solution branches off from and rejoins the 1D mode. The modes are ordered by decreasing separation of the bifurcation points: the first mode is designated a_1b_1 and is the one possessing bifurcation points further apart, the second mode is designated a_2b_2 and is the one possessing the second largest separation between bifurcation points, and so on. Note that a_3b_3 is a 2D mode with one branch associated with a spot at the centre of the cathode and the other with a ring spot at the periphery of the cathode.

The modes a_2b_2, a_4b_4 and a_5b_5 are new. It is interesting to note a retrograde section in the CVC of the mode a_2b_2, which is seen in figure 1b in a narrow current range around 280Am^{-2}. The evolution with $\langle j \rangle$ of the cathodic spot patterns associated with the each mode is shown in figure 2.

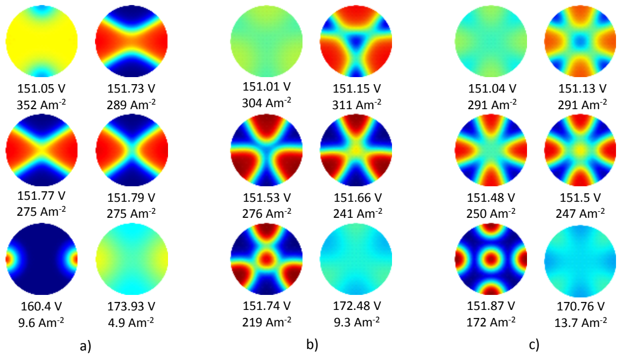


Figure 2: Evolution of distributions of current on the surface of the cathode associated with different modes. a): mode a_2b_2. b): a_4b_4. c): a_5b_5.

Let us consider first the evolution of patterns associated with the mode a_2b_2; figure 2a). The state 151.05V is positioned in the vicinity of the bifurcation point a_2 and the spot pattern comprises two very diffuse cold spots at the periphery. Further away from a_2, the cold phase expands and at state 151.79V start merging. This is accompanied by the above-mentioned retrograde section seen in figure 1b. As current is further reduced towards b_2, the two cold spots expand further and the resulting pattern comprises two well-pronounced hot spots at the periphery; state 160.4V. The state 173.93V is positioned in the vicinity of the bifurcation point b_2 and the hot spots are very diffuse. Patterns with two spots similar to that of the state 160.4V have been observed in the experiment [4].

The patterns associated with the mode a_4b_4 are shown in figure 2b). The state 151.01V is positioned in the vicinity of the bifurcation point a_4 and the pattern is very diffuse. Further away from a_4, the spots become better pronounced and a cold spot appears at the centre. As current is further reduced towards b_4, the cold spot at the centre is gradually tranformed into a hot spot. Eventually, the hot spots become well pronounced and a pattern comprising three (hot) spots at the periphery and a central spot is formed. The state 172.48V is positioned in the vicinity of the bifurcation point b_4 and the hot spots are very diffuse. The transition between patterns with well-defined cold and hot spots is not accompanied by retrograde behaviour, in contrast to the case of the mode a_2b_2. Patterns with three spots similar to that of the state 151.53V have been observed in the experiment [3,4]. The evolution of patterns associated with the mode a_5b_5 shown in figure 2c) follows the same trend as the mode a_4b_4.

A convenient graphic representation of the modes a_4b_4 and a_5b_5 is given in figure 3 with the use of the coordinates (j_c, $\langle j \rangle$), where j_c is the

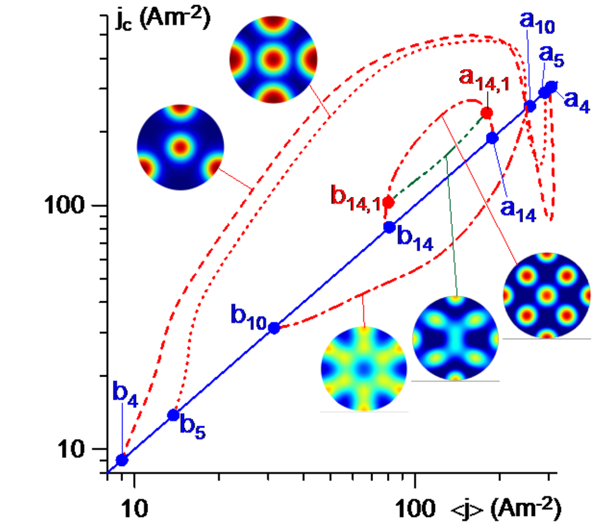


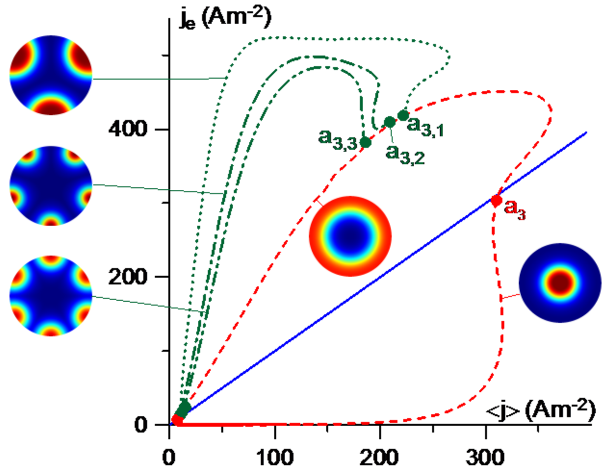
Figure 3: Bifurcation diagram. Solid: the 1D mode. Other lines: 3D modes. Circles: bifurcation points.

$a_{10}b_{10}$ and $a_{14}b_{14}$, which have been computed previously. The representation of figure 3 offers the advantage of quickly identifying a state at which the switching between patterns comprising cold and hot spots at the centre happens: it is the point at which the the line representing the mode in question intersects the straight line representing the 1D mode. For currents higher than the one corresponding to the switching, the current density at the centre is lower than that corresponding to the 1D mode and the pattern comprises a cold spot at the centre; for lower currents the current density at the centre is higher than that corresponding to the 1D mode and the pattern comprises a hot spot at the centre.

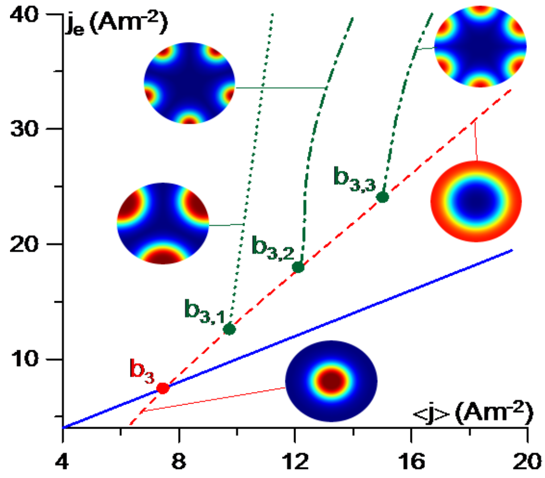
A third-generation mode (i.e., a mode which branches from another multidimensional mode rather than from the 1D mode) is also shown in figure 3; the mode $a_{14,1}b_{14,1}$. This mode branches off from the mode $a_{14}b_{14}$ through period-doubling bifurcations: the central spot ceases being circular and extends both upwards and downwards, thus changing the period of the mode from $\pi/2$ into π.

Three third-generation modes bifurcating from the mode a_3b_3, designated $a_{3,1}b_{3,1}$, $a_{3,2}b_{3,2}$, $a_{3,3}b_{3,3}$, are shown in figure 4. They branch off and rejoin that branch of the mode a_3b_3 which is associated with a ring spot at the periphery. The mode $a_{3,1}b_{3,1}$ is at the periphery of the cathode. $a_{3,2}b_{3,2}$ and $a_{3,3}b_{3,3}$ are associated with five and, respectively, six spots at the periphery. The coordinates (j_e, $\langle j\rangle$) are used, where j_e is the current density at a fixed point on the periphery of the cathode which coincides with the centre of one of the spots.

The evolution of the spot patterns associated with the mode $a_{3,2}b_{3,2}$ is shown in figure 5. At state



a)



b)

Figure 4: Bifurcation diagram. Solid: 1D mode. Dashed: 2D mode a_3b_3. Other lines: 3D modes. Circles: bifurcation points. a): General view. b): Details near the bifurcation point b_3.

151.82V, which is positioned near the bifurcation point $a_{3,2}$, the ring spot is slightly non-uniform in the azimuthal direction. Further away from $a_{3,2}$, the non-uniformity gives rise to well-pronounced spots; states 151.81V and 151.84V. The spots become smaller as the current is further reduced; state 152.26V. As the bifurcation point $b_{3,2}$ is approached, the spots expand, state 167.94V. In the close vicinity of $b_{3,2}$ (state 170.70V) a ring spot with a small non-uniformity in the azimuthal direction is formed.

The patterns associated with the mode $a_{3,2}b_{3,2}$ strongly resemble those observed in [3]. The transition from a spot pattern comprising five spots into a pattern comprising a ring spot seems to be the same that was found in the modelling between modes $a_{3,2}b_{3,2}$ and a_3b_3. Note that in the experiment this transition occurred in a non-stationary way. This may be consistent with the presence of the

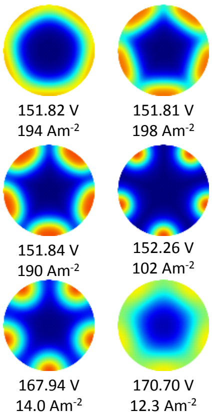


Figure 5: Evolution of patterns associated with the mode $a_{3,2}b_{3,2}$.

two turning points in the modelling in the vicinity of the bifurcation point $a_{3,2}$, which may cause a hysteresis.

The behaviour of the modes $a_{3,1}b_{3,1}$ and $a_{3,3}b_{3,3}$ follows the same trend as the behaviour of the mode $a_{3,2}b_{3,2}$. The patterns are similar to experimentally observed patterns comprising three and six spots inside the cathode [3,4].

In figure 6 it is shown experimentally observed [3] and computed transitions between different modes. The computed distributions of current on the surface of the cathode shown in the figure are associated with the second-generation mode a_4b_4, and the third generation mode $a_{3,2}b_{3,2}$. The qualitative agreement between experiment and modelling is good, which suggests the existence of the corresponding bifurcations a_4 and $a_{3,2}$.

4. Conclusions

Seven new 3D modes have been computed for xenon. Three of these modes branch off from and re-join the 1D mode; second-generation modes. The other four are third-generation modes, i.e., bifurcate not from the 1D mode but rather from another 2D or 3D mode. In the case where the latter mode is 3D as well, the branching happens through period-doubling bifurcations. The patterns associated with computed 3D modes with two, three, four, five and six spots at the periphery of the cathode and three spots at the periphery and a spot at the centre are similar to patterns observed in the experiment.

The transitions from the fundamental mode into a mode with four spots and from a mode with five spots into a mode with a ring spot also have been observed in the experiment. The good qualitative agreement between the computed and experimentally observed transitions is a strong indication that supports the hypothesis that self-organization in DC glow microdischarges stems from the existence of multiple solutions for the same value of the control parameter, i.e. discharge current or discharge voltage.

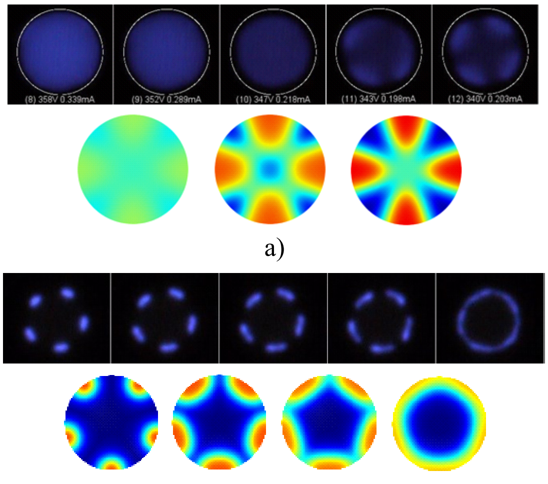


Figure 6: Experimentally observed [3] and computed transitions between different modes. a): fundamental mode into mode a_5b_5. b): mode $a_{3,2}b_{3,2}$ into mode a_3b_3.

Acknowledgments

The work was supported by FCT - Fundação para a Ciência e a Tecnologia of Portugal through the projects PTDC/FIS-PLA/2708/2012 and Pest-OE/UID/FIS/50010/2013. D. F. N. Santos is thankful to FCT of Portugal for the support through the PhD grant SFRH/BD/85068/2012. The authors are grateful to Dr. WeiDong Zhu for discussion of the experiment [3].

References

[1] K. H. Schoenbach, *Plasma Sources Sci. Technol.* **13** (2004) 177.

[2] M. S. Benilov, *Plasma Sources Sci. Technol.* **23** (2014) 054019.

[3] W. Zhu, P. Niraula, *Plasma Sources Sci. Technol.* **23** (2014) 054011.

[4] N. Takano and K. H. Schoenbach, *Plasma Sources Sci. Technol.* **15** (2006) S109.

[5] P. G. C. Almeida, M. S. Benilov, and M. J. Faria, *Plasma Sources Sci. Technol.* **19**, (2010) 025019.