Modelling self-organization in DC glow microdischarges: new 3D modes

P. G. C. Almeida, M. S. Benilov, and D. F. N. Santos
CCCEE, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal

Abstract

Seven new 3D modes of self-organization in DC glow discharges are computed in the framework of the simplest self-consistent model of glow discharge. Some of the modes branch off from and rejoin the 1D mode, while others bifurcate from a 2D or a 3D mode. The patterns associated with computed 3D modes are similar to patterns observed in the experiment. The computed transition from a spot pattern comprising five spots into a pattern comprising a ring spot also was observed in the experiment.

1 Introduction

Self-organization in DC glow microdischarges has been observed for the first time a decade ago [1,2] and represents a very interesting and potentially important phenomenon. Since then, a number of experimental reports on this phenomenon have been published [3–9], as well as a theoretical interpretation in terms of multiple solutions existing in the theory of glow discharge [8, 10–14]; see also [15] where a detailed discussion can be found.

This paper is concerned with computing some 3D modes of self-organization which have observed in the experiment but not in the modelling. This includes modes associated with two to six spots observed, e.g., in [3,8], and a transition from a 3D mode with several spots into a 2D with a ring spot mode that has been observed in [9] and suggests the existence of the corresponding bifurcation.

2 Results

The numerical model is identical to that described in [12] and successfully used in [8] for providing a guide for experiments in krypton microdischarges. Modelling is performed for a cylindrical discharge vessel with interelectrode gap of 0.5 mm and radius of 0.5 mm for xenon at 30 Torr; some results for krypton at 100 Torr and the same geometry are also given for comparison.

Figure 1 depicts the CVC of the 1D mode and of the first five multimensiionl modes. (Here \(\langle j \rangle\) is the average current density evaluated over a cross section of the discharge vessel.) The schematics in 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 $a_1 b_1$ and is the one possessing bifurcation points further apart, the second mode is designated $a_2 b_2$ and is the one possessing the second largest separation between bifurcation points, and so on. The modes $a_4 b_4$ and $a_5 b_5$ have been computed before [12, 13] and are included in figure 1 for the sake of completeness; note that $a_3 b_3$ 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 $a_2 b_2$, $a_4 b_4$ and $a_5 b_5$ are new. It is interesting to note a retrograde section in the CVC of the mode $a_2 b_2$, which is seen in figure 1b in a narrow current range around 280 A m$^{-2}$. The evolution with $\langle j \rangle$ of the cathodic spot patterns associated with the each mode is shown in figure 2. Let us consider first the evolution of patterns associated with the mode $a_2 b_2$; figure 2a). The state 151.05 V 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 151.79 V 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 very diffuse cold spots at the periphery; state 160.4 V. The state 173.93 V 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 160.4 V have been observed in the experiment [3]. A difference between the pattern of the state 160.4 V and the experimentally observed pattern is that in the modelling the spots are positioned at the periphery and not inside the cathode, however this difference will disappear if neutralization of charged particles at the wall of the discharge vessel is taken into account [14].

The patterns associated with the mode $a_4 b_4$ are shown in figure 2b). The state 151.01 V 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 transformed 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. (It is this pattern which is shown in figure 1.) The state 172.48 V 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 $a_2 b_2$. Patterns with three spots similar to that of the state 151.53 V have been observed in the experiment [8,9]; patterns with three spots at the periphery and a spot at the centre similar to that of the state 151.74 V have also been observed in the experiment [7].

The evolution of patterns associated with the mode $a_5 b_5$ shown in figure 2c) follows the same trend as the mode $a_4 b_4$.

Figure 3 depicts mode $a_2 b_2$ computed for krypton and 100 Torr. The trend is the same that was found in xenon, except that the retrograde section associated with the switching between cold and hot spots is much wider in krypton and spans a range of about 300 A m$^{-2}$.  

A convenient graphic representation of the modes $a_4 b_4$ and $a_5 b_5$ is given in figure 4 with the use of the coordinates $(j_c, \langle j \rangle)$, where $j_c$ is the current density at the centre of the cathode. Also shown for the sake of completeness are the modes $a_{10} b_{10}$ and $a_{14} b_{14}$, which
have been computed previously [13]. The representation of figure 4 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 4; 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 $\pi$. Note that third-generation modes branching off from the mode $a_{10}b_{10}$ which have been computed for discharges in helium [14] and krypton [8] branch off through period-doubling bifurcations as well, however these bifurcations occur in a different way: in one case, every second spot in the ring gradually moves from the periphery towards the centre of the cathode (one of the modes in helium and the mode in krypton); in the other every second spot of the inner ring gradually moves towards the periphery and merges with a spot of the outer ring (a mode in helium).

Three third-generation modes bifurcating from the mode $a_{3}b_{3}$, designated $a_{3,1}b_{3,1}$, $a_{3,2}b_{3,2}$, $a_{3,3}b_{3,3}$, are shown in figure 5. They branch off and rejoin that branch of the mode $a_{3}b_{3}$ which is associated with a ring spot at the periphery. The mode $a_{3,1}b_{3,1}$ is associated with a spot pattern comprising three spots 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. Since neither of the patterns shown in figure 5 comprises a spot at the center, the coordinates $(j_e, \langle j \rangle)$ would be inconvenient and 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 6. At state 151.82 V, 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 151.81 V and 151.84 V. The spots become smaller as the current is further reduced; state 152.26 V. As the bifurcation point $b_{3,2}$ is approached, the spots expand, state 167.94 V. In the close vicinity of $b_{3,2}$ (state 170.70 V) 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 [9]. (We remind that when neutralization of charged particles at the wall of the vessel is taken into account in the modelling, spots at the periphery will be shifted inside the cathode.) 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 $a_{3}b_{3}$. Note that in the experiment this transition occurred in a non-stationary way. This may be consistent with the presence of the 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 [30]. Note that the pattern with three spots associated with the mode $a_{3,1}b_{3,1}$ is similar to the pattern with three spots appearing in
some states belonging to $a_4b_4$ (states 151.15 V and 151.53 V in figure 2b)) and it is difficult to know which one of these two modes was observed in the experiments [3,9].

Third-generation modes bifurcating from the mode $a_3b_3$ have been studied also for krypton. The modes which have been computed for krypton (and not shown for brevity) comprise, in addition to the above-described modes $a_3,1b_3,1$, $a_3,2b_3,2$ and $a_3,3b_3,3$, also modes which are associated with patterns comprising nine, twelve, and fifteen spots at the periphery. Note that the latter modes have not been found in xenon, which is consistent with patterns in krypton being in general richer than those in xenon for comparable conditions [8].

3 Conclusions

Seven new 3D modes have been computed for xenon. Three of these modes branch off from and rejoin 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, similarly to what was found in the previous modelling for helium and krypton, however the period-doubling occurs differently. 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 transition from a spot pattern comprising five spots into a pattern comprising a ring spot also was observed in the experiment.

The modelling of self-organization in DC glow discharges has so far been performed for a cylindrical discharge vessel with parallel-plane electrodes. Self-organized patterns of spots have been observed in this geometry [4]. However, the most of observations of self-organized patterns have been performed in cathode boundary layer discharge (CBLD) devices, which comprise a planar cathode and a ring shaped anode separated by a ring-shaped dielectric layer. Computation of patterns for the CBLD configuration is an important topic for future work.

4 Acknowledgments

This work was supported by FCT of Portugal through projects PTDC/FIS-PLA/2708/2012 Modelling, understanding, and controlling self-organization phenomena in plasma-electrode interaction in gas discharges: from first principles to applications and PEst-OE/MAT/UI0219/2011. 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 [9].
Figure 1: CVCs. Xe, 30 Torr. 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.

Figure 2: Evolution of distributions of current on the surface of the cathode associated with different modes. Xe, 30 Torr. a): mode $a_3b_2$. b): $a_4b_4$. c): $a_5b_5$. 
Figure 3: CVCs. Kr, 100 Torr. Solid: the 1D mode. Dashed: 3D mode $a_2b_2$. Circles: bifurcation points.
Figure 4: Bifurcation diagram. Xe, 30 Torr. Solid: the 1D mode. Other lines: 3D modes. Circles: bifurcation points.

Figure 5: Bifurcation diagram. Xe, 30 Torr. Solid: the 1D mode. Dashed: 2D mode $a_3b_3$. Other lines: 3D modes. Circles: bifurcation points. a): General view. b): Details near the bifurcation point $b_3$. 
Figure 6: Evolution of distribution of current on the surface of the cathode associated with the mode $a_{3,2}b_{3,2}$. Xe, 30 Torr.

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