UNDERSTANDING AND MODELLING PLASMA-CATHODE INTERACTION: ROOTS OF GASEOUS AND VACUUM ARCS, SPOTS ON GLOW CATHODES

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ABSTRACT

A new class of stationary solutions in the theory of glow discharges and plasma-cathode interaction in arc discharges has been found in the course of the past 15 years. These solutions exist simultaneously with the solution given in textbooks, which describes a discharge mode with a uniform or smooth distribution of current over the cathode surface, and describe modes with various configurations of cathode spots: normal spots on glow cathodes, patterns of multiple spots recently observed on cathodes of glow microdischarges, spots on arc cathodes. In particular, these solutions show that cathode spots represent a manifestation of self-organization caused by basic mechanisms of near-cathode space-charge sheath; another illustration of the richness of the gas discharge science. As far as arc cathodes are concerned, the new solutions have proved relevant for industrial applications. This talk is dedicated to reviewing the multiple solutions obtained to date and the physics of plasma-cathode interaction in arc discharges in ambient gas and vacuum and in glow discharges revealed by these solutions.

1. INTRODUCTION

Self-consistent theoretical models of dc glow discharges and plasma-cathode interaction in arc discharges, including the most basic ones, admit multiple solutions existing for the same discharge current. One of these solutions is in the simplest case one-dimensional (1D) and describes states with a uniform distribution of current over the electrode surface. In the case of glow discharges between parallel electrodes, the 1D solution describes the Townsend discharge for very low current densities, the abnormal discharge for high current densities, and the unstable discharge with the falling current density-voltage characteristic (CDVC) for intermediate current densities; this solution is similar to the classic solution which is based on a linear approximation of electric field in the near-cathode space-charge sheath and is given in textbooks (e.g., [1, 2]). In the case of arc-cathode interaction, the 1D solution describes the diffuse mode of current transfer and is similar to the solution which for high-pressure arcs is considered in the book [3]. The other existing solutions are in all the cases multidimensional and describe modes with different configurations of cathode spots.

The existence of multiple solutions was hypothesized in 1963 for arc-cathode interaction [4] and derived in 1988 for glow discharges [5]; further references of historical interest can be found in [6] for arc-cathode interaction and in [7] for glow discharges. However, the central role of multiple solutions was fully realized only in the late 1990s in the theory of arc plasma-cathode interaction. By now, solutions describing diffuse and spot modes of current transfer to cathodes of high-pressure arc discharges have been computed under different conditions by different research groups and validated by an extensive comparison with the experiment. Most of effort was invested in low-current high-pressure arcs, which are used in high-intensity discharge lamps. Multiple solutions in the theory of glow discharges have started to be systematically computed and validated experimentally only recently.

2. EXAMPLE: MULTIPLE SOLUTIONS IN PARALLEL-PLANE GEOMETRY

Fig. 1 depicts multiple steady-state solutions computed for glow discharge and plasma-cathode interaction in a high-pressure arc discharge in the idealized geometry which admits a 1D solution and is shown in Fig. 2. In the case of glow discharge, <*j*> designates the average density of electric current to the cathode surface, *R* is the discharge tube radius, *h* is the interelectrode distance, and *U* is the discharge voltage. In the case of arc cathode, *R* and *h* are radius and height of the cathode and *U* is the near-cathode voltage drop. In the idealized geometry being considered, one of the multiple solutions, namely, the one represented by the line *NP*, is 1D (all parameters vary only in the *z* direction) and describes states with a uniform distribution of current over the cathode surface. The other existing solutions are multidimensional and describe modes with different configurations of cathode spots. Note that these solutions are many and only some of them are shown in Fig. 1. 2D (axially symmetric) solutions branch off from the 1D solution; 3D solutions branch off from the 1D, 2D and 3D solutions. The bifurcation points, i.e., the states where this happens, are marked in Fig. 1 by circles.

Each solution in Fig. 1 is illustrated by a typical distribution of current density over the cathode surface (red means the highest value and blue the lowest), which gives an idea of the spot pattern associated with the mode of current transfer described by this solution. Note that the spot pattern varies with current, therefore images shown in Fig. 1 and subsequent figures are representative for some but not all steady states described by the corresponding solution.

In the case of glow discharge (Fig. 1a), the 1D solution *NP* describes the Townsend discharge for very low current densities, the abnormal discharge for high current densities, and the unstable discharge with the falling current-voltage characteristic (CVC) for intermediate current densities. This solution is similar to the classic solution which is based on a linear approximation of electric field in the near-cathode space-charge sheath and is given in textbooks (e.g., [1,2]). Solution a_1b_1 is 3D and describes a mode with a normal spot positioned

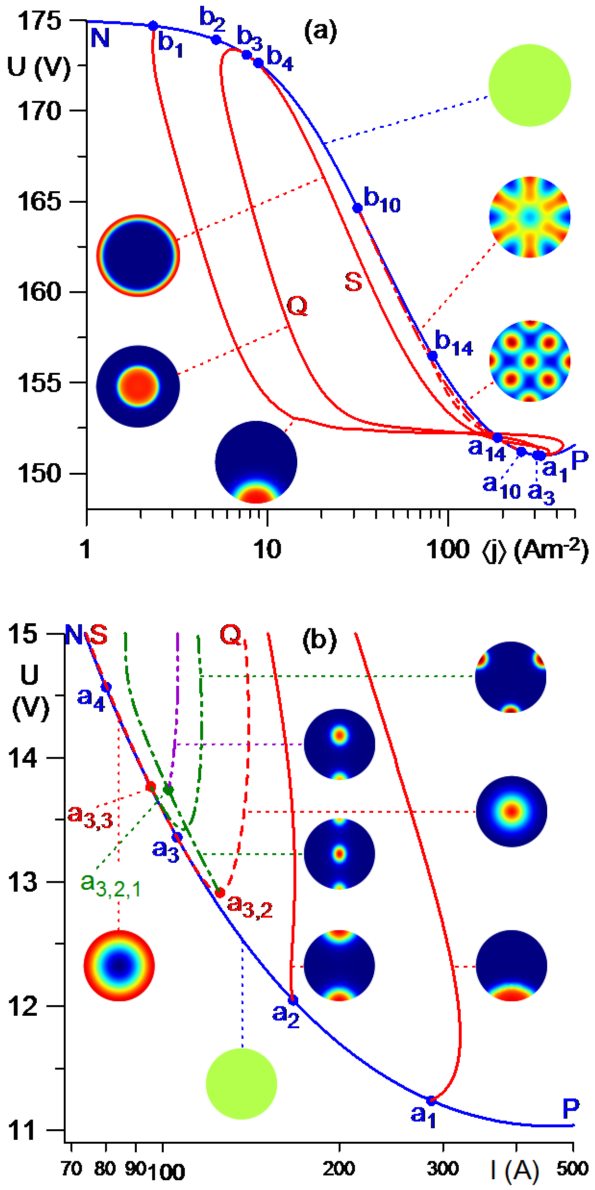

Fig. 1 CVCs and schematics of current density distribution over the cathode surface described by different steady-state solutions. (a) Glow discharge. Xe plasma, p = 30 Torr, R = h = 0.5 mm. Data from [7,10]. (b) Cathode of an arc discharge. Ar plasma, p = 1 bar, W cathode, R = 2 mm, h = 10 mm. Data from [11].

at the edge of the glow cathode. Solution a_3Qb_3 is 2D and describes a mode with a normal spot positioned at the center of the glow cathode. Solution a_3Sb_3 is 2D and describes a mode with a ring spot at the periphery of the cathode observed recently in a glow microdischarge [8]. Solutions $a_{10}b_{10}$ and $a_{14}b_{14}$ are 3D and describe modes with patterns of multiple spots observed in glow microdischarges; e.g., [8,9] and references therein.

It is seen from Fig. 1a that the plane *(<j>,U)* is not suitable for representation of solutions with

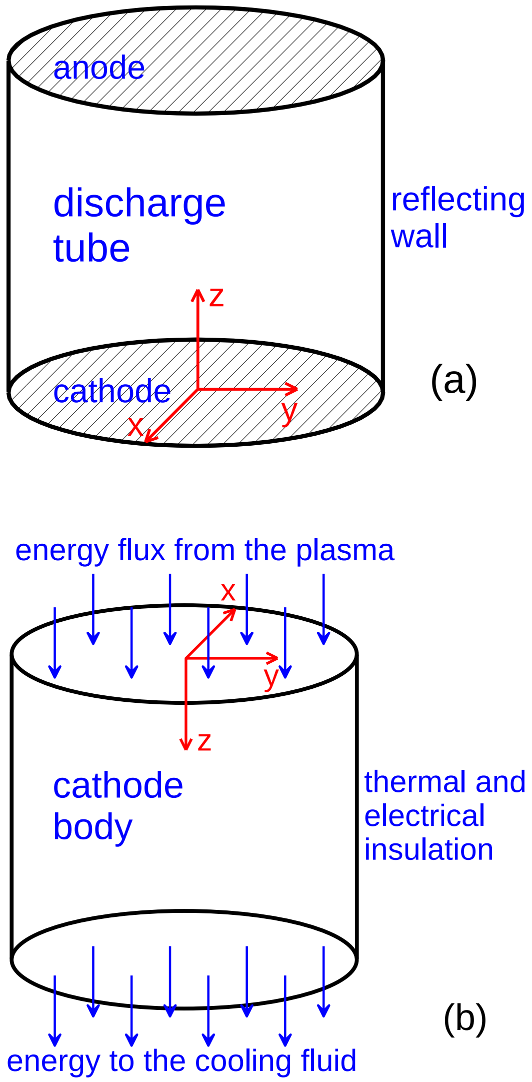

Fig. 2 Geometry admitting a 1D solution. (a) Glow discharge. (b) Cathode of an arc discharge.

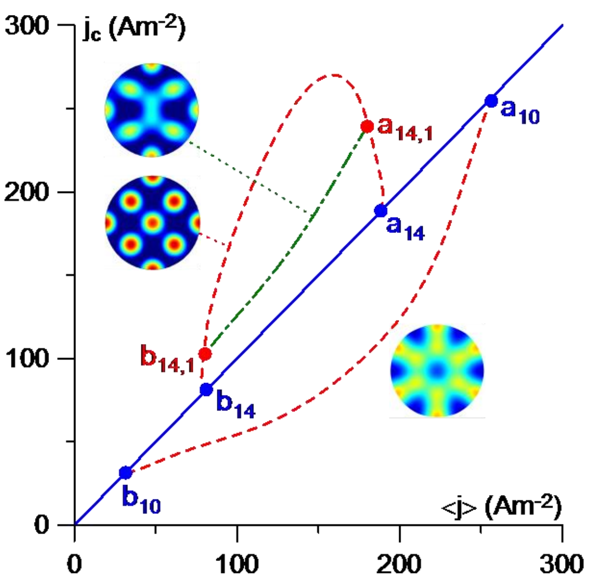

Fig. 3 The 1D solution and 8th and 12th 3D solutions. Glow discharge in Xe plasma, p=30 Torr, R = h = 0.5 mm. Data from [12].

many spots: their CVCs $a_{10}b_{10}$ and $a_{14}b_{14}$ virtually coincide with the CVC *NP* of the 1D solution. Adequate and convenient are coordinates $(\langle j\rangle, j_c)$, where j_c is the current density at the center of the cathode. This representation is used in Fig. 3. One can see that different solutions are indeed clearly visible in this figure. Also shown in Fig. 3 is the 3D solution $a_{14,1}b_{14,1}$, which branches off from $a_{14}b_{14}$ through a period-doubling bifurcation.

In the case of arc-cathode interaction (Fig. 1b), the 1D solution *NP* describes the diffuse mode of current transfer and is similar to the solution considered in the book [3]. The solution that branches off at the state a_1 is 3D and describes a mode with a spot at the edge of the cathode. The other solutions are unstable in this geometry and do not realize in the experiment.

In the case of glow discharge, CVCs described by the first 3D solution a_1b_1 and by the central-spot branch a_3Qb_3 of the first 2D solution in Fig. 1a manifest a plateau. These are regimes with coexistence of phases or, in other terms, with normal spots. The occurrence of these regimes on glow cathodes but not on arc cathodes, revealed by the numerical results, is a consequence of different aspect ratios: the thickness of the near-cathode space-charge sheath in glow discharges is much smaller than the radius of the discharge tube, while thermionic cathodes of high-pressure arcs are thin rather than wide. The CVCs of multi-spot modes in glow discharge, $a_{10}b_{10}$ and $a_{14}b_{14}$, do not reveal regimes with normal spots, since the thickness of the sheath is not small compared to the distance between the adjacent spots.

Of course, patterns of stationary spots shown in Figs. 1 and 3 do not exhaust all possibilities. Some further examples for glow discharges can be found in [12,13].

Most of the results for glow discharges available to date, including those shown in Figs. 1a and 3, have been computed in the framework of the simplest self-consistent model, which accounts for a single ion species produced via a single effective ionization process and employs the local-field approximation. It is important to stress in this connection that an account of detailed plasma chemistry and non-locality of electron kinetics results in an increase of the

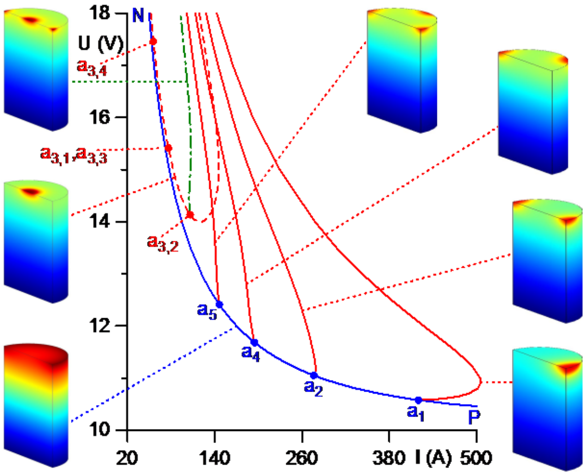

Fig. 4 CVCs and schematics of current density distribution over the surface of a cylindrical arc cathode described by different steady-state solutions. Ar plasma, p = 1 bar, W cathode, R = 2mm, h = 10mm. Adapted from [6].

number of multiple solutions but does not change their pattern [13].

The pattern of computed multiple solutions shown in Figs. 1 and 3 is consistent with the general trends of self-organization in nonlinear bistable systems. Note that while the second-generation multidimensional solutions at low currents re-join the 1D solution in the case of glow discharges, they do not in the case of arc cathodes. This difference originates in the near-cathode voltage drop *U(j)* infinitely increasing for small *j* in the model of arc-cathode interaction being employed and will disappear if the account of glow-to-arc transition has been introduced.

The pattern of multiple solutions seen in Figs. 1 and 3 is the simplest from the theoretical point of view since it has been computed in the idealized configuration admitting a 1D solution. In order to obtain a model relevant to the experiment, one should take into account effects introduced by the lateral wall: absorption of the ions and the electrons by the lateral wall of the discharge tube with their subsequent recombination in the case of glow discharge and collection of electric current and energy flux from the plasma by the lateral surface of an arc cathode. As an example, one can consider Fig. 4, which has been computed for the same conditions that Fig. 1b but with account of collection of electric current and energy flux by the lateral surface of the cathode. Examples for the glow discharge can be found in [11,13].

3. OUTLINE OF THE TALK

This talk is dedicated to a review of multiple solutions in the theory of dc glow discharges and plasma-cathode interaction in arc discharges obtained to date, their systematization, and analysis of their properties and physical meaning. The outline of the talk is as follows. The concept of multiple solutions in the theory of dc glow discharges and plasma-cathode interaction in arc discharges is formalized and properties of these solutions are analyzed on the basis of general trends of the theory of self-organization in bistable nonlinear dissipative systems. Relevant aspects of computation of these solutions are discussed. Typical results of calculations of spots on cathodes of arcs in ambient gas and vacuum and on glow cathodes are shown and compared with the experimental data. Other topics to be discussed include: transition from self-organized modes of current transfer to modes where current spots represent concentrations of current caused by non-uniformities of geometrical and/or physical properties of the cathode surface; solitary cathode spots; role of Steenbeck's principle of minimum power in modern theory and modelling; examples of apparently simple situations where glow discharges and arc-cathode interaction reveal complex behavior; observations of spots and patterns on electrodes of gas discharges and the first-principle theory and modelling where available; the place of the approach based on multiple steady-state solutions in the theory and modelling of gas discharges; possible directions of future work.

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