JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 8, No. 1, February 2006, p. 135 - 138

Investigation of the bistable behaviour of multiple anodic structures in dc discharge plasma

S. CHIRIAC, M. AFLORI, D. G. DIMITRIU*
Department of Plasma Physics,"Al. I. Cuza" University of Iasi, Romania

By applying a positive potential on an electrode immersed in a dc discharge plasma, a complex space charge structure (CSCS), consisting from a positive ion-enriched plasma region confined by an electrical double layer (DL), appears. Under certain experimental conditions, a more complex structure was observed, which was called multiple double layers (MDLs). Depending on the experimental parameters (especially the geometry of the experiment, the gas nature and pressure and the plasma density), this structure can appear in two geometrical forms: concentric (as several bright plasma shells attached to the electrode) and non-concentric (as a network of luminous plasma spots, each near others, almost equally distributed on the electrode surface). Here we present experimental results concerning the dynamic states of multiple double layers in dc discharge plasma. These dynamic states were recorded as strongly nonlinear oscillations of the current collected by the electrode. The oscillations appear because the plasma system performs fast transitions between states characterized by different electrical conductivities. This bistability was analyzed by the modern techniques provided by the nonlinear dynamics. In the case of non-concentric MDLs, a scenario of transition to chaos by torus breakdown was emphasized.

(Received October 14, 2005; accepted January 26, 2006)

Keywords: Bistability, Multiple double layers, Chaos, Torus breakdown

1. Introduction

Double layers (DLs) are non-linear potential structures [1] consisting of two adjacent layers of positive and negative space charges, in which the existing potential jump creates an electric field. One common way to obtain a DL structure is to positively bias an electrode immersed in a plasma being in equilibrium. In this case, a complex space charge structure (CSCS) in form of a quasi-spherical luminous body attached to the electrode is obtained. Experimental investigations (by emissive probes) revealed that such a CSCS consists of a positive „nucleus" (an ion-enriched plasma) surrounded by an electrical DL [2,3]. The potential drop across the DL is almost equal with the ionization potential of the background gas atoms.

Under certain experimental conditions (gas nature and pressure, plasma density, electron temperature) a more complex structure in form of two or more subsequent DLs was observed [4-11], called multiple double layers (MDLs). It appears as several bright and concentric plasma shells attached to the anode of a glow discharge. The successive DLs are precisely located at the abrupt changes of luminosity between two adjacent plasma shells. Emissive probe measurements emphasized that the axial profile of the plasma potential has a stair step shape, with potential jumps close to the ionization potential of the used gas [6,10].

If the used electrode is large in respect to the characteristic length of plasma, or if it is strongly asymmetric (e.g., with one-dimensional geometry), the multiple double layer structure appears non-concentrically, as a network of intense luminous plasma spots, located each near others, almost equally distributed on the electrode surface [12-19]. Each of the plasma spots is a CSCS as described above. We explained the emergence of metastable CSCC by a scenario of self-org [25]. In this paper is presented the experimental results concerning the bistable behaviour of multiple double layers in dc discharge systems.

2. Experiment

The experiments were performed in the double plasma (DP) machine of the University of Innsbruck, schematically represented in Fig. 1. The DP machine consists of a large cylindrical non-magnetic stainless steel cylinder (about 90 cm long and 45 cm diameter), evacuated by a preliminary pump and a diffusion pump. A metallic grid (marked by G in Fig. 1) divides the tube into two chambers: the source chamber (left hand side of the cylinder in Fig. 1) and the target chamber (right hand side of the cylinder in Fig. 1). In the source chamber the plasma is created by an electrical discharge between a hot filament and an inner auxiliary anode. In the target chamber the plasma is created by an electrical discharge between a hot filament and the grounded cylinder as anode. Because of the small dimensions, the filament will collect only a negligible part of the ions, most of them diffusing towards the centre of the tube. The positive space charge will attract many electrons in this region. In this way, a high-ionization degree plasma appears. To avoid plasma losses, at the wall there are magnetic traps, generally in form of permanents magnets with alternate polarity. In our experiments we used only the target chamber of the DP machine, under the following experimental conditions: argon pressure $p = 5\times10^{-3}$ mbar, plasma density $n_{pl} \cong 10^9$ cm^{-3}.

In the target chamber we introduced a tantalum disk electrode (marked by E in Fig. 1) with 3 cm diameter.

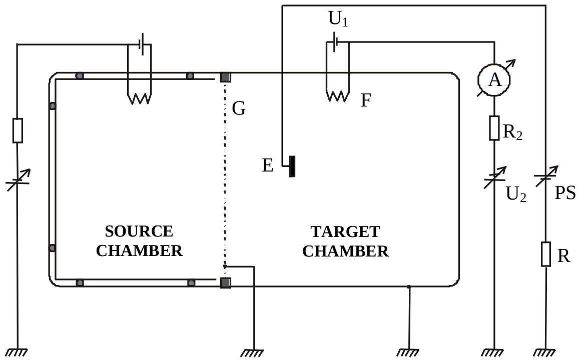

Fig. 1. Schematic of the University of Innsbruck DP machine (F – filament, G – grid, E – electrode, PS – power supply).

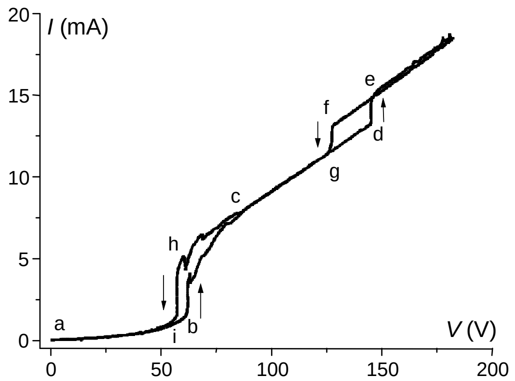

Fig. 2. Static current-voltage characteristic obtained in the conditions when two plasma spots (non-concentric MDLs) appear on a large electrode.

3. Results

Fig. 2 shows the static current-voltage (*I*-*V*) characteristic of the electrode, obtained by gradually increasing and subsequently decreasing the potential on E. When the voltage *V* is increased until the critical value which correspond to point **b** in the static characteristic (Fig. 2), the current *I* through the electrode jumps to a value corresponding to a new state (point **c** in the characteristic, Fig. 2). After this jump, a luminous plasma spot with about 5-6 mm diameter appears in a certain point of the electrode (see photo in Fig. 3), where the current is highest because of the local causes (for example the presence of protuberances on the electrode surface, or local gas emission). Simultaneously, the current *I* becomes time dependent (see the time series of the AC components of the current in the Fig. 4a and the FFT's of it in the Fig. 5a). By increasing the potential between the points **c** and **d** (Fig. 2), the current gradually increases, simultaneously with the extension of the plasma spot. When the potential reaches a second critical value, that one corresponding to point **d** in the static characteristic (Fig. 2), the current *I* jumps again to a value corresponding to point **e**, and its oscillations become more complex (see Figs. 4b and 5b, respectively). Simultaneously, a second plasma spot appears on the electrode E, near the first one (see photo in Fig. 6). At high values of the potential *V* many plasma spots appear. When *V* is gradually decreased, we observed that all current jumps are subject to hysteresis effects. This phenomenon emphasizes that the plasma system can preserve their states in conditions poorly that than required for their emergences, a general characteristic of the complex nonlinear systems.

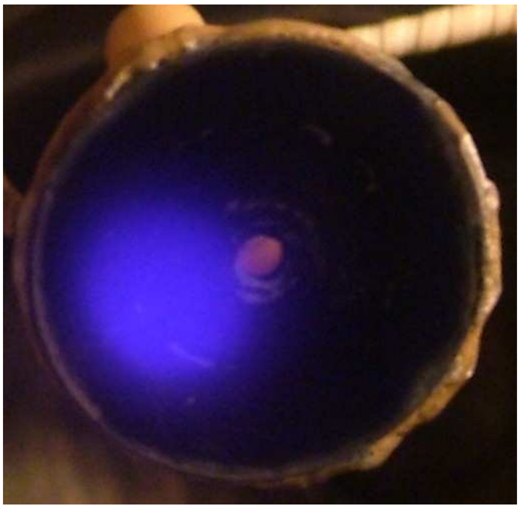

Fig. 3. Photography of a single plasma spot obtained on a large electrode.

4. Discussion

Since the phenomena studied are strongly nonlinear, we decided that a nonlinear dynamic analysis of the signals form Fig. 4 can offer an excellent insight into the state space dynamics of our plasma system. For this purpose, we have recorded the time series of the AC component of the current collected by the electrode E with a sampling rate of 50 kHz, delivering 2500 points in 0.05 s, i.e. the sampling time was τ_s = 20 μs. Fig. 7 show the 3D reconstructed space of the plasma system dynamics, obtained by using the method of delays, proposed by Packard et al. [28], Takens [29] and Ruelle [30], extensively described in ref. [31]. These plots emphasize the phenomenon of torus breakdown (Fig. 8b), which appears after the emergence of the second spot. This phenomenon is a first step in a well-known [32] scenario of transition to chaos. When many plasma spots appear on the electrode surface, the system state becomes chaotic because of the uncorrelated dynamics of each of the spots.

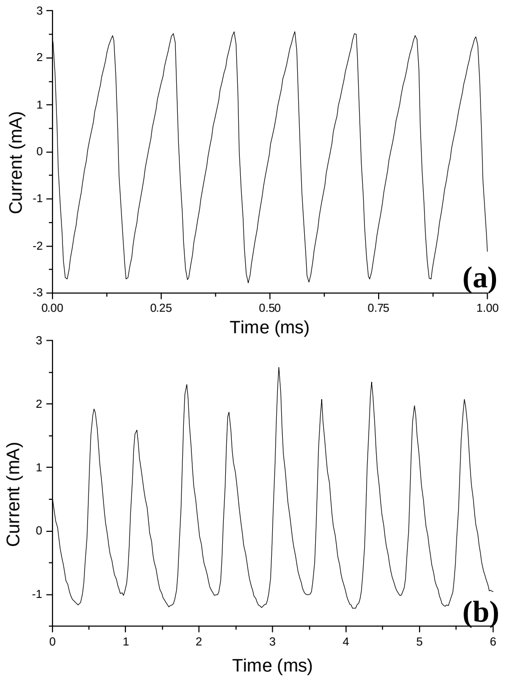

Fig. 4. AC component of the current collected by E in the next conditions (correlated with letters in Fig. 2): after the current jump $\boldsymbol{b} \rightarrow \boldsymbol{c}$ *(a) and after the current jump* $\boldsymbol{d} \rightarrow \boldsymbol{e}$ *(b).*

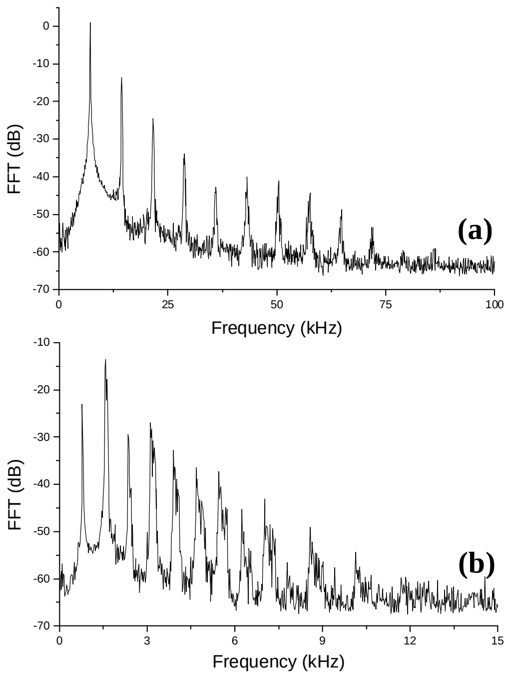

Fig. 5. FFT's of the AC components of the current from Fig. 4.

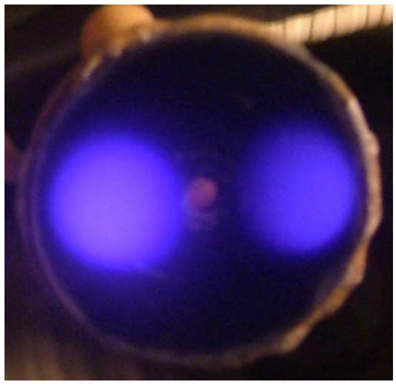

Fig. 6. Photography of two plasma spots (non-concentric MDLs) obtained on a large electrode.

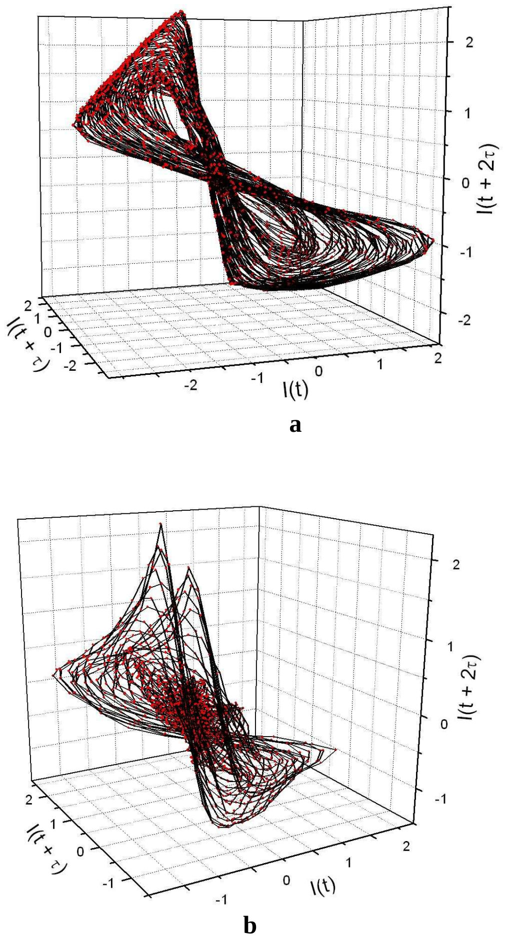

Fig. 7. 3D reconstructed spaces of the AC components of the current from Fig. 4.

5. Conclusions

Experimental results emphasized the appearance of a scenario of transition to chaos by torus breakdown in plasma systems, related to the development and nonlinear dynamics of a non-concentric multiple double layers. The obtained signals were analyzed with methods of nonlinear dynamics.

Acknowledgement

This work was supported in part by the National University Research Council, Romanian Ministry of Education and Research, under grant no. 33373, cod CNCSIS 70, and by the University of Innsbruck.

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* Corresponding author: dimitriu@uaic.ro