

INTERMITTENCY SCENARIO OF TRANSITION TO CHAOS  
IN PLASMA RELATED  
TO THE NON-CONCENTRIC MULTIPLE DOUBLE LAYERS\*

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Non-concentric multiple double layers in form of a network of quasi-spherical luminous plasma spots, approximately uniform distributed on the surface of a positively biased electrode immersed in plasma, are reported. They appear through an instability, namely enhancement of the production of positive ions, which develops for a certain critical value of the potential applied on the electrode. The experimental results emphasize that the multiple double layers evolve from stationary to chaotic state by an intermittency route, involving a succession of bifurcations, including even and inverse period doubling one. Regular current oscillations phases are interrupted by chaotic windows, randomly distributed in the signal. At high values of the potential applied on the electrode these chaotic windows become more frequently, the plasma conductor state going to a chaotic one.

*Key words:* multiple double layers, chaos, intermittency, self-organization, bifurcations.

**INTRODUCTION**

Multiple double layers (MDLs) were evidenced in different discharge plasmas, for example, by additional gas injection in front of the anode of a spherical vacuum chamber [1], by applying a positive potential on a electrode immersed in a diffusion plasma [2], or between two independently glow discharges [3], and also in gas discharges systems [4, 5] in which a semiconductor cathode was used in order to describe the formation of plasma spots through a Turing type scenario [6], using an activator-inhibitor model.

Emissive probe measurements indicate that double layers (DLs) consist of two adjacent sheaths of positive and respectively negative space charges [7], thereby creating a localized electric field extended for several Debye lengths, where the condition for plasma quasi-neutrality is not fulfilled. The DLs confine plasma spots, *i.e.* regions of ion rich plasma [7], developed after an instability process, namely the enhancement of the production of positive ions [8, 9]. The

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elementary processes which are responsible for DLs appearance are mainly electron impact excitation and ionization reactions [2, 7, 8]. They determine the separation of positive and negative space charges, as related to the symmetry breaking of excitations and ionizations cross-section functions [2, 10, 11], due to their dependence on the kinetic energy of electrons accelerated in the electric field created by the positively biased electrode.

Non-linear dynamics of the moving DLs, was put in evidence by recording the time series of the current collected on a load resistor in the electrode circuit. Different stages of the evolution of the MDLs were analyzed and a succession of bifurcations was identified; windows of regular and irregular oscillations alternate, indicating the evolution of MDLs system into chaotic states through a well known intermittency route [12].

In a previous paper [13], we also emphasized, in a double plasma machine, for certain experimental conditions, the evolution of two non-concentric plasma double layers to chaotic states via a torus breakdown scenario, as termed in non-linear dynamics [12].

#### EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results were obtained in a plasma diode, shown in Fig. 1. The vacuum chamber is a glass vessel, with 35 cm diameter and 30 cm height. The initial base neutral pressure was  $10^{-6}$  Torr and was reached by pumping on

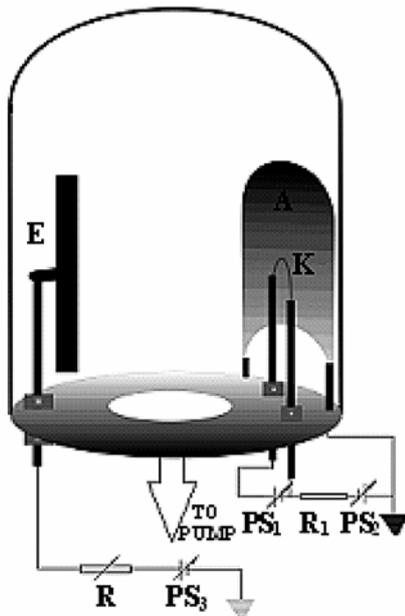


Fig. 1 – Schematic representation of the experimental device (A – anode; K – hot cathode; PS<sub>1</sub>, PS<sub>2</sub>, PS<sub>3</sub> – power supplies; R<sub>1</sub>, R – current limiting resistors; E – rectangular electrode).

with roughing and diffusion oil vacuum pumps. Then, Ar was leaked into the vessel and the desired working pressure ( $4 \times 10^{-2}$ – $7 \times 10^{-2}$  Torr) was attained by balancing the amount of leaked gas with the pumping capability.

The plasma was obtained using a dc discharge between hot emissive filaments (0.4 mm diameter), made of wolfram, working as cathode and a rectangular non-magnetic stainless steel plate (26 cm  $\times$  22 cm), electrically grounded, and working as anode. On the back side of the anode, four horizontal rows and seven vertical rows of permanent magnets with alternate polarity were placed in order to assure a better confinement of the plasma. The distance between the plasma source (PS) and E was 17 cm and was kept constant during the investigations. The discharge current was varied between 20 mA and 60 mA by applying a potential difference ( $-30$  V  $\div$   $-80$  V) between the plate and the hot filaments connected through a 100  $\Omega$  load resistor,  $R_1$  in the PS circuit. The filament was heated by direct current between 10 A and 14 A.

A positively biased rectangular electrode E made of tantalum (6 cm  $\times$  0.1 cm) was immersed in plasma. The electrode was biased between 0 V and 80 V with respect to the ground. The electric field created by the polarized electrode “penetrates” the plasma for a short distance, *i.e.* hundred of Debye lengths, and triggers the condition for the self-assembly of the DLs [2, 7, 10]. A set of non-concentrically plasma spots distributed approximately symmetric on the surface of the electrode appear simultaneously in a stationary state, after a sudden upward jump of the current collected by the electrode. The number of these plasma spots varies in these experiments between two and six, depending on the experimental conditions (gas pressure, discharge current, etc.). The stationary DLs “survive” in this state due to a dynamical equilibrium between the concentrations of electrons and positive ions at the low, and respectively high potential side of them [14].

The AC components of the current collected by E are recorded with a computer-controlled digital oscilloscope with a chosen sampling rate of 1 MHz, delivering 1000 points in 1 ms, *i.e.* a sampling time  $\sigma_s = 1 \mu\text{s}$ . A current-limiting phenomenon developed at a certain critical value of the potential applied to E, *i.e.* 42 V, is related to a spatio-temporal self-organization phenomenon [10], in which coherent oscillations of the current collected by E are recorded. This is caused by periodical disruption of DLs and reformation of new DLs at the boundary of the plasma spots, and was described extensively elsewhere [2, 8, 10]. The stimulation of oscillations in the electrode circuit is related to the appearance of an N-type negative differential resistance, which is a well-known phenomenon in plasma [10, 11]. The current becomes time dependent after a downward sudden jump, as one can see in the time series of the AC components from the Fig. 2. Then, by increasing further the potential on the electrode, several windows of regular and irregular oscillations were observed, and the MDLs system evolves towards chaotic states.

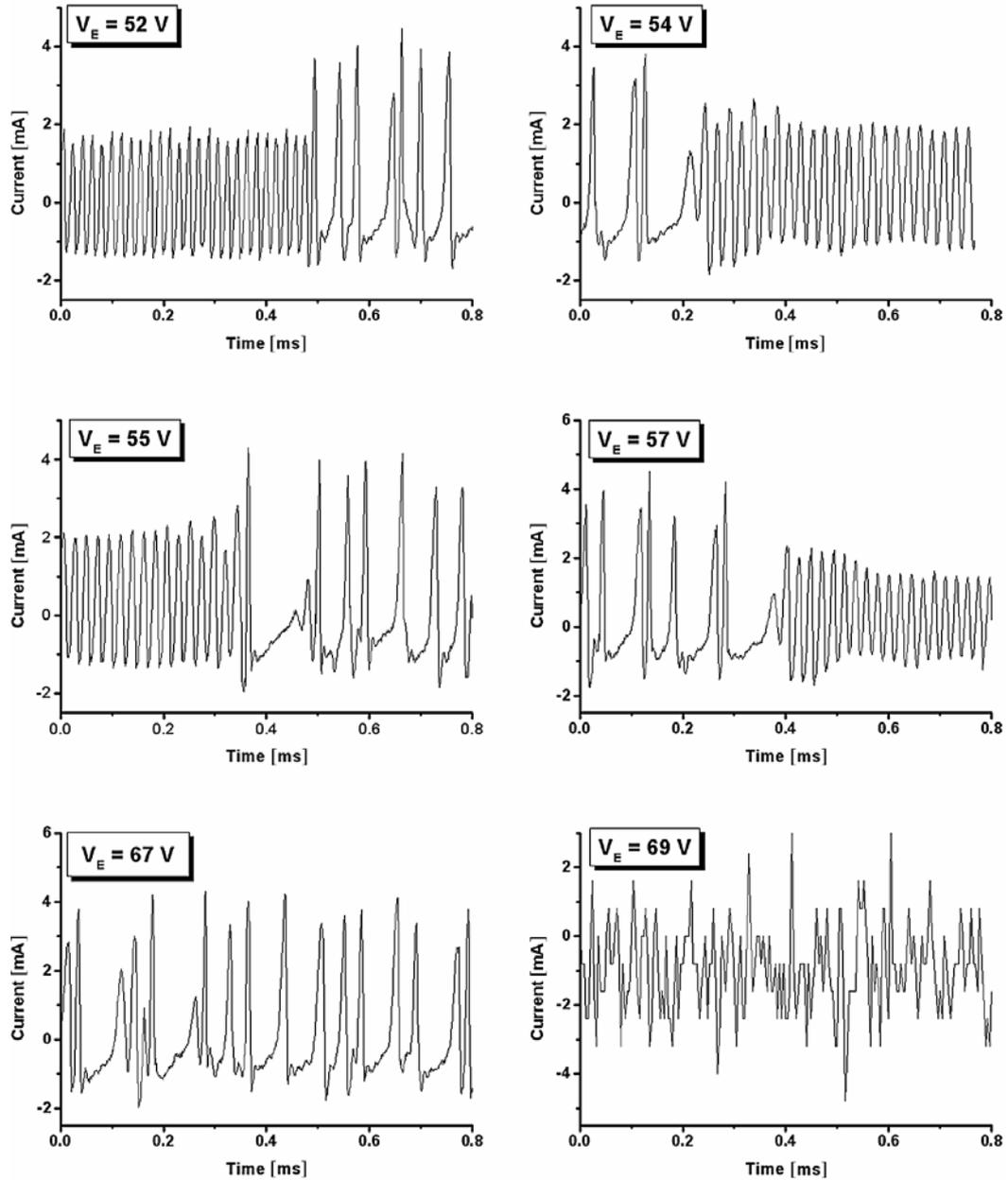


Fig. 2 – The evidence of regular and irregular oscillations for different values of  $V_E$ .

By gradually decreasing the potential on the electrode E, all the current jumps are subjected to hysteresis effects, as already known [2, 7, 13, 15]. This phenomenon emphasizes that MDLs can maintain their states for conditions

poorly than required for their emergence, which is the main fingerprint of the non-linear complex systems.

By using the methods described by Packard *et al.* [16], Takens [17] and Ruelle [18], we reconstructed the 3D state space of the MDLs dynamics. The re-injection of the escaped trajectories in the vicinity of the limit cycle is a well known feature evidenced by non-linear systems that follow a scenario of transition to chaos through an intermittency way [12]. For the values of the potential applied on the electrode E, as in the Fig. 2, the behavior of the plasma oscillators modifies in connection to the alternative appearance of large windows of regular oscillations with large windows of irregular oscillations. The latter type of behavior reflects the appearance of chaotic states when  $V_E$  surpasses a certain value. Finite intervals of regular oscillations alternate with irregular

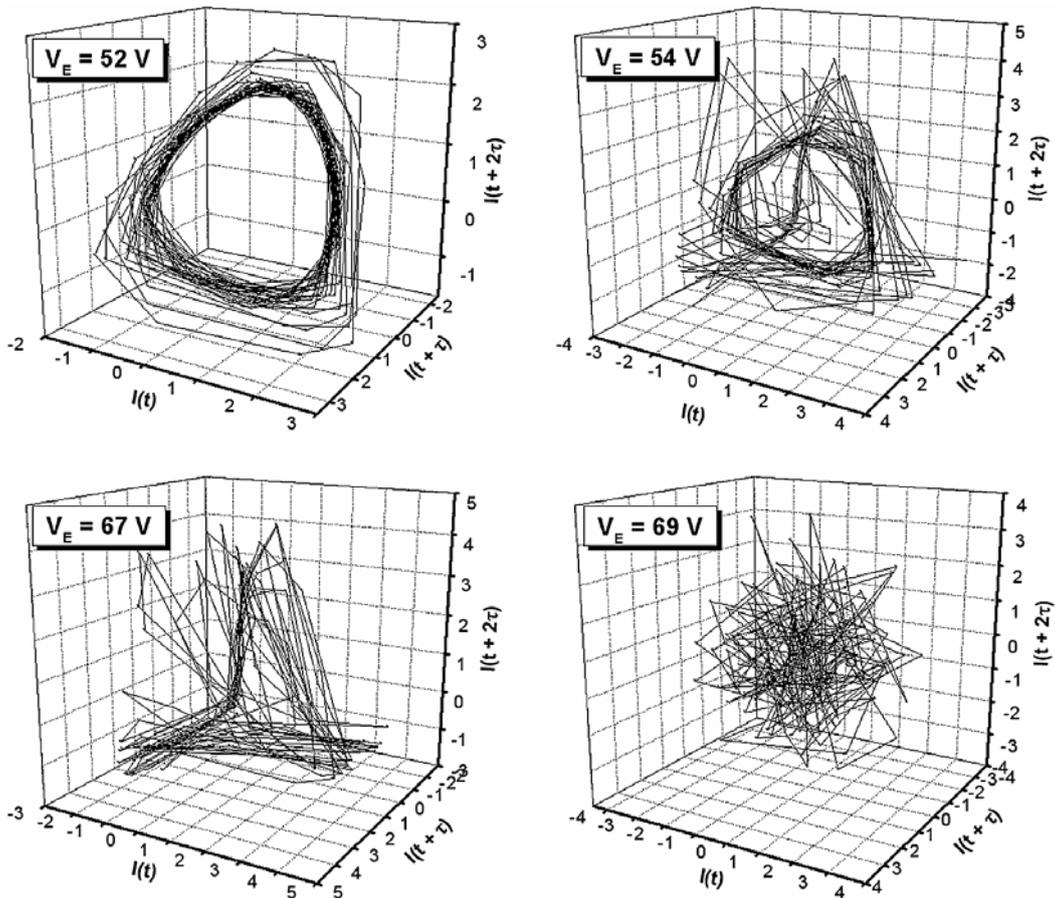


Fig. 3 – The evolution of the 3-D attractors in the reconstructed state spaces towards strange attractors as  $V_E$  is increased from 52 V to 69 V.

oscillations between 52 V and 69 V. When  $V_E$  surpasses 69 V, only the chaotic oscillations will be emphasized.

As a result of successive bifurcations corresponding to each modification of the shape of the oscillations, the periodic orbits are replaced with other orbits which become more and more chaotic. This means that the 3-D reconstructed state spaces contain large attractors and the older periodic attractors are a subset of the new attractors. This can be easily observed in the 3-D reconstructed state spaces evidenced in Fig. 3. During the chaotic bursts, the trajectories go away from the periodic orbits, and when the potential on the electrode surpasses a certain value (69 V in this case), they could not turn back to periodic orbits, as one can see in the last attractor from Fig. 3. In this way, strange attractors develop as  $V_E$  is increased further on.

### CONCLUSION

These experimental results prove that, in certain conditions, MDLs can undergo transitions through a succession of bifurcations, as the voltage on the electrode is increased, emphasizing an intermittency route to chaos.

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