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Order–chaos–order–chaos transition and evolution of multiple anodic double layers in glow discharge plasma

Prince Alex, Saravanan Arumugam, Kaliyamurthy Jayaprakash, K.S. Suraj *

Department of Physics, Pondicherry University, Kalapet, Puducherry 605014, India

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ABSTRACT

Plasma often shows complex dynamic behavior. We present an experimental observation of order–chaos–order–chaos transition in glow discharge plasma. These transitions correspond to the evolution of different stages of a multiple anodic double layer. Multiple anodic double layers were produced in a typical glow discharge condition and associated floating potential oscillations were recorded for monotonous variation of one of the control parameters i.e. the cathode voltage. With a variation in the cathode voltage, the multiple anodic double layers were evolved to different stages. The recorded experimental time series data had been analyzed and quantified using power spectra, phase space trajectories, time-delay reconstructions of state space, Lyapunov exponent and correlation dimensions. The analysis shows that the chaotic behavior corresponds to diffused boundaries between two double layers.

Introduction

A double layer (DL) is a potential structure that consists of two equal but opposite space charged regions. In recent times it finds numerous applications in electrochemical devices, magnetic and non-magnetic plasma and astrophysical plasma [1–3]. The first experimental observation of DL in plasma was reported by Langmuir in 1929 [1], also he noted a sheath like detached structure near the anode known as anodic double layer (ADL). The quasi-neutrality condition for plasma is locally violated within an ADL. It contains few potential maxima and minima through the entire layer. One of the necessary conditions for the existence of DL is the trapping of electrons and ions within the potential structures [4,5]. Order–chaos–order transitions have also been reported in experimental simple glow discharge plasma in which oscillations undergo monoclinic bifurcation [6]. The salient features of ADL such as evolution of ADL from single to multiple ADLs, nonlinear behavior [7–12] including self oscillation, periodic doubling, intermittency, quasi-periodicity, chaos in driven and undriven plasma and transition from chaos to order has been observed in the laboratory [13–19]. Although it is known that, order–chaos–order phenomenon is observed in simple glow discharge plasma when oscillations undergo monoclinic bifurcation [20]; a detailed study on the dynamics of glow discharge plasma in the presence of nonlinear structures such as ADL is not carried out. In the present work, we present first experimental observation of order–chaos–order–transitions corresponding to the evolution of multiple ADLs (MADLs), in glow discharge plasma. Quantitative analysis of order–chaos–order–transitions corresponding to evolution of multiple ADL from power spectrum analysis, Lyapunov exponent and correlation dimension shows that the order is associated with well defined boundaries and chaos is a consequence of diffused boundaries between two ADLs.

Experimental setup

The schematic of experimental set-up is shown in Fig. 1. The discharge chamber consists of a disk shaped cathode C, made up of SS304, with a diameter of 50 mm and 3 mm thickness and anode A made of a tungsten disk with 10 mm diameter and 2 mm thickness. Two dc power supplies V_1 and V_2 were connected to the cathode and anode through resister R_1 and R_2, respectively. Typical glow discharge plasma was produced between cathode C and the grounded chamber by applying a dc voltage V_1 in the range of (300–400) V and the corresponding discharge current measured across R_1. As the positive bias V_2 increases from 0 V, a small anode current starts to flow across the resistor R_2. When the positive bias is in the range of 100–250 V, MADL structure with different configuration is formed in front of the anode surface with a pronounced increase in anode current, where the number of layers in MADL formed can be controlled by suitably fixing the value of V_2 in the given range. The experimental condition has been optimized after several sets of experiments for wide ranges of voltages across V_1

* Corresponding author.
E-mail address: sinha_suraj@rediffmail.com (K.S. Suraj).

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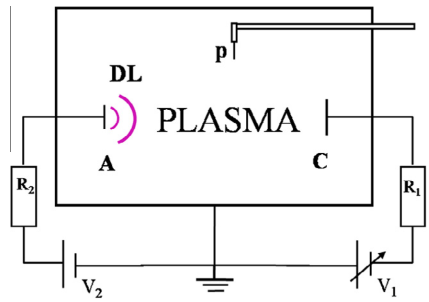

Fig. 1. Schematic of the experimental set up. The discharge chamber consists of a disk shaped cathode C, made up of SS304, with a diameter of 50 mm and 3 mm thickness, and the anode A made of a tungsten disk with 10 mm diameter and 2 mm thickness. Two dc power supplies V_1 and V_2 connected to cathode and anode through resister R_1 and R_2, respectively. The formation of double layers (DL) in front of anode A is schematically shown in the figure.

and V_2, pressure and separation between electrodes. The typical operating conditions maintained for the present investigation were as follows, the anode voltage V_2 = +200 V, the operating pressure p = 0.054 mbar, a separation of 30 cm between electrodes and the discharge current was controlled by varying the cathode voltage V_1 in the range (300–400 V). At this stable condition the DL satisfies the critical current density below which DLs cannot be maintained. As the cathode voltage V_1 changes from 300 V to 400 V and keeping all the other parameters constant, the MADL structure passes through different stages including transition from triple to double DL, double to single DL, single to anode glow and so on. The dynamics of these transitions were studied using an electrostatic probe P placed at the center of the gap between electrodes and a high bandwidth digital oscilloscope (Lecroy Wavejet-354A 500 MHz). The discharge current (I) vs voltage (V_1) measured across R_1 and R_2 corresponding to these transitions for a voltage range of 300–400 V is shown in Fig. 2 using dashed and solid line respectively. Double layers in plasma are always associated with the occurrence of a sudden jump in the current–voltage (I–V) characteristics of the discharge [6,21,22]. As shown in Fig. 2, three vertical dotted lines denote the voltage at which a sudden jump in discharge current is observed across Resistors R_1 and R_2. Three jumps in discharge current (at vertical lines) correspond to the evolution of each of the three ADLs observed in the experiment. The difference in magnitude of the current is attributed to the different size of the cathode and anode as well as to the corresponding bias voltage.

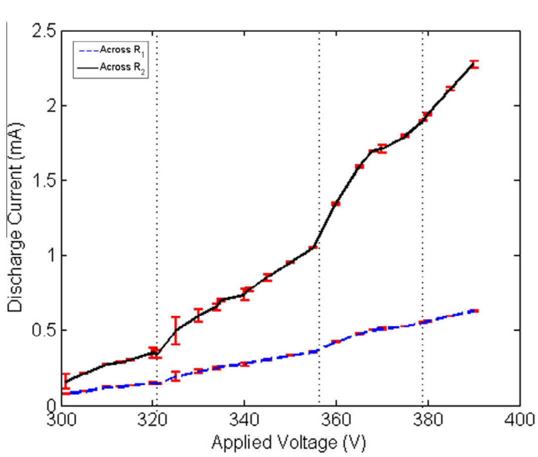

Fig. 2. The I–V characteristic across anode (solid line) and cathode (dash line) under multiple ADL condition. Three vertical dotted lines represents the voltage at which a sudden jump in discharge current is observed across Resistor R_1 and R_2. Each of these jumps corresponds to the evolution of three ADLs observed in the experiment.

Evolution of ADL and its analysis

Evolution of ADL

The complete dynamics of MADLs had been studied by manually varying the cathode voltage V_1 from 300 to 400 by keeping all the other parameters fixed. The different stages of MADLs evolution and the corresponding floating potential oscillations are shown in Fig. 3 I and II, respectively. These oscillations were analyzed using Fast Fourier Transform (FFT), phase space trajectories and time – delay reconstruction of state space are respectively shown in Fig. 3 III–V. For the minimum value of voltage V_1 = 301 V to maintain the discharge, an optically bright column of plasma appeared between the anode and cathode as shown in Fig. 3(a) I. The plasma parameters measured by a Langmuir probe for this state are; electron density $n_e \sim 6 \times 10\,cm^{-3}$ [8], electron temperature $T_e \sim 5$ eV and ion saturation current 5 μA. The oscillation representing this state is highly periodic in nature and as expected the FFT shows only a single frequency component, similarly, the phase space trajectories and state space reconstruction confirm the limit cycle motion are shown in Fig. 3(a) II–V, respectively. This is a clear indication that the system is in a highly ordered state.

The cathode voltage V_1 is increased in steps of 1 V and for V_1 = 313 V the bright plasma column transformed into 3 alternate dark and bright plasma regions, shown in Fig. 3(b) I. These alternate dark and bright regions, with visually clear boundaries, constitute three ADLs, representing localized positive and negative space charges. For this typical discharge condition the multiple ADL emerged from the bright column of plasma, and the system undergoes a periodic doubling bifurcation from Period-1 oscillation. The Fig. 3(b) III–V represents a power spectrum containing two peaks, period-2 limit cycle motion in phase space and state space reconstruction respectively shows the period doubling nature.

On further increases of V_1, the ADLs begin to contract towards the anode and at V_1 = 321 V multi-harmonics power spectrum confirms the chaotic nature of the system as shown in Fig. 3(c) III. The phase space diagram and reconstructed state space are shown in Fig. 3(c) IV and V. This typical condition represents the *first* transition state of the multiple ADL. The *first* transition state is referred to the condition where the inner most ADLs (i.e. ADL nearest to anode) and consecutive ADL contract sharply, and the boundary between these two is not well separated but diffused. In Fig. 3(c) I, the optical image shows the contraction of ADLs in comparison to V_1 = 313 V. The 1st transition state remained up to V_1 = 333 V. As the voltage on the cathode is increased to V_1 = 334 V only two optically visible ADLs remained and the first ADL, close to the anode, vanishes. An interesting phenomenon has been observed in floating potential oscillation for this condition i.e., the system undergoes a transition from chaotic to multi-periodic state. The corresponding oscillations, FFTs, phase space and reconstructed state space confirm that the system has transformed from chaotic to multi-periodic state as shown in Fig. 3(d) II–V respectively.

The 2nd transition state is observed by further increase of voltage at V_1 = 341 V. Out of the two remaining ADLs, the ADL close to the anode diffuses with the anode glow as shown in Fig. 3(e) I. The obtained power spectrum shows that the system has undergone reverse bifurcation, from multi-periodic oscillation to single periodic state. The phase space trajectories and state space reconstruction represent period-1 limit cycle motion which support the