Characterization of order-to-chaos-to-order transition in co-axial DC discharge plasma of different inter-electrode distances

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This paper attempts to understand the role of the electrode dimensions in the evolution of order-to-chaos-to-order transitions in a co-axial DC electrode discharge system, wherein the ratio of the anode-to-cathode radii is observed to determine the evolution path of the transition. Further the anode dimensions is observed to determine the discharge conductivity after the 1st negative differential resistance (NDR) region and the onset of the order-to-chaos-to-order transition is linked to the cathode dimensions.

1. Introduction

Plasma discharges being a nonlinear medium, observations of associated hysteresis effects at negative differential regions (NDR) are signatures of the nonlinear dynamical evolution of the system. Such hysteresis loops are quite commonly observed near the Townsend breakdown and abnormal glow discharge regions of a planar electrode DC plasma discharge. However, there have also been observations of NDR regions in discharge current (I_d) – discharge voltage (V_d) characteristics of systems such as the DP machine [1] and coaxial electrode geometry systems [2, 3], in which the dynamical evolution of the system has been characterized using fluctuation signals [2-6] obtained from the plasma. In different systems and under different operating conditions, the fluctuation signals have been observed to undergo order-to-chaos [7] as well as chaos-to-order [8, 9] transitions. Order-to-chaos-to-order transitions [3, 10] have also been observed recently.

As reported earlier, the I_d-V_d characteristics [3] of the DC coaxial electrode discharges with a powered central anode have been observed to have two consecutive negative differential regions (NDR). The 1st NDR has been observed to be correlated to an upper voltage threshold whereas the 2nd NDR is seen to be linked to the discharge current [11]. The voltage drop across the 1st NDR is seen to trigger relatively large amplitude floating potential oscillations in comparison to those prior to the 1st NDR region. These oscillations, thereafter, are seen to undergo an order-to-chaos-to-order transition with increasing discharge current. As the I_d-V_d characteristic behaviour seems to be linked to the polarity direction of the electrode configuration, the role of the dependence on the electrode geometry seems to be an important factor. Keeping this in mind, it was envisaged to carry out a study of the discharge characteristics of the co-axial electrode geometry with different inter-electrode distances, by varying the diameters of the anode/cathode.

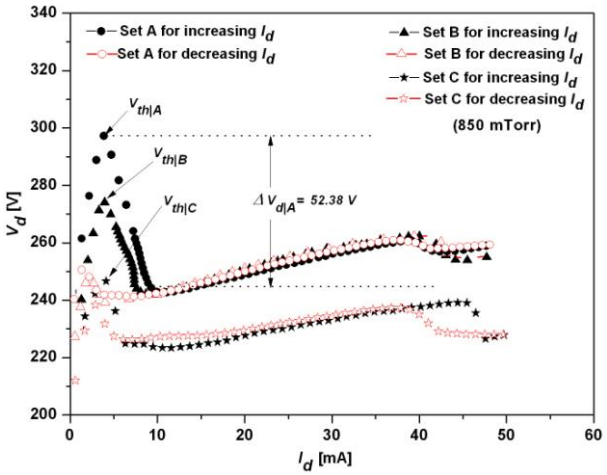

Fig 1: I_d-V_d discharge characteristics for increasing (black) and decreasing (red) I_d for different inter-electrode distances at p=850 mTorr. $V_{th|A}$, $V_{th|B}$ and $V_{th|C}$ are the threshold voltages at 1st NDR for Set A, B & C respectively. $\Delta V_d|A$ is the voltage drop across the 1st NDR for Set A.

In this paper, the variation of the order-to-chaos-to-order transitions in the floating potential fluctuations with configurations of different inter-electrode distances are presented and characterized. The characterization has been done with new electrode installed [12]. Thus the characteristics are slightly different as compared to that expressed for longer duration [3, 11].

2. Experimental Results and Discussions

The experimental setup [3] consists of a coaxial stainless steel electrode system (≈ 60 mm long), with central axial rod acting as the powered anode and the outer cylindrical tube (thickness≈ 1 mm) acting as the grounded cathode. In this paper, experiments have been carried out with central anode diameters of 1.5 mm and 12 mm and inner diameters of the grounded cathode being 50 mm and 70 mm. Experimental results from three different inter-electrode distances [viz., (1.5, 50), (1.5, 70)

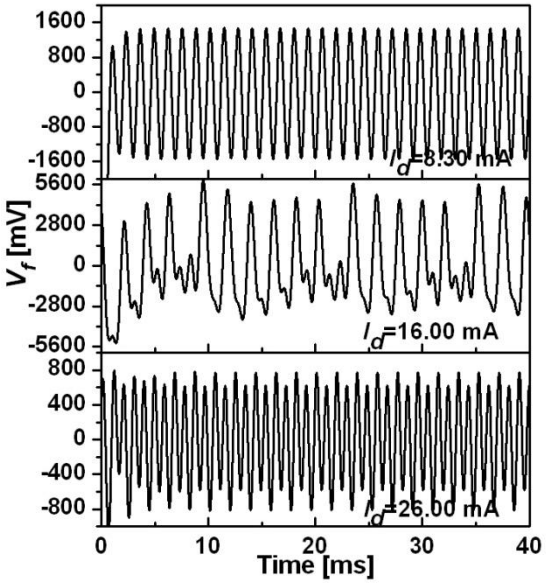

Fig 2: Floating potential oscillations for increasing discharge current for Set A at p=850 mTorr.

and (12, 70)] with an anode to cathode radii ratio of (1/33), (1/47) and (1/6) respectively are presented in this paper. The three configurations are henceforth called Set A, Set B and Set C respectively. A single Langmuir probe has been used for plasma parameter radial profile measurements at an operating pressure of 850 mTorr.

Figure 1 shows the I_d-V_d characteristics, both for increasing and decreasing currents, for the three different inter electrode distances. The voltage threshold voltage (V_{th}) at which the 1st NDR occurs is seen to decrease with an increase in the cathode/anode diameters, with the threshold dropping from 297 V to 273 V to 250 V in Set A, B and C electrode configurations respectively. It is interesting to note that the discharge current at which the 1st NDR is triggered is the same (~3.5 mA). The dominant effect is observed when the anode rod diameter is increased. The voltage drop (ΔV_d) across the 1st NDR is seen to decrease from 53 V to 35 V to 25 V. It is further observed that the conductivity of the system after the first NDR seems to increase with change in the central anode diameter, as seen by the sustenance of the discharge at a lower discharge voltage for Set C configuration, which however, does not seem to change much for Set A and Set B.

The region between the 1st NDR and 2nd NDR is seen to undergo an order-to-chaos-to-order transition [3, 11] in the floating potential oscillations in all three sets. Similar features have been observed for all the different electrode configurations reported here. However, the regions of onset of this transition and their behaviour are not same for all the configurations. Figs. 2, 3 and 4; show three representative oscillations, for each of the Sets A, B & C, depicting an order-to-chaos-to-order transition as one increases I_d. It is to be noted that oscillations at other I_d's have also been recorded but not shown here.

For Set A, it is observed that after the 1st NDR, the oscillations have an ordered behaviour from $I_d \approx$ 8.34 mA to 15.9 mA whereas the chaotic zone is from $I_d \approx$ 16.0 mA to 18.0 mA. Thereafter the oscillations remain ordered up to the maximum discharge current (46.0 mA) recorded.

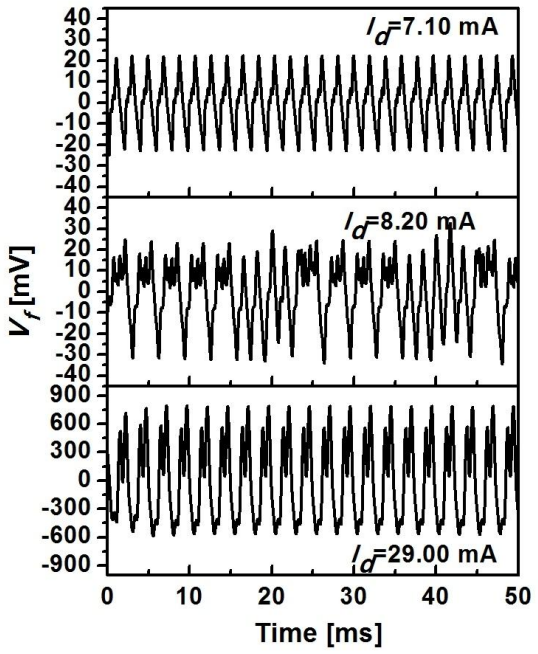

Fig 3: Floating potential oscillations for increasing discharge current for Set B at p=850 mTorr.

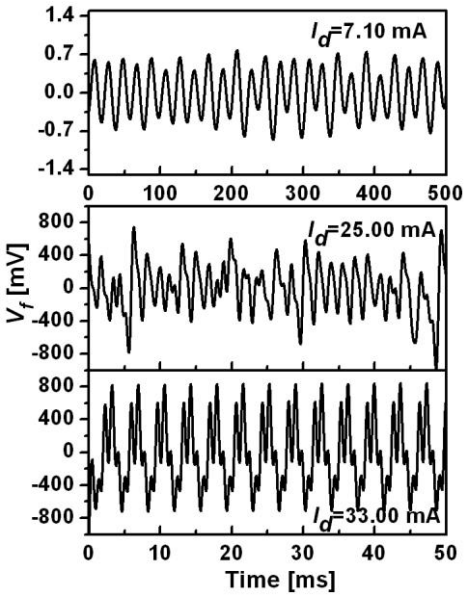

Fig. 4: Floating potential oscillations for increasing discharge current for Set C at p=850 mTorr.

For Set B, the oscillations show order at $I_d \approx$ 7.10 mA, just after the 1st NDR. These remain ordered up to 8.10 mA of I_d value. The chaotic zone is observed to widen from $I_d \approx$ 8.20 mA to 28.8 mA. The oscillations at $I_d \approx$ 29.0 mA is observed to be ordered. At $I_d \approx$ 31.10 mA and $I_d \approx$ 33.0 mA, the system again becomes chaotic. At $I_d \approx$ 35.5 mA, it is ordered again. At $I_d \approx$ 37.0 mA to 42.0 mA, the system is chaotic. As the control parameter limit is reached, the system becomes ordered again (i.e. between $I_d \approx$ 42.8 mA to 45.0 mA). Thus it is seen that in this configuration, the system traverses the order-chaos-order path again and again.

In Set C, the oscillations depict order in the current range $I_d \approx$ 7.10 mA to 24.5 mA whereas from $I_d \approx$ 25.0 mA to 29.0 mA, it is chaotic and thereafter at higher I_d's, the system tends to become ordered as I_d is increased to 48.0 mA.

4. Characterization of the Fluctuations

The onset of the chaos-order-chaos region and it's evolution pattern seems different and thus a basic characterization of these fluctuations were carried out with respect to I_d. The amplitude bifurcation of the oscillations shown in Fig. 5 for Sets A, B and C show that the onset of the chaotic region starts at higher and higher I_d values as one shows from Set A to Set B to Set C configurations respectively. The current jump is more significant from Set A to Set B. Further, the behaviour of the bifurcation diagram seems to evolve differently in the three cases, with the system tending to become ordered more slowly when the inter electrode distance is maximum (Set B).

The amplitude levels also show an interesting trend. As seen in Set B of Fig. 5, at $I_d \approx$ 21.3 mA, the amplitude of oscillations suddenly increase and tends to remain in this increased level up to $I_d \approx$ 31.10 mA. Thereafter at $I_d \approx$ 33.0 mA, the amplitude levels of oscillations show a decreasing trend till the control parameter limit. Comparing this with Set A and Set C, one finds in these sets that the large amplitude phenomenon tends to decrease relatively

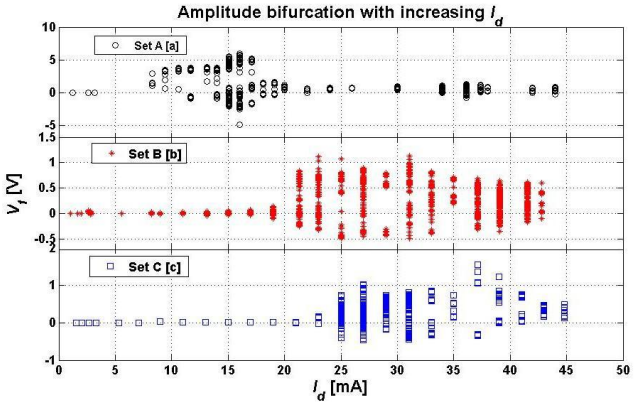

Fig. 5: Amplitude bifurcation diagram from the different electrode dimensions at p= 850 mTorr: (a) Set A, (b) Set B, and (c) Set C.

faster after a certain current limit with the amplitudes remaining at lower levels (~ 20 mV). Thereafter, the amplitude decay rate is slightly slower in Set C as compared to Set A. It may be possible that one observes such reduction in amplitude levels at higher I_d in Set B also but at present the experimental set up does not have the facility to go to such high discharge currents.

In order to understand the deviation of the oscillations from the DC level, their variance has been estimated (Fig. 6) which reveals that the variance is large in the region of the chaotic regions and hence onset of maximum variance tends to shift to the right i.e. linked to the onset of the order-to-chaos-to-order transition with the largest shift being observed when the cathode diameter is changed (i.e. Set A to Set B/C) as observed in Fig. 5 also.

3. Conclusions

The changes in the onset of the 1st NDR when one characterizes Set A, Set B and Set C configuration; show that the NDR is triggered at significantly higher conductivity as the electrode

surface area is increased and the system transits to a significantly higher conducting state after 1st NDR

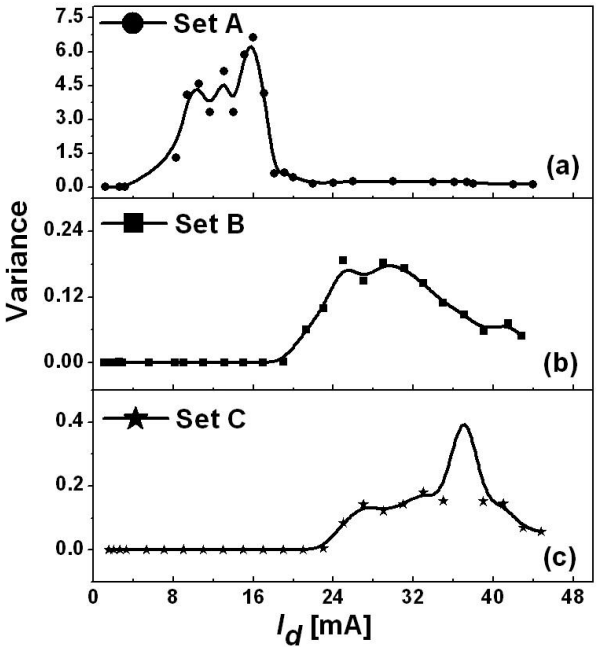

Fig. 6: Variance versus I_d for the different electrode dimensions at p= 850 mTorr: (a) Set A, (b) Set B, and (c) Set C.

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when the anode diameter is changed. However, the onset of the order-to-chaos-to-order transition seems to be governed by the cathode dimensions. Further it needs to be stated that the evolution of the order-to-chaos-to-order zone seems dependent on a critical value of the ratio of anode-to-cathode radii which needs to be investigated further.

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