Self-organization of double layer structures in glow discharge regime

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Abstract. Numerous research investigations have been carried out on the development of multiple charged layers in hollow cathode discharge in recent years. However earlier research failed to investigate the underlying mechanism using a controlled plasma source in the formation of multiple double layers (MDLs) and complex anode spots. The present study primarily focus on the role of negatively biased rectangular grid acting as a secondary plasma source placed between the asymmetrical cathode and the anode under an external magnetic field. The trapping of the non-thermal electrons by the negatively biased grid results in the nonlinear dissipation of energy in the plasma column, leading to the formation of MDLs in different Negative Differential Resistance (NDR) regimes close to the anode. The study also emphasizes the self-organization of MDLs and the associated sheath plasma interactions during different glow discharge regimes. Due to the insufficient transport of electrons from the biased rectangular grid, the sheath structure forms near the anode resulting in the charge localization and complex structure formations. With the enhancement of applied potential, the electrons surpass the barrier potential of the grid and the sheaths develop into concentric anode spots. Further nonlinear approaches confirm the formation of MDL enhancing the sheath dynamics and the associated NDR phenomenon to understand sheath-plasma instabilities present in the system. Various plasma applications related to self-organized MDLs includes medical technologies and nanomaterial synthesis.

1 Introduction

In recent years, various researches have been conducted on the formation of layered structures in hollow cathode discharge (HCD) in different kinds of laboratory environments [1]. The trapping of ions and electrons and the acceleration of these trapped electrons result in the formation of Double Layers (DLs) with relative energy and potential of the charged elements [2, 3]. The significant study of instabilities and self-organization of charged layers (MDLs) in a controlled plasma condition reveals the behaviour of complex nature of the system in dusty plasmas [4] and tokamaks [5]. The correlation between the layer mitigation phenomenon with associated NDR in the development of DLs triggers the Self-Organized Criticality (SOC) phenomenon during progressive DC discharge regimes [6]. The SOC is a

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characteristic of complex natural systems which progress into the point of criticality without additional modifications. In this state, small disturbances can trigger chain reactions or avalanches, following a power-law pattern just like how tiny fluctuations can lead to large-scale events or patterns, similar to how small sand avalanches can reshape the whole pile [7]. The potential distribution controls the ongoing development of many localized complex sheaths, following the entrapment of charged elements and the creation of complex structures in the existence of a negatively biased grid [2]. The variation through different discharge regimes in this study are caused by the re-organization of charged elements, which self-organize to undergo layer reduction process in the DC discharge with increasing applied voltage. A set of detailed nonlinear dynamical analyses is also performed to investigate and verify the SOC present in the system. Using a rank function helps determine whether SOC behavior exists in the avalanche of fluctuations.

2 Experimental setup

The current investigation is performed inside a cylindrical stainless steel (SS) chamber featuring an electrode design consisting of a 6 cm diameter spherical SS anode and 15 cm length coaxial cylindrical cathode (diameter = 6 cm), built with a fine mesh spacing of approximately 4 mm. A square, biased grid (10 cm x 10 cm) with analogous mesh spacing is placed in the very middle of cathode and anode, perpendicular to both, as shown in Figure 1. The cathode, anode, and the biased rectangular grid are connected to three resistors as R_C (~190 Ω), R_A (~400 Ω), and R_G (~80 Ω) respectively. To establish a default pressure of 0.01 mbar using a rotary oil pump, N_2 gas (99.99%) is constantly pumped into the chamber in order to ensure steady neutral surroundings, which is necessary to sustain the discharge near the electrodes. The Langmuir probes used to examine the dynamic nature of the DC discharge are made of tungsten tips that are about 4 mm long and diameter of approximately 0.5 mm. The overall measurement uncertainty was within ±3% for probe calibration, and the optimized pressure was maintained stable during the discharge. A power supply with high-voltage DC (1 kilovolt, 1 Ampere) generates plasma in pulsed discharge mode. For accurate nonlinear analysis, a length of 100,000 data points is considered and the probe output is recorded with an oscilloscope that has a bandwidth as high as 500 MHz.

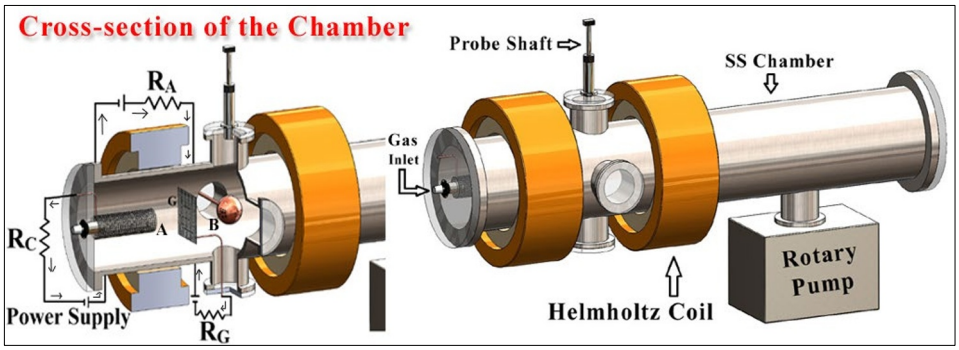

Fig. 1. An illustration of the chamber showing current paths (represented by the arrow in the cross-section) and the potential regions (A and B) used to examine the study of DL formations near the electrodes.

3 Results and analysis

3.1 Measurement of characteristic DC discharge with NDR

A unique dynamical activity in the plasma is initiated in the novel plasma triode arrangement when a negative bias is applied to the intermediary grid in an environment of an additional magnetic field. As illustrated in Figure 2a, the discharge is characterized by an abrupt spike in potential signal measured close to the anode. This initial surge is indicative of rapid sheath restructuring and potential barrier formation near the grid, possibly associated with the transient formation of a double layer or a strongly localized space-charge region. The initial spike in Figure 2a suggests the enhanced motion of accelerated electrons towards the anode in the presence of asymmetric electric field established by the electrodes and the confinement produced by the ambient magnetic field [8].

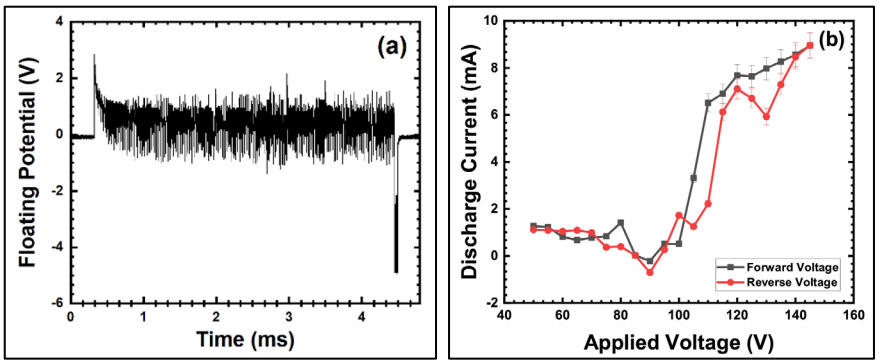

Fig. 2. (a) Raw signal of the floating potential oscillations in the presence of a rectangular grid with applied voltage (V_A = 125 V), (b) Hysteresis plot of discharge current (I) and Applied voltage (V) across the resistor connected to the anode.

The potential oscillations attain a lower and steady value compared to its peak value which is reliable with the emergence of complex sheath structure close to the electrodes. Thus, the biased rectangular grid acts as energy filter providing anisotropy in the diffusion of electron and control over the flux of nonthermal electrons towards the anode for ionization. The hysteresis traces shown in Figure 2b signifies that the discharge initiates with low current and in stable regime. The electric field at the early stage of discharge is insufficient in providing the avalanche of energetic electrons and ionization fronts. Plasma parameters which include temperature of electrons (T_e), density (n_e) and debye length (λ_D) are estimated from probe measurements along the axial direction to provide a quantitative inside into the discharge dynamics. These parameters are depicted in Figure 3 with different potential regions, reflecting the ionization and the exchange of energy near the anode region. The subsequent stabilization corresponds to the onset of MDL formation, while the decreasing λ_D confirms stronger space-charge coupling consistent with the NDR behavior. The behavior of charged particles in plasma is largely controlled by this increase in plasma potential, which may change local electric fields as well [2]. A confined ionization front develops close to the anode as the applied voltage rises and the electron energy exceeds the ionization threshold of the gas. This gives rise to the first double layer, a region of localized potential drop that accelerates electrons and generates a sharp increase in ionization, depicted in Figure 4a. This regime is characterized by an NDR, where the current remains nearly constant with increasing voltage, and the energy is consumed in DL formation.

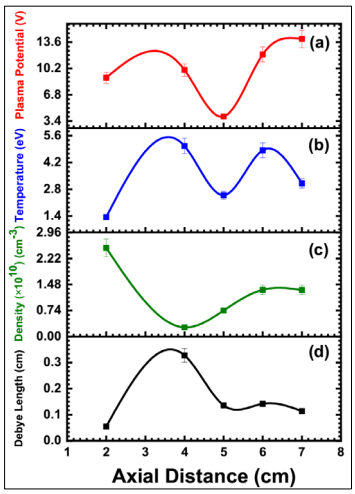

Fig. 3. Discharge profiles of (a) plasma potential, (b) temperature (T_e), (c) density of plasma (n_e), and (d) Debye length (λ_D) calculated using the probe current-probe voltage plots of the Langmuir probe at V_A = 125 V.

After the first NDR, the system self-organizes to reach a new quasi-stable configuration with the first DL stabilized. The plasma accommodates the newly formed structure, leading to a sudden drop of current till V_A = 85 V with the formation of MDLs as depicted in Figure 4b. These DLs may form sequentially from the grid to the anode, forming a cascade of potential steps in the plasma. The MDLs effectively divide the plasma into sub regions, each with different potentials, leading to self-organization and confinement behavior [9]. At sufficiently high voltages, the MDL structure becomes fully developed. The discharge current increases smoothly again, as the system stabilizes in a multi-layered potential profile to form a localized spot in the vicinity of the anode, as illustrated in Figure 4c.

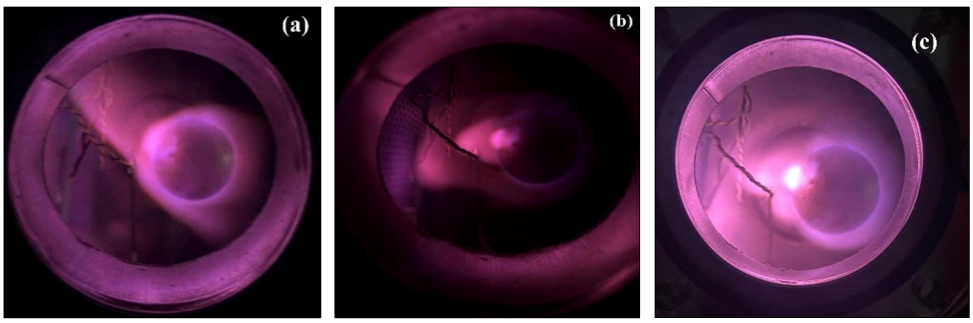

Fig. 4. Image of the MDL formation close the anode at (a) lower NDR regime (V_A = 85 V), (b) transition point (V_A = 105 V), (c) higher NDR regime (V_A = 125 V).

The emergence of such a spot signifies the endpoint of the DL cascade and the saturation of the discharge in a fully developed MDL configuration. Self-organized Criticality (SOC) behavior is primarily suggested by such MDL formations with progressive applied voltage (V_A) via reorganization of the numerous sheaths, which progresses through successive layer reductions towards a critical point of DC discharge. The layer reduction occurs as the negatively biased grid modifies the potential wells, altering the confinement of trapped electron populations. This redistribution destabilizes DLs, causing their collapse and subsequent reorganization of the plasma potential structure.

The process reflects self-organized criticality, where grid-controlled electron trapping drives large-scale structural transitions.

3.2 Self-organized criticality during multiple double layer formations

The power law behaviour of the potential oscillations using Probability Distribution Function (PDF) characterizes the probability of the observable within a definite range of variables to determine the presence of SOC in the system. For a system with an avalanche exhibiting SOC behavior, the self-similarity in the oscillations indicates that the downward slope of the PDF falls as a power law [10]. The system whose stability is demonstrated by the plot of log-frequency with the log-power, illustrates the transition through different layers of the discharge. In the logarithmic plot of frequency and power, the power spectrum analysis associated with the layer reduction procedure follows the power law as $1/f^{\beta}$, where 'f' is the frequency and 'β' is its fractional power [9]. The slope of such plots is used to get the β value. A sharp drop with $\beta < 1$ implies the transition state, but $\beta = 0$ indicates that the corresponding state of discharge does not display power-law behavior and essentially exhibits a stable state in the system [11]. β lesser than 1 indicates that the discharge experiences a state of transition near V_A ~85V during the initial development of localized MDL close the anode in the presence of the rectangular grid, which is in good agreement with the power spectrum displayed in Figure 5a. As seen in Figure 5b, with the rise in the applied voltage, there is an apparent rise in $\beta > 1$. It suggests that the plasma fluctuations are dominated by large-scale, low-frequency processes, possibly linked to the anode spot formation through SOC, corresponding to persistent, long-range correlated behavior in the higher discharge regime. The rank function is another reliable tool to evaluate whether SOC behavior is present in the avalanche of fluctuations since the downward slope (tail) of the function falls as a power law for a system with SOC behavior [11].

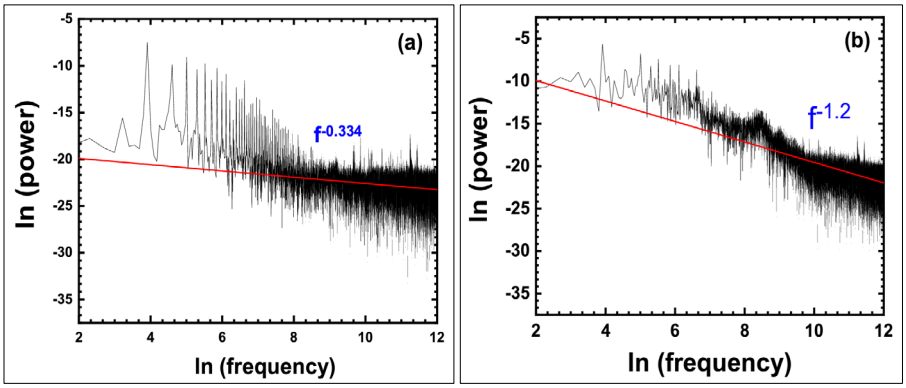

Fig. 5. Log plot of power law characteristics showing the frequency scaling behavior of the plasma exhibiting the power-law $1/f^{\beta}$ with applied potential at (a) $V_A = 85$ V, and (b) $V_A = 125$ V.

Figure 6 displays the rank function for the potential oscillations at the crucial point, with $V_A = 125$ V. The curve of the distribution falls to an exponent that is approximately 3.9. The findings of the power spectrum analysis technique are in agreement with the observation and the avalanche shows a clear evidence of SOC behavior. The illustration of Figure 6 shows how the power law vanishes due to the rapid decline in the PDF tail. The severe flux of negative charges dropping from the MDL resulting from a significant amount of applied potential may be the basis for the lack in the fall of power law curve in the PDF. The fact that the power spectrum of the data shows such characteristics with $\beta = 1.2$ at those region where the power law appears, suggesting the transition towards more turbulent regime

through the layer reduction process, is consistent with this explanation.. Hence, the rank function can also possibly show the transition of the discharge from a periodic to a turbulent undergoing the SOC phenomenon as it passes through different stages of NDR regimes [12, 13]. In some dusty plasma and gridded discharge configurations, β values typically range between 1.0 and 1.3, indicating self-similar avalanche dynamics and long-range correlations in fluctuation behavior. The present result thus confirms that the observed plasma fluctuations follow a similar universal scaling trend, suggesting that the self-organized critical state achieved in the glow discharge shares similar dynamical features as other SOC-driven plasma environments [3, 8].

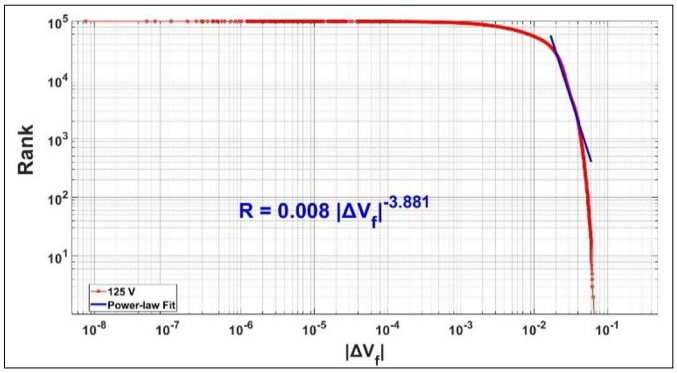

Fig. 6. Rank function of the potential oscillations at V_A = 125 V showing a distinct power-law tail with an exponent of 3.9, indicating scale-free behavior associated with the critical state of the plasma.

4 Conclusion

Parametric investigation of reduction and addition of layers by the evolution of complex sheaths emphasizes the introduction of the rectangular biased grid in the evolution of the NDR phenomenon near the electrodes. The different NDR zone signifies different regimes of MDL formations through which the transition occurs, leading to the formation of the SOC phenomenon. The visual interpretation of MDL hierarchy and the spot formation near the anode is evident from the physical interpretations inferred from potential oscillations and hysteresis measurements. The esteem calculation of β value suggests the power law behaviour and its consistency with PDF provides a strong correlation with the rank function in higher discharge regimes. These investigations provide the importance of SOC in the system's avalanche by merging of MDL and the transport of nonthermal electrons to the potential shift in the turbulent regime. One of the typical applications is RF sputtering experiments where the discharge transit to SOC behavior to produce self-organized structures by ion energy flux, which activates the surface energy for micro etching and sterilization. Additionally, the creation of nanostructures using SOC aids in the processing of carbon plasma. Thus, SOC is associated with the generation of ion beam, micro discharge devices, surface coating and nanomaterial processing generated by the interplay of electric and magnetic fields with the space-charge dynamics.

References

1. S. D. Baalrud, B. Scheiner, B. T. Yee, M. M. Hopkins, and E. Barnat, Interaction of biased electrodes and plasmas: sheaths, double layers, and fireballs, Plasma Sources Sci. Technol. **29,** pp. 053001 (2020). https://doi.org/10.1088/1361-6595/ab8177
2. A Debnath, S. Bose, S. K. Maroju, and M. K. Paul, Nonlinear study of transition modes in the chaotic time series obtained in different negative differential resistance regimes, Phys. Plasmas **32**, pp. 043507 (2025).https://doi.org/10.1063/5.0243787
3. T. R. Singh, S. L. Kommuguri, and S. K Sinha, Trapping and detrapping of electrons in a typical DC glow discharge plasma under double layer condition, Phys. Plasma **31,** pp. 092102 (2024).https://doi.org/10.1063/5.0222639
4. J. R. Heinrich, S. H. Kim, and R. L. Merlino, Observations of a structure-forming instability in a dc-glow-discharge dusty plasma, Phys. Rev. E **84**(2), pp. 026403(2011).https://doi.org/10.1103/PhysRevE.84.026403
5. Y. N. Dnestrovskij, A. Yu. Dnestrovskij, and S. E. Lysenko, Self-organization of plasma in tokamaks, Plasma Phys. Rep. **31**(7), pp. 529-553(2005).https://doi.org/10.1134/1.1992581
6. P. Alex, B. A. Carreras, S. Arumugam, and S. K. Sinha, Self-organized criticality: An interplay between stable and turbulent regimes of multiple anodic double layers in low discharge plasma, Phys. Plasma **25**, pp. 053514 (2018).https://doi.org/10.1063/1.5019930
7. P. Bak, C. Tang, & K. Wiesenfeld, Self-organized criticality: An explanation of 1/f noise, Physical Review Letters, **59**(4), pp. 381–384 (1987).https://doi.org/10.1103/PhysRevLett.59.381
8. S. K. Tiwari, and S. D. Baalrud, Reduction of electron heating by magnetizing ultracold neutral plasma, Phys. Plasmas **25**, 013511 (2018).https://doi.org/10.1063/1.5013320
9. S. Bose and M. K. Paul, Study of self-organised criticality in a coaxial plasma source with gridded cathode, Contrib. Plasma Phys. **62**, e202100173 (2022).https://doi.org/10.1002/ctpp.202100173
10. P. Alex, B. A. Carreras, S. Arumugam, and S. K. Sinha, Self-organized criticality in a cold plasma, Phys. Plasma **24**, pp. 120701 (2017).https://doi.org/10.1063/1.5005560
11. B. A Carreras, B. Ph. van Milligen, M. A. Pedrosa, R. Balbín, C. Hidalgo, D. E. Newman, E. Sánchez, R. Bravenec, G. McKee, I. García-Cortés et al., Experimental evidence of long-range correlations and self-similarity in plasma fluctuations, Phys. Plasmas **6**, pp. 1885–1892 (1999). https://doi.org/10.1063/1.873490
12. R. L. Stenzel and J. M. Urrutia, Phys. Plasmas **19**, pp. 082105 (2012).https://doi.org/10.1063/1.4743019
13. A. Debnath, D. Pal and M. K. Paul, Instability in a hollow cathode discharge under optimized boundary conditions due to negative differential resistance, Indian J. Phys. **99**, pp. 9 (2025).https://doi.org/10.1007/s12648-025-03692-z