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# Comparative study on nonlinear dynamics of magnetized and un-magnetized dc glow discharge plasma

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**Abstract**
Various nonlinear dynamical behaviors are experimentally observed to exist in magnetized dc glow discharge plasma. Nonlinear plasma fluctuations are seen evolving when the initial parameters such as discharge voltage, filling pressures, etc are changed in the presence of external magnetic field. A transition pattern of chaotic to quasiperiodicity is experimentally observed when a magnetic field is applied, which is not the case in the un-magnetized one. Hence, a comparative analysis is being conducted for both the cases of magnetized and un-magnetized plasma. The nonlinear behavior of the plasma oscillations are diagnosed by different techniques namely: power spectrum, phase space plotting, correlation dimension, Liapunov exponent, fractal dimension and Hurst exponent. Furthermore, it is noticed that with increasing discharge voltage, the glow emerges from the cathode, slowly moves toward the anode and finally sinks into the anode in a ballooning manner.

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(Some figures may appear in color only in the online journal)

## 1. Introduction

The importance of nonlinear dynamical studies in magnetized plasma is increasingly in demand due to its applications in various areas such as fusion reactors, space plasma experiments, plasma processing, etc [1–4] and also for understanding various oscillation mechanisms in bounded plasmas [5, 6]. Nonlinear relaxation oscillations of discharge current and plasma potential in a magnetized thermionic plasma discharge have been investigated by Klinger *et al* [7]. They confirmed two different stable discharge modes namely the low-current space–charge-limited and the high-current temperature-limited mode. Time-resolved probe measurements of the plasma potential distribution demonstrate that the current oscillations result from a strongly nonlinear instability of the potential structure in the weak current discharge mode. The oscillation process consists of three distinct phases. The sequence of events and the observed parameter dependences of the oscillation frequency are in accordance with the model. The periodically driven system shows the characteristic behavior of nonlinear oscillators, namely quasiperiodicity, mode locking and period doubling sequences toward chaos. In their subsequent studies [8], model experiments and numerical simulation on chaos control and turbulence in three different plasma configurations such as chaotic oscillations in simple plasma diodes, ionization wave turbulence in the positive column of glow discharges and drift wave turbulence in a magnetized plasma column have been investigated. They have primarily emphasized investigation of current flow instabilities in plasma diodes, ionization instabilities in the positive column of glow discharge plasmas and electrostatic drift wave turbulence in low-$\beta$ plasmas. It is shown that by using various types of feedback schemes, it is possible to establish periodic operation in plasma diodes,

 

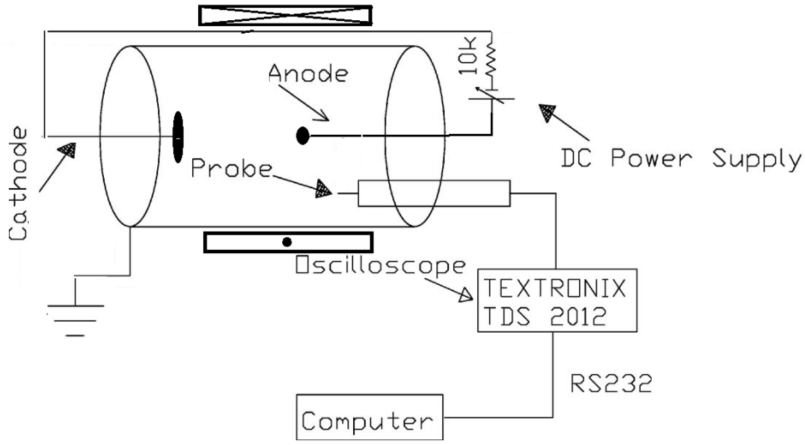


**Figure 1.** Schematic diagram of the experimental setup.

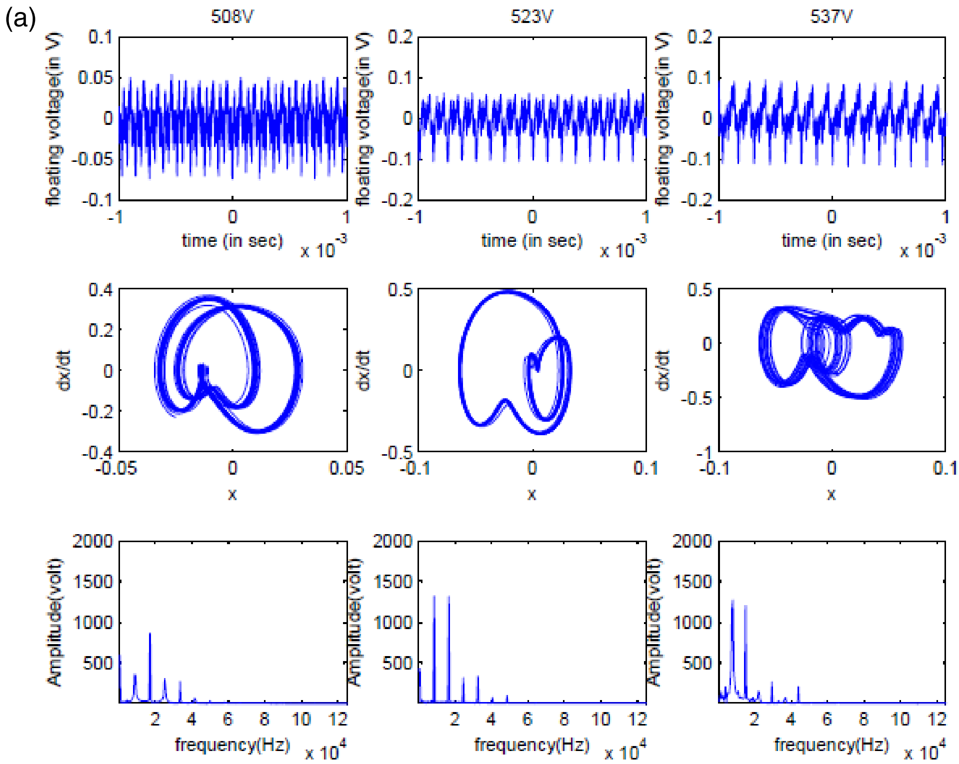


**Figure 2.** (a) Plasma floating potential oscillations in the presence of the magnetic field $B = 46$ G with increasing discharge voltage (508, 523 and 537 V) and at 0.4 mb (phase space plotting along with the power spectrum of plasma floating potential). (b) Plasma floating potential oscillations in the presence of the magnetic field $B = 46$ G with increasing discharge voltage (597, 603 and 612 V) and at 0.4 mb (phase space plotting along with the power spectrum of plasma floating potential). (c) Chaotic to relaxation oscillations in the presence of the magnetic field $B = 46$ G with increasing discharge voltage (616, 649 and 655 V) and at 0.4 mb (phase space plotting along with the power spectrum of plasma floating potential).

glow discharge plasmas and magnetized plasmas in the regimes where usually chaotic oscillations occur. It has been found that strong low-frequency self-oscillations, frequently observed in magnetic box discharges are expected to be of great importance for a real understanding of chaotic behavior [9, 10]. In earlier experiments of a unmagnetized parallel plate electrode system, a transition from periodic to chaotic state has been observed with increasing input energy. However, a reverse phenomenon has been reported in cylindrical electrode system by Nurujjaman *et al* [11]. They found that a transition of chaotic to stable state occurs when the input energy of the system in the form of discharge voltage is increased. Similar observations are reported in this present paper i.e. chaotic to stable state transition with parallel plate electrode system but in the presence of magnetic field. In this paper, various observations on periodic and quasiperiodic oscillations and its analysis have been conducted in a magnetized glow discharge plasma system.

In this paper, section 2 gives the details of the experimental setup and diagnostics. Section 3 explains various experimental data analysis and discussions. Finally, the conclusion is given in section 4.

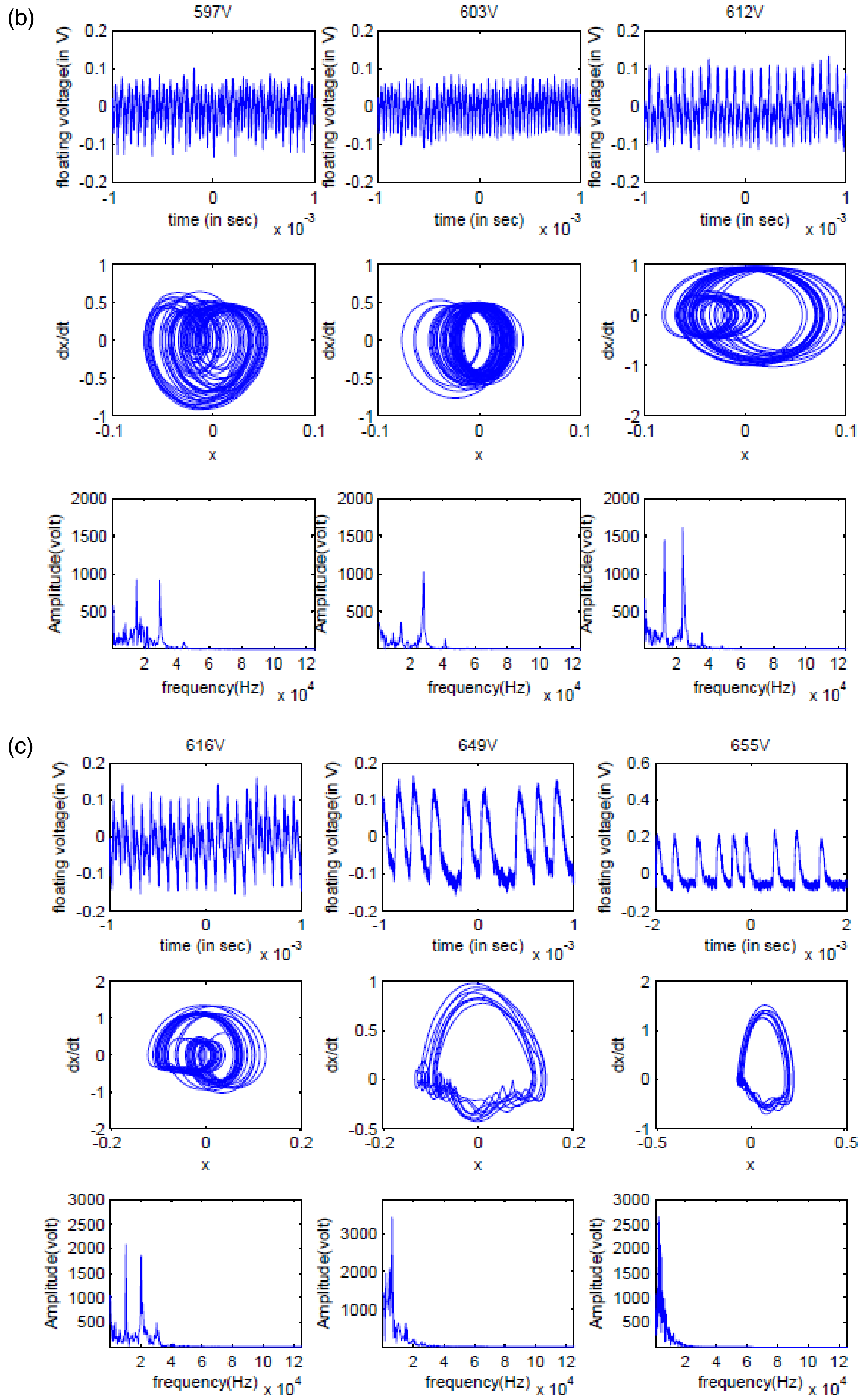


**Figure 2.** (Continued.)

## 2. Experimental setup and diagnostics

The experimental observation of nonlinear plasma oscillations are conducted in a dc glow discharge plasma chamber. Dimension of the SS device is 50 cm in length and of diameter 20 cm. The chamber is evacuated by rotary pump to attain a base pressure of $10^{-3}$ mb. Argon gas is then inserted into the chamber keeping the desired working pressure of around 0.2–0.6 mb. Plasma is produced by dc glow discharge method applying dc voltage across the circular parallel

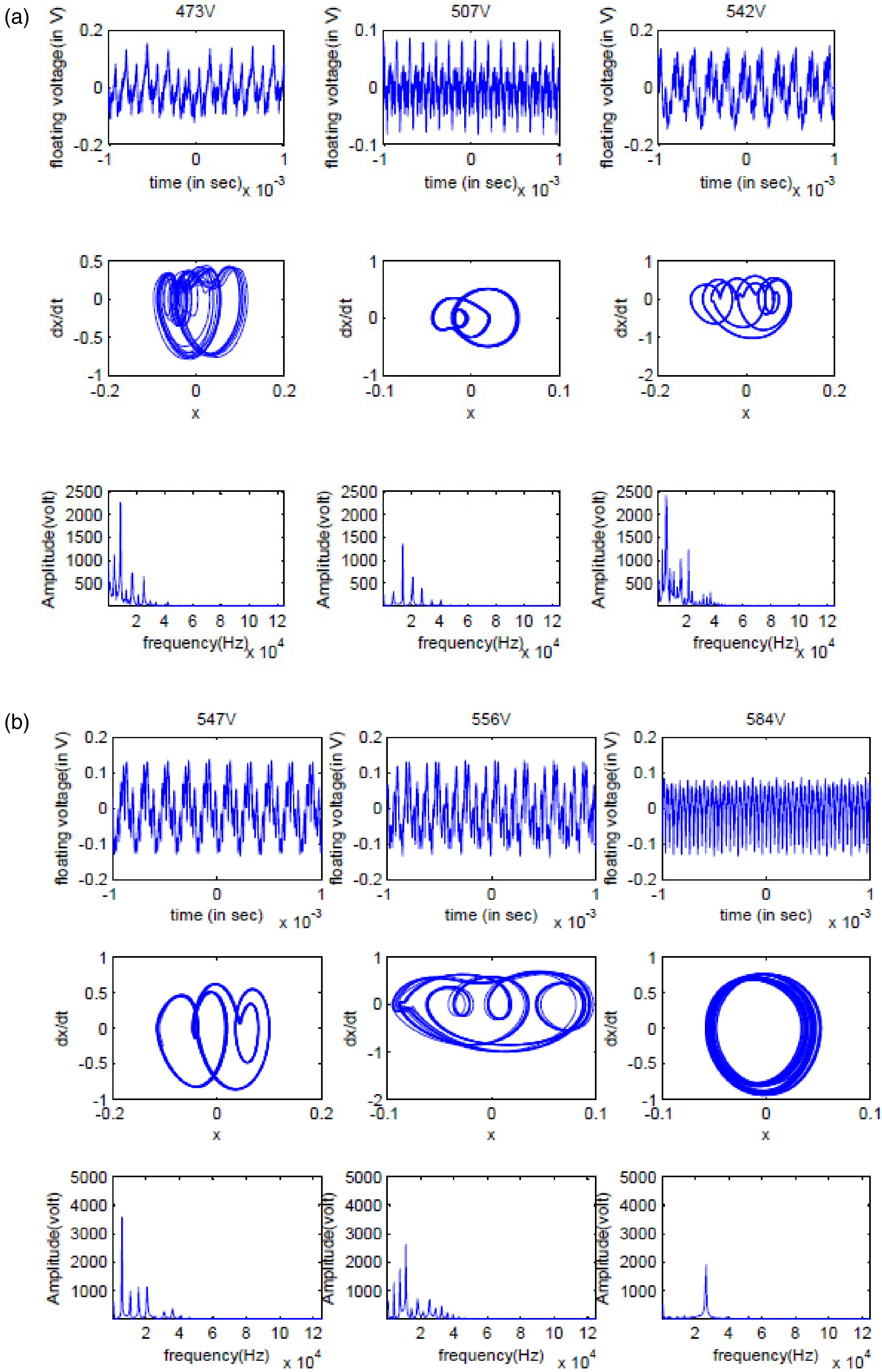


**Figure 3.** (a) Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (473, 507 and 542 V) and at 0.4 mb, $B = 0$ G. (b) Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (547, 556 and 584 V) and at 0.4 mb, $B = 0$ G. (c) Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (604 and 619 V) and at 0.4 mb, $B = 0$ G.

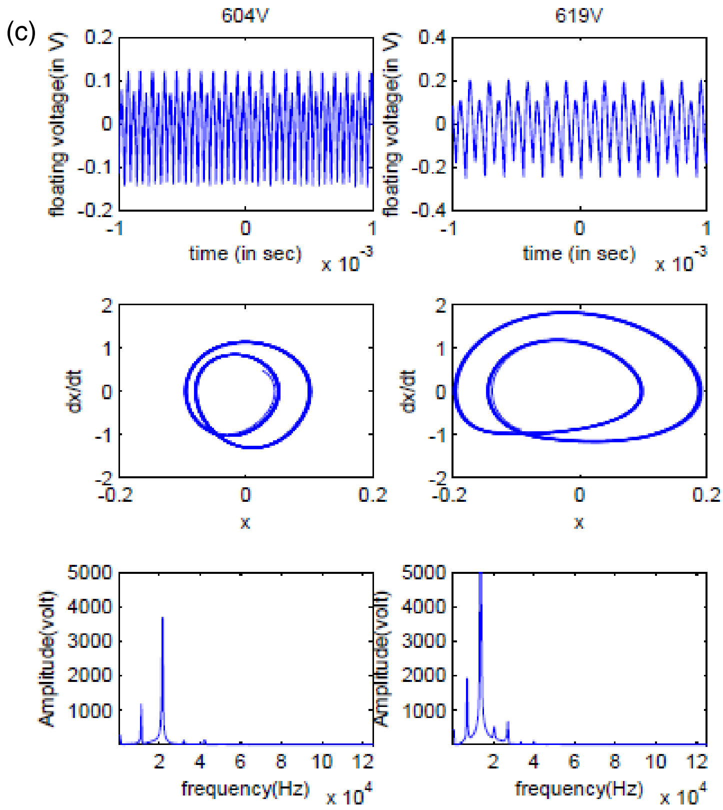


**Figure 3.** (Continued.)

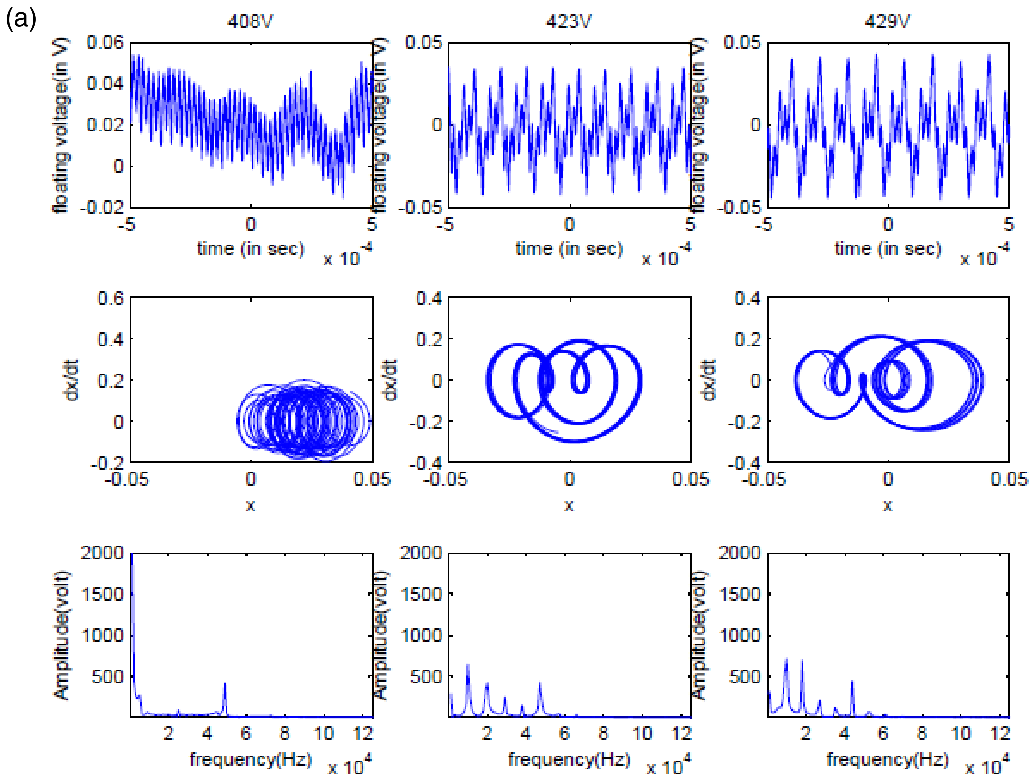


**Figure 4.** (a) Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (408, 423 and 429 V) and at 0.4 mb, $B = 9$ G. (b) Phase space plotting along with power spectrum of plasma floating potential with increasing discharge voltage (471, 480 and 499 V) and at 0.4 mb, $B = 9$ G. (c) Phase space plotting along with power spectrum of plasma floating potential with increasing discharge voltage (558, 566 and 569 V) and at 0.4 mb, $B = 9$ G.

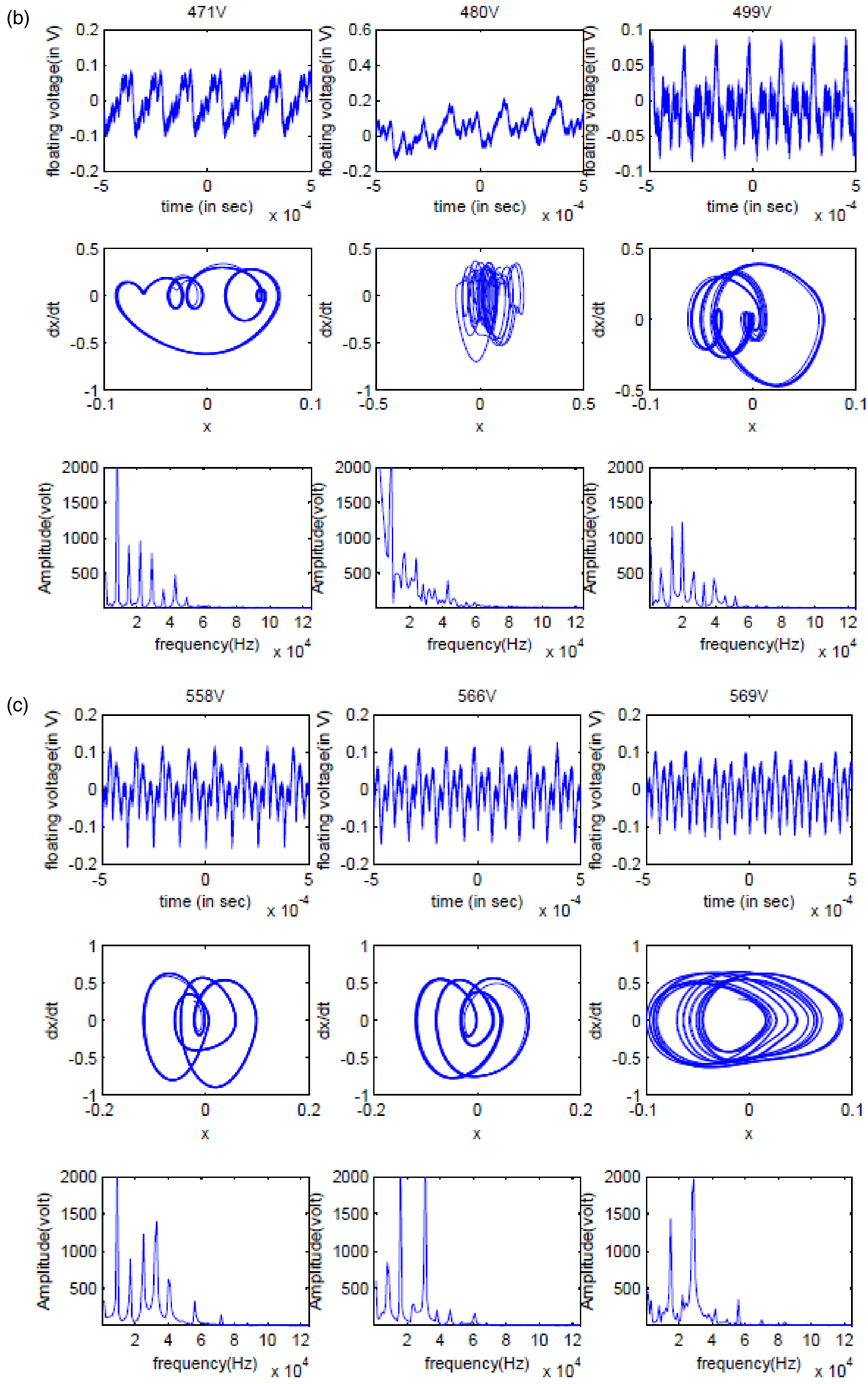


**Figure 4.** (Continued.)

electrodes. To conduct the observations in the presence of magnetic field, an external magnetic field of strength 10–60 G is applied to the plasma by passing dc current through the Helmholtz coils wound over the cylindrical chamber. The experimental setup is shown in figure 1. Plasma oscillations are extracted from the device as floating potential by the Langmuir probe which is inserted between the cathode and the anode. The characteristic plasma density and the temperature are found to be $10^7\,\text{cm}^{-3}$ and 2 eV. The time-series floating potential data are collected in the oscilloscope and further,

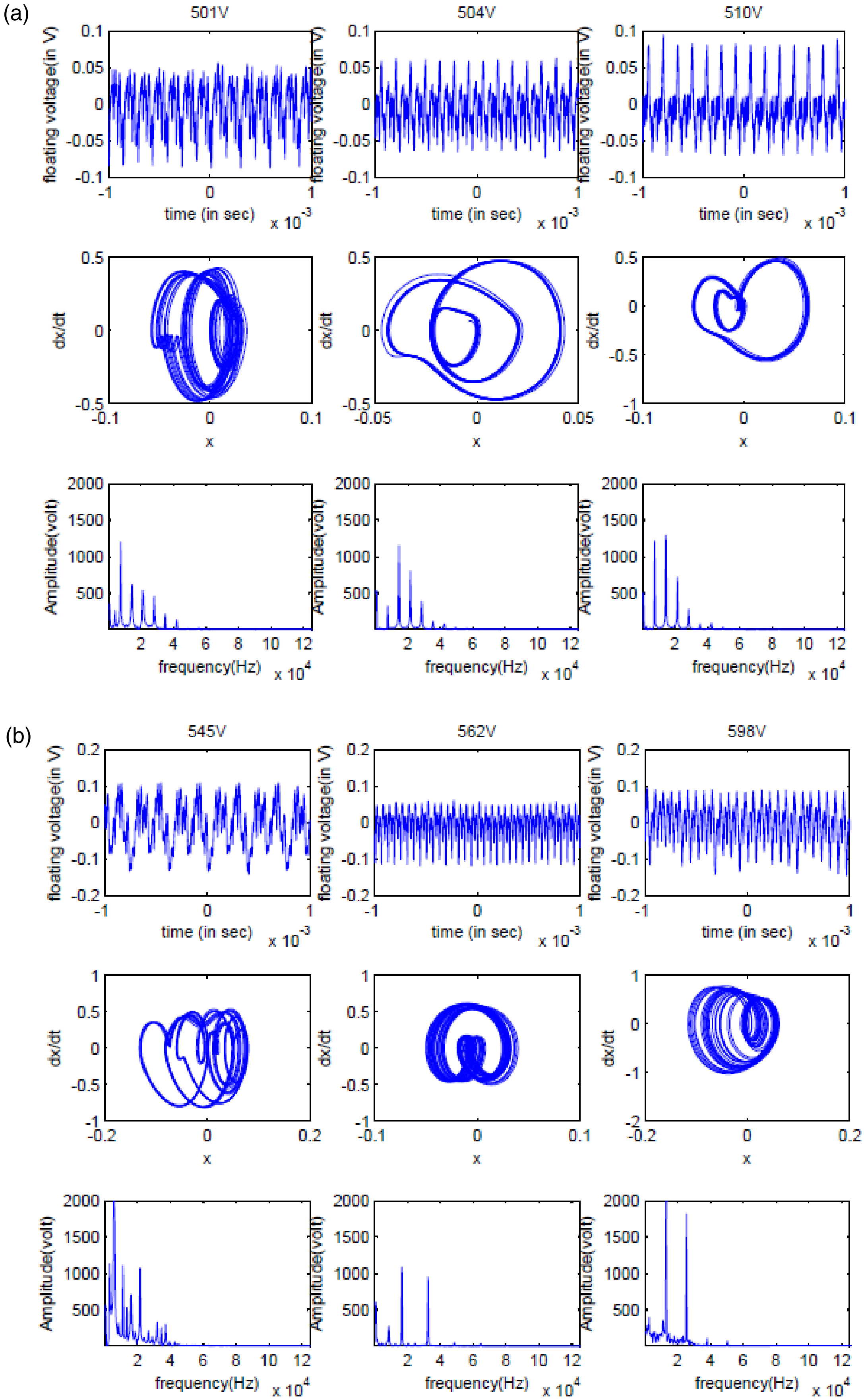


**Figure 5.** (a). Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (501, 504 and 510 V) and at 0.4 mb, $B = 28$ G. (b) Phase space plotting along with the power spectrum of plasma floating potential with increasing discharge voltage (545, 562 and 598 V) and at 0.4 mb, $B = 28$ G.

various nonlinear analyses are conducted with the help of MATLAB software.

### *2.1. Diagnostics tool—Langmuir probe*

In the present experiments, the floating potential and its fluctuations have been measured with the help of a Langmuir probe by using a Tektronix digital oscilloscope.

## 3. Analysis of experimental data and discussions

The plasma floating potential fluctuations are observed at a filling pressure of 0.4 mb in the absence and in the presence of the magnetic field. It is found that with increasing discharge voltage, the pattern of the time-series data gradually changes toward relaxation oscillation mode. At higher pressure (0.4 mb) and higher magnetic field $B = 46$ G, a transition from chaotic to periodic behavior of the floating potential is recorded (figures 2(a)–(c)) whereas periodic oscillations are observed for the un-magnetized one (figures 3(a)–(c)).

Figures 2(a)–(c) display the power spectrum and phase space plotting of various signals at different discharge voltages and at $B = 46$ G. The mode of the oscillations traced at these discharge voltages are as follows:

- $V_d = 508$ V—10, 20, 25 and 30 kHz.
- $V_d = 523$ V—10, 18, 25 and 30 kHz.
- $V_d = 537$ V—10, 18, 30 and 45 kHz.
- $V_d = 597$ V—15 and 30 kHz.
- $V_d = 603$ V—15 and 30 kHz.
- $V_d = 612$ V—15 and 30 kHz.

Then, the trend is as follows: at $V_d = 616$ V, three modes of frequencies 10, 20 and 30 kHz; at $V_d = 649$ V, relaxation oscillation starts and remains till $V_d = 655$ V. At $V_d = 655$ V, one periodic oscillation with frequency 2 kHz is observed. Hence, it is found that at a higher magnetic field, relaxation oscillation remains for a longer applied discharge voltage which is not the case for a lower magnetic field and also without a magnetic field.

Figures 3(a)–(c) show the time-series data at 0.4 mb, magnetic field $B = 0$ G with increasing discharge voltage. It is found that with increasing discharge voltage, an overall periodic oscillation prevails. The phase space plotting along with raw plasma oscillation data and power spectrum with increasing discharge voltage and $B = 0$ is illustrated in figures 3(a)–(c). It is seen that at initial discharge voltage $V_d = 473$ V, the floating potential oscillations are chaotic in manner. At $V_d = 473$ V, four period oscillations with frequencies 5, 10, 20 and 25 kHz; at $V_d = 507$ V, oscillations with frequencies 5, 15, 20 and 25 kHz; at $V_d = 542$ V, 5, 10, 15 and 20 kHz; at $V_d = 547$ V, oscillations with frequencies 5, 10, 15 and 20 kHz; and at $V_d = 556$ V, it remains the same. As we increase the discharge voltage further, one period oscillation at frequency 25 kHz at $V_d = 584$ V, followed by two period oscillations with frequencies 10 and 22 kHz at $V_d = 604$ V. Furthermore, the trend is at $V_d = 619$ V, four period oscillations with frequencies 10, 15, 20 and 25 kHz.

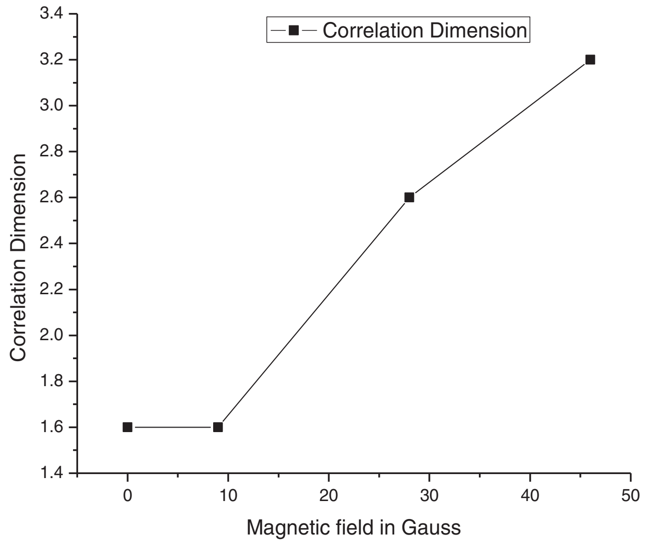


**Figure 6.** Correlation dimension of the time series data for the increasing magnetic field keeping fixed discharge voltage $V_d = 596$ V at pressure 0.4 mb.

In the presence of the external magnetic field $B = 9$ G (figures 4(a)–(c)), initially discharge is struck at 408 V and a one periodic signal is traced with frequency 50 kHz. After that at $V_d = 423$ V, it becomes chaotic with enhanced amplitude till $V_d = 499$ V. Frequencies observed during these discharge voltages are as follows:

- $V_d = 423$ V—10, 20, 30, 40 and 50 kHz.
- $V_d = 429$ V—10, 20, 30 and 42 kHz.
- $V_d = 471$ V—10, 15, 20, 30kHz, 35 and 45 kHz.
- $V_d = 480$ V—10, 20, 25, 30 and 42 kHz.
- $V_d = 499$ V—10, 15, 20, 25, 30 and 40 kHz.

After that at $V_d = 558$ V, periodicity occurs with six modes of frequencies 10, 18, 25, 30, 40 and 50 kHz. Then, the trend is: at $V_d = 566$ V, six modes of frequencies 10, 20, 30, 40, 50 and 60 kHz; at $V_d = 569$ V, three modes of frequencies 15, 30 and 55 kHz.

Figures 5(a) and (b) depict the pattern of plasma fluctuations, power spectrum and the phase space plotting at $B = 28$ G with increasing discharge voltage. Discharge is struck at 501 V and a five-periodic signal is traced. After that at $V_d = 504$, 510 and 545 V, four-periodic signals are observed. A three-periodic signal is traced at $V_d = 562$ V and finally at $V_d = 598$ V, periodicity occurs with two modes of frequencies. The frequencies observed at these discharge voltages are as follows:

- $V_d = 501$ V—10, 15, 20, 30 and 35 kHz.
- $V_d = 504$ V—10, 15, 20 and 30 kHz.
- $V_d = 510$ V—10, 15, 20 and 30 kHz.
- $V_d = 545$ V—8, 10, 15 and 22 kHz.
- $V_d = 562$ V—10, 20 and 30 kHz.
- $V_d = 598$ V—15 and 25 kHz.

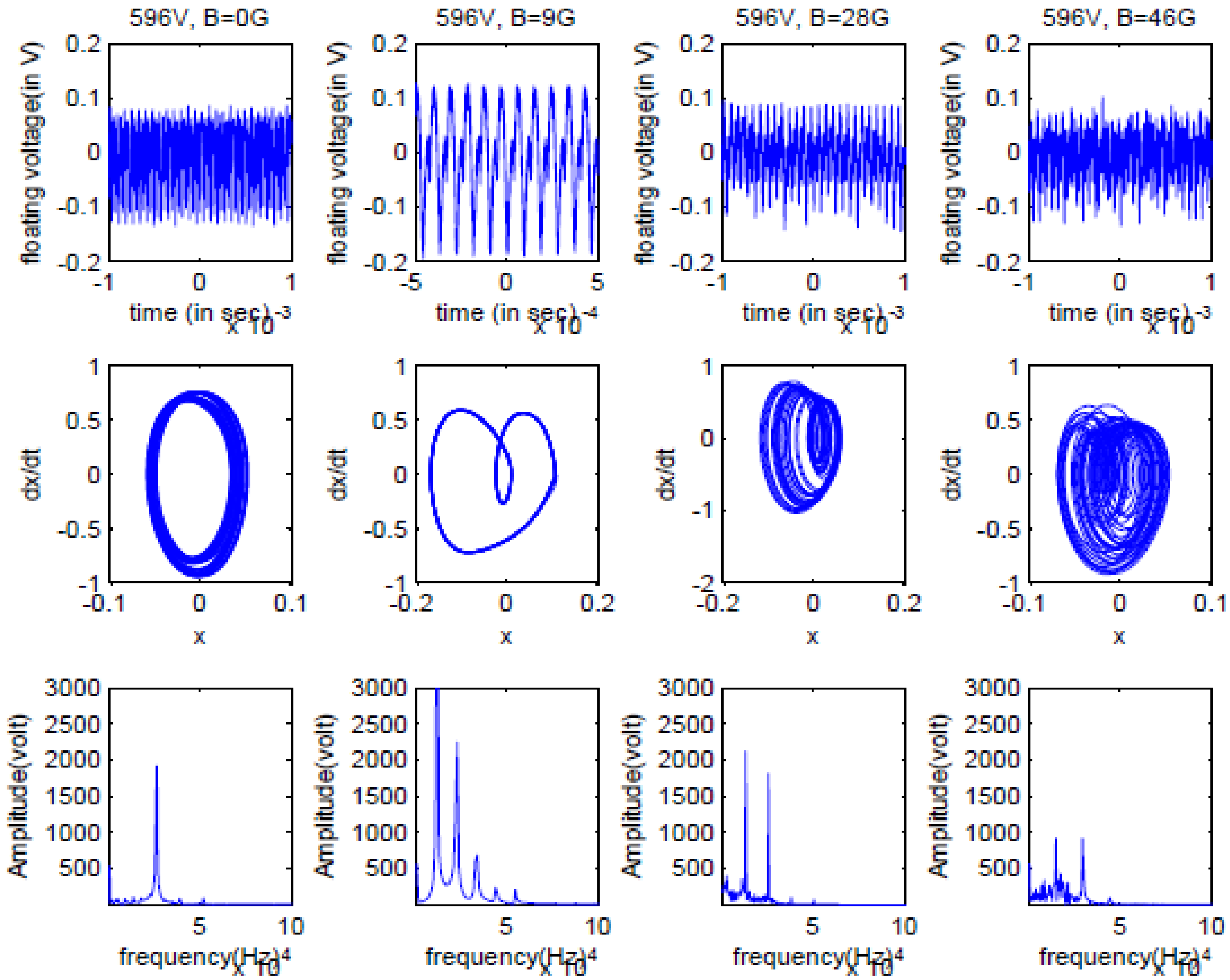


**Figure 7.** Plasma oscillations at fixed discharge voltage 596 V with varying magnetic fields ($B = 0$, 9, 28 and 46 G).

### *3.1. Estimation of correlation dimension of the floating potential data in the presence of the external magnetic field to find the complexity evolved*

From figure 6, it is evident that with the increasing magnetic field, the complexity of the system is also enhanced. This fact can also be verified from figure 7 which shows the chaotic plasma fluctuations at a fixed discharge voltage of 596 V and varying magnetic fields of 9, 28 and 46 G. It is evident from the figure that a transition from periodic to chaotic has occurred when the magnetic field is increased toward 46 G by keeping the discharge voltage fixed. This may be attributed to the fact that the increasing magnetic field makes the plasma oscillations more complex as the plasma particles are moving with various gyro frequencies and making the system more nonlinear. However, at the same time if we increase the discharge voltage keeping magnetic field constant say 46 G, it is seen that the chaoticity decreases and relaxation oscillations prevail. Hence, it can be concluded that a transition pattern from chaotic to periodic has been observed (figures 2(a)–(c)).

### *3.2. Estimation of Hurst exponent of the floating potential oscillation to measure long-range correlation by fractal dimension method and R/S rescaled analysis: a comparison of the results between the two methods*

To further the nonlinear investigation of the above plasma potential behavior, long-range correlation is found by estimating the Hurst exponent of the signals by adopting two methods namely fractal dimension method and R/S rescaled method (table 1). For all the chosen signals i.e. for the increasing magnetic field and the fixed discharge voltage, the Hurst exponent is calculated to be ∼1 which depicts that even though the plasma system becomes more complex, still there exists a persistence long-range correlation in the signal. Table 1 gives the Hurst exponent of the same signal estimated by the R/S rescaled method. It also shows that the Hurst exponent is more than 0.5 for all of the conditions of the external magnetic field, which reveals a persistence long-range correlation.

Hurst exponents estimated by the R/S rescaled analysis for the above plasma oscillations are tabulated below.

**Table 1.** Hurst exponents estimated by R/S rescaled analysis.

| External magnetic field (G) | Hurst exponent |
|---|---|
| 9 | 0.7906 |
| 28 | 0.6048 |
| 46 | 0.5230 |

*3.3. Measurement of Liapunov exponent to determine chaotic behavior*

The chaotic behaviors of the signals at various conditions of the external parameters of the magnetic field and discharge voltage that are traced by the techniques stated above are further tested by using Rosenstein's largest Liapunov technique. The chaotic signals at some fixed discharge voltage $V_d = 596$ V and external magnetic field $B = 28$ and 46 G, respectively, are tested for the Liapunov exponent, the values for which again come as 0.1138 and 0.1324. The positive values of the Liapunov exponent reveal that these plasma floating potential signals are chaotic in nature. On the other hand, the exponent for the signals at discharge voltage $V_d = 596$ V and $B = 0$ and 9 G are not positive that tells about the periodic pattern which is evident by phase space plotting also. An extensive work on the chaotic behavior of the plasma floating potential oscillations in magnetized dc glow discharge plasma adopting continuous wavelet transform method has been done by Bornali Sarma *et al* [12].

## 4. Conclusion

A comparative study of magnetized and unmagnetized plasma oscillations in dc glow discharge plasma has been conducted. It is found that compared to the unmagnetized one, the magnetized plasma system is more chaotic in nature. The complexity of the system is observed to increase while increasing the magnetic field. However, under such circumstances of chaoticity also, persistent long-range correlation of the signals is observed. Moreover, it is observed that at the higher magnetic field, a transition from chaotic to quasiperiodic pattern is occurring with increasing discharge voltage. The main focus of the paper is to study the nonlinear behavior of the plasma oscillations numerically. However, theoretical modeling of the system is required in order to understand the behavior completely, which will be our future work.

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