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Chaotic-to-ordered state transition of cathode-sheath instabilities in DC glow discharge plasmas

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Abstract. Transition from chaotic to ordered state has been observed during the initial stage of a discharge in a cylindrical DC glow discharge plasma. Initially it shows a chaotic behavior but increasing the discharge voltage changes the characteristics of the discharge glow and shows a period subtraction of order 7 period → 5 period → 3 period → 1 period, i.e. the system goes to single mode through odd cycle subtraction. On further increasing the discharge voltage, the system goes through period doubling, like 1 period → 2 period → 4 period. On further increasing the voltage, the system goes to stable state through two period subtraction, like 4 period → 2 period → stable.

Keywords. Cathode-sheath; instabilities; chaos; period subtraction; bifurcation; DC discharge.

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1. Introduction

Nonlinear phenomena are abundant in nature and laboratory plasma. Plasma is a typical nonlinear dynamical system with a large number of degrees of freedom, and a medium for testing a wide variety of nonlinear phenomena such as self-oscillation, period doubling, bifurcation, period subtracting, period adding, chaos, intermittency etc. [1,2]. Characteristics of chaos have been observed in externally driven and self-driven plasma systems. In externally driven systems, chaotic behavior can be seen in pulsed plasma discharge and period doubling cascade to chaos in thermionic plasma discharge [3], and in self-driven case, i.e using no external perturbation in the system, periodic to chaotic transition has been observed [4,5]. Experiments on plasma that exhibits period doubling and chaos using external driver (oscillator) in a double plasma device has been done by Ohno *et al* [6]. The period subtracting phenomena, have been observed in externally driven ion-beam plasma systems [7]. In this experiment oscillation periods decrease in the sequence 6 period→ 5 period → 4 period and so on. Another phenomenon in the driven plasma system is period adding opposite to the period subtracting. Here periods successively increase with control parameters.

In all the above-mentioned experiments, the fluctuations are observed in the bulk region of the plasma, whereas in the present experiment we are reporting the chaotic oscillation, period subtraction and period doubling phenomena that are observed in the sheath region. The plasma sheath is a region with large electric fields where charged particles can encounter acceleration to high energies. This can give rise to various types of fluctuations through wave particle interaction. These reasons motivated us to investigate the fluctuations in the sheath region of a cylindrical DC glow discharge plasma. Moreover, the sheath region is important from the application point of view like material processing, dust levitation etc. Chaotic oscillations were observed during the initial phase of high pressure discharges. With increase in the discharge voltage it goes to an ordered state through period subtraction and finally the modes vanish and the plasma becomes stable via period doubling and period subtraction.

2. Experimental set-up

The experiment was carried out in a coaxial cylindrical DC glow discharge system with argon as shown in figure 1. The hollow stainless steel (SS) outer cylinder of 45 mm diameter is the cathode and the SS rod of 1 mm diameter inside the cathode is the anode, which is grounded. The whole system has been placed in a vacuum chamber and evacuated to a base pressure of 0.001 mbar by means of a rotary pump. Argon gas is introduced into the chamber using precision needle valve. Neutral gas pressure has been maintained at a particular pressure and discharge voltage to initiate a glow discharge plasma. A Langmuir probe made of tungsten has been used to measure floating potential fluctuations. It is of diameter 0.2 mm and length 4 mm, and movable along the plasma column. The probe holder is also very thin with a diameter of 2.5 mm and made of glass. The probe was kept at one location and the experiment was carried out, instead of inserting the probe after plasma was formed, and hence the disturbance to the plasma conditions were much less. It is connected to the digital tektronix oscilloscope. The probe was placed in the sheath region, i.e. about 0.5 cm from the cathode wall. Data have been transferred to the computer through the USB port.

3. Results and discussions

Though plasma could be formed at low pressures, the chaotic oscillations in the floating potential were observed only above 0.4 mbar. The present experiments were carried out at a neutral gas pressure of 0.95 mbar of argon. At this particular pressure the discharge voltage between the anode and the cathode was increased slowly till the discharge was obtained at 283 V. The DC floating potential is about -21 V. AC fluctuations are recorded through oscilloscope. The plasma density in the bulk region was about $3 \times 10^7/\text{cm}^3$, and temperature $T_e \approx 2$–8 eV. At this voltage the fluctuating signal and its power spectrum are shown in figure 2a (raw data), figure 2b (corresponding power spectrum), and figure 2c (phase-space plot).

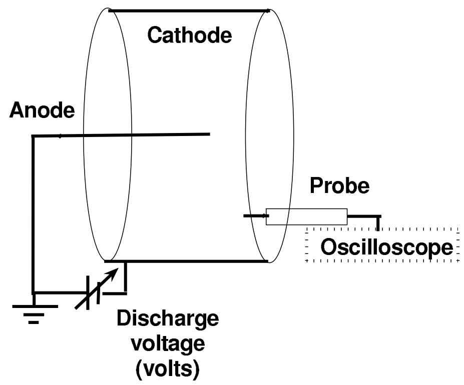

Figure 1. Schematic diagram of experimental set-up of cylindrical DC discharge plasma system with Langmuir probe fitted with digital oscilloscope. A DC voltage has been applied to the cathode (outer cylindrical surface) with respect to the grounded coaxial cylindrical rod and plasma is formed inside it.

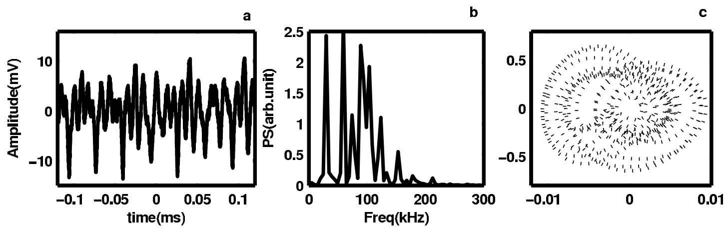

Figure 2. (**a**) Raw data, (**b**) power spectrum (PS) and (**c**) phase-space plot at 283 V respectively. From power spectrum and phase-space plot it is obvious that the signal is chaotic in nature.

The broadband power spectrum and phase-space plot indicate the chaotic state at the initial stage of the DC discharge. On further increasing the voltages we observed a period subtraction and at 284 V two modes of frequencies 69.17, 93.87 kHz with maximum power, and five modes of frequencies 4.9, 24, 44.47, 113.6, and 123.5 kHz with smaller power were seen (figure 3b), i.e. seven periods appear. When the discharge voltage is 286 V, by period subtraction the system reaches the state having five periods as shown in figure 3b′. When the voltage was increased to 288 V three modes of frequencies 29.64, 59.29 and 88.93 kHz, and at 289 V only one period of frequency 59.29 kHz were seen as shown in figures 4b and 4b′ respectively. These are also clear from the phase-space plots of the data at different voltages. From the respective phase-space plots, it is also clear that the system goes from chaotic to coherent oscillations through period subtracting sequences.

Further increase in discharge voltage generates new modes and a period doubling is seen. It is clear from figure 5b that for the power spectrum at 290 V the frequencies are respectively 44.47 and 74.11 kHz. Four new modes of frequencies 14.82 kHz, 39.53 kHz, 49.42 kHz, and 64.23 kHz emerge through period doubling at 291 V as shown in the power spectrum in figure 5b′. So again, the system evolved through period doubling in the following sequences: 1 period → 2 period → 4 period, for

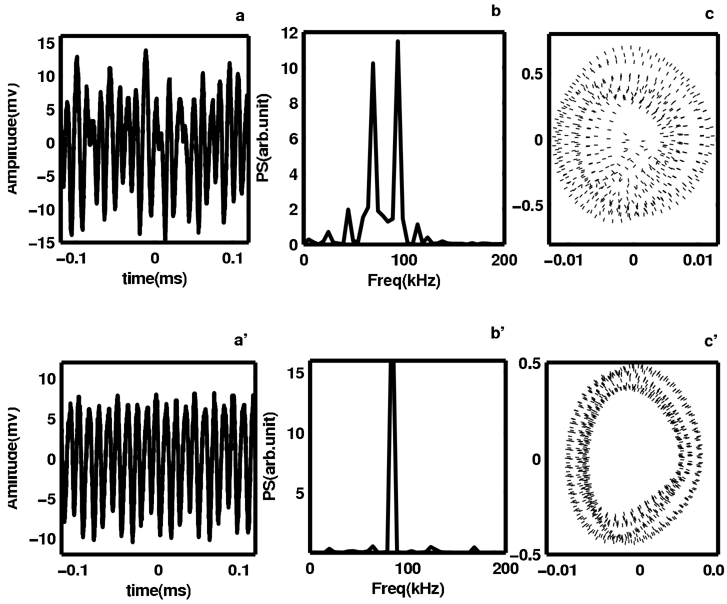

Figure 3. (**a**,**a**$'$) Raw data, (**b**,**b**$'$) power spectrum and (**c**,**c**$'$) phase space plots at 284 and 286 V respectively. Through period subtraction the system attains five period at a discharge voltage of 286 V from the seven period state at a voltage of 284 V.

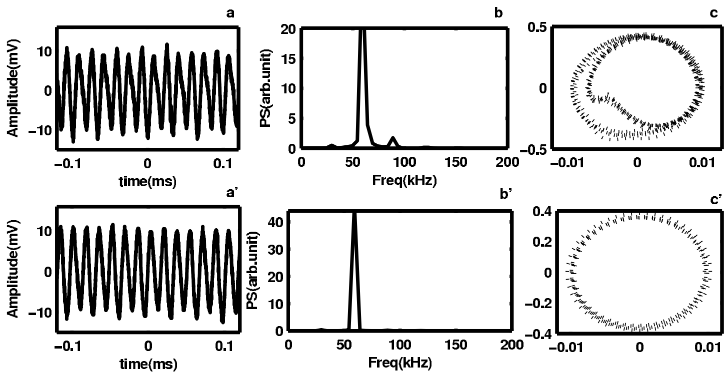

Figure 4. In this figure in sequence (**a**) $\rightarrow$ (**b**) $\rightarrow$ (**c**) the system goes to a three-period state at 288 V from five-period state at 286 V (shown in 3b$'$) and in sequence (**a**$'$) $\rightarrow$ (**b**$'$) $\rightarrow$ (**c**$'$) to single period at 289 V.

the discharge voltage sequence 289 $\rightarrow$ 290 $\rightarrow$ 291 V. On further increasing the discharge voltages, the system generates new modes of frequencies 24.7 and 44.47 kHz through period subtraction at 292 V as shown in figure 6b, the new modes having almost half of the frequencies that appears at 290 V, i.e. at the first bifurcation. On further increasing the voltages, all the instabilities vanish, i.e. plasma floating potential becomes steady at -19 V.

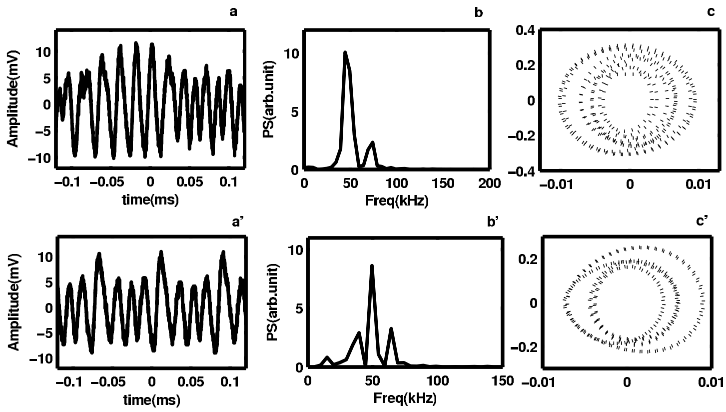

Figure 5. Further increasing the voltage the system goes through two successive bifurcations. The sequences (**a**) → (**b**) → (**c**) and (**a′**) → (**b′**) → (**c′**) show that mode appears at 290 and 291 V respectively due to bifurcation.

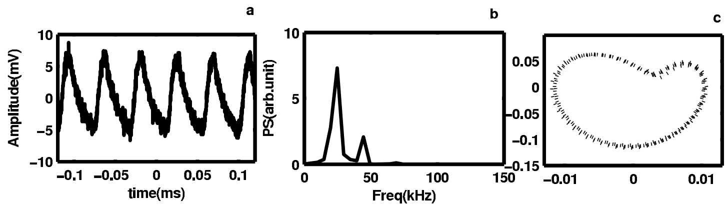

Figure 6. (**a**) → (**b**) → (**c**). (**a**) Raw data, (**b**) power spectrum and (**c**) phase-space plot at 292 V.

Figure 7 shows the 3D plot of power spectrum of the data at different voltages. From this figure it is clear that with increase in the discharge voltage, frequencies of the oscillation decrease.

An interesting phenomenon is that an anode glow appears with the oscillations. Initially, a spot-like glow appears on the anode and with increasing voltage it spreads on the whole anode, and with the vanishing of the oscillations the glow also vanishes. So this can be related to anode glow instabilities and then transition to stable potential structures like double layers etc.

Since the measurements were carried out in the cathode sheath regions, it is most likely that these oscillations could be due to ions that are accelerated within the cathode sheaths. The lower limit to the frequencies observed would be of the order of inverse of ion transit time [8] across the cathode sheath.

$$\frac{1}{\tau} = \frac{1}{(eV_c/kT_e)^{3/4}} w_i, \tag{1}$$

where V_c, T_e and w_i are the potential difference between plasma and cathode, plasma electron temperature and ion plasma frequency respectively. For the electron temperature $T_e \approx 2$ eV, $V_c = 270$ V, this frequency is about 7.5 kHz. The upper limit would be of the order of ion plasma frequency, which is about 300 kHz

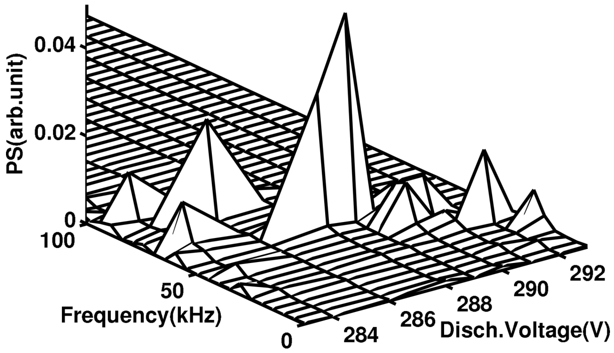

Figure 7. Changes of power and frequencies with discharge voltages. X-Axis represents discharge potential, y-axis represents frequencies, and z-axis represents power spectrum (PS) of the signals at different discharge voltages. With increase in the discharge voltage low modes appear.

for our parameters. The observed frequencies are from about 5 to 170 kHz, which fall within the range that could be expected.

As a part of our future plan, we intend to investigate the period subtraction and doubling phenomena in the bulk region of the plasma and also investigate their long-range correlation.

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