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Dynamical Behaviour of a Plasma Discharge in the Current Regime Limited by the Cathode Temperature

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Abstract. Experimental observations of plasma self-oscillations are presented. In the current regime limited by the cathode temperature of a continuous multipolar discharge, they appear for low gas pressure (collisionless plasma), low cathode heating current and above a discharge voltage threshold. Their frequency and amplitude are strongly dependent on the discharge parameters. The scaling laws of their variation and an example of a period-doubling route to chaos are reported.

1. INTRODUCTION

Under particular conditions, plasmas discharge can display chaotic behaviour. The main routes to chaos have been experimentally identified: the period doubling route sequence [1,2], the intermittent [1] and the quasiperiodic routes [3]. The present paper gives a contribution to this subject with a description of the conditions producing low frequency self-oscillations of a continuous discharge. The experiments were performed in a magnetic multipolar device with hot filaments cathodes used to produce a collisionless plasma. In this kind of discharge, the current-voltage characteristic $I(U)$ displays a typical hysteresis curve [4,5] indicating a bistable behaviour. The lower branch of $I(U)$ represents the "space charge current regime" governed by Langmuir's law. The upper branch of $I(U)$ corresponds to the "temperature limited current regime" governed by Dushman-Richardson's law.

We report here, new results about self excited oscillations occurring in the $I(U)$ hysteresis upper branch. We observe them in discharge current, saturation probe currents and floating potential, in the absence of any pulsating external force. They appear above a discharge voltage threshold V_{ds} . Their amplitude and their frequency depend strongly on the argon pressure P_{ar} , the filament heating current I_f and the discharge voltage V_d . We have established the scaling laws of their variations according to these parameters. They qualitatively agree with the cathode instability arising when the Bohm sheath stability criterion is not fulfilled.

2. EXPERIMENTAL SET-UP AND RESULTS

The plasma device consists of a stainless steel cylinder (45 cm diameter and 80 cm length). Along the chamber axis, 14 rows of permanent magnets with alternate biasing, completed by 4 rows on each cylinder end door, are arranged to provide primary

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electron confinement. The plasma is produced by a dc discharge between the grounded chamber wall and 4 spiral tungsten filaments (27 cm long, 0.03 cm diameter). The filaments are heated by a current I_f delivered by a current regulated power supply. The primary electrons emitted from these hot filaments are accelerated by a negative voltage $|V_d|$ provided by a voltage regulated power supply. The discharge current I_d is detected as a voltage drop across a resistor in series with the discharge.

Figure 1 shows an example of the observed self-oscillations which behave like low frequency ($F=220$ Hz) relaxation oscillations: a) of the electron saturation probe current ΔI_{ep} , and b) of the discharge current ΔI_d superimposed to the dc level I_{ep} and I_d respectively. The continuous discharge parameters are: $P_{ar} = 8 \cdot 10^{-5}$ Torr, $I_f = 27$ A and $|V_d| = 60$ V ($|V_{ds}| = 54$ V), providing the average electron (ion) density $N_e = N_i = 5 \cdot 10^8 \text{ cm}^{-3}$, the average electron temperature $T_e = 3.5$ eV and the ion temperature $T_i \ll T_e$.

ΔI_{ep} is measured with a Langmuir probe located in the plasma center and positively biased at $V_b = 20$ V, higher than the plasma potential. In this situation: $\Delta I_{ep}/I_{ep} = 0.065$. The Langmuir current for electrons and the Bohm criterion for ions allow us to write: $\Delta I_{ep}/I_{ep} = \Delta N_e/N_e + 1/2(\Delta T_e/T_e)$. So, the measured ratio $\Delta I_{ep}/I_{ep} = 0.065$ gives a global information about the relative variation of the electron density and temperature during one self-oscillation period of the ionization process. ΔI_d is measured at the same time [Figure 1(b)]. I_d is proportional to N_{ep} , the primary electrons density injected into the discharge volume. As a consequence, when N_{ep} increases (respectively decreases) the ionization probability and then the plasma density, also increases (respectively decreases). So, both signals in Figure 1(a) and 1(b) have the same shape and are in phase.

Figure 1

Figure 2

Figure 1: Self-oscillations amplitude: a) of the electron saturation probe current ΔI_{ep} , b) of the discharge current I_d

Figure 2: Amplitude variation of ΔI_{ep} normalized to the corresponding dc current I_{ep} versus P_{ar} , for different I_f .

The self-oscillations are sensitive to the discharge parameters. Their amplitude and frequency depend on P_{ar} , I_f and V_d . Figure 2 gives the variation of $\Delta I_{ep}/I_{ep}$ versus P_{ar} ($1.5 \cdot 10^{-5} \text{ Torr} \leq P_{ar} \leq 9 \cdot 10^{-3} \text{ Torr}$), for different I_f . For a given I_f , when P_{ar} is

increased, the ratio $\Delta I_{ep}/I_{ep}$ decreases while, at the same time, the mean self-oscillation frequency increases. So, the oscillations turn into noise when the neutral

Figure 3: Period doubling route to chaos. The left traces show the oscillations ΔI_{ep} obtained for: a) $V_d=40.45\text{V}$, b) $V_d=40.75\text{V}$, c) $V_d=40.82\text{V}$, d) $V_d=41.4\text{V}$. The right traces are the corresponding trajectories obtained by plotting the data at time step $(k+5)$ versus the data at time step k .

gas pressure rises or when the plasma density is increased. The same observation can be done for a given P_{ar} : when I_f increases, the mean self-oscillations frequency increases and $\Delta I_{ep}/I_{ep}$ decreases. So, when N_{ep} is important (the plasma density N_e is important), the ionization oscillations disappear.

In Figure 3, we present an example of the frequency change with V_d . The left-most traces show ΔI_{ep} oscillations sampled by a 12 bit DA converter. The graphs on the right side are the corresponding trajectories. They are obtained by plotting the amplitude $\Delta I_{ep(k+5)}$ of the $(k+5)^{th}$ time step sample versus the amplitude $\Delta I_{ep(k)}$ of the k^{th} time step sample. By rising the control parameter $|V_d|$, we observe a period doubling route to chaos. Oscillations follow the sequence $T \rightarrow 2T \rightarrow 4T \rightarrow \text{chaos}$, where $2T$ and $4T$ mean the state of period 2 and 4 respectively and $T=11$ ms.

3. DISCUSSION

A possible explanation for the onset of the self-oscillations arises from the Bohm sheath stability criterion given by: $\frac{j_{ep}}{j_i} \leq \sqrt{\frac{m_i}{m_e}} = 270$ for argon, where j_{ep} and j_i are the primary and ion current densities. The particle balance expression for fast primary electrons is: $\frac{j_{ep} A_f}{e V_{ol}} = \left[N_n S_{in} + \frac{1}{\tau_{ep}} \right] N_{ep}$ and for the positive ions: $\frac{j_i A_i}{e V_{ol}} = N_n S_i N_{ep}$. The

primary electrons are emitted from the filaments of area A_f , S_i is the ionization rate and S_{in} , the inelastic collision rate. A_i is the total ion loss area (including filaments), τ_{ep} is the fast electron confinement time and V_{ol} is the discharge volume. Eliminating N_{ep} and using the Bohm stability criterion, we obtain: $\sqrt{\frac{m_i}{m_e}} \geq \frac{S_{in}}{S_i} \frac{A_i}{A_f} + \frac{A_i}{\tau_{ep} N_n S_i A_f}$. This

inequality can only be satisfied if the ratio A_i/A_f is sufficiently small or if the discharge is at a sufficiently high gas pressure and high heating current. This agrees qualitatively with the curves, presented in Figure 2 where the oscillations disappear at high values of P_{ar} and I_f .

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