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The Influence of a RF-field on a Self-organized Plasma Structure

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1. Introduction

The appearance of the self-organized structure in plasma is of a particular importance from the point of view of the possible applications it could provide not only in technology but also in the fundamental scientific research [1, 2]. In this paper, by a self-organized structure (SS) we understand a structure that breaks the spatial-temporal symmetry of the previous state and of the external constraints. A SS in plasma behaves similarly to a living cell: it appears under certain external conditions; its existence is ensured in a dynamical equilibrium (characterized by a temporal rhythm) during of which the entropy produced as a consequence of the dissipative processes is expelled outside the structure; it has a boundary through which it "feeds" with particles and energy. Its dynamics is driven by non-linear processes in which the reactions (excitations, ionizations and de-excitations) play an important role. A SS could be seen as self-confined structure. The control of the state of such a structure is performed through the external parameters of it. One of these parameters is the electric field. In this paper we investigate the influence of a radio-frequency field (rf-field) upon a SS.

2. Experimental results

The experimental device is presented in Fig.1. It mainly consists of a rf-plasma source (RFPS) and a glass tube (GT) (5 cm inner diameter, 30 cm length) separated from RFPS by the grids G1 and G2 (0.2 mm stainless steel wire, 25 meshes per cm^2). Inside the RFPS we obtain plasma by a rf-glow discharge which is produced using a rf-generator (RFG1) working at 13.5MHz and 60W. We worked in argon at a pressure range of ($10^{-2} \div 10^{-3}$)Torr. The symmetrical output of it is connected to two electrodes inside the RFPS. This one is made of hard-aluminium and is connected to the ground through a 0.1μF capacitor with respect to the rf-signal. Though a rf-glow discharge can be produced with outer electrodes, this solution assures a better screening of the jamming rf-signal. The grid G1 is directly connected to the RFPS, while the grid G2, which is placed 1cm apart from G1, is connected to the ground via a 1KΩ resistor R_3. The plasma from the RFPS diffuses through the two grids into the GT forming here a relative homogeneous plasma column ($n_e \approx 10^9$ cm^{-3}; $T_e \approx 1.2$eV). The voltage delivered by the PVS2 controls the electron density of the plasma diffusing from the RFPS into GT through the grids G1 and G2. This column is subjected to the electric field produced by the voltage (delivered by the programmable voltage supply PVS1) between the positively biased electrode P (4.5cm diameter) and the grid G2 (the distance between P and G2 is 23 cm). This voltage is in the range of (0-145)V. A second rf-generator (RFG2) (Fig.2) working at 80MHz is coupled to two ring-electrodes E1 and E2 placed outside the GT in the region where the SS appears. For a stabilized anodic voltage U_a (between 150 and 450V) we could choose the value of the anodic current I_a by adjusting U_{g2}, in the case that the equivalent impedance of the SS remains constant. In this way we can control the power delivered by this generator in the frfield in the range (0.5 ÷ 10)W. Voltages proportional to I_p (the average current flowing through the plasma column) and I_a are available to be recorded on a XY-recorder (not shown in Fig.1).

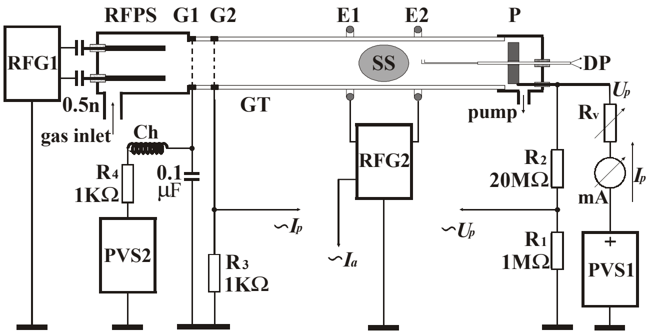


Fig.1: *The experimental device:* RFG1(2) = *rf-generators*, RFPS = *rf-plasma source,* GT = *glass tube*, G1, G2 = *grids,* GT = *glass tube*, P = *plane electrode,* E1, E2 = *ring electrodes*, DP = *axially movable double probe,* PVS1(2) = *programmable voltage supply,* Ch = *rf-choke,* SS = *self-organized structure,* R_v *= (0÷20)kΩ.*

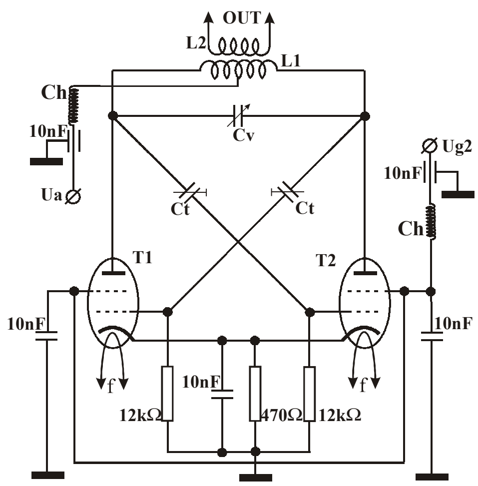


Fig.2: *The layout of the second rf-generator*: T1, T2 = *double tetrode QQE03/20 (or Γ 29),* Ch = *rf-choke.*

The second rf-generator operates in class B and for a constant anodic voltage U_a the power P_{rf} delivered to the rf-field is proportional to the anodic current I_a:

$$P_{rf} = \frac{\pi}{4} \cdot U_a \cdot I_a \tag{1}$$

Depending on the working pressure in the range specified above, it is possible, by adjusting the positive voltage applied on P, to obtain a SS in front of P looking like in Fig.3. Once the SS is formed, a further increase of the voltage on P determines the modification of the size and position of the SS relative to P. Usually the SS pulsates and, as a consequence, the current i_p (collected by P) has an oscillating component.

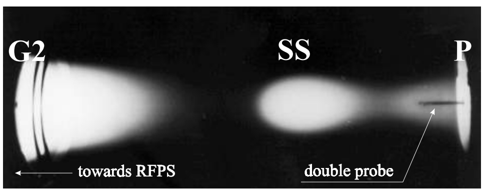
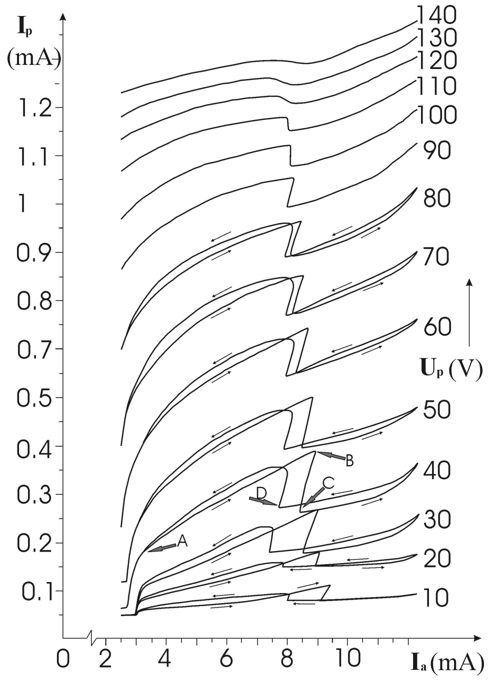


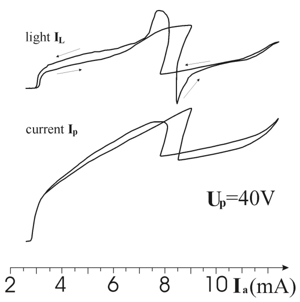
Fig.3: *Photo of the plasma column in which a SS is formed: In front of P another SS begins to form and is connected to the already formed SS through a channel.*

In the absence of the rf-field the SS does not form for U_p in the range (10÷37)V. In this range of voltages the application of the rf-field determines the formation of the SS for a certain value of the anodic current I_a. For higher voltages the SS forms independently of the rf-field. The presence of the rf-field produces changes in the dynamics of the SS, a fact visible in the oscillation pattern of the current i_p and of the light emitted from inside of the SS. We have investigated the dependence of both the average current I_p and the intensity of the light I_L emitted from a cross-section of the SS versus the anodic current I_a for different voltages U_p (Fig.4 a,b). The anodic voltage in the point of operation of the second rf-generator was U_a = 200V and the anodic current was modified in the range (2÷25)mA in a closed cycle. The diagram in Fig.4 put in evidence the appearance of a hysteresis whose area decreases as the voltage U_p increases, becoming zero for voltages greater than 85V. The jumps correspond to drastically changes in the dynamics of the SS. When a SS is formed (the region A in the curve corresponding to U_p = 40V) the current oscillates with a relative low frequency in the range (1÷20)KHz, depending on the voltage U_p. As the current I_a increases the oscillation frequency also increases while the oscillation amplitude decreases.



a)

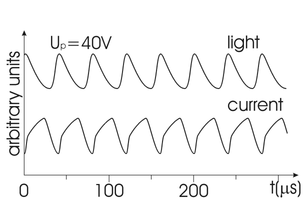
Fig.4a: *The dependence $I_p = I_p(I_a)$ with U_p as parameter. The arrows indicate the moving direction on the curve for an increasing and a decreasing of the anodic current I_a in a complete cycle. The curve corresponding to U_p = 40V is analyzed.*
Fig.4b: *Comparison between the curves $I_p = I_p(I_a)$ and $I_L = I_L(I_a)$. The curves exhibit similar characteristics. They present jumps for the same values of the anodic current and the hysteresis loops behave similarly.*



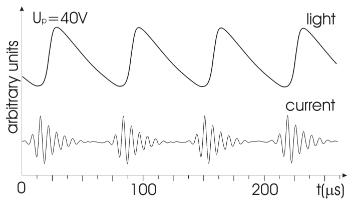
b)

The current and the light have the same oscillation frequency (Fig.5a). This happens until the first jump takes place (region B in the same curve). After the jump (C) they have different patterns and oscillation frequencies (Fig.5b).

A further increase of I_a determine an increasing of the oscillation frequencies of both i_p and light while the amplitude diminishes. On the returning branch (the region between C and D in the analyzed curve), the damping of the oscillation of the current i_p decreases until about zero when another jump (region D) takes place. The oscillating patterns become similar to those corresponding to the region A, though the oscillating frequencies are slightly different.



a)



b)

Fig.5: *Oscillation patterns of i_p and of the light intensity emitted from a cross-section in the middle of the SS, corresponding to different regions: a) region* A, *b) region* C

3. Theoretical considerations

From the point of view of an a. c. circuit, the SS exhibits (like any other space charge structure) a complex impedance $Z = R+iX$. The resistive part R of Z contains not only the effect of the dissipative processes on the dynamics of the SS but also the effect of those processes responsible for a negative resistance behavior of the SS. Therefore, R could have even negative values. The reactive part X of Z results from those processes that determine space charge separation creating so a double layer characterized by an electric capacity C and also from the dynamics of the heavy particles (ions, excited atoms) that are within the SS, being characterized by an inductance L. All the above processes are based on reactions like excitations, ionizations and de-excitations, a fact also confirmed by Fig.4b. From Fig.4a we can obtain valuable information concerning the components R and X of the SS. For example from the curve corresponding to U_p = 40V we can deduce that the jump from region B to C is provoked by an increase of R from the value R = 105KΩ to the value R = 154KΩ. During this jump the total impedance Z_{tot}, seen by the rf-generator, has changed from Z_{tot} = 22KΩ to Z_{tot} = 24KΩ. The total impedance is expressed versus Z and the equivalent impedance of the coupling circuit (L_2, electrodes E1, E2). To describe the SS we need a set of equations that must contain the condition of self-organization. Following [3] we consider the Glansdorff-Prigogine universal evolution criterion (UEC) as the condition for self-organization. Taking into account reactions (characterized by reaction functions $R_{\alpha r}$; α stands for the particle species and r for the r-th reaction) in a BGK model, the system of equations reads:

$$\left(\frac{-C_\alpha Q}{q_\alpha} + D_\alpha \nabla^2 n_\alpha\right)\left(\frac{q_\alpha}{K_B T_\alpha}\frac{\partial \Phi}{\partial t} + \frac{\partial(\ln n_\alpha)}{\partial t}\right) + \sum_r \frac{R_{\alpha r}}{K_B T_\alpha}\left(2q_\alpha \frac{\partial \Phi}{\partial t} - \frac{\partial U_{\alpha r}}{\partial t}\right) = 0 \qquad (2)$$

$$\frac{\partial n_\alpha}{\partial t} = \frac{C_\alpha}{q_\alpha}\nabla^2 \Phi + D_\alpha \nabla^2 n_\alpha + \sum_r R_{\alpha r} \qquad (3)$$

$$\nabla^2 \Phi = -Q \qquad (4)$$

Where: n_α and q_α are the particle densities and their charges, $\left(\sum_\alpha n_\alpha q_\alpha + \mu\right)/\varepsilon_o = Q$, μ is the control parameter taking into account the external electric field with the two components: one due to U_p and the other due to rf-field, D_α are the diffusing coefficients, C_α are the conductivities and must be positive definite, $U_{\alpha r}$ represents the internal energy changed by particles during the reactions and could be calculated following indications from [4], Φ is the resulting potential. The reaction terms $R_{\alpha r}$ are expressed in function of reaction rates conform to the BGK model. The unknowns are n_α, C_α and Φ. $C_\alpha > 0$ is a consequence of the UEC and put in evidence the necessity of a negative resistance behavior of the SS. As will result from the above system of equations, the R component (expressed in terms of C_α) of Z will be a function of the plasma parameters and of μ, i. e. of U_p and the rf-field.

References

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