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On the Microscopic Basis of the Negative Differential Resistance

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Abstract

Abrupt transitions and multiple states evidenced in the I(V) characteristic of a Q-machine are analyzed in the frame of an intermittent self-organization scenario able to reveal new aspects concerning the negative differential resistance behavior of a non-linear conductor.

Keywords:

non-linearity, instability, self-organization, negative differential resistance, oscillations

1. Introduction

The aim of this paper is to emphasize that the "vital" part of an oscillator working with a gaseous conductor showing **n**egative **d**ifferential **r**esistance (NDR) is located in the unstable space charge configuration formed by self-organization in front of the anode. Based on these results and also on many strong similarities between a plasma oscillator and a Gunn oscillator [1], we propose a mechanism that explains the occurrence of the NDR in the frame of a new self-organization physical scenario [2-5] potentially possible in all non-linear conductors.

2. Experimental Device and Results

The experiment was performed on a Q-machine schematically presented in Fig. 1. The low-density plasma of a Q-machine is traditionally considered collisionless. Nevertheless, as it was recently emphasized [6,7], the inelastic collisions are not only possible but also obviously necessary for explaining the astonishing similarities between the strong non-linear behavior of the plasma created in a Q-machine and that of a plasma in which inelastic collisions are present.

Taking into account the above said and also the radical changes in science concerning systems exhibiting abrupt transitions and a multiplicity of states [8], we explain the non-linear behavior of the Q-machine plasma considering an intermittent scenario of self-organization in the frame of which the creation of **d**ouble **l**ayers (DL) has its origin in the symmetry breaking and spatial separation of the excitation and ionization cross section functions [2-5]. Because the assemblage of a DL by the above mentioned phenomena is a cumulative process, its presence is not excluded in a Q-machine. Evidently in such conditions the time span

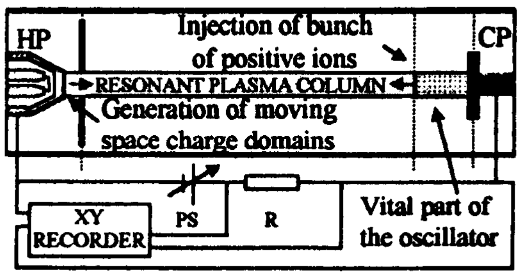

Fig. 1 The Q-machine working as a plasma oscillator.

Corresponding author's e-mail: erloz@uaic.ro necessary to produce the space charge separation depends, for a fixed current intensity, on the concentration of neutrals. This is the reason why the $I(V)$ characteristic of a Q-machine very clearly reveals strong non-linearity only for low currents and plasma densities (Fig. 2).

For elucidating the physical processes related to the non-linearity emphasized in this $I(V)$ characteristic we put forward the assertion that the experimental results obtained from a collisional plasma are a guide to understand also the phenomena taking place in a Q-machine. Consequently we explain the multiplicity of states of the plasma created in a Q-machine (revealed in the $I(V)$ characteristic by the presence of critical points marked by V with subscript numbers) by considering a "scenario" including a succession of states. The first is one in which plasma is in thermodynamic equilibrium and is asymptotically stable. A second state appears when on the plasma acts an external constraint, in the form of a positive voltage $V < V_1$ applied on the cold plate (CP). In this state the plasma behaves as a normal conductor, i.e. I proportionally increases with V. The following state, that is an "anomalous" one, appears when $V = V_1$. In that state I decreases in spit of the increasing V from V_1 to V_2. This anomalous behavior is caused by the accumulation of those electrons that have lost their momentum by neutrals' excitation [2-7]. The negative space charge formed in this way in front of the CP acts as a barrier for I determining its decrease. The appearance of the following new state is marked by the abrupt increase of I when $V = V_2$. It appears when a DL, able to accelerate electrons at energies for which the ionization cross section function suddenly increases, is spontaneously created. In the voltage range $[V_2 - V_3]$ the DL is stationary but it departs from the CP when V increases. During this departure the net negative space charge accumulated at the negative side of the DL increases so that I remains nearly constant although V gradually increases (a stationary DL is that whose location with respect to CP depends on V when the other parameters are maintained constant). Another very important state, directly related to the mechanism of the NDR, appears when $V = V_3$. During this state I becomes periodically limited (Fig. 3). This characteristic was obtained by linear increasing of the voltage of the external dc power supply with a slope sufficiently high to reveal the temporal variations of I.

In order to explain the weak modulation of I appearing when $V = V_3$ we remind that in a collisional plasma such phenomena are related to the successive generation and disruption of DLs in front of the anode [2-5]. These phenomena appear after the transition of the stationary DL, located at a certain distance from CP, into a self-consistent state. During that state it departs from the CP although V remains constant. Its "motion" away from CP is governed only by internal processes possible when the electron flux across the DL is sufficiently high. The dynamics of the self-consistent DL produces weak modulations of I, evidenced in Fig. 3, for every value of V in the voltage range $[V_3 - V_4]$. During this self-consistent state, the conditions for the formation of a new DL in front of the CP re-appear. The negative space charge accumulated during the formation of a new DL and that one present in front of the self-consistent (moving) DL act as barriers for I determining its decrease (branch a-b in Fig. 3). Simultaneously with the development of this new DL, the existence conditions for the formerly self-consistent one cancel so that it disrupts releasing the opposite space charges from its two sides. As a consequence, the conductivity of the plasma column suddenly increases determining a corresponding increase of I and also a diminishing of the potential difference supported by the plasma column (branch b-c in Fig. 3). The electrons released during the

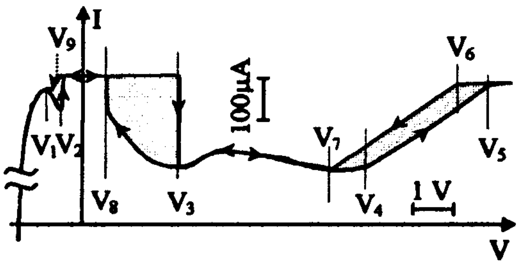

Fig. 2 Static $I(V)$-characteristic of a Q-machine. The plasma density is $n = 6.8\ 10^{14}\,m^{-3}$.

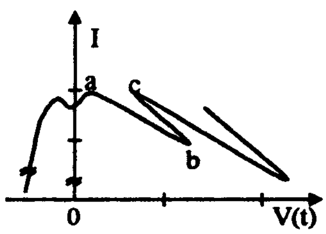

Fig. 3 Dynamic $I(V)$-characteristic proving the appearance of weak current modulation under the conditions that the PRI does not appear.

disruption of the self-consistent DL are collected by CP contributing to the formation of a new DL that repeats the above described dynamics. In this way the phenomenon becomes a periodical one.

The transition towards the strong I-oscillations, usually referred as potential relaxation instability (PRI) [8], emphasized in the in the voltage range $[V_4 - V_5]$ of the $I(V)$ characteristics shown in Fig. 2 and Fig. 4, is not related to the presence of a NDR as generally considered [9], but rather to the appearance of a positive differential resistance. This is a very important experimental result because, to the best of our knowledge, that has not been previously reported. The amplitude growing process shown in Fig. 4 proves the presence of a resonance phenomenon. It appears in a Q-machine when the plasma column is able to support a half-wavelength ion-acoustic standing wave excited by periodical injection of bunches of positive ions produced in the moment when the DLs, successively generated in front of the CP, disrupt.

We remind that the similarities between the phenomena observed in a Q-machine and those observed in a Gunn diode are referring to the generation of barriers for I at the HP and to their propagation towards the CP [8]. The appearance of such barriers for I was observed in a Q-machine only during the presence of the strong I oscillations shown in Fig. 4 when $V > V_5$. Similar phenomena, but experimentally difficult to reveal, are very probably present also during the weak I modulations.

In agreement with the above-described phenomenology, the generation of barriers for I in front of the HP is the consequence of the disruption of a DL generated after self-organization in front of the CP. This disruption is accompanied by a sudden gathering of electrons by the positive CP and a jump of the potential of the plasma column (except a small region in front of the HP) to a potential value close to that of the CP. In this way the region where the electrons are accelerated is shifted in front of the HP. Obtaining here the kinetic energy for which the excitation cross section function increases suddenly, a new barrier for I forms in front of the HP. This negative barrier departs from HP and, after running a certain distance, meets the negative side of the stationary DL localized at a certain distance from CP. The addition of the net negative space charge carried by the barrier to that existing at the negative side of the stationary DL transforms this in a self-consistent state whose dynamics, sustained only by internal processes, is finished by its disruption [2-4]. After that the plasma potential suddenly jumps again to a value closed to that of the CP. So, the phenomenon cyclically repeats. We point out that the above described mechanism does not involve the suppression of the weak I modulations whose presence is obviously necessary to stimulate the strong I modulations. On the other hand during the strong I modulation the current barriers formed at the HP triggers the injection of a bunch of positive ions in the disruption phase of the self-consistent DL and consequently the stimulation of PRI. For higher plasma density, the weak modulation regime of I is compressed (Fig. 5) and the dynamical $I(V)$ characteristic becomes similar to those of a Gunn diode [1].

The last described phenomenology, taking place in

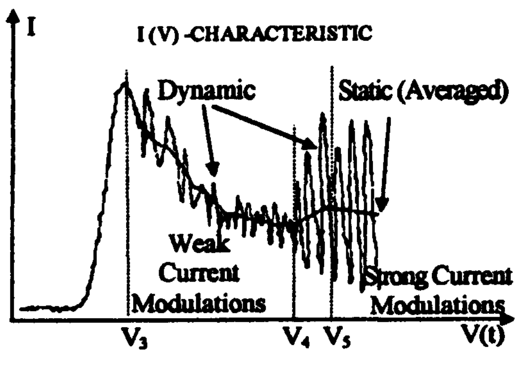

Fig. 4 Dynamic $I(V)$-characteristic proving the transition from weak to strong oscillations observed under the conditions that the plasma column length and concentration are appropriate to support a ion-acoustic standing half wave.

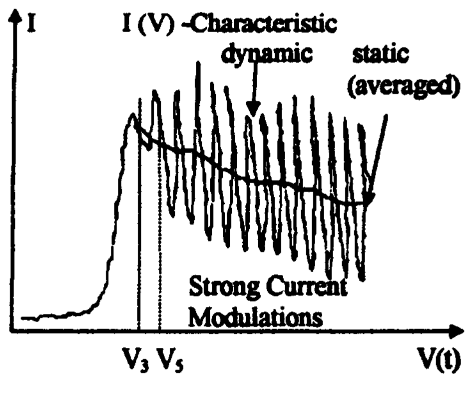

Fig. 5 Dynamic $I(V)$ characteristic obtained when the plasma density is so high that the transition through the weak I modulation is compressed and the PRI seems to appear directly.

front of the CP, clearly proved in a nonlinear plasma conductor, was not investigated up to now at the anode of a Gunn diode.

When the voltage applied between HP and CP is gradually decreased, the $I(V)$-characteristic shows hysteresis. That reveals a sort of memory by which the state of the system depends on its past history. As generally accepted, such phenomena are characteristic for complex structures formed after self-organization [10].

3. Conclusions

The similarity between the phenomena observed in a Q-machine and in a Gunn diode was firstly remarked by Iizuka et al [8]. Extending this similarity, we propose in this paper to consider the dynamical behavior of complex structures formed after self-organization in front of the positive electrode as the genuine origin of the NDR in both mentioned non-linear conductors. Our results prove that the spontaneous creation of a DL, emphasized by the sudden increase of I, is observed before the appearance of the ion acoustic instabilities. Therefore the invocation of the instability as a possible cause of the sudden changes of the plasma conductivity is excluded.

In agreement with the above said we explain the periodical limitation of I considering the successive generation and disruption of DLs formed, after self-organization, in front of the CP. The dynamics of these DLs has its origin in their peculiar propriety to be able to sustain and control, like a cell membrane, a rhythmic exchange of matter and energy between two regions of the plasma column. The rhythmic matter and energy exchange triggers also the formation of moving current barriers at the HP and the stimulation of an ion acoustic half-wavelength standing wave in the plasma column. We presume that a similar self-organization phenomenon, taking place at the anode of a Gunn diode, triggers the generation of space charge domains at the cathode and implicitly stimulates oscillations in the resonant cavity suitably connected to it.

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