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A New Insight into the Self-Assemblage Mechanism of Complex Space Charge Configurations in Plasmas

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Abstract

Self-organization grounded on the spatial separation of the regions where the excitation and ionization cross section functions suddenly increase is identified to be at the origin of spatial and spatiotemporal patterns in plasma. Space-charge-limited flow and other challenging problems of Plasma Physics and, implicitly, of the Physics of Complexity are approached starting from a new point of view justified by recent experimental results.

Keywords:

collective effects of elementary processes, plasma sheet, pattern formation, space-charge-limited flow, negative differential resistance, self-organized system

1. Introduction

Basic ideas on pattern formation and instability mechanism in open, spatially extended, nonlinear systems have gained special interest not only in plasma physics but also in other fields of science [1-3]. Despite of the collective effort, the progress in this new field of scientific investigation is far from being satisfactory [2,3]. Apparently this state-of-the-art is related to the lack of systematic experimental investigations concerning self-organization aspects observed in different physical devices. Answers for the following important questions of nonlinear science are missing [2]: Which perturbations and parameters are the sensitively controlling ones? What are the mechanisms by which small effects govern the dynamics of pattern formation? What are the interrelations between physics at different length scales in pattern-forming systems? When and how do atomic-scale mechanisms control macroscopic phenomena?

The goal of this paper is to point out that the informational content of the scenario of self-organization already published [4] is able to suggest plausible answers to the aforementioned challenging problems. This scenario is grounded on collective effects of quantum processes, related to the spatial separation of the regions where the excitation and ionization cross section functions suddenly increase. Additionally, the presented experimental results offer a new insight into the physical basis of the so-called space-charge-limited flow, recently appreciated as the "most celebrated diodic event" [5].

Based on a special strategy of simulation science, T. Sato has derived a universal rule proving that "self-organization evolves in an intermittent fashion for a continuous excitation from an external world, while it relaxes towards a minimum energy state in a stepwise fashion for a sudden excitation" [6]. The self-organizing aspects revealed in this paper represent potentially new arguments in favor of such a universal rule.

2. Experimental Results and Discussion

The experimental device is a plasma diode using as

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plasma source (PS) a negative biased heated oxide coated filament surrounded by a grounded Ta cylinder. The plasma created by ionization of the Ar atoms, by the electrons accelerated towards the cylinder, diffuses into a glass tube (5 cm inner diameter) where it is confined by an axial magnetic field (B~0.03 – 0.07 T). A Ta-plate (2.5 cm in diameter) used as anode (A) was placed at 30 cm from the PS. The plasma parameters where in the range: p = 10^{-4} T, $n_e = (10^9 - 10^{10})$ cm^{-3}, T_e = (3 – 5) eV and λ_D = (0.2 – 0.4) mm. In contrast with the plasma diodes previously used [4], the plasma in the present diode is produced at lower gas pressures and is confined by an axial magnetic field. This justifies some comparisons between the present experimental results and those recently obtained from a Q-machine plasma [7-9] traditionally considered collisionless [5].

The plasma column, initially in a state nearly in thermal equilibrium and asymptotic stable, is driven away from equilibrium by connecting it to a dc power supply (external constraint). The response of the plasma is emphasized in the typical static *I-V* characteristic [Fig. 1(a)] where *V* is the potential difference measured between PS and A. Ranges of *V* and *I* variations were 0–40 Volts and, respectively, 0–12 mA. This characteristic reveals the presence of critical values of *V*, marked by subscripts, for which the plasma column transits between distinct conduction states. One of them is the space-charge-limited flow which produces the decrease of *I* when $V = V_4$. In the frame of the collisionless plasma model this phenomenon is explained considering a "virtual cathode" whose appearance is associated with instability [5].

For establishing the actual causes that determine the space-charge-limited flow and the appearance of instability, we have identified (by using modern methods for plasma investigation) the physical processes that explain the transition between the distinct current conduction states of the plasma column when the applied voltage is gradually increased [Fig. 1(a)]. The existence of distinct conduction states proves that before the instability appearance a series of physical processes take place in the plasma. Their successive occurrence creates the premises for the instability excitation. Note that $V = V_4$ is a critical value for which *I* abruptly decreases and the instability spontaneously appears. The averaged value of *I*, after the instability appearance [Fig. 1(b)], reveals the presence of a **n**egative **d**ifferential **r**esistance (NDR). The connection between the NDR and the instability appearance is well known [5,9]. What is little known is the origin of the abrupt transition (for

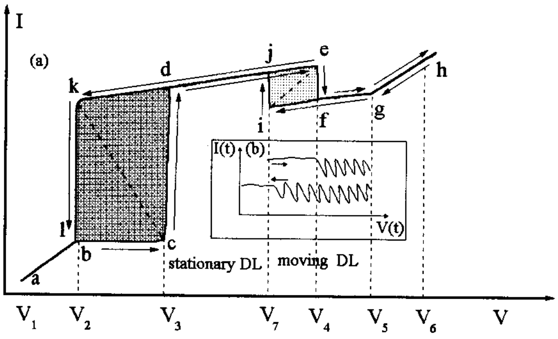

Fig. 1 (a) Typical static *I-V* characteristic of the plasma diode.
(b) Parts of the dynamic I(V) characteristic proving the appearance and disappearance of the periodical decrease of the current.

$V = V_3$) between two conduction states of the plasma diode before the appearance of the instability. Thus, from Fig. 1(a), we observe that the first deviation from Ohm's law appears in the voltage range $V_2 \leq V \leq V_3$ where *I* remains nearly constant in spite of the increasing *V*. Probe measurements revealed that this anomalous behavior of the plasma column is related to the appearance of a net negative sheet in front of A. Simultaneously performed, spectral measurements have revealed that the cause of the sheet formation is the accumulation of those electrons that have lost their momentum after excitation of Ar atoms on different levels. Since the excited Ar atoms return into the ground state, this region appears as a luminous sheet. We note that the formation of the net negative space charge, located at a certain distance from A, is the first sequential step in the self-assembling of a space charge configuration in plasma. This process proves the presence of an atomic-scale mechanism in the formation of spatial patterns. The electrons, thermalized after excitations, form a net negative space charge located at a certain distance from A where the excitation cross section function of neutrals suddenly increases.

The following important event observed in the diode is the sudden increase of *I* when $V = V_3$. This phenomenon indicates the appearance of a new internal source of charged particles. This source was identified as a **d**ouble **l**ayer (DL) whose potential-drop equals/ exceeds the ionization potential of the gas. Its presence is shown by the measured potential, electric field and light intensity [Fig. 2(a)]. Its appearance critically depends on *V* because its self-assembling takes place when the electrons accelerated towards A obtain energies for which the production of positive ions becomes a self-enhancing process. Under such conditions, the electrostatic forces, acting as long-range correlations between the two adjacent opposite net space charges, become suddenly dominant with respect to those forces that have initiated the DL self-assembling process. This fact explains the spontaneous transition of the space charge configuration into a state characterized by a local minimum of the free energy [4]. The self-enhancement mechanism stops when the concentration of the neutrals in the plasma does not allow a further increase of the net space charges at the two sides of the DL. In this way a self-consistent DL is self-assembling [Fig. 3(a)]. The self-consistence quality is attributed to the DL because its potential drop is so self-adjusting that the electrons accelerated by it produce all the processes required for its continuous self-maintenance [4]. This is possible only in a current carrying plasma when the potential-drop over the DL reaches/exceeds the ionization potential of the gas atoms. In this state the DL is stable and located at a certain distance from A. When the applied external voltage is gradually decreased, the *I-V* characteristic reveals a hysteresis phenomenon that indicates the existence of a voltage range for which the plasma conductor becomes bistable [Fig. 1(a)]. Note that the spontaneous generation of the self-consistent DL in front of A is an example of spatial pattern formation after self-organization. The described sequential steps, which explain the self-assembling process of the self-consistent DL, suggest answers to the above-mentioned questions for which, until now, the answers are missing [2].

The space-charge-limited flow, the understanding of which is considered of crucial importance [5], is revealed in Fig. 1(a) when $V = V_4$. It appears after the self-assembling of the self-consistent DL when $V = V_3$. This is a very important experimental fact proving that a stable DL arises in the plasma diode before the appearance of the instability. This is proved in Fig. 1(b) where the instability, i.e. the periodical decrease of I appears when $V = V_4$. This is a part of the dynamic characteristic obtained when the applied voltage is linearly increased, sufficiently fast to highlight the periodical I-decrease when it reaches a critical maximal value. In the static *I-V* characteristic, where the averaged value of I is measured, this decrease appears abruptly when the circuit does not contain a resistor, and as a usual NDR when the value of the resistor is high with respect to the internal resistance of the plasma column. The transition of the initially stationary DL into one that moves away from A is illustrated in Fig. 3(b) by the space time evolution of the profiles of the potential, of the electric field and of the light intensity in the plasma column in front of the anode. This transition of the self-consistent DL into a moving phase was identified to be at the origin of the periodic limitation of the current. The DL motion starts when the voltage supported by the plasma column corresponds to the critical value $V = V_4$. The cause of this transition is a new self-enhancement process of the production of positive ions at the high potential side of the DL when the potential drop over the DL surpasses the value for which it is in a stable state. The self-enhancing mechanism becomes possible

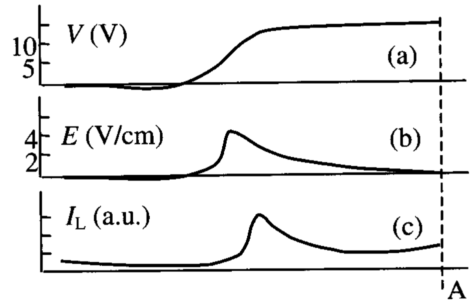

Fig. 2 Axial distribution of (a) the potential V; (b) electric field E; (c) light intensity I_L in a DL formed at 1.5 cm in front of A.

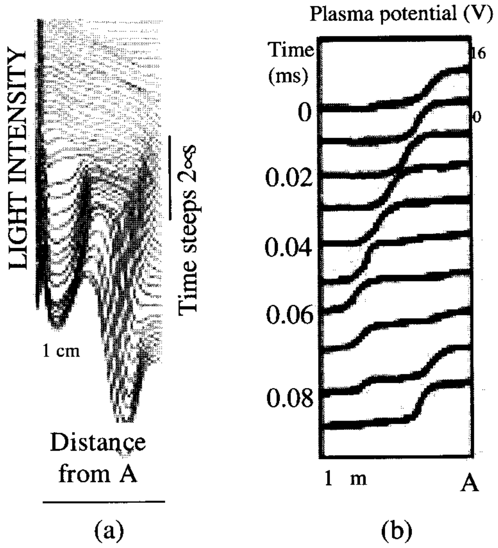

Fig. 3 (a) Sequential steps of the stable DL self-assembling process in front of A when $V = V_3 \leq V_4$; (b) Temporal evolution of a DL in front of A after its transition into a moving phase when $V \geq V_4$.

because every small increase of the positive space charge in this region implies an increase of the potential drop over the DL that, at its turn, determines the increase of electron kinetic energy. Because of the energy dependence of the ionization cross-section function, the net positive charge at the positive side of the DL ensures the balance between the ionization rate and the disappearance rate of charged particles by recombination, diffusion and so on. The moving phase starts because the net positive charge at the positive side of the DL acts as a gas anode whose appearance produces an increase of the electric field in front of A. In this way the region where electrons are accumulated after neutral excitations shifts away from A. Because the net positive space charge is bounded to the net negative space charge by electrostatic forces, the whole DL transits into the moving phase [4]. Running through the plasma column, the DL becomes able, by self-adjusting its velocity, to ensure the flux of electrons required for its autonomous state. Evidently, this autonomy is only a partial one because a part of the flux of electrons and the neutral concentration required for its continuous self-assembling process is ensured by the current flowing between PS and A. Since during the moving phase of the DL a new DL is self-assembling in front of A, another barrier for I appears in the plasma column [Fig. 3(b)]. Its development determines a decrease of I at a value for which the previously formed DL (which is in a moving phase) de-aggregates. During this de-aggregation phase, at a certain distance from A, a bunch of positive ions is injected into the plasma column between PS and the region where the DL de-aggregates. Simultaneously, the electrons initially bounded in the DL space charge configuration move, as a bunch, towards A. Arriving the region where the new DL is in a forming phase, these electrons abruptly increase the flux of electrons at values for which the new DL starts its moving phase. In this way, DLs are successively self-assembled and de-aggregated in the plasma column [Fig. 3(b)]. We remark that the static I-V characteristic [Fig. 1(a)], proves the presence of a new hysteresis phenomenon in the voltage range $V_4 \geq V \geq V_7$ and, implicitly, the appearance of a Z-shaped I-V characteristic. This new hysteresis phenomenon reveals that the described DL dynamics takes place when the applied voltage is decreased also for V-values smaller than those necessary for its starting. In the vocabulary of complexity [1] this means that the plasma column displays a sort of memory of a past event produced at a critical moment, a phenomenon usually considered to be specific to self-organization [1]. The dynamic I-V characteristic [Fig. 1(b)] shows that NDR appears in the static I-V characteristic only because I is the averaged value of the current collected by A. Since these limitations are produced by the successive self-assemblage (storage of energy from the external power supply) and de-aggregation (energy release in the circuit) of DLs, these results reveal that spatiotemporal patterns, formed by self-organization, act as the "vital" part of systems able to generate oscillations [8,9].

3. Conclusions

We presented experimental results able, in our opinion, to offer a new insight into the elucidation of challenging problems of nonequilibrium physics [1-3]. Additionally, we revealed that the space-charge-limited flow, a phenomenon recently investigated in a comprehensive work [5], is physically based on: (i) the arise, by self-organization, of a stable DL (spatial pattern); (ii) the transition of the stable DL into a proper, self-sustained dynamical state (spatiotemporal pattern). Striking phenomena observed in Nature, as for example, the appearance of ball lightning [10] and the acceleration of charged particles by moving DLs in the aurora region of the Earth atmosphere [11] also could be explained considering a self-organization mechanism similar to that present in a plasma diode.

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