# HABILITATION THESIS

## Complex space-charge structures in plasma

### SUMMARY

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# SUMMARY

The study of nonlinear phenomena in plasma is a very important research field from both theoretical and applied point of view. Among others, this involves the investigation of the self-organized space-charge structures formation, such as double layer, multiple double layer, soliton, or even more complex structures, but also the analysis of their dynamics, which often strongly influence the global behaviour of the plasma device where these structures appear.

The electrical double layer is composed by two space-charge layers, one of electrons and the other one of positive ions, being the simplest self-organized structure that appears in plasma. The self-assembling of the two space-charge layers takes place due to the long range internal forces that arise between large groups of particles. By accelerating the thermal electrons from plasma in the voltage between the two space-charge layers until they reach energies enough to produce excitation and ionization collisions with the neutrals (gas atoms), the double layer can maintains its structure, compensating the particles (electrons and positive ions) losses by recombination and diffusion. When the experimental conditions doesn't allow anymore the stability of the structure (by driven the system far from equilibrium), the double layer passes into a dynamic state, consisting of periodic disruptions and re-aggregations of the structure, a phenomenon that determines the appearance of oscillations of the plasma parameters (discharge current, plasma potential, electrons and ions densities). In both static and dynamic states, the double layer possesses memory, being able to maintain its stationary state in worst conditions than those required for its appearance. This is emphasized in the static current-voltage characteristic of the exciting electrode by the existence of the hysteresis effect. Also, both the appearance and transition of the double layer in dynamic state take place simultaneously with current jumps, emphasizing the phenomenon of negative differential resistance of S- and N-type (Z-type).

The most common way to obtain a double layer is to apply a positive potential to an electrode immersed into plasma, up to a critical value for which the structure develops in the existing experimental conditions. In this way, an almost spherical intense luminous structure appears in front of the electrode, known as fireball. The spectral analysis of the fireball emphasized the important role of the excitation and ionization collisions with neutrals in the assembling and dynamics of the structure. The appearance and dynamics of the fireball can be controlled by using a supplementary ring electrode, concentric with the exciting electrode and biased in a suitable way. Several scenarios of transition to chaos (by type-I intermittency, by quasiperiodicity – Ruelle-Takens scenario, or by cascade of sub-harmonic bifurcations) of the double layer dynamics, as well as order-chaos-order successive transitions were experimentally observed and analysed. By using passive external circuit elements (capacitor in parallel with the exciting electrode and coil in series with the exciting electrode), the chaotic dynamics of the fireball can be controlled, obtaining a harmonic dynamics. In the frame of the Scale Relativity Theory, the double layer can be theoretically modelled as an interface generated at the contact of two fractal fluids with different properties.

In certain experimental conditions (gas nature and pressure, plasma density, electrons temperature), a more complex space-charge structure can appear in front of the electrode consisting of several double layers and known as multiple double layer. Depending on the electrode geometry, the multiple double layers can be concentric or non-concentric (as a network of fireballs uniformly distributed on the electrode surface). The number of the double layers composing the multiple structure increases with the increase of the gas pressure or the potential applied on the electrode. The multiple double layer dynamics is a complex one, a correlation of the individual dynamics of the component double layers could exist, as well as uncorrelated dynamics may appear, with the presence of flicker noise or chaos. Thus, in the case of both concentric and non-concentric multiple double layers, a transition to chaos by cascade of spatio-temporal sub-harmonic bifurcations was experimentally recorded. All the experimental observations lead to the conclusion that both types of multiple double layers have the same fundamental mechanism of appearance and dynamics. The simultaneous existence of both types of multiple double layers, concentric and non-concentric, was experimentally evidenced on the same exciting electrode. A fractal theoretical model was built in the frame of Scale Relativity Theory, able to explain different experimental observations related to multiple double layers.

For a better understanding of the assembling and dynamics of multiple double layers, the interaction between two fireballs obtained on different electrodes was experimentally

investigated. It was observed that the oscillation frequency of both structures depends on the distance between the two electrodes, the potential applied on the electrodes and the discharge current (proportional with the plasma density). These dependencies were confirmed by the fractal theoretical model developed in the frame of Scale Relativity Theory. The spectral investigation of the interaction between the two fireballs emphasized once more the important role of the excitation and ionization collisions between the electrons and neutrals for their dynamics, but also the influence of small quantity of helium addition on the spectral lines of argon, used as working gas.

The interaction between two complex space-charge structures that appear inside and around of a spherical grid cathode provided with a small orifice was analysed. The electrical and spectral diagnosis evidenced the presence of double layers in dynamic states, in the region near the orifice. The analysis of the discharge current oscillations emphasized the existence of the self-modulation mechanism, determined by the interaction between the space-charge structures existing there. This phenomenon was theoretically modelled as solution of a fractal equation of Riccati type. In the next step, it was investigated an electrical discharge in argon with two concentric spherical grid cathodes with axially aligned orifices. Also in this case, the electrical and spectral diagnosis emphasized the presence of several space-charge structures, being in mutual interaction.

Several research topics were proposed, which continue the study of interaction between complex space-charge structures in low-temperature plasma, but also new research topics were proposed aimed the study of these structures in magnetic field, or the structures that appears at the interaction plasma-liquid. Also, new research directions can be opened, regarding the assembling of self-organized structures in environments other than plasma (liquid, chemical and biological environments, electronic circuits), or the investigation of interdisciplinary or transdisciplinary complex phenomena in economic or social systems.

The capacity of the author to coordinate research teams (as director of several research grants, member in guidance commissions of several PhD students, member in analysis committees of several PhD thesis, coordinator of several postdoctoral research projects) and to manage educational activities (new introduced courses, seminars and laboratory works, coordination of bachelor and master thesis) was demonstrated.