2019

Oscillatory behavior of hollow grid cathode discharges

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Recommended Citation

R. Schrittwieser et al., "Oscillatory behavior of hollow grid cathode discharges," 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA), 2019, pp. 1359-1362, doi: 10.1109/ICEAA.2019.8879126.

Funder: CEEPUS; Romanian Ministry of Research and Innovation

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Oscillatory behavior of hollow grid cathode discharges

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***Abstract*—Multiple complex space-charge structures in unmagnetized low-temperature plasmas arise from ionization phenomena near additional negatively or positively biased electrodes or due to local constraints. Because of their usually spherical form, such structures are called fireballs. If they appear inside hollow grids, they are called inverted fireballs or plasma bubbles. The temporal evolution of such structures is often accompanied by strong plasma instabilities. The dynamics of complex space-charge structures have been investigated by using single spherical grid cathode with an orifice. Langmuir probe and optical emission spectroscopy were used to diagnose the structures. Measurements delivered the axial profiles of the plasma potential, electron temperature and density, and the densities of excited atoms and ions, that confirmed the formation of a fireball in the region near the orifice (also evidenced by visual observation). Inside the grid, a plasma bubble has developed, with a high ion density inside due to the hollow cathode effect. Information on the nonlinear dynamics of the complex space charge structures was obtained from the analysis of the oscillations of the discharge current.**

Keywords—fireball, plasma bubble, hollow cathode, oscillations

I. Introduction

Plasmas are complex systems very suitable for the study of non-equilibrium phenomena. At the equilibrium, a plasma system reacts to external constraints, shielding any outer influence. However, when the external constraint exceeds a certain critical value, plasma adapts itself, displaying strong nonlinear spatial and/or temporal behaviors. One of the consequences is the appearance of complex space-charge structures near negatively or positively biased electrodes, known as fireballs [1,2], inverted fireballs [3,4], plasma bubbles [5-8] or multiple double layers [9-11]. These structures are bounded by plasma double layers, whose stability is ensured by the balance between the production of charged particles (electrons and ions) through excitation and ionization electron-neutral collisions and charged particle loss through recombination and diffusion. When the external constraint pushes the plasma system far away from equilibrium, this balance cannot be maintained and the structures pass into dynamic states, consisting of periodic disruptions and recreations of the double layers at their borders. During the disruptions, bunches of charged particles are periodically released into the plasma, triggering low-frequency plasma instabilities that manifest as strong oscillations of the plasma parameters (e.g. plasma potential, ion and electron densities, discharge current). Under certain experimental conditions, these instabilities can lead to chaotic states of the plasma system through different scenarios [11,12].

In recent years, great attention has been paid to the investigation of the dynamics of such individual complex space-charge structures on various geometrical electrode configurations [13-20]. Thus, here we report on the investigation of the oscillatory behavior of a discharge with a spherical grid cathode with an orifice, a geometry that is used in applications like a DC-electron bombardment ion thruster [21]. For this, we recorded and analyzed the oscillations of the discharge current. First, a diagnosis of the complex space-charge structure was performed by using Langmuir probes and optical emission spectroscopy, in order to understand the phenomenology.

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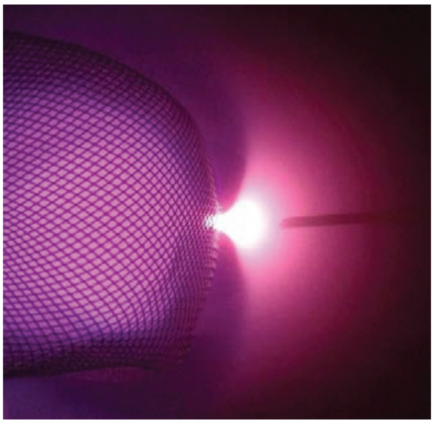

Fig. 1. Photo of the experimental arrangement for measuring the radial profiles of the plasma parameters.

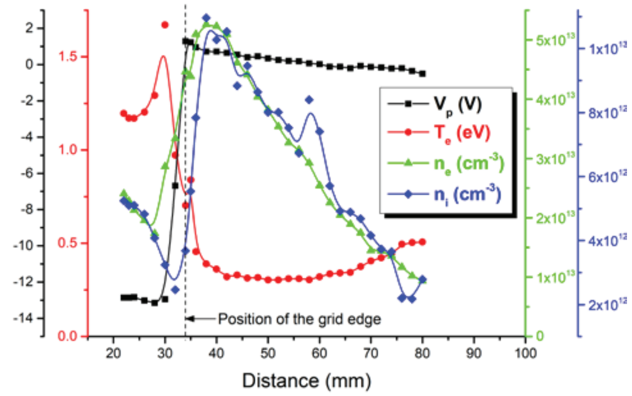

Fig. 2. Axial profiles of the plasma potential V_p, electron temperature T_e and density n_e, and ion density n_i, estimated from Langmuir probe measurements.

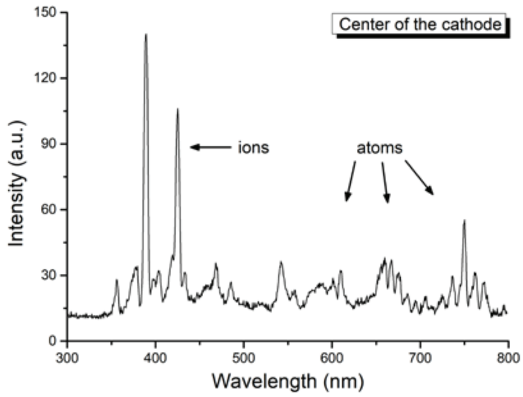

Fig. 3. Optical spectrum recorded from the center of the grid cathode.

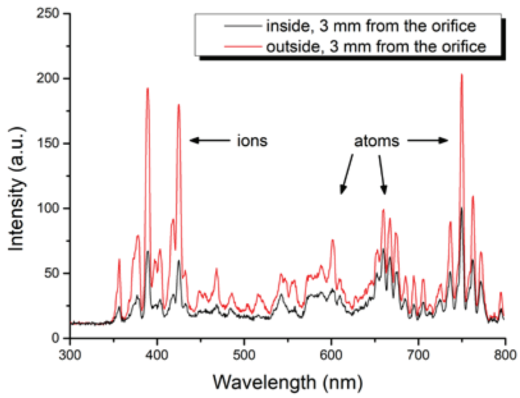

Fig. 4. Optical spectra recorded from the regions localized at 3 mm from the orifice, inside and outside the grid cathode, respectively.

II. Results and Discussions

The experiments have been performed in a plasma diode with grounded metallic walls acting as anode. The cathode is a spherical metallic grid with a diameter of 68 mm, the diameter of the wires being 0.1 mm, while the mesh width is 2 mm. A small orifice with a diameter of 6 mm was made in this cathode. A cylindrical Langmuir probe with 1 mm length and 0.125 mm diameter was used for diagnosis of the plasma near the cathode, movable in the axial direction through the orifice (see photo of the experimental arrangement in Fig. 1). Spectral measurements were performed by focusing the light coming from a small volume of plasma (1 mm^3) along the axis through the orifice onto the end of an optical fiber connected to a spectrophotometer. Argon was used as the working gas at the pressure $p = 5\times10^{-2}$ mbar. The applied discharge voltage was kept at $V_d = 400$ V during the electrical and spectral diagnosis.

Fig. 2 shows the axial profiles of plasma potential, electron temperature and density, and ion density. These were obtained by analyzing the probe characteristics recorded at every 2 mm on the axis, through the orifice. The existence of a double layer near the orifice can be observed in the axial profile of the plasma potential, with the potential drop close to the ionization potential of the used gas. This confirms the presence of a fireball in that region, which is also visually observed. The axial profile of the electron temperature presents a maximum inside the grid, at approximately 7 mm from the orifice. The axial profiles of both electron and ion densities present a maximum outside the grid, near the orifice, due to the ionization collisions between the electrons accelerated by the double layer and the neutrals.

Spectral measurements have evidenced the existence of a strong population of ions inside the grid cathode, which is due to the hollow cathode effect (see Fig. 3). For comparison Fig. 4 shows the spectra recorded at 3 mm from the orifice, inside and outside the grid cathode, respectively, revealing a strong increase of populations of both ions and excited atoms outside the grid. The data confirm the acceleration of the electrons in the double layer's potential drop to the energies high enough to produce excitation and ionization collisions with the neutrals in the region outside the grid cathode, near the orifice.

Time series of the discharge current were measured for different values of the discharge voltage V_d, by means of a digital oscilloscope with a sampling rate of 2.5 GS/s. They have revealed strongly nonlinear dynamics of the complex space-charge structures inside and around the grid cathode. Fig. 5 shows the evolution of the oscillatory state of the plasma system for increasing discharge voltage for an argon pressure of $p = 7.5\times10^{-2}$ mbar. The time series of the discharge current oscillations are shown in the left column, their Fast Fourier Transforms (FFT) in the central column and the reconstructed attractors of the plasma system's dynamics by the time delay method in the right column, respectively. This method is extensively described in [22].

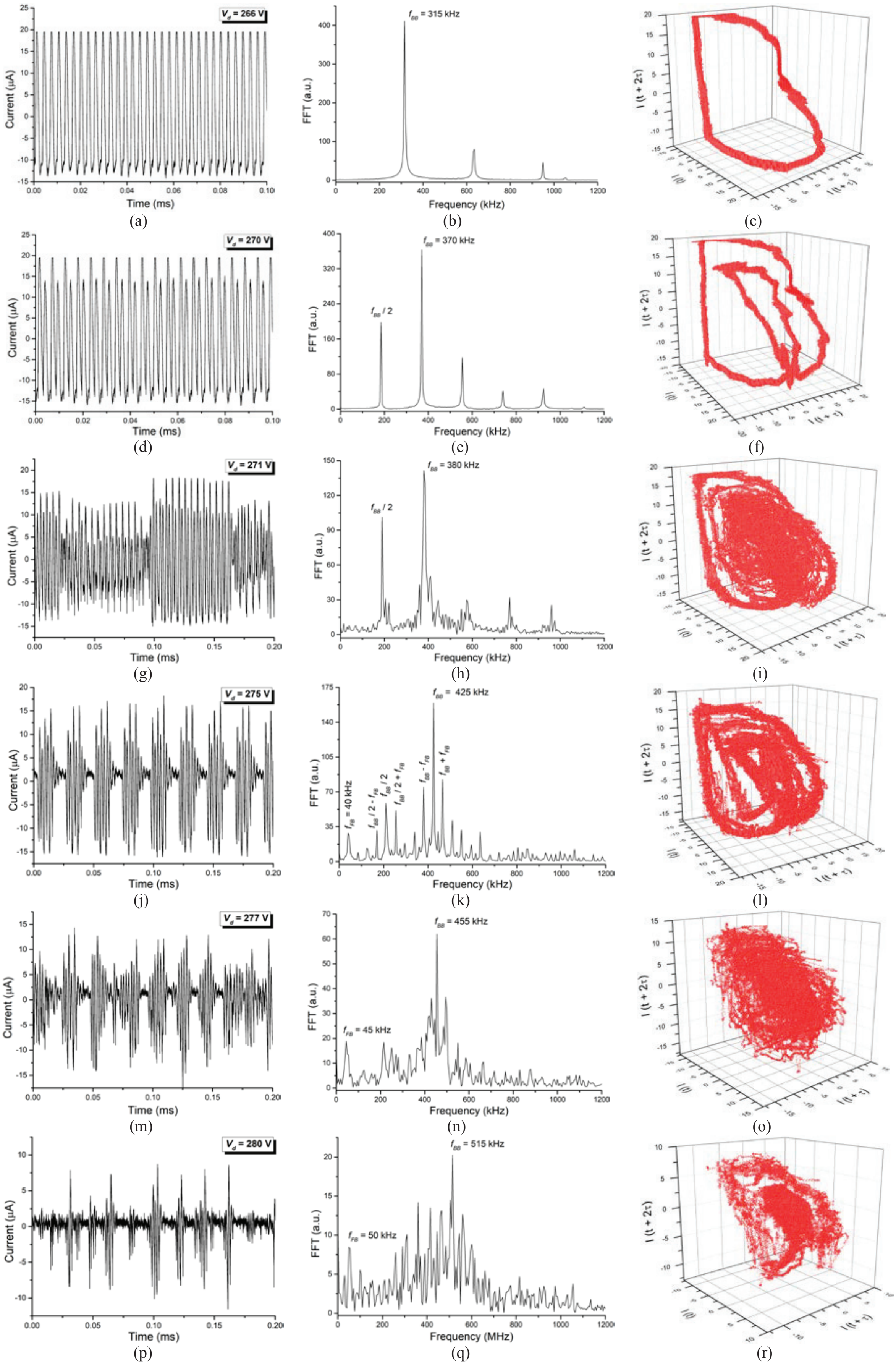

Fig. 5. Time series of the oscillation of the discharge current (left column), their FFTs (central column) and the reconstructed attractors of the plasma system dynamics by time delay method (right column), respectively, for different values of the applied discharge voltage (266 V, 270 V, 271 V, 275 V, 277 V and 280 V, respectively).

As it turns out, for V_d = 266 V the first space-charge structure that appears is the plasma bubble inside the grid cathode, due to the high rate of ionization processes in this region resulting from the hollow cathode effect. This structure is in a dynamic state, oscillating with a frequency of f_{BB} = 315 kHz (see Figs. 5a-c). By increasing the discharge voltage, for V_d = 270 V a double-period bifurcation appears in the plasma bubble dynamics, identified by the appearance of the first sub-harmonic ($f_{BB}/2$) in the FFT spectrum (Fig. 5e) of the discharge current oscillations (Fig. 5d), as well as by the splitting of the limit cycle (Fig. 5f), characteristic for oscillatory states of a dynamical system. At V_d = 271 V, a transient phase starts (see Figs. 5g-i) simultaneous with the development of the space-charge structures outside the grid cathode, including the fireball in the region of the orifice. The transient phase ends at V_d = 275 V, with complex dynamics involving oscillations modulated both in amplitude and frequency (Figs. 5j-l). Sidebands around f_{BB} and $f_{BB}/2$ peaks can be observed, with the frequencies $f_{BB} \pm f_{FB}$ and $f_{BB}/2 \pm f_{FB}$, respectively (see Fig. 5k), where f_{FB} is the frequency of the fireball dynamics. This is a common phenomenon in plasma, when two coupled oscillatory processes with comparable amplitudes exist [22]. In our case, the dynamics of the plasma bubble and fireball are coupled through the discharge current, the frequencies of both phenomena depending on its value [5,23]. Starting from V_d = 277 V, the level of noise in the system increases, leading to a weakening of the correlation between the two dynamics (see Figs. 5m-o) and the development of an intermittent route to chaos (see Figs. 5p-r).

III. Conclusion

Complex space-charge structures were obtained inside and around a hollow grid cathode with an orifice, in a low-temperature discharge plasma. Langmuir probe and spectral diagnosis revealed the presence of a plasma bubble inside the hollow grid cathode and a fireball near the orifice. The analysis of the time series of the discharge current oscillations, recorded for several increasing values of the applied discharge voltage, highlighted a strong interaction between the dynamics of the two structures, the fireball dynamics modulating in both amplitude and frequency the plasma bubble dynamics. For high values of the discharge voltage, the increase of the noise level in the plasma system leads to the development of an intermittent route to chaos.

Acknowledgment

This work was supported by the CEEPUS network AT-0063 and by a grant of Romanian Ministry of Research and Innovation, CNCS-UEFISCDI, project number PN-III-P4-ID-PCE-2016-0355, within PNCDI III.

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