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SELF-MODULATION OF A HOLLOW CATHODE DISCHARGE PLASMA DYNAMICS
I. EXPERIMENTAL

BY

BEDROS ANDREI AGOP[1,*], ȘTEFAN ANDREI IRIMICIUC[2] and DAN GHEORGHE DIMITRIU[2]

[1]"Gheorghe Asachi" Technical University of Iași,
Faculty of Material Science and Engineering
[2]"Alexandru Ioan Cuza" University of Iași,
Faculty of Physics

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Abstract. A discharge plasma with the hollow cathode in form of a spherical grid with a hole was experimentally investigated. Two complex space charge structures appear: a plasma bubble inside the cathode and a fireball localized outside the cathode, near the hole, respectively. These two structures exist in dynamic states, oscillations of the discharge current being recorded. A self-modulation of the plasma system dynamics was evidenced in the time series of discharge current oscillations. This phenomenon is due to the dependence of the oscillations frequency on the current and the coupling between the two structures through the plasma.

Keywords: plasma; hollow cathode; self-modulation; fireball.

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[*]Corresponding author; *e-mail*: andrei.agop@yahoo.com

1. Introduction

According to National Aeronautics and Space Administration (NASA), European Space agency (ESA), Japan Aerospace Exploration Agency (JAXA), Marshall Space Flight Centre, etc., one of the main objectives of the future aerospace missions will be focused on the next generation of microsatellites (Alderson *et al*., 2003). Also, NASA and ESA space technology programs, like Gravity Recovery and Climate Experiment (GRACE), Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), Microscope, or Laser Interferometer Space Antenna (LISA) Pathfinder, emphasized the importance of small spacecraft as dominant trend in aerospace. Both the microsatellites and the small spacecraft will need novel propulsion technologies.

Plasma thrusters proved to be good candidates for space propulsion, since they deliver a high specific impulse and allow long-term space missions (Lemmer, 2017). Ion and Hall thrusters use hollow cathodes and the properties of the cathode material, the geometry of the hollow cathode and the structure of the cathode plasma determine the performance and life of both types of thrusters (Goebel and Katz, 2008).

Here we report on the experimental investigation of a hollow cathode discharge plasma that can be suitable for application as plasma thruster. The cathode is a spherical grid with a hole. The Paschen's curve and the current-voltage characteristics of the discharge were obtained in order to establish the working parameters of the discharge. During the discharge, two complex space charge structures appear: a plasma bubble inside the cathode and a fireball outside the cathode, near the hole. These structures exist in dynamic states, oscillations of the discharge current being recorded. A self-modulation of the plasma system dynamics was evidenced in the time series of the discharge current, due to the coupling between the individual dynamics of the two complex space charge structures.

2. Experimental Results and Discussion

The experiments were performed into the hollow cathode discharge plasma diode from Self-Organization Laboratory of the Faculty of Physics, "Alexandru Ioan Cuza" Univeristy of Iași, Romania, schematically shown in Fig. 1. The diode is made by glass, the anode is a rectangular tantalum plate of 25 cm × 20 cm size, while the cathode is a spherical metallic grid with a diameter of 4 cm (with 0.5 mm the diameter of the metallic wires and 2 mm the mesh width), having a small hole with the diameter of about 6 mm on one side. The distance between the cathode and anode is d = 25 cm. For experiments, argon has been used as working gas.

To establish the optimal parameters for the discharge, the Paschen's curve was obtained by recording the discharge breakdown voltage function of the gas pressure, the distance between the anode and the cathode being kept constant. The result is shown in Fig. 2, from which it can be observed that the minimum of the breakdown voltage, of approximate 300 V, corresponds to a value of the argon pressure of approximate 10^{-1} mbar.

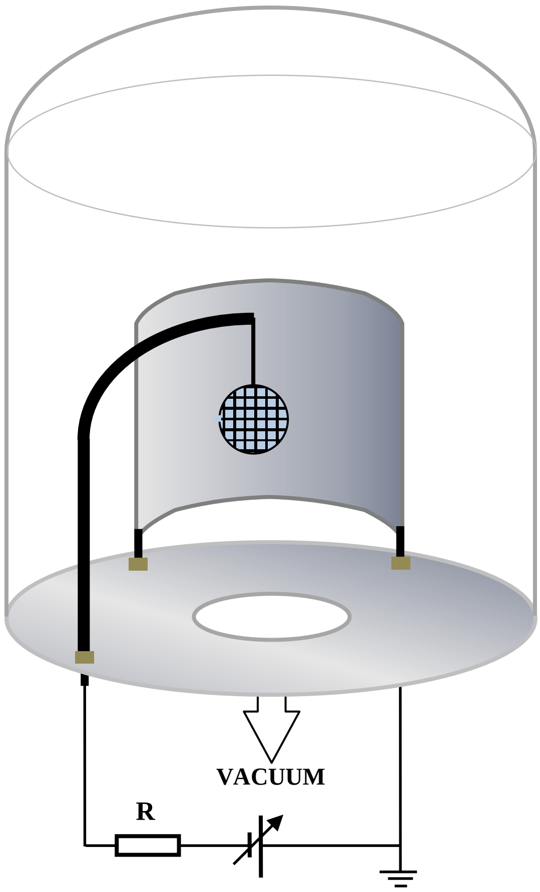


Fig. 1 – Experimental setup.

Fig. 3 shows the static current-voltage (*I*-*V*) characteristic of the discharge, obtained by recording the dc component of the discharge current simultaneously with the increasing and subsequent decreasing of the voltage applied to the discharge. By changing the discharge voltage, the complex space charge structures inside and around the hollow cathode pass through different stages. Thus, at the increasing of the discharge voltage, after the small current jump A→B (see *I*-*V* characteristic in Fig. 3), a diffuse spherical structure appears inside the cathode, while a strong electron beam escape from inside the cathode through the hole, producing excitations and ionizations of the gas atoms along the direction of propagation (see photo in Fig. 4*a*). In this stage, there is no breakdown of the discharge, but the increasing of the current is due only to the ionizations of the gas atoms inside the cathode, amplified by the hollow cathode effect, and to the electrons escaping from the cathode through the hole, which produce local ionizations of the gas atoms along the direction of propagation. The plasma bubble (Stenzel and Urrutia, 2012a, b, c, d) inside the cathode appears due to the electron-neutral impact excitations and ionizations processes, a high density of electrons existing there because of the hollow cathode effect.

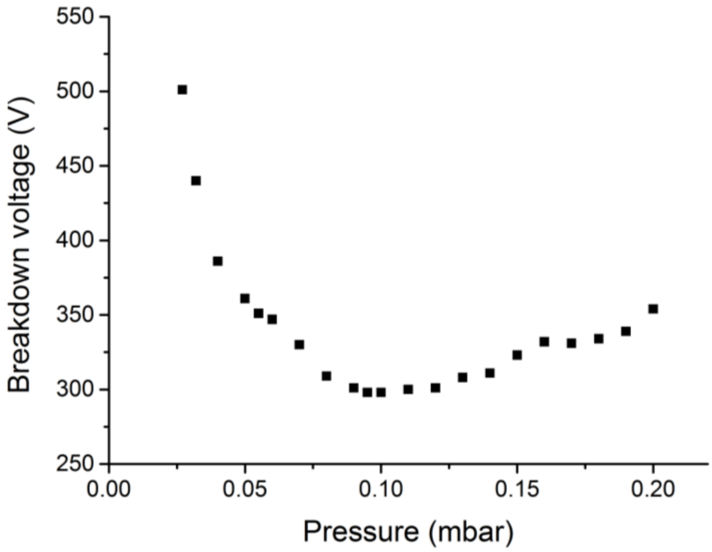


Fig. 2 – Paschen’s curve for argon and 25 cm distance between the cathode and anode.

By further increasing the discharge voltage, a strong jump of the current appears in the current-voltage characteristic (marked by C$\rightarrow$D in Fig. 3), corresponding to the breakdown of the discharge. In Fig. 4*b* it can be observed the negative glow of the discharge around the cathode, which is coupled with the bubble inside the cathode through an asymmetric fireball. The right part (towards the cathode) of this fireball is smaller and penetrates inside the cathode through the hole, while its left part (towards the negative glow of the discharge) is larger and diffuse into the negative glow. The increase of the voltage up to the discharge breakdown voltage leads to an increase of the luminous intensity of the structures (see Fig. 4*c*), while the fireball becomes more and more asymmetric, its left part strongly increasing and expanding into the negative glow of the discharge, while the right part is expulsed outside the cathode in the vicinity of the hole.

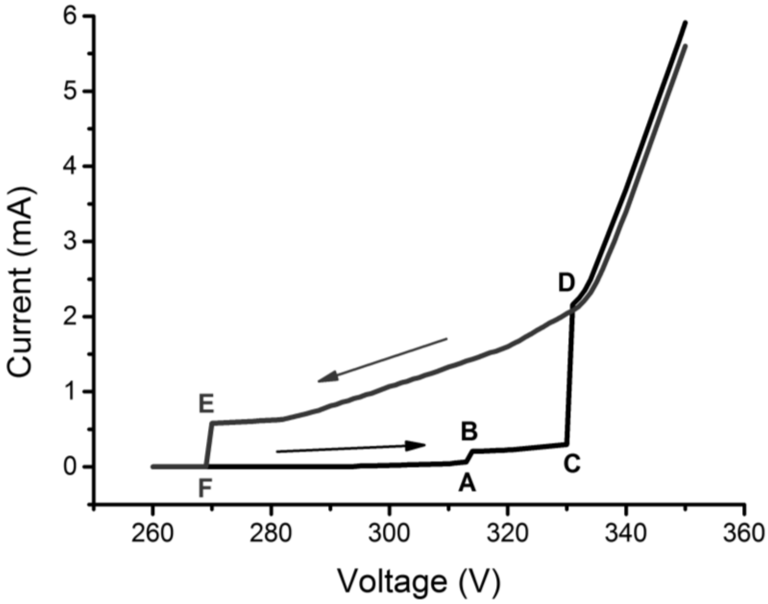
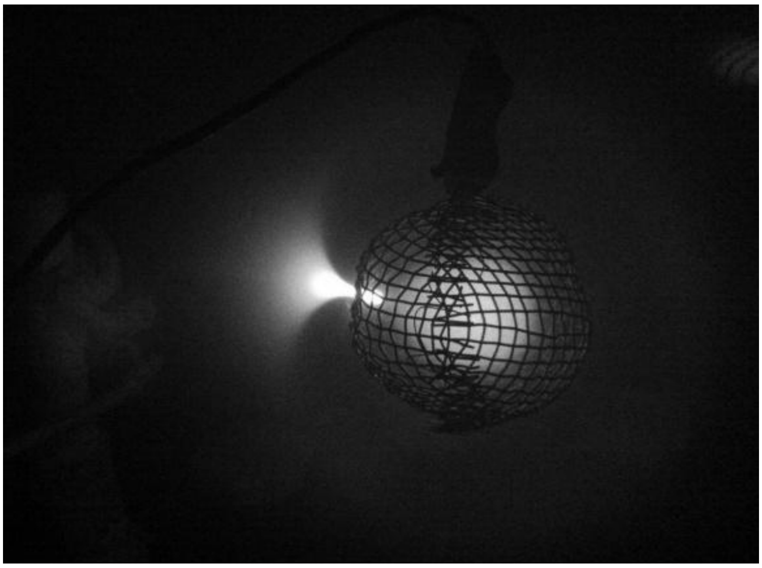


Fig. 3 – Static current-voltage characteristic of the discharge.

a

b

c



d

Fig. 4 – Photos of the complex space charge structures inside and around the cathode, in different stages of their development.

When the discharge voltage is decreased, a large hysteresis (of about 60 V) can be observed (as expected) in the static *I-V* characteristic of the discharge (Fig. 3), in connection with the breakdown and quenching of the discharge. The fireball decreases in dimension and luminosity, being almost symmetrical (see photo of the structure in Fig. 4*d*). Its right part penetrates again inside the cathode. In this state, on the branch D→E of the static *I-V* characteristic (Fig. 3), interesting nonlinear dynamic phenomena were observed by investigating the time series of the discharge current oscillations.

The time series of the discharge current oscillations were recorded with a sampling rate of 2.5 GS/s. Fig. 5 shows such a time series, recorded for a discharge voltage value U = 289 V. Fig. 6 shows details from this time series (on the left column) and their corresponding fast Fourier transforms (FFT) (on the right column). Different dynamic states can be observed. These states are the result of the nonlinear interaction between the individual dynamics of inner plasma bubble and the fireball, respectively. Both structures exist in dynamic states, the oscillation frequency depending on the value of the current (Stenzel and Urrutia, 2012a, b, c, d; Niculescu *et al.*, 2010). The inner plasma bubble periodically release bunches of electrons, which act as forcing drive of the oscillating fireball. The fireball passes through different dynamic states as the forcing frequency changes because of the modification of the discharge current value. In other words, the forcing frequency determines the dynamic state, *i.e.* the amplitude and frequency of the discharge current oscillations, which, at their turn, modify the frequency of the inner bubble dynamics, *i.e.* the forcing frequency. In this way, a continuous self-modulation of the plasma system dynamics exists, as can be observed in Figs. 5 and 6.

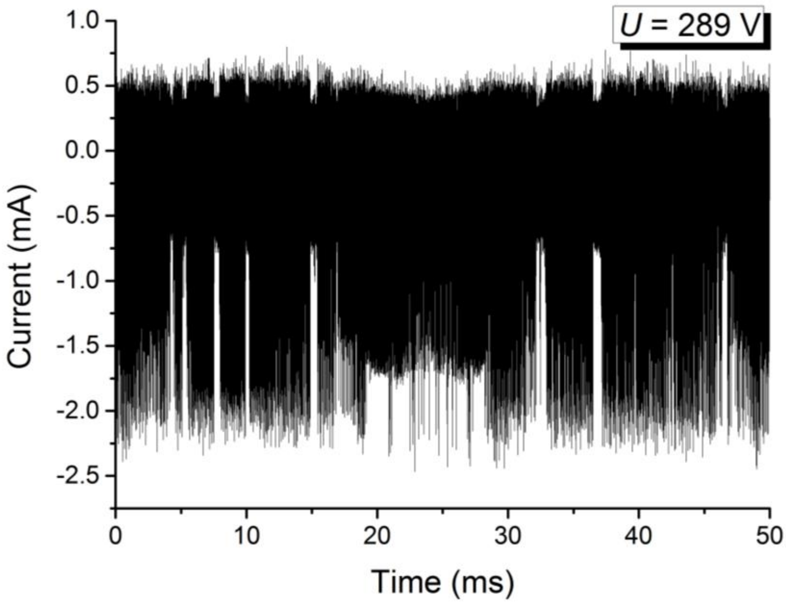
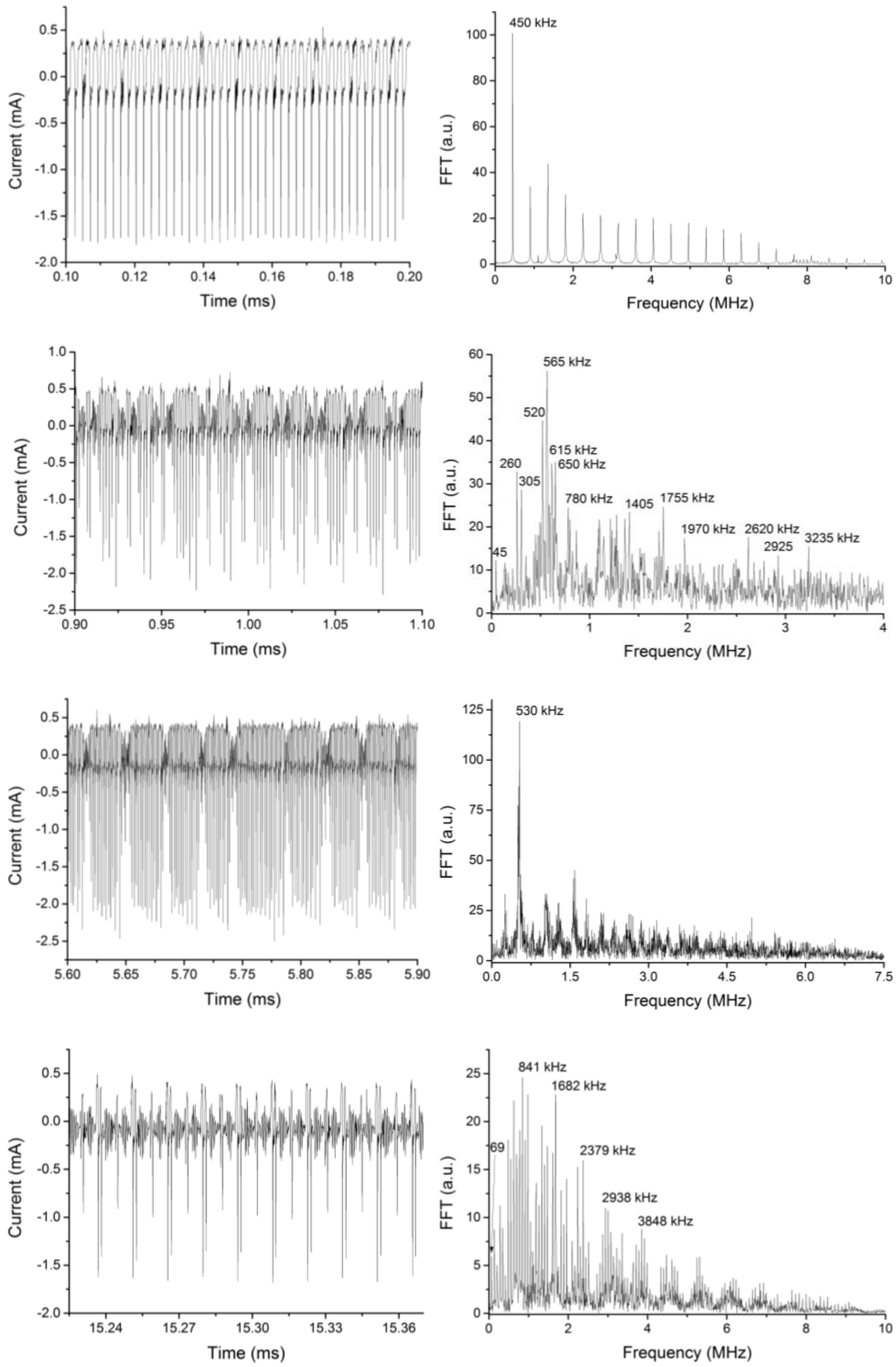


Fig. 5 – Time series of the discharge current oscillations for the value of the discharge voltage U = 289 V.

3. Conclusions

A hollow cathode discharge plasma was experimentally investigated, the cathode being a spherical metallic grid with a hole. Two complex space charge configuration appears, namely a plasma bubble inside the cathode and a fireball outside the cathode, near the hole. The static current-discharge characteristics evidenced two current jumps and a strong hysteresis, related to different states of the discharge plasma. Self-modulation of the plasma system dynamics was evidenced in the time series of the discharge current oscillations, due to the nonlinear interaction of the individual dynamics of the complex space charge structures.


Current (mA)
Time (ms)
FFT (a.u.)
Frequency (MHz)
450 kHz
565 kHz
520
260
305
615 kHz
650 kHz
780 kHz
1405
1755 kHz
45
1970 kHz
2620 kHz
2925
3235 kHz
530 kHz
841 kHz
1682 kHz
69
2379 kHz
2938 kHz
3848 kHz

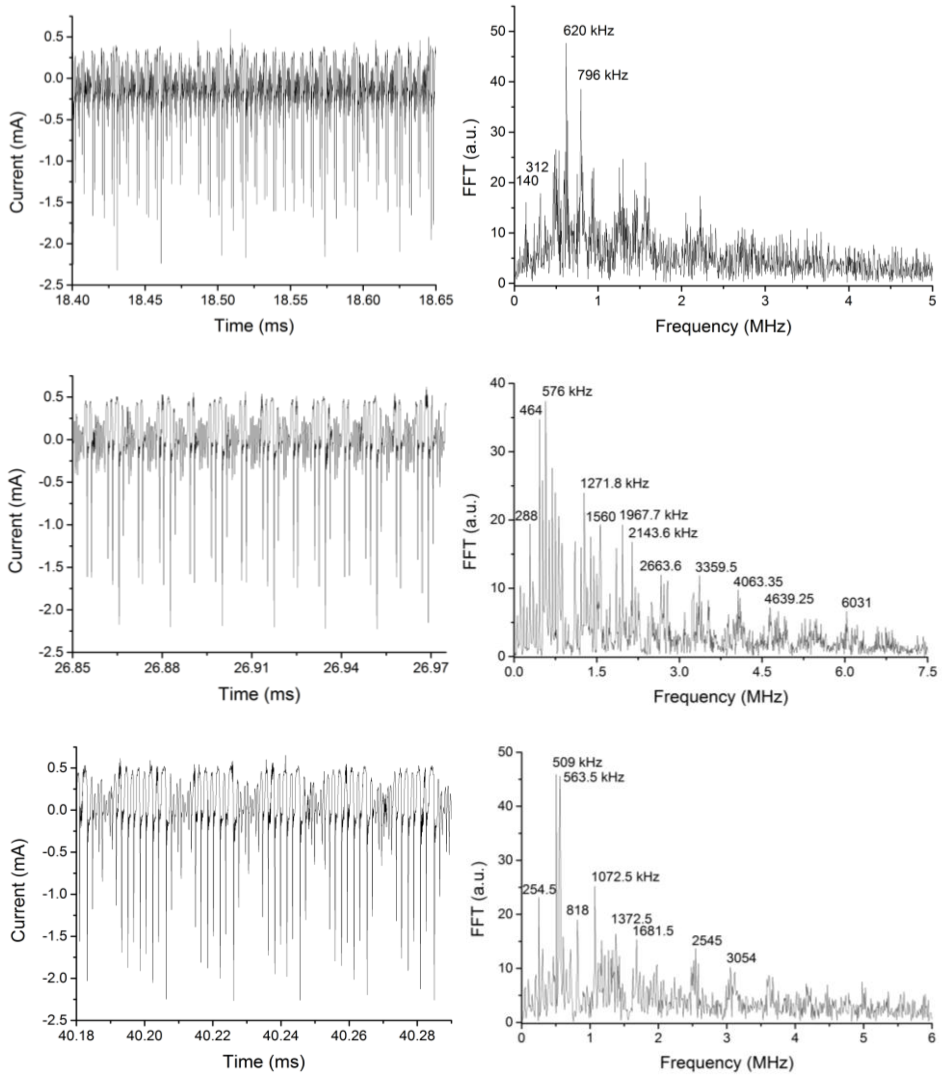


Fig. 6 – Details of the time series of the discharge current oscillations from Fig. 5 (left column) and their corresponding FFTs (right column).

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AUTOMODULAREA DINAMICII UNEI PLASME DE DESCĂRCARE CU CATOD CAVITAR
I. Experiment

(Rezumat)

A fost investigată experimental o plasmă de descărcare cu catod cavitar sub forma unei grile sferice cu un orificiu. S-a observat apariția a două structuri complexe de sarcini spațiale: o bulă de plasmă în interiorul catodului, respectiv o minge de foc localizată în exteriorul catodului, în vecinătatea orificiului. Aceste două structuri se află în stare dinamică, fiind înregistrate oscilații ale curentului de descărcare. În seriile temporale corespunzătoare oscilațiilor curentului de descărcare a fost evidențiat un fenomen de automodulare a dinamicii sistemului cu plasmă. Acest fenomen se datorează dependenței frecvenței oscilațiilor de valoarea curentului, precum și cuplajului prin plasmă a celor două structuri.