PHENOMENA OBSERVED IN LABORATORY PLASMAS RELEVANT FOR THE SO-CALLED ANOMALOUS TRANSPORT OBSERVED IN PLASMA DEVICES

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The storage of matter and energy in confined plasma configurations is limited by an intermittent loss of particles and energy, usually referred to as anomalous transport. For tentatively explaining this phenomenon, we present in this paper experimental evidence of intermittent shelling off of electrical double layers generated at the border of confined plasma following a self-organization scenario. Moving against the electrons kinetic energy gradient, these structures enable the anomalous transport of matter and energy from the plasma to the surrounding. Our study can be related to the flicker noise observed in fusion devices, phenomenon associated with the loss of particles and energy from confined plasma.

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1 Introduction

Explaining the physical basis of the so-called anomalous transport observed in fusion devices is of a great interest nowadays [1]. Similar problems had not raised a special interest in usual plasma devices although, as recently shown, such phenomenon could explain one of the essential parts of plasma oscillation theory [2], namely the cause determining the stimulation of different kinds of natural frequencies [3–6]. Thus, Space Charge Configurations (SCC), whose self-confinement has its origin in the presence of an electrical Double Layer (DL) located in front of the anode of a plasma diode, are able to stimulate ion acoustic oscillations [5, 7]. The stimulation mechanism involves an intermittent extraction of particles and energy from the SCC during the self-assemblage and the shelling off process of the DL from its border. The oscillations of the clouds of positive ions around a negatively biased grid observed in a DP machine could be explained in the same way [8].

In this paper we present new experimental results concerning the mechanism by which DLs intermediate particles and energy transport from a self-confined SCC produced in a cold plasma device to the surrounding and, implicitly, the cause of flicker noise appearance. We start from the well established fact that a sufficiently strong gradient of electrons kinetic energy is able to produce a separation of the regions where the excitation and ionization cross section functions suddenly increase. This initiates a self-organization phenomenon whose final product is a SCC

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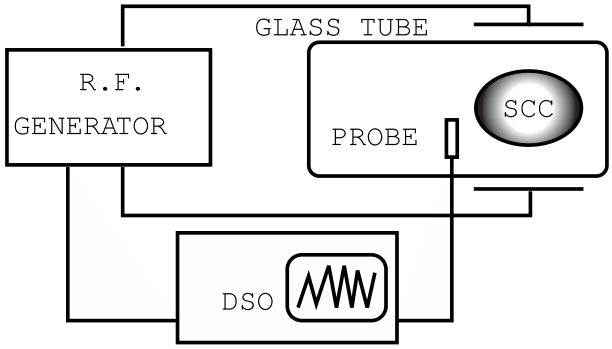

Fig. 1. Experimental device

bordered by a nearly spherical DL [3–6]. When the gradient of electrons kinetic energy exceeds a certain critical value, the SCC transits into a steady state. A rhythmic matter and energy exchange with the surrounding plasma ensures its existence [5, 6]. This exchange is realized by a mechanism driven by internal causes that initiates the shelling off of the DL from the SCC border.

2 Experimental results and discussion

The dynamics of the DL bordering a SCC obtained in a Radio-Frequency (RF) discharge, known as a radio frequency "plasmoid", was studied. The experimental setup, schematically presented in Fig. 1, consists of a capacitively coupled discharge obtained in a glass tube, 60 mm in diameter, placed between two plate electrodes connected to a RF power supply. The working gas was Argon at 1 Pa. The r.m.s. output voltage $(V_{\rm rms})$ of the RF supply was continuously varied by the mean of the potential applied to its control input. As the response parameter of the system we used the control grid current (E) of the RF supply, whose value decreases when the amount of the absorbed energy is rising. The two mentioned parameters were recorded using both a digital multimeter (DM) and a digital storage oscilloscope (DSO). The applied sine peak-to-peak voltage ranged from 0V to a few tens of volts at a frequency of 100 MHz. Therefore the necessary conditions determining the control of the discharge by the secondary electrons emitted by the glass wall were fulfilled [9].

The E versus $V_{\rm rms}$ characteristic (Fig. 2) emphasizes a nonlinear behavior of the plasma. When $V_{\rm rms}$ was gradually increased one could observe that E had abrupt variations for certain critical values. $V_{\rm rms}$ was initially set at a value for which a usual HF discharge was ignited in the glass tube $(V_{\rm rms} = V_1)$. Decreasing $V_{\rm rms}$, the well-localized SCC suddenly appeared inside the tube when $V_{\rm rms} = V_3$. It had the appearance of a luminous ellipsoidal body, namely the plasmoid. Its spontaneous self-assemblage was accompanied by a sudden fall of E, indicating a strong energy absorption and thus a passage to a resonant state [10]. Moreover, E evidenced

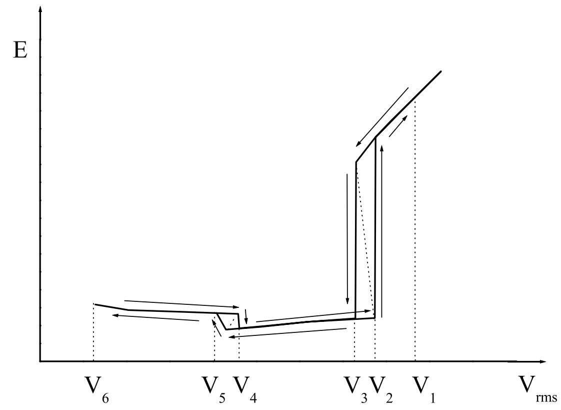

Fig. 2. Dependence of E versus V_{rms} characteristic of the RF plasmoid

periodic variations with a base frequency f_m in the range of tens of kHz. A further decrease of V_{rms} determined an increase of E for a certain critical value of V_{rms} $(V_{\mathrm{rms}} = V_5)$, indicating that the SCC absorbed less energy from the power supply. Moreover, its border became sharper, its luminosity increased and E became constant, showing that the plasmoid was in a stable state. No significant modification could be observed in the plasmoid behavior for further diminution of $\mathrm{V}_{\mathrm{rms}}$. For a new critical value of V_{rms}, when $V_{\mathrm{rms}} = V_6$, the plasmoid disappeared. If the critical point V_6 was not reached, V_{rms} could be increased without disabling the plasmoid. After a small decrease of E at $V_{\mathrm{rms}}V_4$ the plasmoid became diffuse and E was periodically varying again. The forthcoming increase of V_{rms} had as an effect the instant disappearance of the SCC for $V_{\mathrm{rms}} = V_2$ and the passage to a common "diffuse" RF discharge.

Our analysis focuses on the system behavior for V_{rms} ranging between V_5 and V_2. As mentioned, in these experimental conditions E evidenced a modulation with frequencies in the domain of tens of kHz. Analyzing the power spectra of the temporal series recorded as variation of E, one can remark that one well-defined frequency f_1 with its harmonics (Fig. 3) is present for low values of V_{rms} in the $V_5 - V_2$ range. When V_{rms} is increased, a second incommensurate frequency f_2 with its harmonics emerges (Fig. 4). The two frequencies are both present within a certain range of the control parameter, V_{rms}, the magnitude of f_2 becoming negligible if V_{rms} is further raised.

This behavior is determined, as already shown [11], by the dynamics of DLs successively generated at the border of the SCC (plasmoid). The scenario of this dynamics involves elementary processes, namely excitation and ionization of neutrals by electron collisions. These processes are taking place in two adjacent regions, determining the accumulation of opposite space charges and the genesis of a DL that borders the plasmoid. At a certain critical value of the absorbed energy, the region where electrons experience excitations is shifted away from the plasmoid border and the DL is moving toward the tube wall, where it disrupts. Electrons released by this disruption trigger the shelling off of a newly formed DL and the process becomes peri-

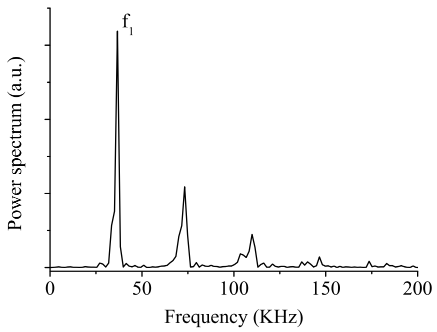

Fig. 3. Power spectrum of E performing one basic frequency

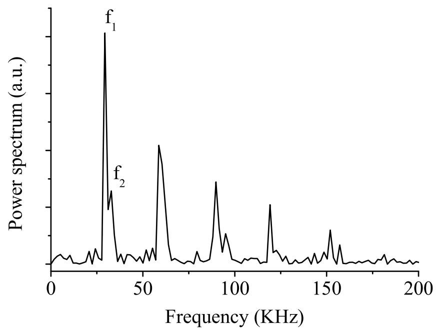

Fig. 4. Power spectrum of E performing two basic frequencies

odic. Therefore, the lead frequency emerging in the power spectrum of E can be determined by the shelling off process of the DL. The second frequency f_2 can be correlated, in our opinion, with the formation and the dynamics of a concurrent second DL at the border of the plasmoid. Experiencing their own dynamics, the two DLs meantime created determine the co-existence of two frequencies in the power spectrum. If E is further raised, the strong value of the external constraint determines a coupling between the two DLs and the f_2 frequency vanishes from the power spectrum.

One can remark the existence of a S-shaped hysterezis (marked by dotted line) in the E versus V_{rms} characteristic. It appears between V_2 and V_3, revealing a bistable behavior of the system. If particular discharge conditions are chosen, minimizing the hysterezis width, this bistable behavior is replaced by intermittent appearances and disappearances of the SCC. The second bistability phenomenon appears in the range $V_5 - V_4$ revealing a Z-shaped hysterezis. This can be associated to the transition between the stable and unstable states of the DL at the SCC edge.

Phenomena like abrupt changes of the plasma conductivity, emphasized in the $E - V_{\mathrm{rms}}$ characteristic and the bistable behavior, can be easily explained by the physical phenomena leading to the SCC formation in a RF discharge. Thus, when the RF voltage exciting a common RF discharge is gradually decreased, the discharge becomes more and more dependent on processes like secondary electron emission at the glass wall [9]. In a common RF discharge the potential of the middle region is higher than the one of the border regions. Therefore, the physical phenomena become similar to those taking place in a DC discharge between the “cathode region”, represented by the plasma borders at the tube walls, and the “gaseous anode”, represented by the central positive region of the discharge placed on the tube axis. For each half period of the external applied RF electric field, a bunch of electrons is extracted from the plasma and is accelerated toward one of the walls, producing spatially localized low-energy secondary electrons. On the next half period these electrons are accelerated toward the central region of the plasma column. A part of them produces exciting collision with neutrals, loosing their kinetic energy. Consequently, low-energy electrons are accumulated at a certain distance in front of the walls, forming a net negative space charge. Acting as a barrier for other electrons, this region behaves as a region with an anomalous electrical resistance, accumulating all the low-energy electrons passing through it. Because only a part of the electrons accelerated toward the tube axis produces neutrals excitation, the rest of them could accumulate energies for which they are able to ionize the neutrals at a larger distance than those corresponding to excitation processes. The electrons rapidly leave this last region by drift motion, due to their high mobility with respect to the ions. Therefore, a plasma region enriched in positive ions appears between the negative space charge and the tube axis. This positive space charge will supplementary accelerate the electrons coming from the tube walls. Long-range electrostatic forces establish between the two opposite charge space regions. These forces modify the charge carriers distributions and correlate them so that space charge regions can suddenly re-arrange into a DL. Because the lifetime of this charges arrangement is longer than the period of the RF oscillations, the two DLs formed during each half-period persist until the next cycle of DL formation proceeds. As a consequence, when $V_{\rm rms} = V_3$, two symmetrically placed DLs develop in the plasma. The long-range electrostatic forces tend to shape the space charge forming the DL in a way providing a minimum for the potential energy. Therefore, when the DLs potential energy increases enough, they are spontaneously self-assembling in a nearly spherical SCC positioned along the tube axis.

This self-assemblage mechanism involves that electrons accelerated in the potential drop developed across the DL obtain energies for which a self-enhancement of the production rate of positive ions is initiated. This also means that the DL potential drop has to be about the same with the ionization potential of neutrals. This process is initiated by the local increase of the concentration of positive ions in the region where the ionization cross section function is raising abruptly, in the same way as in the case of the SCC in a DC discharge. This increase of the ion concentration determines an additional increase of the DL potential drop, initiating a forthcoming increase of the production rate of positive ions. As a result, a DL expanding off process takes place. The spreading of the self-enhanced process of the production of positive ions and the expansion of the DL is not stopping until the SCC border reaches the border region of plasma. This process occurs concurrently with the additional negative charge accumulation at the low side of the DL, as in the case of a DC discharge.

The SCC appears in a non-stable state rather that in a stable one. This behavior can be explained considering that the SCC is appearing for the highest critical value of $V_{\rm rms}$ in the $E - V_{\rm rms}$ characteristic. At this point, the production rate of secondary electrons at the tube wall and the plasma parameters (e.g. plasma density) are so high that the DL surface increases due to its expansion and can no longer compensate the increase of the electron energy and flux through its surface. This expansion stops only at the plasma boundary where the DL de-aggregates. The same processes that has lead to its formation could initiate the development of a new DL. This occurs when the previously formed DL is sufficiently far from the central region, so that its influence becomes negligible, or immediately after its de-aggregation – depending on the discharge parameters. The de-aggregation of the DL releases a part of the charge carriers (especially electrons that have higher mobility). This influences the evolution of the newly formed DL and, consequently, a mechanism of coupling between the two DLs dynamics develops. The SCC can maintain its non-stable state for $V_{\rm rms}$ values between V_2 and V_5, ending by gradually turning on to a stable state. When $V_{\rm rms}$ is varied between V_4 and V_6, the electron production rate at the wall becomes so small that the expansion of the DL and its surface increase can determine the flux of electrons and their energy to fit the DL stability condition. The inverse transition in $V_{\rm rms} = V_4$ is, evidently, more abrupt. For $V_{\rm rms} = V_6$ the secondary emission at the wall is so weak that the

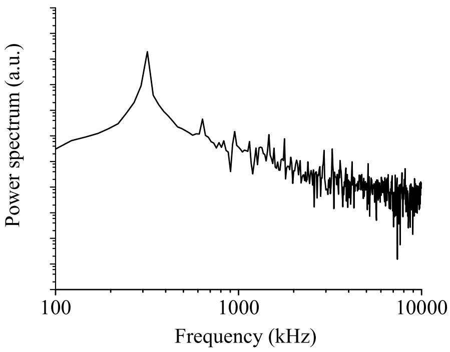

Fig. 5. The $1/f$-like spectra of E

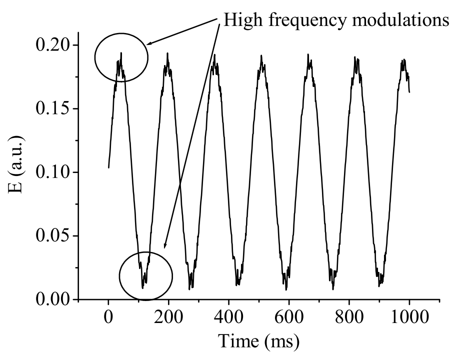

Fig. 6. Modulations of E

DL existence conditions can not be satisfied. The SCC suddenly disappears and the discharge turns off.

These experimental results allowed us to perform an analysis of the power spectrum generated by the RF SCC (Fig. 5) which exhibits the so call "flicker noise" phenomenon. The spectrum results from the overlap of frequencies due to the following: phenomena in the range of hundreds of Hz related to the intermittent disruption and formation of the SCC as a whole, phenomena in the time scale of tens of kHz related to the DL shelling off processes and, finally, phenomena taking place at frequencies above hundreds of kHz related to the development of the DL negative side as a "fine" structure. The influence of the "fine" structuring of the DL due to the existence of several levels of the neutrals excitations can also be observed in the shape of the modulation of the electric field in the discharge region (Fig. 6). Because the electric field is dependent on the plasma conductivity and therefore on the number of electrons released or captured by the DL, the "fine" processes involved in DL appearance and disappearance will have an impact on the field modulation.

3 Conclusions

In this paper we reported on a new experiment studying the loss of particles and energy from a self-confined SCC by means of the shelling off from its border. The DL is self-assembled in the region where a sufficiently strong gradient of electrons kinetic energy is present. This gradient ensures the spatial separation of the regions where the electrons cross section functions for impact excitation and ionization of neutrals steeply increase. In our plasma device, this gradient is generated by the local acceleration of electrons in the RF electric field. Comparing the experimental conditions with those existing in magnetically confined plasma, like in a fusion device, some similarities can be pointed out. Thus, in a magnetically confined plasma the gradient of electrons kinetic energy is present at the edge of the plasma column, where the temperature of the plasma undergoes strong variations. For example, in the Caltech tokamak [12], the edge parameters are in the range $T_e = 10 \div 50$ eV and the plasma density $n = 10^{17} \div 10^{19}$ m^{-3}. The neutral excitations are evidenced by the light emitted by edge fluctuations in the TFTR Tokamak [13]. In our opinion, under such conditions, the premises for the formation of DLs could arise, considering a self-organization mechanism similar to those present in non-fusion plasma. Consequently, we presume that the anomalous transport of particles and energy through the agency of DLs could explain the flicker noise observed in fusion devices. Since the increase of the energy injection determines a raise of the DLs frequency, the loss of particles and energy from the confined plasma could increase with the injected energy. An attempt to prevent that such undesirable phenomenon takes place in a fusion plasma device could be done by modifying the magnetic field profile in such a manner that the spatial distribution of the gradient of electrons kinetic energy determines the appearance of DLs moving towards the inside of the confined plasma. Finding such a magnetic field profile, if possible, is a problem of further theoretical and experimental studies.

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