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On the Origin of Flicker Noise in Various Plasmas

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Abstract

The current-voltage characteristic of a bounded plasma system often shows more or less strong fluctuations superimposed on the average current. Often these fluctuations are correlated with the formation of complex space charge configurations, which in turn lead to the transport of charged particles and energy through the plasma. A comparison of the fluctuation spectra obtained from (i) a plasma diode, (ii) a high frequency plasmoid and (iii) a Q-machine shows certain similarities that could indicate a common basis for the anomalous transport of matter and energy associated with such space charge structures. Whereas the plasmas in a plasma diode and in a plasmoid are collisional, a Q-machine plasma is usually presumed to be collisionless. The similarities are tentatively explained by considering a self-organization process of the space charge structures, which is able to successively generate double layers. The matter and energy stored in these double layers are transported simultaneously with their transition into a self-sustained propagating state.

Keywords:

self-organization, double layer, flicker noise, fireball, plasmoid, Q-machine

1. Introduction

A plasma driven away from thermal equilibrium can perform a spontaneous transition towards a critical state, where an intermittent exchange of matter and energy with the surroundings ensures a kind of dynamical stability, which is particular to systems resulting from a self-organization process [1]. This self-organization process becomes possible when an external constraint produces a local gradient of the kinetic energy of the electrons, which leads to a spatial separation of the regions where the excitation and ionization cross section functions of neutrals maximize. Such phenomena were observed in non-fusion collisional plasma. They can explain the stimulation of different kinds of instabilities that appear when the system is able to perform natural oscillations [2,3].

Recent investigations in non-fusion collisional plasmas [4] have yielded characteristic fluctuation spectra [5-7] that are considered as a sign for self-organized criticality (SOC). In such spectra, in a certain range, the amplitude is proportional to $1/f$ (f being the frequency), wherefore we speak of $1/f$-noise or flicker noise. A SOC-system can be defined [8] as: (i), a medium through which (ii) a disturbance propagates, which causes (iii) a modification of the medium, so that (iv) eventually the medium attains a critical state, after which (v) the medium is modified no more.

2. Experimental Results and Discussion

In the following we will compare the noise spectra of three strongly different plasma devices: (i) a dc

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plasma diode in which a complex space charge configuration (CSCC) was formed, (ii) a high frequency (hf) discharge in which a plasmoid was created and (iii) a Q-machine. It is generally presumed, that the cold alkaline plasma of a Q-machine is collisionless, and that such a plasma is able to simulate experimentally some of the phenomena in magnetic fusion devices. The presence of inelastic collisions in a low pressure plasma, like that of a Q-machine, is not only possible but necessary in order to explain the striking similarities between the experimental results obtained in so different plasma devices, like those aforementioned [3]. Moreover, the arguments for the presence of inelastic collisions under special working conditions in a Q-machine are given in [5,9].

We start our considerations by pointing out some of the similarities in the initial conditions, or the causes for the appearance of flicker noise in a Q-machine, in a plasma diode and in a fusion plasma. In a fusion device the anomalous transport of matter and energy takes place perpendicular to the edge (and to the magnetic field lines that confine the plasma column). In this region strong temperature gradients result in strong gradients of electron kinetic energy $E_{e,kin}$. As we will show in this paper, in a Q-machine, as well as in a plasma diode, the anomalous transport of matter and energy has its origin in double layers (DLs) created in front of the positively biased cold plate (CP) or electrode (E), respectively. In this region a strong gradient of $E_{e,kin}$ is maintained by a local acceleration of electrons. In all cases the anomalous transport takes place into a direction corresponding to the gradient of $E_{e,kin}$. However, in this case the gradient of $E_{e,kin}$ is parallel to the magnetic field.

The experimental devices are schematically presented in Fig. 1(a), Fig. 2(a) and Fig. 3(a) respectively. The *I-V* characteristic shown in Fig. 1(b) was obtained from the plasma diode. In the case of the hf plasmoid, the dependence of the absorbed power versus the injected one from a Hartley oscillator are monitored via the control grid current I_g and the screen grid voltage V_s respectively. The I_g - V_s characteristic has a similar shape, as shown in Fig. 2(b). The self-organization process that explains the origin of the strong non-linearity of the I_g - V_s characteristic was already described in detail elsewhere [10]. Fig. 3(a) presents the Q-machine of the Institute for Ion Physics, University of Innsbruck. In this case a potassium plasma with a density $n_{pl} \cong 10^7$ cm^{-3} was produced by surface ionization on the hot plate (HP) and magnetically confined between the HP and the CP. The dependence of the current I_{CP} collected by the CP versus the voltage V_{CP} applied on the same electrode is represented in Fig. 3(b).

An important value of V for analyzing the I - V characteristic in the plasma diode is the critical one at point e in Fig. 1(b), where the averaged current suddenly drops. This is due to an intermittent decrease from a maximal value of the current, wherefore it starts to be limited. A similar phenomenon is observed in the case of the hf plasmoid [10]. Starting from low values of the injected energy (proportional to the screen grid voltage V_s), the current I_g, collected by the control grid, suddenly decreases for a critical value V_s (corresponding to the point g), indicating an increase of the power absorbed by the plasmoid. This is accompanied by the transition to an unstable phase, in which the hf field is modulated by a frequency in the range of tens of kHz. As shown in Fig. 3(b), also in the I_{CP} - V_{CP} characteristic of a Q-machine strong nonlinear changes of the electrical conductivity of the plasma occur, shown by the presence of critical points [9]. When the voltage applied to the CP reaches the critical value V_{CP} (corresponding to the point e), self-sustained oscillations are excited in the device, resulting in a drop of the mean value of the current, in a similar way as in the plasma diode. Moreover, the power spectra of all three signals show $1/f$ noise. The $1/f$ shape of these spectra could be an indication that, in all three different plasmas, anomalous transport of particles and energy occurs, leading to flicker noise and, implicitly, to SOC.

The intermittent modulation of the current in the plasma diode is correlated to the appearance of propagating DLs. These originate from the border of the CSCC that forms in front of E [1]. The anomalous transport of matter and energy due to propagating DLs is proved by varying the parameters of the plasma column bounded by the plasma source, on one side, and by the CSCC in front of E, on the other side. If V exceeds the value corresponding to the point e in Fig. 1(b), ion-acoustic oscillations in the range of tens of kHz, excited in the plasma column, trigger a periodical detachment of DLs from the CSCC so that the current collected by E varies periodically. When V is further raised, the gradient $E_{e,kin}$ becomes higher, so that the frequency of the periodical DL detachment from the CSCC differs from the eigenfrequency of the plasma column. The eigenfrequency of the plasma column is the frequency of ion acoustic half-standing wave, which depends on the length of the plasma column comprised between the CSCC and the cathode.

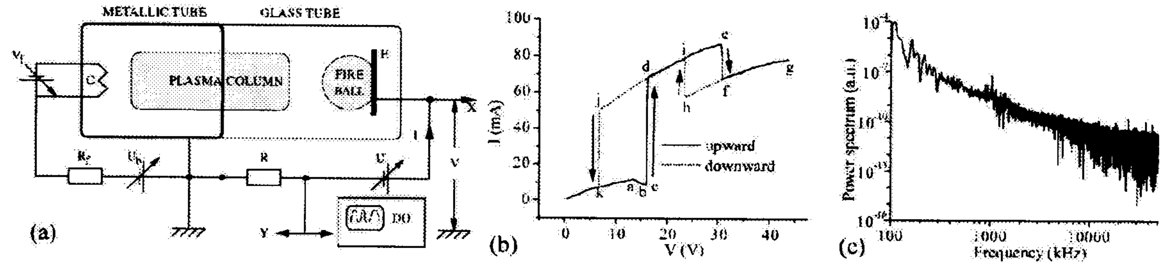

Fig. 1 (a) Schematic representation of a plasma diode; (b) *I* - *V* characteristic; (c) power spectrum of *I* exhibiting 1/*f* noise.

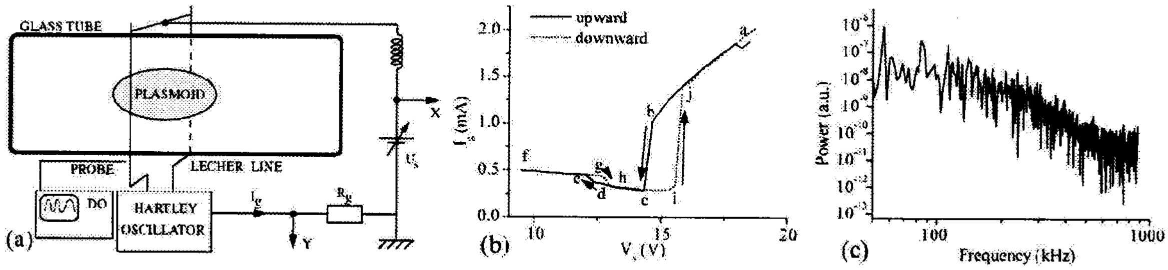

Fig. 2 (a) Experimental device used to produce a hf plasmoid; (b) I_g - V_s characteristic; (c) power spectrum of the external hf field exhibiting 1/*f* noise.

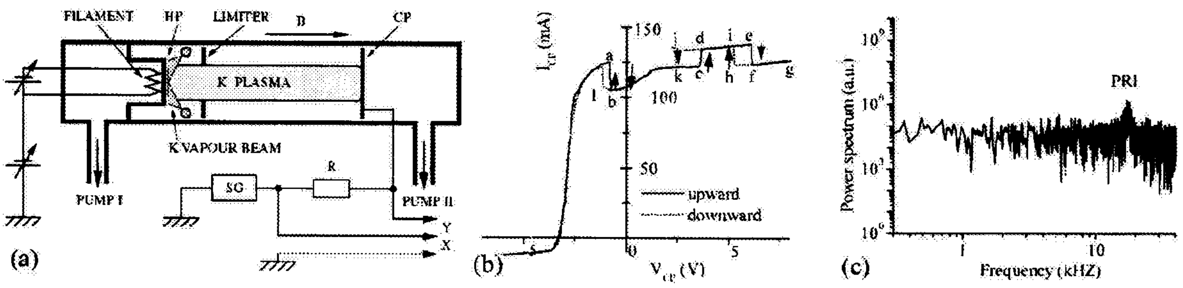

Fig. 3 (a) Q-machine device; (b) I_{CP} - V_{CP} characteristic; (c) power spectrum of the ion saturation current exhibiting 1/*f* noise.

Now we try to explain the behavior of the system by assuming that it pursues a route towards chaos by period doubling [2]. A continuous increase of *V* leads to a further deviation of the frequency from the plasma column eigenfrequency and to the disappearance of the feedback mechanism. Under such conditions the DL dynamics is controlled only by internal random fluctuations [2]. The gradient of $E_{e,kin}$ in front of E determines the spatial separation of the excitation and ionization cross-section functions. Since the disruption of the CSCC, with a frequency in the range of hundreds of Hz, is often preceded by a periodical detachment process of the DL from the CSCC border, with a frequency of hundreds of kHz [1,3], the superposition of the above two processes leads to the observed 1/*f* shape of the power spectrum, seen in Fig. 1(c).

As already shown [10], the hf plasmoid is also confined by a DL. Its formation can only be achieved by a decrease of the screen grid voltage V_s [branch *ab* in Fig. 2(b)], starting from a usual hf discharge. First, the plasmoid is in an unstable state [branch *cd*], than it attains a stable state [branch *ef*]. The increase of V_s determines a comparable behavior with the CSCC formed in the plasma diode. The transition through a critical state [point *g*] is accompanied by a decrease of I_g, indicating the passing through a resonant state where energy is absorbed from the internal oscillatory element of the system. This fact can be explained by the proper dynamics of DLs, which are periodically detaching from the surface of the plasmoid, modulating the hf field. Moreover, the modulation changes its shape with the increase of the injected energy, passing through period doubling states. Anomalous transport of particles and energy is possible during the propagation of the DLs, in a similar way as that one in a plasma diode. The power spectrum of the high frequency field also has $1/f$ shape, confirming our assumption that flicker noise is present in such devices.

For explaining the observed current jumps in the Q-machine we have invoked global effects also related to the spatial separation of the regions where the neutral excitation and ionization cross-section functions maximize [5]. After the creation of a DL in front of CP [1,2], the transport of matter and energy is initiated by the effect of propagating DLs. This takes place when the voltage applied to CP reaches the critical value corresponding to the point e in Fig. 3(b) and an instability well-known as potential relaxation instability [PRI in Fig. 3(c)] sets on [11]. For this CP potential value the DLs transit into a similar dynamical state as that in a plasma diode. By their dynamics the DLs transport matter and energy accumulated in them during their creation. After the detachment of one DL from the region where it was generated, the conditions for the creation of a new DL reappear. Therefore an internal positive feedback mechanism, already described [1-3], ensures the transition of the DL into a propagating phase. In this way the effect repeats on a time scale determined by this internal feedback process. This phenomenon appears as a high-amplitude half standing wave in the Q-machine [12]. Obviously the sustenance of such a wave requires the periodical transport of matter and energy by moving DLs to the plasma column able to support such oscillations.

Our results can be considered as arguments supporting our opinion that certain plasmas, which show SOC, require the periodical transport of matter and energy by the effect of DLs. These DLs are generated in a region where a sufficiently strong gradient of the kinetic energy of the electrons creates the prerequisites for their self-generation process. We stress that the mechanism of propagating DLs differs from that of an "avalanche", recently proposed at the origin of SOC in toroidal discharge devices. The DLs are created because of internal reasons, and then the production of positive ions at their high potential side is enhanced. Additionally, the DLs ensure by themselves the mechanism for their propagation, which, in contrast to avalanches, can take place also in field free regions similar to solitons.

3. Conclusions

Although the plasma parameters and the confinement mechanism in the devices investigated by us are strongly different from fusion devices, there exist similar conditions at the edge of the plasmas created therein, including gradients of $E_{e,kin}$ towards the edge [13]. Therefore the striking similarity, emphasized in this paper, between the power spectra observed in our devices and those obtained from many fusion devices [13,14] suggests a common physical basis. Considering the energy dependence of the excitation and ionization cross sections for Ar [15], it results that their energetic separation occurs at 17 eV. This value corresponds to the order of magnitude of $E_{e,kin}$ obtained in both collisional plasmas investigated by us. For the Caltech Tokamak plasma $E_{e,kin}$ at the edge is about 5–25 eV [16]. Because of the presence of a gradient of $E_{e,kin}$ at the edge of fusion plasmas a spatial separation of the regions where excitation end ionization reactions also occurs in that region. The emission of visible light from certain fusion devices proves, for example, the presence of neutral excitation reactions, a necessary condition for the creation of DLs in our model.

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