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Physical basis of anomalous transport observed in plasma devices

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Introduction

Anomalous transport of particles and energy in magnetic self-confined plasma systems is generally related to turbulent phenomena. The magnitude of the turbulent transport is considered the parameter the most affecting the confinement properties and hence the economical performance of a fusion reactor. Usually, turbulent phenomena are connected with the inhomogeneity of the temperature profile across the magnetic-field lines. Starting from experimental studies of the flicker noise observed in connection with turbulence in fusion devices, the so called self-organized criticality (SOC) concept was recently considered as a possible model for the strong anomalous radial transport of particles and energy [1]. The idea of SOC [2] is considered today as a powerful concept that offers an attractive model for many physical systems. However the true physical phenomenology at the origin of flicker noise in systems as for example, magnetic confined plasmas remained up today one of the mysteries in physics.

This paper presents experimental results on the anomalous transport of particles in a cold plasma device. In the presence of a gradient of electrons' kinetic energy, self-organization phenomena can determine the genesis and evolution of space charge complexities [3,4]. Such structures are bordered and confined by double layers protecting them from the surrounding plasma by a cell like membrane [3]. When matter and energy is additionally injected in the system the complexity reaches a critical state during which its steady existence is assured by a nearly rhythmic transport of matter and energy by moving double layers (DL) [3,4]. Such a dynamics determines the appearance of flicker noise in the system [5].

The aim of this paper is to propose a common explanation for anomalous transport of particles and energy in different plasma devices including those used to produce energy by fusion. It starts from the presumption that the conditions at the edge of magnetically confined plasma created in fusion devices are similar to those at the boundary of self-confined plasma configurations, formed after self-organization, in non-fusion plasma devices. This assumption is justified by experimental results proving that the flicker noise usually related to anomalous transport is due to turbulent processes related to the dynamical behavior of DLs. Taking into account the described experimental results we present experimental evidence concerning a possible new physical basis of SOC, concept presumed to be able to explain the anomalous transport also in fusion devices.

Experimental results and discussion

The experimental device is a plasma diode schematically shown in Fig. 1. The plasma was produced in a stainless grounded metallic tube (MT) connected with a glass tube (GT) filled with Argon at a pressure of 10^{-2} Torr. An emissive cathode (C) was negatively biased (40V) with respect to MT and a discharge was ignited. The plasma diffused into GT in which a disk tantalum electrode E (15 mm in diameter) was placed. The distance between E and MT could be varied in the range 5-30cm. A dc. power supply was used for positively biasing E with respect to MT at a voltage U. A resistor R was inserted between MT and the power supply. The self-adjusted

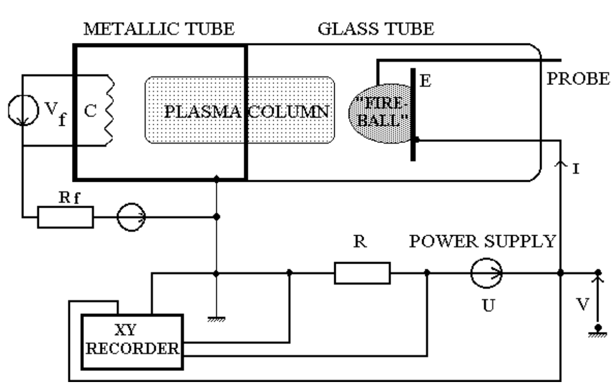

Figure 1. Experimental device

voltage V between E and MT and the current I collected by E were recorded using digital multimeters. Additionally, a digital storage oscilloscope was used in order to record the temporal variation of I..

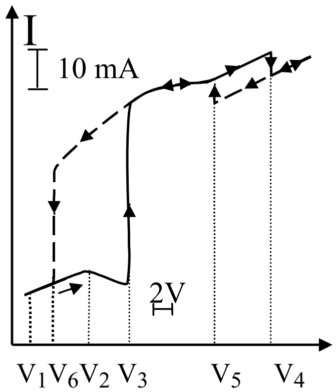

Figure 2: I versus V characteristic of a plasma diode

The nonlinear behavior of the plasma was emphasized by plotting the current I versus voltage V characteristic (Fig. 2). When the voltage V was gradually increased, the current I showed abrupt variations for certain critical values of V (marked with subscripts). Such a shape of the characteristic is typical for plasma diodes [3,4]. These nonlinear phenomena are correlated with the spontaneous self-assemblage and the dynamics of a well confined space charge configuration known as fireball (FB) [3,4].

It was already shown that the genesis of FB is related to the presence of a sufficiently strong gradient of electrons' kinetic energy created by an external constraint (electric field of E). When this gradient reaches a critical value (realized when $V=V_3$) the neutral excitation and ionization cross functions become spatially separated. This spatial separation is able to maintain two adjacent opposite space charges by accumulation of electrons and production of positive ions related to the sudden increase of aforementioned cross section functions. The spatial configuration of the two opposite net space charges transit into a self-consistent DL when the electrostatic forces that act as long-range correlation overcompensate the external constraint [3]. The presence of hysteresis phenomena emphasized in Fig. 2 when V is gradually decreased is an additional argument for self-organization [3] and proves that the system exhibit bistability for certain ranges of V.

If V is in the range V_1-V_2, the dependence of I obeys Ohm's law. The accumulation of electrons in the regions where the cross section function of excitation suddenly increases determines a negative resistance behavior of I versus V in the range V_2-V_3. When $V=V_3$ the space charge configuration transit into a self-consistent DL [3]. Its existence, in a steady state, is not possible because its development is accompanied by accumulation of electrons that forms a barrier for I. Consequently, I decrease at a value for which the FB disappears. This fact is emphasized by the emergence of spikes of I, correlated with variations of the light intensity emitted by the plasma [3]. In our case the distance between the anode and the plasma source is so long that the present plasma column is able to sustain ion acoustic oscillations. Therefore the intermittent appearance of FB can stimulate the plasma column to perform damped oscillations (Fig. 3).

The FB remains in a steady state when V overlap V_3 and the potential drop over the DL excedes the value corresponding to the gas ionization potential. Therefore, the production of positive ions on the positive side of the DL suddenly increases so that the long range electrostatic forces acting between the two adjacent opposite charges reaches a critical value. Under such conditions a stable rearrangement of the space charges in the front of E occurs. In our experimental device (where no external magnetic field determines the profile of the plasma configuration) the self assemblage of the stable space charge configuration in front of E is a natural process because the resulting structure corresponds to a minimum of the free energy (realized for a nearly spherical shape [3]). In magnetic confinement systems the region where the gradient of electrons kinetic energy able to determine the self-assemblage of a DL is present at the edge regions.

If V is further increased, the production of positive ions enhances so that the concentration of the two opposite space becomes time dependent because the electric field on DL is also additionally increased. Thus the production of positive ions is enhanced and consequently the region where the excitation cross section function increases is shifted away from E. This fact determines a shelling-off process of DL [3]. During this process DLs transport particles and energy from the boundary of FB toward the surrounding plasma. Since this shelling-off process repeats periodically [4] it becomes possible to stimulate ion-acoustic oscillations when a plasma column suitable to support such natural oscillations is present. Under such conditions coherent oscillations are generated by the plasma diode (Fig. 4). Having a frequency equal to the one corresponding to the plasma column natural oscillations, the successively formation and disruption of the moving DL stimulate nearly linear oscillations in the plasma column.

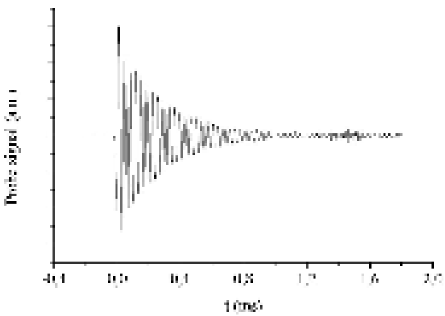

Figure 3: Ion acoustic waves excited by the unstable FB

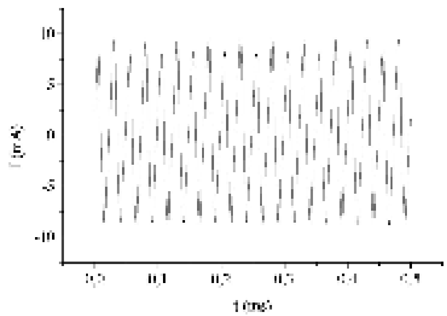

Figure 4: Temporal variations of I excited and maintained by the DL proper dynamics

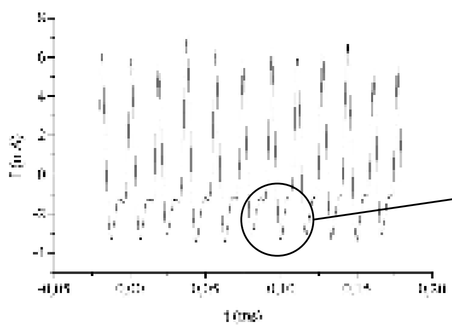

Figure 5a: Temporal variations of I determined by the DL formation and disruption (as a whole)

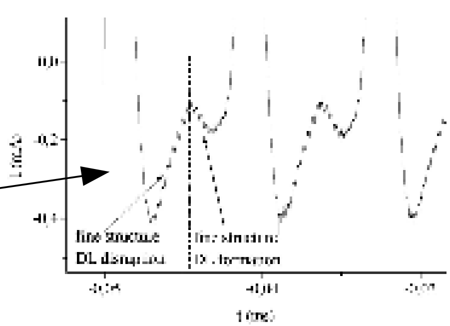

Figure 5b: Detail of the signal evidencing the genesis and disruption of the "fine" structure of the negative side of the DL

For higher values of I the frequency of the consecutively creation and disruption of DL changes [4] and are no more close to the one of eigenvalues the plasma column. Under such conditions the signal generated by the plasma diode consists of almost periodic nonlinear variations of the current separated by a "noisy" region (Fig. 5a). Using a high speed sampling oscilloscope we emphasize high frequency burst occurring in this time interval. It corresponds to the formation and disruption of a "fine" structure at the negative side of the DL [7]. The intermittent disruption of such "fine" structure as well as its similar formation process produces high frequency variations of I (Fig. 5b).

If the eigenvalues of the plasma column oscillations differs from that of the DLs shelling off frequency the feedback mechanism disappear and the DL dynamic becomes controlled by internal random fluctuations [4]. In that case low time scale phenomena related to the described DL dynamics overlap to the high frequency time structures related to the formation and disruption of the "fine" structure of DL. Performing FFT transform of the signal under such conditions we evidence the presence of 1/f noise in the whole DL dynamics (Fig. 6).

As it is known the 1/f noise illustrated on the model of “running” sandpile involves single avalanches produced at very short time scales that overlap to intermediate time scales phenomena related to stochastic “catastrophic” disruption of the sandpile structure as a whole. A similar superposition of phenomena produced at different time scales can be related to the genesis and the disruption of DL generated at the border of FB. In this region a gradient of electrons’ kinetic energy is present, determining the spatial

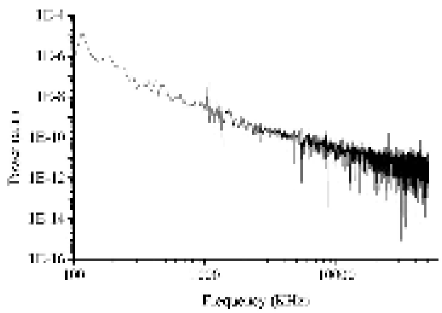

Figure 6: 1/f like spectra of I

separation of the excitation and ionization cross section function. Since there are several levels of neutrals excitation, each of them produces a local accumulation of electrons. Thus a "fine" internal structure of the electron layers at the negative side of the DL appears. The intermittent forming process as well as the disruption one determines the rapid variations of the current I presented in Fig. 5b. The shelling off process of the DL appears in the moment when, because of the increase of V at V_4 (Fig. 2), the accumulation of opposite adjacent net space charges determines the potential drop over it to attain a critical value. In this state electrons from the surrounding cold plasma are accelerated inside the DL so that the production of positive ions at its high potential side is enhanced. At its turn, this enhancement determines the increase of the electric field of DL and hence the enhancement of the kinetic energy of accelerated electrons. Consequently a further enhancement of the production of positive ions takes place at the high potential side of the DL so that the shelling off of DL from the FB border is started [3,4]. After traveling a certain distance (from the region where the DL was self-assembled) the DL disrupts so that a new DL, meantime created in front of E, can repeat the above-described phenomenology. This phenomenology involves low frequency temporal structures related to the shelling off of the DL from the external side of FB. In the absence of a plasma column that acts as a resonator the shelling off of DL and its catastrophic disaggregation as a whole is controlled by fluctuations at intermediate time scales (in the range of kHz). Intermittent formation and disruption of bi-polar structures related to the development of its internal “fine” structure is produced at very short time scales (in the range of MHz and greater). Thus the sandpile like [6] disruption mechanism of the fine structure of DL is experimentally proved by the results obtained in plasma devices (Fig. 6).

Conclusions

We describe a new experiment that relate the anomalous transport of particles and energy in a plasma device with the dynamics of a self-consistent DL at the border of a complex space charge configuration formed after self-organization. The self-consistent 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 cross section functions for electron impact excitation and ionization of neutrals suddenly increase. In fusion devices such gradients usually appear at the edge of the confined plasma in the normal direction to the magnetic field lines. Consequently, the anomalous transport of particles and energy by means of DL takes place from the confined plasma to the outside. Since the increase of the energy injection modifies the frequency of DL shelling off process so the anomalous transport of particles and energy becomes greater. Thus the only possibility to avoid such undesired phenomenon is to modify the magnetic field profile so that the gradient of electrons’ kinetic energy determines the DL shelling off process towards inside the confined plasma. Finding such a magnetic field profile is a problem of further theoretical and experimental studies.

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