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On the Excitation of Low-Frequency Instabilities in Magnetized Plasmas

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Abstract

We propose a new phenomenological model, based on self-organization phenomena, which is able to explain the role of complex space charge configurations in the excitation of low frequency instabilities in a Q machine. Our model can also explain the recently observed interaction between them. We assume that for instabilities nonlinear space charge accumulations are relevant. These are created due to the different locations where the neutrals excitation and ionization cross section reach their respective maxima in a region where a gradient of the electron kinetic energy is present.

Keywords:

self-organization, double layer, Q-machine, ion instabilities, interaction between PRI and EICI, hysteresis, sidebands

1. Introduction

Plasmas are systems with strong nonlinearities, which are manifested, among others, by abrupt changes of the electrical transport properties, when an externally applied constraint is gradually varied [1]. In these cases the constraint is an external electric field. The abrupt changes are shown by critical points in the static current-voltage characteristic (I-V trace) where I suddenly changes for certain critical values of V. The following reasons for the nonlinear properties of plasmas were identified [1,2]: (i) the spontaneous generation of a stationary electric double layer (DL) in front of a current-collecting electrode; (ii) the transition of the DL into a propagating state so that new DLs are successively generating and decaying. All nonlinear variations of I show hysteresis when V is gradually increased and decreased. The DLs stimulate oscillations, which are related to the accumulation of matter (electrons and ions) and energy (stored in the electric field of each DL) originating from the external dc power supply during the generation of each DL. The matter and energy are released into the electrical circuit when each DL disrupts [1,2]. The generation process of a stationary DL actually represents the creation of "long-range spatial order", and its successive generation and decay, triggered by internal processes, reveals the appearance of "spatio-temporal order". Therefore both of these phenomena prove the presence of self-organization [3]. The hysteresis phenomenon, also a specific property of a self-organized complexity, demonstrates the bistability of the plasma state, which is a premise for its ability to stimulate oscillations. The oscillations appear when, besides the DL, which is localized in a certain region of the plasma, another part of the plasma works as a resonant system able to perform natural oscillations [1,2]. The shape of the DL depends on the plasma device, in which it is produced.

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When the positively biased electrode is on all sides surrounded by plasma, the DL appears at its border as a nearly spherical luminous space charge configuration called fireball [4]. When an external magnetic field confines the plasma in the form of a column, the DL appears at the border of a U-shaped luminous space charge configuration dubbed firerod [5]. The latter space charge configuration was observed in a Q-machine filled with different noble gases at a pressure of the order of 10^{-4} mbar.

2. Double Layers Acting as Stimulators of Oscillations

As recently shown, the most important phenomenon in connection with the dynamics of a plasma diode, is the bifurcation of states, a process the understanding of which is crucial for all systems exhibiting a space-charge-limited flow. A typical device, in which current limitation was observed, is the Q-machine, the plasma of which is presumed collisionless. Usually the generation of a so-called "virtual cathode" is

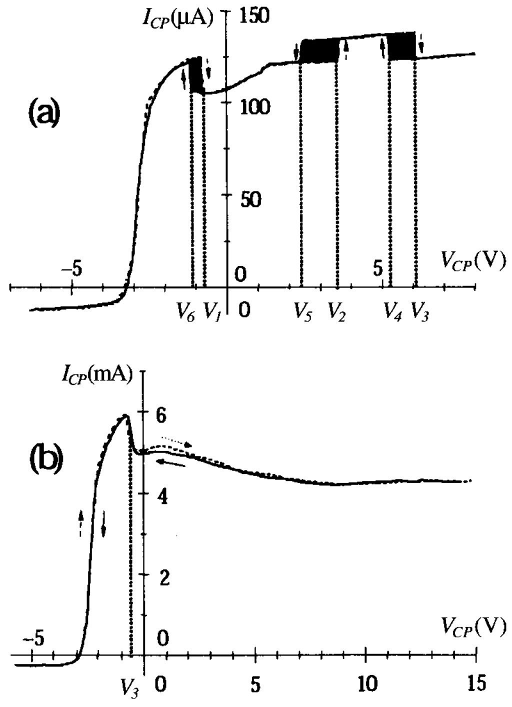

Fig. 1 a, b: Current voltage characteristic of the cold plate of a Q-machine for two different plasma densities. For (a) the density is $n_{pl} \cong 10^7$ cm^{-3}, for (b) $n_{pl} \cong 10^9$ cm^{-3}. The diameter of the plasma column is 3.6 cm and the diameter of the cold plate 7 cm.

considered as the cause for the current limitation [6]. The phenomenology of such a virtual cathode in the framework of collisionless plasma models is far from being well understood.

As recently shown [7,8], there is another possibility to explain the current limitation in a Q-machine when collective effects related to the spatial separation of neutral excitation and ionization cross sections by electrons impact are taken into account. Such phenomena can appear in a Q-machine in front of the cold plate (CP), where thermal plasma electrons are accelerated. Experimental arguments supporting this presumption are the I_{CP}-V_{CP} characteristics shown in Fig. 1(a) and (b), which are taken when the potential relaxation instability (PRI) is excited [7].

The nonlinearity of the I_{CP}-V_{CP} characteristic in Fig 1(a) yields important information concerning the succession of processes which lead to the excitation of PRI. This instability appears when V_{CP} surpasses the critical value V_3. Essential for a complete understanding of PRI is also the identification of the causes that produce the current jumps before the PRI appearing, since these jumps are related to phenomena that create the necessary conditions for the PRI. These phenomena successively appear when V_{CP} is gradually increased in the voltage range $V_1 \leq V_{CP} \leq V_3$. First, we note that the collection of plasma electrons by the CP, indicated by the general rise of the current from the ion saturation regime, proves that the potential of the CP is positive with respect to the unperturbed plasma potential [7]. So, thermal plasma electrons are accelerated towards CP.

Fig. 1(a) shows that, before the current limitation at $V_{CP} = V_3$, a sudden decrease of I occurs for $V_{CP} = V_1$. This has its origin in the formation of a net negative space charge in front of CP by accumulation of those electrons that have lost their kinetic energy after the excitation of neutrals. Thereby a localized space charge barrier for the electron current I is created causing its drop. Another important nonlinear phenomenon which precedes the appearance of the PRI is the current jump for $V_{CP} = V_2$. Such a sudden increase becomes possible e.g. when a new source of charged particles appears in the plasma column. The sole effect able to produce new charged particles is ionization of neutrals. Ionization can appear when a DL with a potential drop equal or greater than the ionization potential of the potassium atoms is present in the plasma column. Based on experimental results from a collisional plasma diode [1,9], we presume that such a DL is created by self-organization in front of the CP. Under such conditions, we explain the current limitation for $V_{CP} = V_3$ by relating it to the transition of the DL from a stable state in the voltage range $V_2 \le V_{CP} \le V_3$ into an unstable state that appears for $V_{CP} \ge V_3$. This transition involves the successive formation, detachment and disruption of DLs formed in front of CP, *i.e.* the PRI appearing, the temporal evolution of which matches the above sequence of events [9,10]. The barriers for I_{CP} that on the time average produce the current limitation for $V_{CP} \ge V_3$, are the negative dips at the low potential side of each DL. We point out that until recently in the phenomenological model of the PRI only I_{CP}-V_{CP} characteristics have been considered with a single current limitation as that one shown in Fig. 1(b). Such I_{CP}-V_{CP} traces appear for relatively high plasma densities where the PRI is obviously excited for lower values of V_{CP}, and where the I_{CP}-V_{CP} trace shows a **n**egative **d**ifferential **r**esistance (NDR) around V_3 [9]. The lack of current jumps in Fig. 1(b), like those observed in Fig. 1(a) for V_1 and V_2, is not an argument that the above described effects (which give rise to the jumps) would not take place also in the case of higher densities, but because of the earlier onset of the PRI they are not observable. This is easy to understand since the accumulation of opposite space charges in the DL strongly depends on the excitation and ionization rates, which depend on I_{CP}, but also on the neutral density in front of CP. For higher plasma densities additional neutrals can be created by recombination of ions and electrons, the concentration of both being high in front of CP.

Based on the above-described phenomenological model we tentatively explain the recently re-investigated interaction between the PRI and the **e**lectrostatic **i**on-**c**yclotron **i**nstability (EICI) in a Q-machine [11-13]. We base our explanation on the presumption that both instabilities involve space charge DLs, which, during the temporal evolution of the instabilities, are first created at the positively biased CP, then start propagating away from CP. The decay of the DL at a short distance from CP determines a sudden increase of the plasma column potential shifting in front of HP the region where electrons are accumulated after neutral excitation. Consequently, a barrier for I appears in front of HP. Its development and propagation towards CP, as a bipotential structure, determine the main part of the PRI period [9].

3. Interactions between Low Frequency Instabilities in a Q-machine

The interaction between the PRI and the EICI is experimentally proved by the I_{CP}-V_{CP} trace shown in Fig. 2. This trace was obtained in the Q-machine of the University of Innsbruck under the conditions that the diameter of the magnetized plasma column exceeded the diameter of CP. In that case in front of the CP a DL is formed, which divides the column in two different regions. One of these regions is located between the CP and the DL, which performs its self-sustained dynamics (its position depending on V_{CP}). The other part is placed between the region where the DL disrupts and the HP.

The I_{CP}-V_{CP} characteristic in Fig 2 shows that the appearance of the EICI is accompanied by a sudden decrease of the time-averaged current for $V_{CP} \ge V_1$ (Fig. 2 – left-hand side of the vertical dashed line) [7]. This can also be seen in the observed frequency spectrum [Fig. 3(a)], which shows a peak at 57.6 kHz; this corresponds well to the gyrofrequency of a K^+ ion at the applied magnetic field (B = 0.13T). Such a current drop can be explained by the transition of the DL, generated in front of the CP, into an unstable state. In this state the barriers for I are successively self-assembled and disrupted at the low potential side of the DL. The plasma potential in front of CP jumps as soon as a DL is created. The sudden increase of the plasma potential gives rise to the simultaneous ejection of ions from the plasma channel between the DL and the CP, almost perpendicular to the magnetic field lines [14,15]. After this ejection the ions perform a cycloidal motion so that

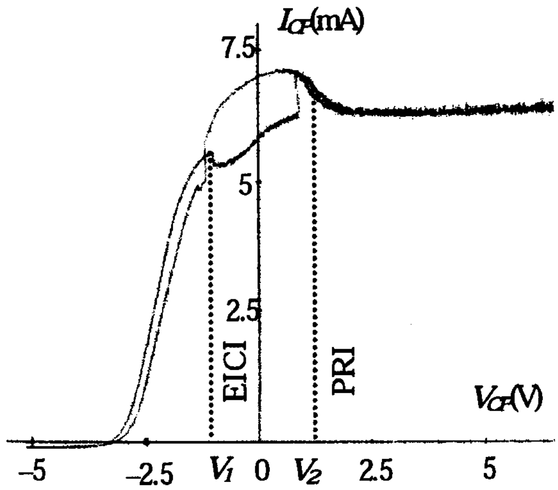

Fig. 2 Typical I_{CP}-V_{CP} characteristic. CP diameter (1 cm) is smaller than that of the plasma column (3.6 cm), when both instabilities, the EICI and the PRI, are excited. The two vertical dashed lines show the threshold values of V_{CP}, above which the EICI and the PRI, respectively, start. Above the PRI threshold, both instabilities exist.

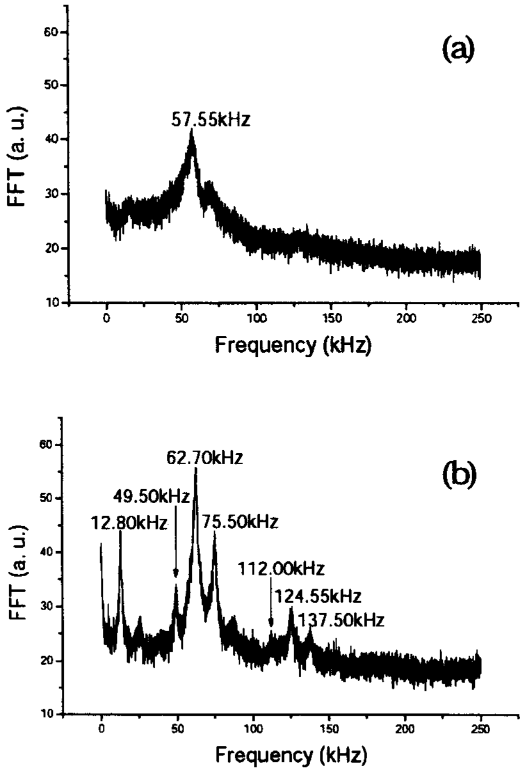

Fig. 3 Two typical frequency spectra obtained for a small CP, taken for the same conditions as the I_{CP}-V_{CP} trace of Fig. 2, once above the EICI threshold (a), once above the PRI threshold (b) where both instabilities are present, i.e. for different currents collected by CP.

they return into the channel after one gyroperiod. In this way the synchronous cycloidal motion of the ions gives rise to the EICI oscillations, while after each cycle the DL self-assembles and decays. The return of the ions into the channel produces a fast re-increase of the potential drop. The accumulated matter and energy in each DL is periodically transferred to the EICI oscillations. Simultaneously with the DL decay during each EICI cycle, the channel opens for the current so that a new DL can be built up in front of the CP and the entire cycle repeats itself [9].

On the other hand, the PRI does not appear before I_{CP} jumps up again for $V_{CP} \geq V_2$, followed by a region of NDR (Fig. 2 – right-hand side of the vertical dashed line). This part of the characteristic is very similar to that one shown in Fig. 1(b) above V_3, so that we are led to the conclusion that the PRI is excited [10]. Also this mechanism of the PRI has recently been linked to the periodical generation of DLs in front of the CP by the mechanism already described above (cf. section II) [7].

Above the PRI threshold there is a region where both instabilities appear with comparable amplitude, strongly interacting with each other. This is seen in the spectrum [Fig. 3(b)] not only by the appearance of a peak at the expected PRI frequency under these conditions (12.8 kHz) but also of sidebands on both sides of the EICI frequency peak at a distance of ±12.8 kHz [13]. In this way, the EICI is strongly modulated by the PRI [12].

The experimental results presented in Fig. 3(b) prove the presence of a system, which is able to perform two independent natural oscillations. One oscillation involves the entire plasma column between the DL in front of CP and the HP, where the PRI is excited, and the other one involves only the region in front of CP, where the EICI appears. In our picture, both instabilities are sustained by the dynamics of the DL. During the DL-self-assembling process energy from the external dc power supply is accumulated. This energy is released in the circuit during DL decay. This dynamics is triggered by the natural oscillations above mentioned.

As we have described above, the main feature of the EICI is the periodical expulsion of a group of ions, originating mostly from the region in front of the CP, from the current channel into the surrounding unperturbed plasma during every maximum of the EICI. This ion expulsion occurs because of a periodically created radial electric field at the edge of the current channel, which is due to a periodically appearing positive space charge inside it. The space charge appears in front of the positively biased CP simultaneously with the formation of a frontal double layer. Thus, the space charge in front of the CP is confined both axially and radially by double layers. For higher collected currents the number of electron impact ionizations in front of the CP increases. Consequently, the electron density in the current channel between the double layer and the CP is higher and the radial electric field smaller, so that the ions are ejected from the current channel with lower energy. This leads to a decrease of the EICI frequency, as emphasized by our experimental data (obtained for fixed magnetic field strength) in Fig. 4. We see that the EICI frequency is inversely proportional to the current I_{CP}. Under our conditions the PRI, taking place between the DL and HP, produces a strong modulation of the current collected by the CP, and since the EICI frequency depends on the current, the appearance of the sidebands around the EICI frequency is also plausible. As shown in Fig. 3(b), sidebands were also observed around the second harmonic of EICI at 124.6 kHz. The presence of the large hysteresis loop, shown in Fig. 2,

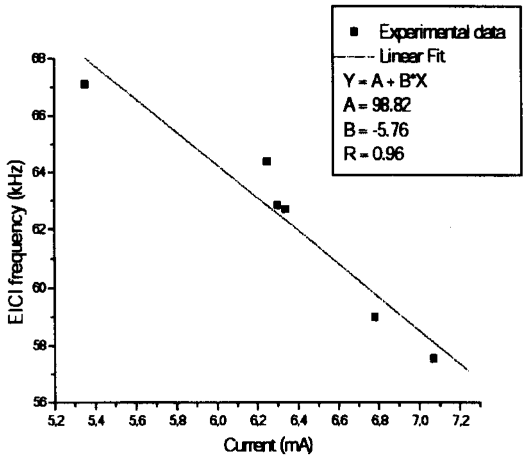

Fig. 4 Dependence of the EICI frequency on the current I_{CP} collected by the CP.

demonstrates that the currents for which the EICI and PRI appear, overlap in the range of V_{CP} where the plasma conductor shows the strong nonlinear behavior. The condition for the overlapping of the EICI and PRI and, consequently, the appearance of modulations is, as already shown [12], due to a certain relationship between the diameter of the CP and the diameter of the plasma column.

4. Conclusions

We believe that unstable complex self-organized space charge configurations in the form of DLs, generated in front of the CP of a Q-machine, can act as sources of matter and energy, which in turn are able to excite different kinds of low frequency instabilities. If the current variations, related to the DL dynamics, triggered by one of the instabilities, cover the current range of another instability, two in principle independent oscillators are present, in which the oscillations are stimulated by the same source. Under such conditions the oscillators are "coupled" by the common source so that in the spectrum sidebands appear with frequencies corresponding to the sum and respectively the difference of the two instabilities frequencies.

More precisely, the sidebands appear around the EICI frequency, because the EICI frequency depends not only of the magnetic field induction B, but also on the current collected by CP (Fig. 4). This current modulation is produced by the PRI oscillations that take place in the plasma column between the DL and HP. To sustain them, a periodical extraction of positive ions from the current channel between the DL and CP is necessary. This density modulation of the positive ions produces a corresponding modulation of the current collected by the CP. As we have seen, the EICI frequency is inversely proportional to the current collected by the CP (Fig. 4). The linear fit of the experimental data in Fig. 4 allows for the calculation of the amplitude of the current modulation needed to obtain a shift of the EICI frequency with the PRI frequency (sidebands). This result is in good agreement with the observed amplitude modulation of the current, thus demonstrating that the measured frequency – usually related to the cycloidal motion of individual ions – is actually due to the gyromotion of „bunches of ions", which can be considered as complex space charge configurations, the properties of which also depend on the overall ion density.

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