

CURRENT JUMPS AND HYSTERESIS EFFECTS IN THE CURRENT-VOLTAGE CHARACTERISTIC OF A SINGLE-ENDED Q-MACHINE

Codrina Avram*, Roman Schrittwieser, Patrick Winkler and Mircea Sanduloviciu*

Institute for Ion Physics, University of Innsbruck, A-6020 Innsbruck, Austria

**Faculty of Physics, University „Al. I. Cuza“, RO-6600 Iasi, Romania*

Hysteresis of current-voltage characteristics (*IV*-trace) is well known e.g. from hot-cathode or glow discharges where it can be a sign for the ignition and breakdown of the discharge, respectively, but also for the formation of sheaths and their transition to distinct potential structures as for instance space charge double layers (DL) [1,2]. Hysteresis is often accompanied by sudden jumps of the current. On the other hand, also in nearly collisionless thin plasmas like e.g. that of a Q-machine [3], hysteresis of the *IV*-trace has been observed, apparently associated with the potential relaxation instability (PRI) [4]. This nonlinear high-amplitude instability is characterised by a DL that moves or oscillates between the two axial boundaries of the system and that usually leads to a current limitation [5,6].

The experiments have been performed in the Innsbruck single-ended Q-machine in a potassium plasma which was produced on a 6 cm diam. tungsten hot plate (HP). In order to provide for a flat radial density profile, the diameter of the plasma column was restricted by a floating 3.5 cm diam. tantalum limiter, inserted 3.6 cm in front of the HP. The density was in the range of $10^7 < n_{\text{pl}} < 10^9 \text{ cm}^{-3}$, the background pressure was less than 2×10^{-6} mbar and the magnetic fields strength was in the range of $0.05 < B < 0.2$ T. The length of the plasma column was only 15 cm and it was terminated by a cold endplate (CP) with a diameter of 70 mm. We emphasise already here that under electron-rich conditions the unperturbed plasma potential Φ_{pl} is a few volts negative. The short plasma column was advantageous for achieving a high coherence of the PRI.

We present three different cases for various densities and various values of the magnetic field strength in which the *IV*-trace of the CP showed various numbers and types of current jumps and/or hysteresis. Moreover, we present evidence which clearly shows that the PRI is not necessarily the only process to cause a sudden current limitation in a Q-machine plasma. This sheds a new light on a long-disputed question, namely the relevance and necessity of inelastic collisions for the excitation of strongly nonlinear oscillatory phenomena and of nonlinear potential structures in a “collisionless” Q-machine plasma.

Fig. 1 (a-c) shows typical *IV*-traces of the CP for (a) $n_{\text{pl}} \cong 1.1 \times 10^7 \text{ cm}^{-3}$ and $B = 0.073$ T, (b) $n_{\text{pl}} \cong 3.3 \times 10^7 \text{ cm}^{-3}$ and $B = 0.073$ T, and (c) $n_{\text{pl}} \cong 1.2 \times 10^9 \text{ cm}^{-3}$ and $B = 1.47$ T. The characteristics have been taken by slowly increasing and decreasing the voltage V_{CP} at the CP with a symmetrical triangle signal with around 0.05 Hz in the range of about $-7 < V_{\text{CP}} < +10$ V. The most spectacular and most interesting case is shown in Fig. 1 (a): Here, for this very low density, we find even three clearly distinguishable sudden jumps of the electron current I_{CP} , and all three are associated with hysteresis, marked by **I**, **II**, and **III**. At first, for $V_{\text{CP}} \cong -1.2$ V, even before reaching full electron saturation, I_{CP} jumps down by about 15%, but no coherent instability is found as yet, only rather strong low-frequency noise. For $V_{\text{CP}} \cong +2.3$ V (again with hysteresis) a sudden rise to the expected saturation value of I_{CP} occurs, and then the cur-

rent is stable up to a value of $V_{CP} \cong +5.5$ V. Ignoring the hysteresises, the difference between **I** and **II** is around 4 V. Then the current drops again (with a small hysteresis) and only here a low frequency instability starts that shows some characteristics of the PRI. For a detailed description of the different oscillations seen above **III**, see [7].

Also the IV -trace of Fig. 1 (b), for just a three times higher plasma density, shows a similar behaviour with three current jumps, but only the third one shows a clear hysteresis and is again associated to the onset of a PRI-like instability. In this case, however, the two hysteresises **I** and **II** have been shifted together, and the distance in between **I** and **II** has shrunk to about 0.5 V. Indeed, **I** and **II** are only observable for very low densities, and the difference in between them strongly decreases with the density. Already for about 5×10^7 cm⁻³, **I** and **II** have disappeared completely, and for higher densities, the appearance of the IV -trace of the CP (see Fig. 1 (c)) is conventional and well known from many earlier experiments (see e.g. [5]). In this case, there is only one current jump (**III**) left over, almost without hysteresis, which is identical with the onset of a PRI-like instability. In Fig. 1 (b), we also note that the region between **I** and **II** is a very unstable region, not as for any remarkable unstable oscillations in the plasma but concerning the static value of the current I_{CP} which sometimes shows wild jumps when the XY-recorder is passing through this region. Spectra of superimposed oscillations on I_{CP} do, however, only show noise.

In view of the low plasma density at first sight it appears to be out of question that the observed phenomena could be due to any collisional interactions. But whereas the sudden downward current jump **III** in Fig. 1 (a) and (b) can, in the framework of the conventional phenomenological model of the PRI, be explained by the current limiting action of the strong PRI oscillations [6], it is not easy to find any plausible explanation for the current jumps **I** and **II** in Fig. 1(a) and (b).

Here we present a tentative model that is able to explain the current jumps **I** and **II** in terms of inelastic collisions between the plasma electrons and the background neutral potassium vapour that is inevitably present in a Q-machine, especially in such a short system as used here. To get the clearest picture, we mainly concentrate on Fig. 1 (a), but for higher values of V_{CP} we will partly refer also to Fig. 1 (b). In addition, for a case similar as Fig. 1 (b), a dynamical characteristic is presented which shows that there are two different kinds of oscillations along the characteristic (see Fig. 2), and only the larger one is the well known PRI:

As for **I**: The sudden decrease of the current can be due to excitation interactions right in front of the CP. As soon as the actual accelerating potential difference between the plasma and the CP (notice that Φ_{pl} is a few volts negative!) surpasses the lowest excitation level for neutral K (about 2 eV), electrons involved in these interactions lose their kinetic energy and a negative space charge builds up there that acts as a thermal barrier for the electrons.

As for **II**: Now, due to the higher bias of the CP, the electrons have gained enough energy to surpass also the ionisation level of K (4.34 eV), and are able to produce additional K⁺-ions and electrons. This has on one side the effect that the thermal barrier of electrons is filled up with ions and thereby dissolved so that now again more current can flow to the CP, but on the other hand also a real DL can be formed in front of the CP. Note that now similar effects as described above (first excitation and then ionisation) can take place at the ascending potential of this DL (see next point).

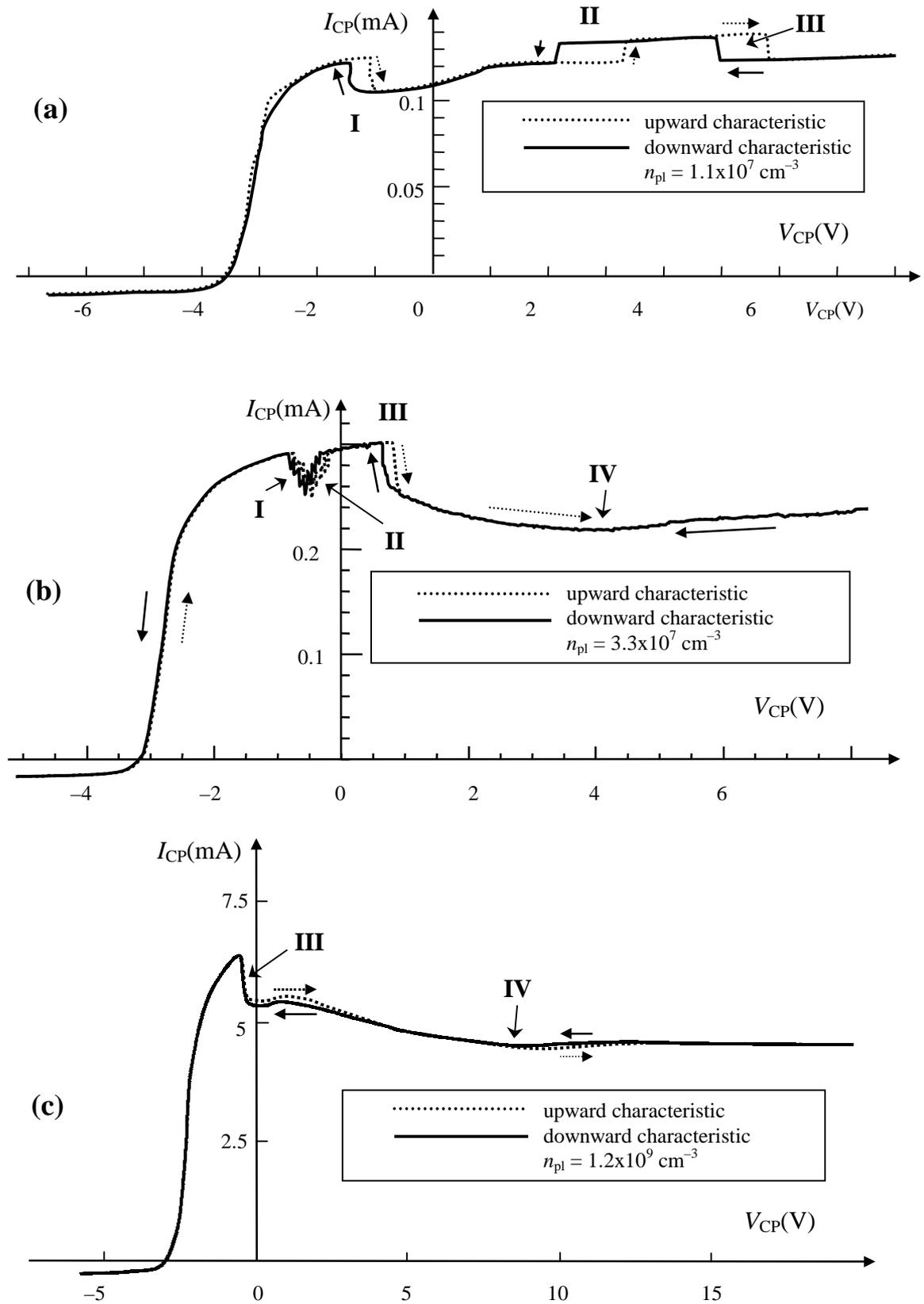


Fig. 1. IV-traces of the cold plate (CP) for three different plasma densities as indicated in the figures (a) to (c). The Roman capitals I to III refer to the hysteresis effects, discussed in the text. Note that for case (c) the hysteresises I and II have completely disappeared and only the hysteresis III, which is usually considered as the onset of the PRI, remains. But the actual onset of the PRI occurs rather at the value of V_{CP} , marked by IV.

As for **III**: The current suddenly decreases, since here the threshold for rather weak and not very coherent oscillations of I_{CP} is surpassed (see also Fig. 2). Yet these oscillations lead on the average to a reduction of the current and are related to the presence of two DLs in front of the CP (one forming in front of the CP and the other one at a certain distance of the CP due to excitation and ionisation in front of the first DL). From Fig. 1 (b) we discern that the current keeps on decreasing slowly until the point marked by **IV**.

Above **IV**: According to the measured spectra (see also Fig. 2), here is now the onset of the real PRI! Now more or less the well-known mechanism of this instability sets in [6]. But we should take into account that here the average value of I_{CP} starts to re-increase slowly (Fig. 1 (b) and Fig. 2). This fact could be due to inelastic collisions of the same kind as described above. Such interactions can now periodically occur in front of the moving DL that is an essential part of the PRI cycle and can lead to an overall change of the charge carrier balance.

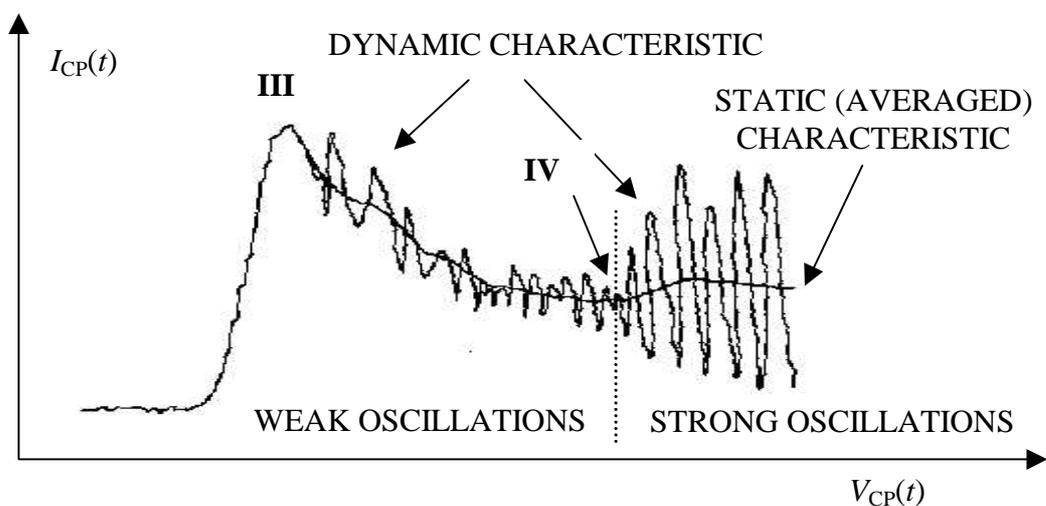


Fig. 2. Dynamic characteristic of the cold plate. The Roman capitals refer to Fig. 1 and to the corresponding description in the text.

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