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Possible excitation and ionisation processes in a "collisionless" alkaline plasma

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Abstract

We report on an investigation in the magnetised alkaline plasma of a single-ended Q machine where the current-voltage characteristic of the cold endplate showed some new nonlinear features, which could be due to fundamental ion processes. The most interesting of these features were sudden jumps of the electron saturation current which were partly accompanied by hysteresis. Besides that, the characteristic showed a smooth type of hysteresis that was due to a temporary covering of the cold plate by alkaline metal from the plasma. The current jumps could be an indication that the well known nonlinear potential structures that can appear in the plasma column when an electron current is drawn through it, are initiated by excitation and ionisation interactions of accelerated electrons with alkaline vapour present in the plasma column. (Int J Mass Spectrom 184 (1999) 129–143) © 1999 Elsevier Science B.V.

Keywords: Current jumps; Hysteresis; Excitation; Ionisation; Alkaline plasma

1. Introduction

The current-voltage characteristic (IV trace) of a plasma system often shows sudden jumps of the electron current that are sometimes accompanied by hysteresis. Such a behaviour is a general characteristic of a nonlinear dynamical system [1–4]. In hot-cathode or glow discharges, such jumps occur in connection with the ignition or breakdown of the discharge, respectively, or with the transition between different discharge types [5]. Moreover, the formation of distinct nonlinear potential structures, such as space charge double layers (DL) [6], are also often observed in this context [2,3,7].

Whereas in discharge plasmas such phenomena are clearly connected with inelastic collisional processes (electron impact excitation and ionisation interactions) [2,3], in thin plasmas such as that of a Q machine [8] various sudden jumps in the electron current branch of the IV trace of the cold end plate have also been observed [9–11]. Traditionally, a Q machine plasma is considered collisionless, and up to now only current jumps (without hysteresis) have been observed related to the onset of the so-called potential relaxation instability (PRI) [12–14]. The phenomenology of this high-amplitude nonlinear instability involves the periodic formation and disruption of a moving DL near the hot plate of the Q machine. Thence, it propagates along the plasma

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column to the cold end plate, where it dissolves. Also in certain gas discharges, PRI-like phenomena have been observed [15].

In the present investigation, different current jumps and hysteresis effects are investigated that appear under certain conditions in the *IV* trace of the cold end plate of a single-ended *Q* machine. In the most interesting case, four such effects are found: (1) a smooth hysteresis caused by a short-term coating effect by alkaline metal in spite of the heating of the end plate; (2) a hysteretic downward current jump without regular oscillations but with strong turbulence; (3) a hysteretic upward current jump related to relatively small incoherent oscillations of the current; (4) a hysteretic downward current jump associated with the onset of a low-frequency instability of the PRI type.

In Sec. 2 the experimental setup is described; Sec. 3 contains the description of the experimental results and delivers an explanation for case (1). Cases (2)–(4) are discussed in Sec. 4, where they are tentatively explained as the result of excitation and ionisation processes that could take place in the *Q* machine plasma despite the traditional opinion that such a plasma should be considered collisionless.

2. Experimental setup

The experiments were performed in the Innsbruck single-ended *Q* machine in a potassium plasma which is produced by contact ionisation on a 6 cm diameter tungsten hot plate (HP). By a circular tantalum limiter, inserted 3.6 cm in front of the HP, the diameter of the plasma column is restricted to 3.5 cm. This has been done in order to achieve a flat radial density profile. The plasma density was in the range of $10^7 < n_{pl} < 10^9$ cm^{-3}; the background pressure was less than 10^{-5} mbar. The magnetic field strength was in the range of $0.05 < B < 0.2$ T.

Measured from the HP, the length of the plasma column was 15 cm, and the column was terminated by an end-plate construction of tantalum that consisted of a small collector of 10 mm diameter, surrounded concentrically by a co-planar ring of an inner diameter of 10.5 mm and an outer diameter of 70 mm. Both electrodes could be biased separately.

When only the inner part (the collector) of this end-plate construction (10 mm diameter) was biased positively to draw an electron current, the so-called electrostatic ion-cyclotron instability could be excited [16]. Also, in this case a hysteretic current jump was observed in the *IV* trace of this collector. This effect is described in previous papers [17]. When the collector and the outer ring is electrically connected, this end electrode is called cold plate (CP), and mainly the PRI was observed in the electron saturation current regime. The CP was heated by radiation from the HP so that no permanent K coating was to be expected. Fig. 1 shows a schematic of the setup. Similar end-plate constructions have been used in previous experiments [18–20]. Because of the shortness of the system, no further diagnostic tools have been used for this investigation.

3. Experimental results

Figs. 2(a)–(c) show three typical current-voltage characteristics of the CP: (1) for a density of $n_{pl} \cong 1.1 \times 10^7$ cm^{-3} and $B = 0.073$ T; (b) for $n_{pl} \cong 3.3 \times 10^7$ cm^{-3} and $B = 0.073$ T; (c) for $n_{pl} \cong 1.2 \times 10^9$ cm^{-3} and $B = 0.147$ T.

These characteristics have been taken in a conventional way with an *XY* recorder by using a slowly sweeping triangle voltage (about 0.05 Hz) between $-6 < V_{CP} < +14$ V, approximately. The symmetry was 50%, i.e. the increase and the decrease of V_{CP}, respectively, took place with the same speed. The resulting current curves $I_{CP} = I_{CP}(V_{CP})$ are shown as dashed lines (increasing V_{CP}) and solid lines (decreasing V_{CP}), respectively. In all three cases, spectra of the oscillations that are superimposed on the dc electron current I_{CP} have been taken, and these spectra are shown in Figs. 3–5. The corresponding values of V_{CP} are indicated in the figures.

In passing, it should be mentioned that for such a purpose, most modern digital data acquisition systems are still not very suitable because such characteristics are, especially for low densities, so noisy that a digital

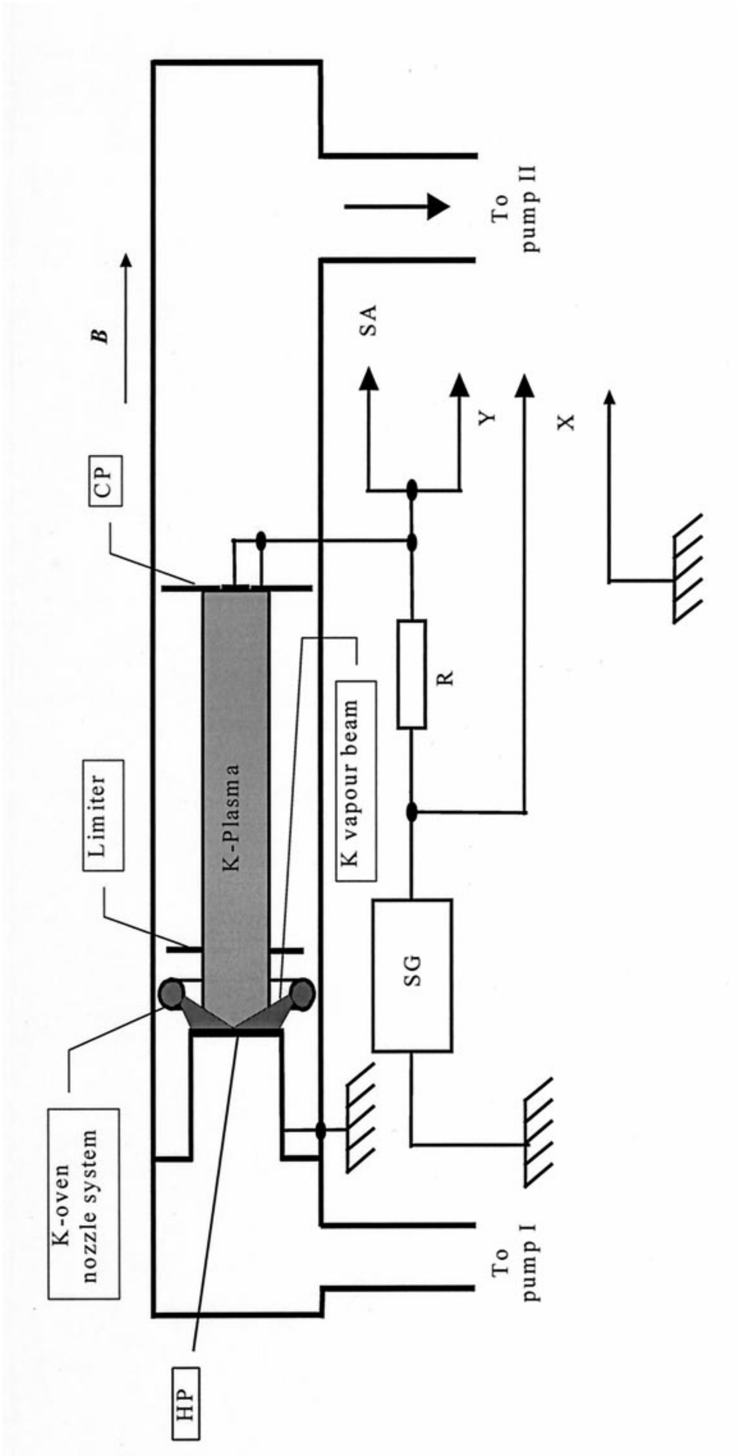
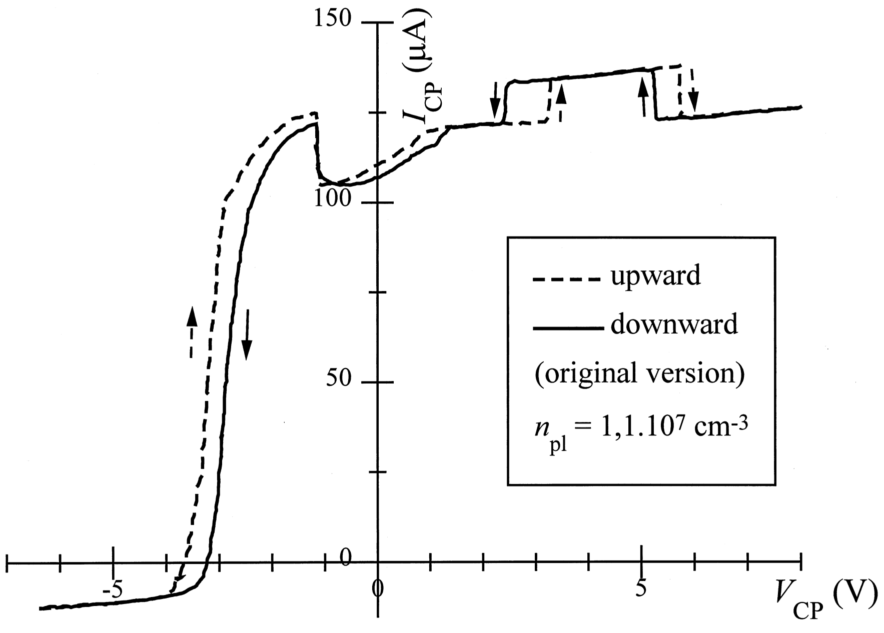


Fig. 1. Schematic of the Innsbruck single-ended *Q* machine. HP = hot plate (plasma source), CP = cold plate, SG = signal generator, SA = spectral analyser, X/Y = to XY recorder.



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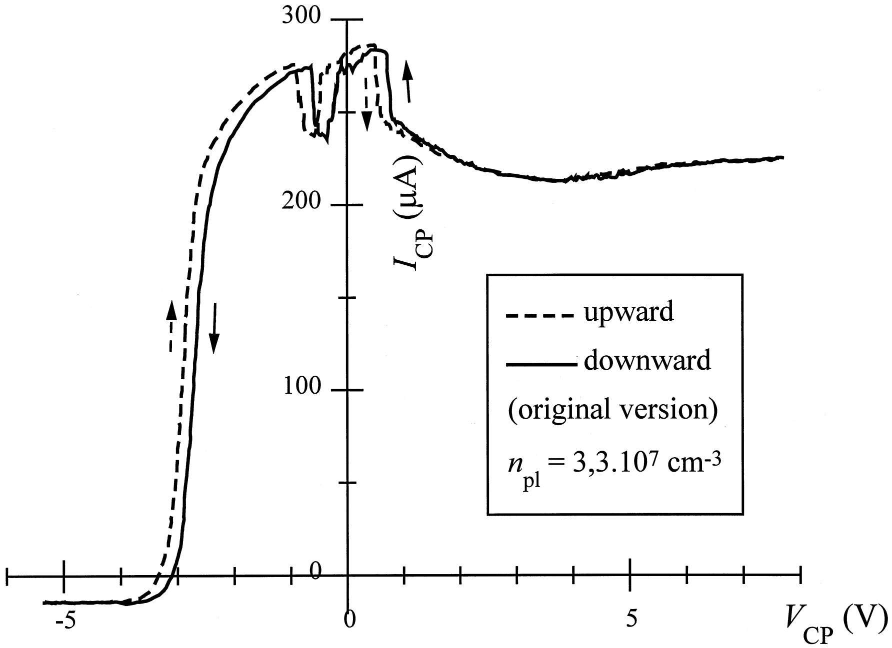

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Fig. 2. (a)–(c) Original (uncorrected) versions of the static current-voltage characteristics of the cold end plate for three different plasma densities as indicated in the insets. The dashed lines show the upward characteristics, the solid lines show the downward characteristics.

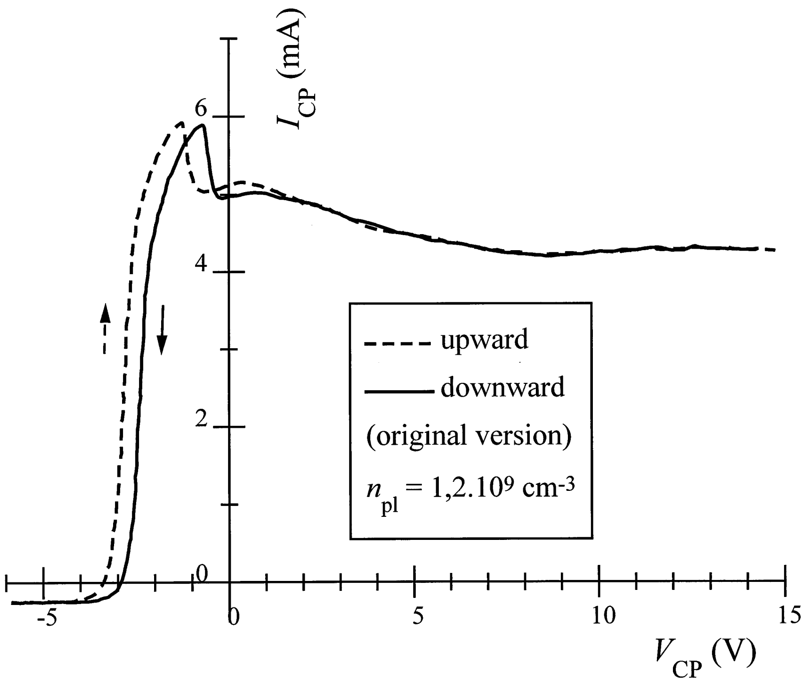


Fig. 2 *(continued)*

acquisition system would bury the essential effects among the noise.

The observed more or less hysteretic effects and/or current jumps [see Figs. 2(a)–(c)] in the static *IV* trace [sometimes even four, as e.g. in Fig. 2(a)], can, upon closer examination, be classified in two categories:

Type 1: In the electron retarding-field region for about $-4 < V_{CP} < 0$ V, we discern an almost constant horizontal spacing of about 0.35 V [Fig. 2(a)] 0,5 V (b) and 1,2 V (c), respectively, between the upward and the downward branch of the three characteristics. This type of hysteresis corresponds to the above mentioned case (1) (see Sec. 1. Introduction).

Type 2: In the electron saturation current region, especially in Fig. 2(a), above a voltage of about -1.2 V, we observe a much more complex behaviour with various sudden jumps of the current up and down, all accompanied by hysteresis. Fig. 2(b) also shows signs of similar phenomena. Fig. 2(c), however, only shows a rather inconspicuous downward current jump at around -0.5 V. All these phenomena belong to one of the cases (2), (3) or (4) (see Sec. 1. Introduction).

3.1. Type-1 effect: hysteresis because of short term coating effects

This type of hysteresis is caused by a short-term coating effect of the CP by potassium, as V_{CP} is varied up and down. Although the CP was cleaned carefully before inserting it into the *Q* machine, and even though in principal the heating by radiation from the HP suffices to keep it free from coatings (see below), as long as V_{CP} is negative, ions are attracted toward the CP and, upon recombination, are adsorbed there as a thin layer of K atoms. This leads to a change of the work function and in general to a parallel left shift of the entire characteristic [21]. Other adsorbants may also possibly form coatings on the CP [22]. However, when V_{CP} is increasing and when an electron current is drawn toward the CP, this coverage gradually is desorbed until the turning

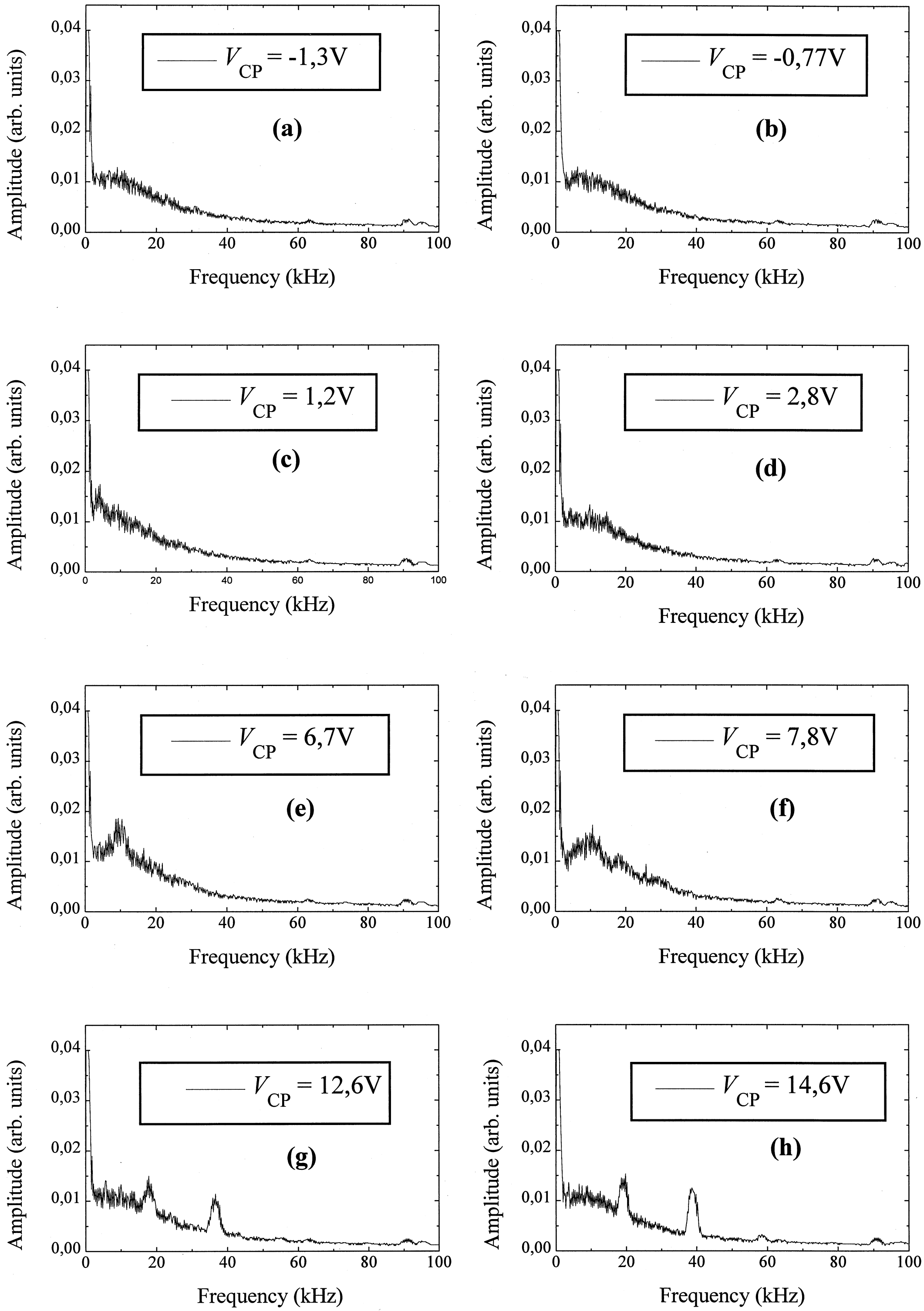


Fig. 3. (a)–(h) Spectra of the ac component superimposed on the cold plate current for the plasma density in Fig. 6(a). The cold plate voltages V_{CP} where the spectra are taken are indicated in the insets.

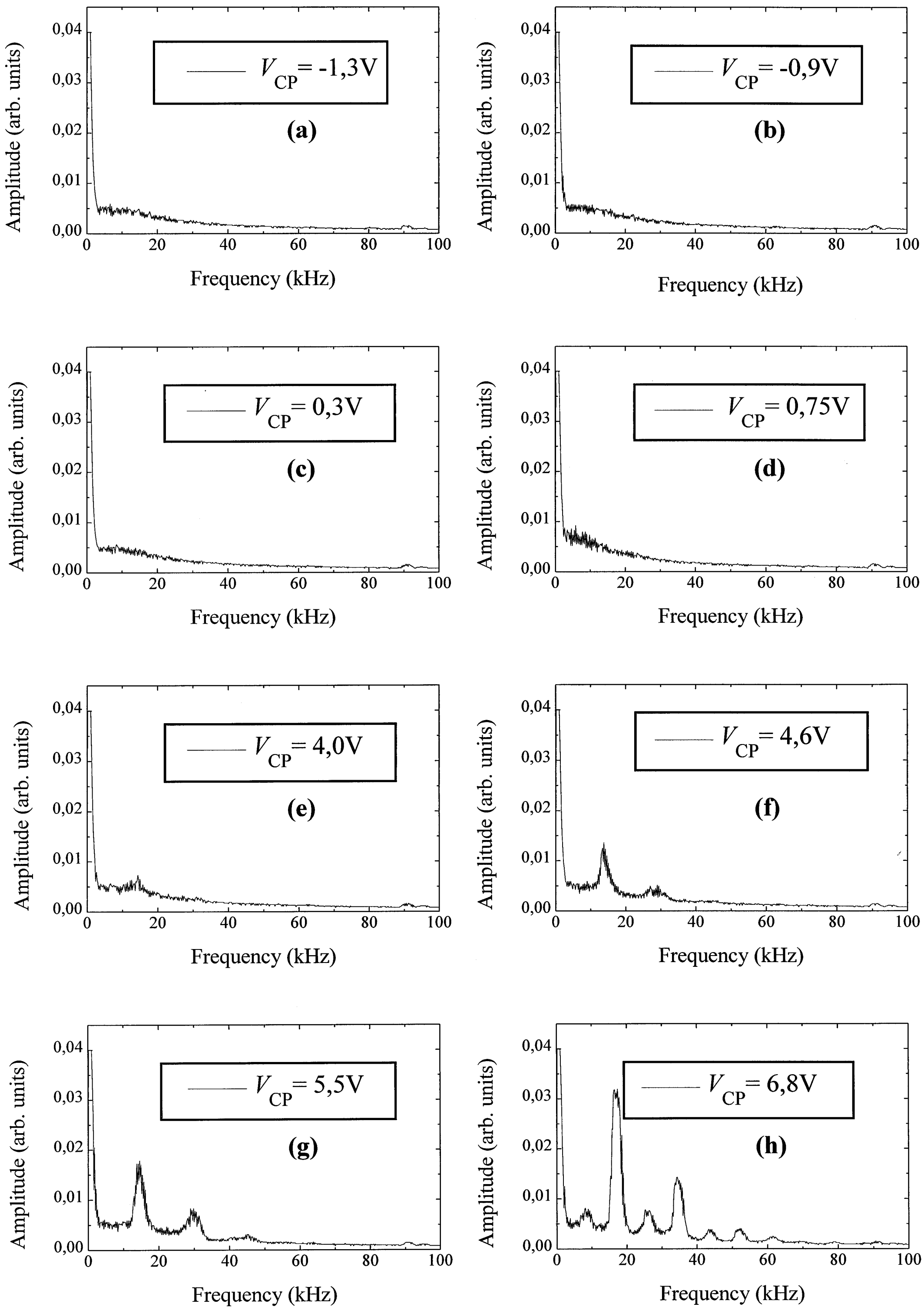


Fig. 4. (a)–(h) Spectra of the ac component superimposed on the cold plate current for the plasma density in Fig. 6(b). The cold plate voltages V_{CP} where the spectra are taken are indicated in the insets.

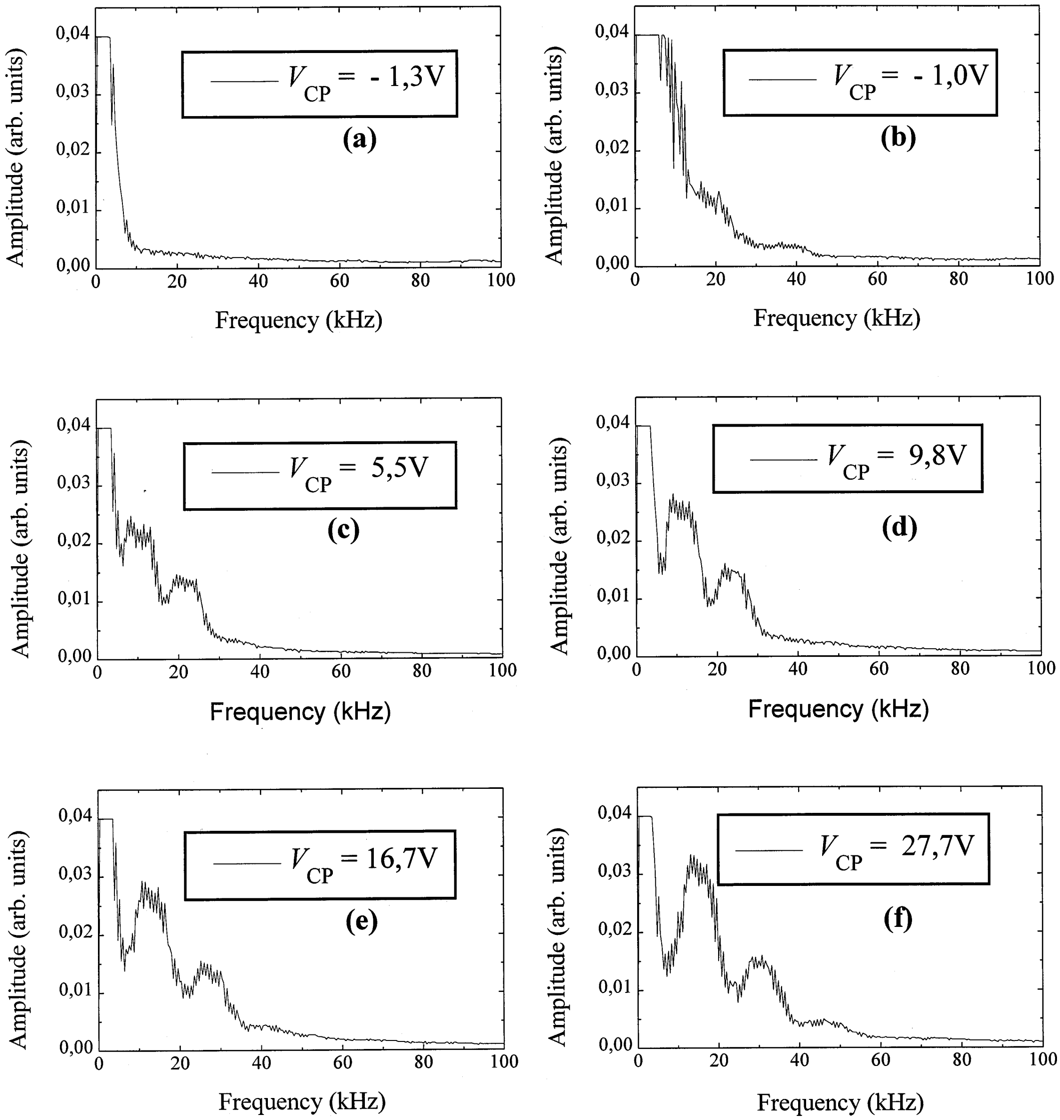


Fig. 5. (a)–(f) Spectra of the ac component superimposed on the cold plate current for the plasma density in Fig. 6(c). The cold plate voltages V_{CP} where the spectra are taken are indicated in the insets.

point of the characteristic. Such an effect has also been seen on Langmuir probes in *Q* machines in spite of thorough cleaning, bombardment, and strong indirect heating [23]. Since the downward characteristic (solid line) starts from the most positive bias of the CP where it is the least covered by K, we must also conclude that this one is more reliable than the upward characteristic which starts from a potassium-covered CP. For a thorough discussion of this phenomenon, see [24–26].

3.2. Type-2 effects: current jumps with the coating effect subtracted

In view of the strong evidence that the type 1 hysteresis is only caused by a slight coverage by potassium, and under the assumption that the downward characteristic is the more realistic one because the CP is cleaner at the start, we have attempted to reconstruct the "true" characteristics in which the potassium coverage is no longer relevant. To this end we have shifted the upward characteristics (dotted lines) of Figs. 2(a)–(c) horizontally to the right-hand side over the solid ones so that each time both characteristics are as congruent as possible in the electron retarding-field region. The results of these modifications are shown in Figs. 6(a)–(c). Thereby we obtain *IV* traces that now only show "true" current jumps and hysteresis effects, which must be caused by plasma or other volume effects (but not surface effects). These effects will be discussed in Sec. 4.

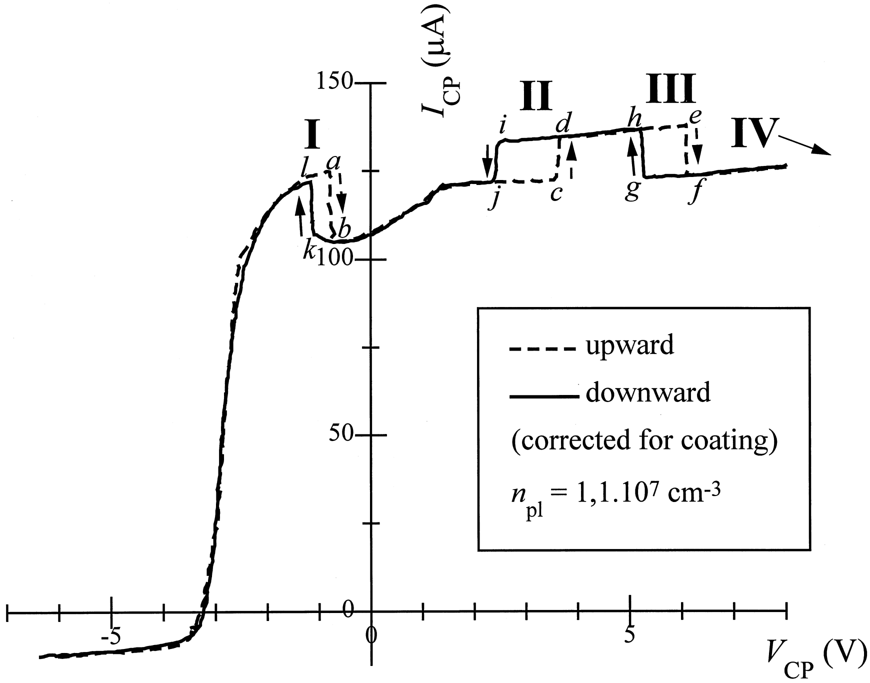
After the correction of the coating effect, the "true" *IV* trace of Fig. 6(a) (which is the case with the lowest plasma density and the weakest magnetic field) shows *three* current jumps which are accompanied by a more or less large hysteresis (marked by I–III). These belong to the above mentioned type-2 effects. It should be emphasised that the first of these jumps (I) would not show any hysteresis at all without the correcting process (i.e. the shift of the upward characteristic over the downward one), because the upward and downward trace are incidentally one over the other in the *uncorrected* version of the *IV* trace [Fig. 2(a)]. Thus, the coating effect (1) has been concealing this hysteresis.

In all three cases [Figs. 6(a)–(c)], in the entire ion saturation current regions and the electron retarding-field current regions of the *IV* traces (i.e. for about $V_{CP} < -1$ V), the plasma appears to be rather stable. However, approaching the knees of the *IV* traces (i.e. for $V_{CP} \cong -2$ V), near the value of the unperturbed plasma potential Φ_{pl}, the plasma at first becomes noisy, and later also develops more or less coherent unstable oscillations. This is not only to be expected intuitively, since an electron current is well known to destabilise that plasma and to excite various instabilities, but it is also well known from numerous previous investigations [12,13].

The most spectacular and most interesting case is shown in Fig. 6(a): here, for this very low plasma density, we find three jumps of the electron current I_{CP}, marked by **I**, **II**, and **III**. At first, for $V_{CP} \cong -1.2$ V, even before reaching full electron saturation, I_{CP} jumps down by about 15%, but no coherent instability is found as yet, only an enhanced low-frequency noise [cf. the spectra in Fig. 3(a)–(d)]. For $V_{CP} \cong +2.3$ V, a sudden re-rise of I_{CP} occurs, and then the current is stable up to a value of $V_{CP} \cong +5.5$ V. The difference between **I** and **II** is approximately 4 V. Then the current drops again, and a low frequency instability starts [cf. Figs. 3(e) and (f)]. And only for even higher values of V_{CP}, these relatively small low frequency oscillations turn into the well known PRI [cf. Figs. 5(g) and (h)]. We emphasise that the lower case bold italic letters ***a–l*** at the edges of the current jumps **I–III** do not refer to the spectra [Figs. 3(a)–(h)]. They are explained in the next section.

Also, the *IV* trace of Fig. 6(b), for just a three times higher plasma density, shows a similar behaviour with three current jumps, but almost no hysteresis. Again, the third current jump is associated with the onset of an instability. In this case, however, the distance between the two jumps **I** and **II** has shrunk to about 0.5 V. Indeed, **I** and **II** are observable only for very low densities, and the difference between them strongly decreases with the density. In this case, above **III**, PRI-like oscillations are to be seen [cf. Fig. 4(e)], but the real PRI appears only for the value of V_{CP} marked by **IV** [cf. Figs. 4(f)–(h)]. Already for about 5×10^7 cm^{-3}, **I** and **II** have disappeared completely, and for higher densities the *IV* trace of the CP [see Fig. 6(c)] looks very conventional and well known from many earlier experiments (see e.g. [12]). In this case, there is only one current jump (**III**) left over, almost without hysteresis, which coincides with the onset of a PRI-like instability [cf. Figs. 5(b) and (c)], while again the real PRI does not start before **IV** [Figs. 5(d)–(f)].

To see the temporal evolution of the plasma oscillations more clearly, in Fig. 7 a dynamic characteristic of the CP for similar plasma conditions as Fig. 6(b) is presented. This means that the voltage V_{CP} is swept in only one direction (upward) with a frequency somewhat *lower* than the frequency of the PRI and other expected plasma oscillations. Thus, at each point of the characteristic, only one or two oscillations



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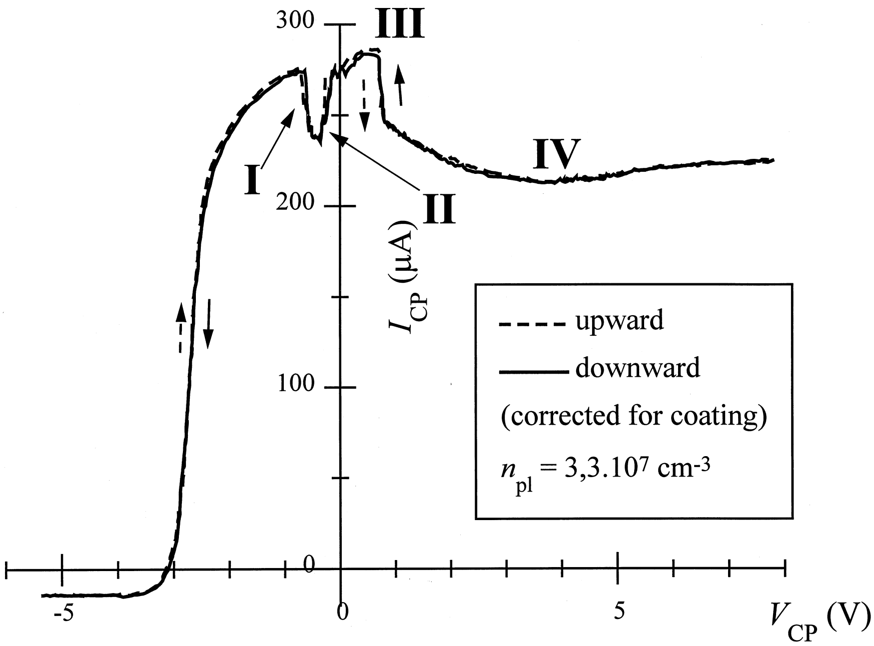

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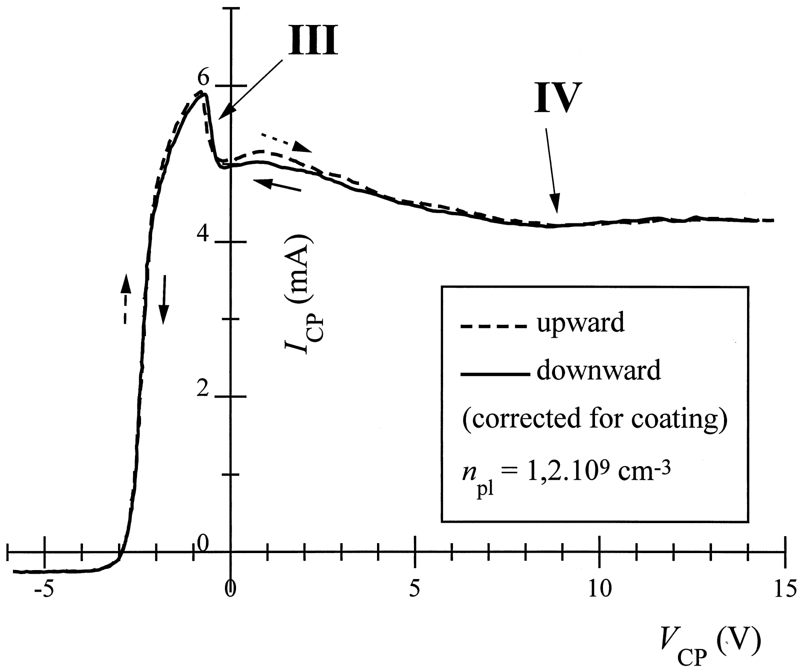
Fig. 6. (a)–(c) Static current-voltage characteristics of the cold end plate for three different plasma densities as indicated in the inserts, *corrected* for the short-term coating effect, as described in the text. The dashed lines show the upward characteristics, the solid lines show the downward characteristics. (a) The small italic letters ***a–l*** are referred to in the text. (a)–(c) The Roman numerals **I–IV** refer to the current jumps and other effects described in the text.



c

Fig. 6 *(continued)*

are seen that are typical for the respective range of V_{CP}. The bottom x axis shows the time t and the top x axis shows the corresponding values of $V_{CP}(t)$. The dashed line shows the time average, i.e. it is the equivalent of the static characteristic of Fig. 6(b). The roman numerals **III** and **IV** refer to the same points of transition, and we clearly see that in the transition regime only more or less incoherent irregular oscillations appear, whereas above **IV** the regular PRI oscillations become visible. Here we even see indications for a period doubling of the PRI, which agrees very well with the spectrum shown in Fig. 4(h).

Figs. 3(a)–(h) show spectra of the electron current oscillations taken at the indicated values of V_{CP} for the case of Fig. 6(a), Figs. 4(a)–(h) show the respective spectra for the case of Fig. 6(b), and finally Figs. 5(a)–(f) show the respective spectra of Fig. 6(c).

4. Discussion

In view of the low plasma density and the usual low background pressure in a Q machine, at first sight it appears to be improbable that the observed phenomena could be caused by any collisional interactions. Traditionally a Q machine with its low density plasma ($<10^9$ cm^{-3}) and its low background gas pressure ($<10^{-5}$ mbar) is considered collisionless (and this point has so far very seldom been questioned seriously). Nevertheless, in Q machines often there is a considerable background pressure of unionised alkaline vapour (which is, however, not so easy to measure or to estimate). In our special setup (cf. Fig. 1), with only 15 cm system length and an end-plate construction that covers up a large part of the cross section of the Q machine, locally a higher K vapour pressure could be expected. Moreover, in [27] it was clearly shown that in gas discharges, down to pressures as low as 10^{-5} mbar, inelastic collisions are not only possible but obviously also necessary for the creation of the discharge, in spite of the fact that a conventional calculation of the mean free path for electron impact ionisation would deliver values that are much higher than the length of the system.

In our case, with an estimated K background

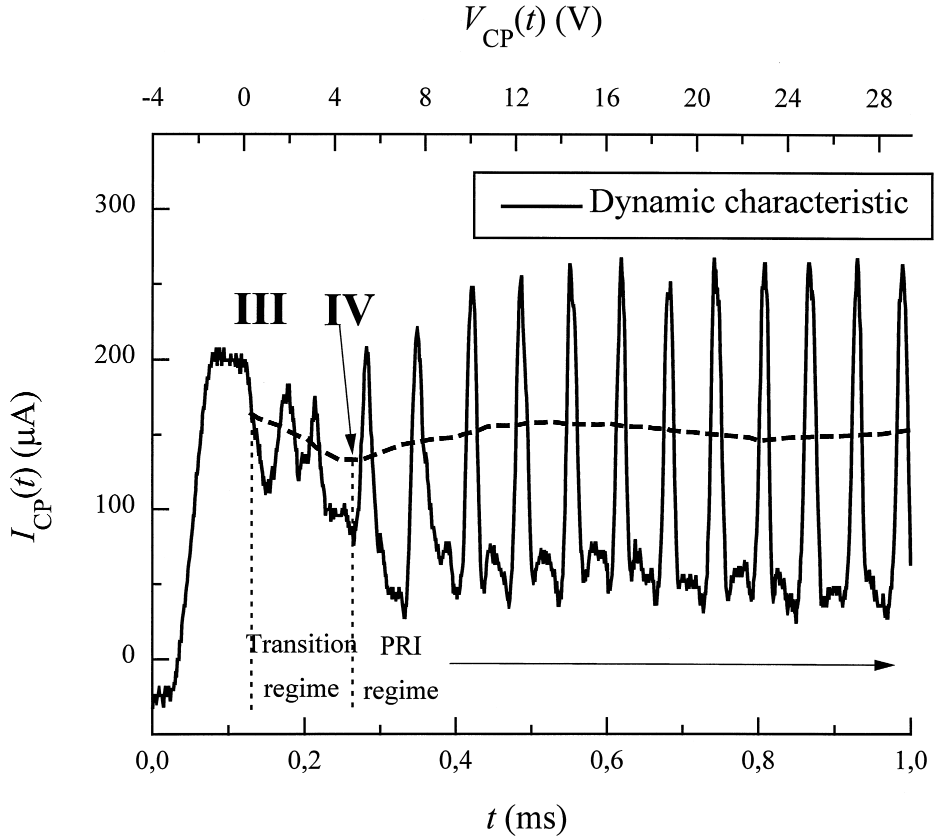


Fig. 7. Dynamic current-voltage characteristic of the cold end plate, taken with a sweeping frequency somewhat lower than that of the plasma oscillations. The bottom x axis shows the time and the top x axis shows the corresponding values of the voltage at the cold plate. The dashed line shows the time average, i.e. it is the equivalent of the static characteristic of Fig. 6(b). The roman numerals **III–IV** refer to the same points as in Fig. 6(b).

pressure of 5×10^{-4} mbar and a K-vapour temperature of about 400 K (determined by the potassium oven temperature), we obtain a number K density of $n_K \cong 10^{13}$ cm^{-3}. With a maximum ionisation cross section for K of about $\sigma_i \cong 8 \times 10^{-16}$ cm^2 [28], we find a mean free path for electron impact ionisation of $\lambda_{mfp} \cong 125$ cm. Thus, this value is just eight times the system length, and we also have to take into account the influence of the strong magnetic field that increases the interaction length. Also, excitation cross sections for electron impact excitation are of a similar order of magnitude.

Returning to the characteristics of Figs. 6(a) and (b), we would like to point out that in the framework of the conventional *collisionless* phenomenological model of the PRI, if at all, only the downward current jump **III** in Figs. 6(a) and (b) [and 6(c)] can be explained, namely by the current limiting action of the potential barriers formed at the HP during strong PRI oscillations [13]. However, in our opinion, it would hardly be possible to find a plausible explanation for the current jumps **I** and **II** in Figs. 6(a) and (b) without invoking additional effects.

Here we would like to present a model (see also [2,3]) that is able to explain at least qualitatively the current jumps **I** and **II** in terms of inelastic collisions between the plasma electrons and the background neutral potassium vapour that is present in our *Q* machine.

To get the clearest picture, we mainly concentrate on Fig. 6(a), but for higher values of V_{CP} we will also partly refer to Fig. 6(b) and to the dynamic characteristic presented in Fig. 7.

Current jump **I (*a*→b, *l*←*k*)**: The sudden decrease of the current can be caused by excitation reactions directly in front of the CP. As soon as the actual accelerating potential difference between the plasma and the CP (notice that from the electron retarding field region of the characteristic, we can estimate the plasma potential Φ_{pl} to be a few volts negative!) surpasses the lowest excitation levels for neutral K (at about 2 eV), electrons involved in these interactions lose their kinetic energy and a small negative space charge builds up that can act as a thermal barrier for the other electrons. Thereby, more negative space charge is accumulated and the thermal barrier deepens.

Current jump **II (*c*→*d*, *j*←*i*)**: Now, because of the higher bias of the CP, those electrons that have not undergone excitation interactions have gained enough energy to also surpass the ionisation level of K (4.34 eV), and are able to produce a small amount of additional K^+ ions and electrons. Although, because of their high mobility, the produced electrons are rapidly collected by the CP, an ion-rich plasma appears between the aforementioned located negative potential barrier and the CP, i.e. a DL is formed. This transforms into a self-consisted "anode" DL in the moment when the potential drop across it exceeds the ionisation potential of the potassium atoms. Its appearance is marked by the sudden increase of the current when V_{CP} attains the value corresponding to the transition **g→h**.

Current jump **III (*e*→*f*, *h*←*g*)**: The current suddenly decreases, because here the threshold for rather weak and not very coherent unstable oscillations of I_{CP} is surpassed [see also Figs. 3(e) and (f)]. These are PRI-like oscillations that are caused by the periodic formation of thermal barriers at the low potential side of the DL (in a similar way as described above for **I**) and *on the average* they lead to a reduction of the current. They are related to the proper dynamics of the DL formed in front of the CP, as already described [2,3,11]. From Fig. 6(b) we discern that the current keeps decreasing slowly until the point marked by **IV**.

Above **IV**: According to the measured spectra [see Figs. 3(g) and (h) and Figs. 4(g) and (h)], here is now the onset of the real PRI! Now, the well-known mechanism of this instability sets in, and also the measured frequency coincides well with previous investigations [13]. However, starting from **IV**, the average value of I_{CP} again increases slowly [see Figs. 6(b) and (c) and Fig. 7]. This fact could be caused by inelastic collisions related to the strong oscillations in the plasma column which would lead to a general increase of the plasma density.

Although we have concentrated on the most spectacular characteristic of Fig. 6(a), we believe that also in the other two cases the same effects are present, but are, for higher plasma densities, not so clearly visible because they are overshadowed by the much more sudden onset of the PRI.

5. Conclusion

In general, up to now, a sudden downward jump of the electron current in the current-voltage characteristic of the cold end plate of a *Q* machine has been ascribed to the onset of a more or less strong instability (the so-called potential relaxation instability—PRI—or a similar type of oscillation) which, because of the periodic formation of a space charge DL and a thermal barrier, on the time average, gives rise to an enhanced anomalous resistivity of the plasma system [9]. This can in our case be used to explain the current jump **III**, above which we see strong plasma oscillations (see Fig. 7 above the current jump **III** and especially **IV**). In this investigation [especially in Fig. 6(a)], however, we also have seen a sudden current decrease (**I**) *without* the onset of any strong oscillation, and moreover, we have also seen an *upward* current jump (**II**) which is not explicable at all in terms of such a picture.

We should like to emphasise again that hitherto the standard (and only) explanation for a more or less sudden reduction of the electron current after the knee of the *IV* trace has been the immediate onset of the PRI [12]. Moreover, this model was assuming that the *IV* trace of the system has only *one downward current jump* (corresponding to **III** in our cases) because of the strong potential oscillations of the PRI. This standard characteristic corresponds to our highest density case [Fig. 6(c)] (see also the characteristic given in [12]). But even in this case, a fully developed PRI is seen only above a still higher onset (**IV**) (see also Fig. 7). These findings are also in keeping with the spectra which in all three cases [Figs. 6(a)–(c)] show more or less sharp frequency peaks only for relatively high values of V_{CP}. In all our three cases, V_{CP} at **IV** is at least 3 V greater than at the current jump **III**. We note here that the original investigation on the temporal evolution of the PRI was performed with a cold plate voltage of + 30 V [13]!

Thus, we tentatively conclude that all phenomena below **III** are related to collisional processes (which we have explained in Sec. 4), but not to strong plasma instabilities such as the PRI. Nevertheless, we believe that these nonlinear effects, which have not yet been taken into consideration, are essential for the PRI phenomenology, because in any case these processes will occur (perhaps on a much faster time scale) when the plasma passes from a stable state to an unstable one.

However, the following questions still need further intensive investigations: (1) Why are the current jumps **I** and **II** discernible only for very low plasma densities? (2) Why do they approach each other for increasing densities? (3) Why does the current jump **III** also move to lower values of V_{CP} for increasing density?

Acknowledgements

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