

## On the current-voltage characteristics of different electrodes in an alkaline plasma with surface coating

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**1. Introduction:** The current-voltage characteristic (*IV*-trace) of an electrode in a plasma depends (i) on **nonlinear space charge structures (NSCS)** formed in front of it and (ii), on a contamination of the electrode surface with plasma and residual gas particles. In the **Innsbruck Q-machine (IQ)** an investigation has been performed on such phenomena in a potassium plasma of a density of  $10^7 - 10^9 \text{ cm}^{-3}$ , produced by a tungsten **hot plate (HP)** with 6 cm diameter. The electron and ion temperatures are  $T_e \cong T_i \cong 0.2 \text{ eV}$ , respectively. The magnetic field strength is 0.1 - 0.25 T. The tantalum end plate was radially segmented, into a **collector (CO)** of 10 mm diameter and a surrounding ring of 10.5 mm inner diameter and an outer one of 70 mm, respectively [1,2,3]. When both electrodes were connected, the end plate acted as a conventional **cold plate (CP)**. Also an indirectly heated probe with a plane tungsten collector was used. By shifting the CP, the length of the plasma column was varied between 15 and 65 cm.

**2. Nonlinear spaces charges in front of the electrode:** The nonlinear behaviour of a plasma system is often manifested by unusual features of its *IV*-trace, such as sudden current jumps and hysteresis [4,5]. In discharge plasmas such phenomena are well-known and clearly connected with electron impact excitation and ionisation reactions. Recently, also in a so-called collisionless Q-machine plasma, various sudden jumps in the electron current branch of the *IV*-trace of the CP have been observed [1]. Also the *IV*-trace of the CO alone showed such a jump [2]. Especially at densities around  $10^7 \text{ cm}^{-3}$  these effects become very pronounced. Fig. 1 shows an *IV*-trace of the CP for such a case, and we discern even three current jumps up and down (termed **I – III**), each with hysteresis. Hitherto, at most one downward current jump was found [6], and it was ascribed to the sudden onset of the **potential relaxation instability (PRI)**. However, from the related oscillation spectra (see Fig. 2), it is clear that the first two current jumps (**I, II**) are not associated with an instability, but PRI-like oscillations start only at the third current jump (**III**). We have found arguments that **I** and **II** can be explained by invoking a mechanism that takes into account inelastic electron collisions with neutral K-atoms in front of the CP [1]. Although a Q-machine plasma is traditionally considered collisionless, often there is a considerable partial pressure of neutral alkaline vapour, i.e., K-atoms that have not been ionised on the HP. We estimate the neutral K pressure to be  $5 \times 10^{-4} \text{ mbar}$  at 400 K. This gives a number density of  $n_K \cong 10^{13} \text{ cm}^{-3}$ . With a maximum ionisation cross-section for K of  $\sigma_i \cong 8 \times 10^{-16} \text{ cm}^2$  [7], the mean free path for electron impact ionisation is  $\lambda_{\text{mfp}} \cong 125 \text{ cm}$ , which is just about eight times the system length. So there can be a significant number of inelastic collisions of plasma electrons with K-atoms. As soon as the kinetic energy of those electrons, which are accelerated towards the positively biased CP or CO, at a certain position exceeds first various excitation levels of K, these interactions cause the electrons to lose their energy and to accumulate, forming a NSCS in front of the CP or the CO and a first small potential

barrier for the following electrons. This gives rise to a further reduction of the current and to the initiation of the first of the observed current jump **I**. Similar arguments apply for the case when the kinetic electron energy surpasses the ionisation energy  $V_i$  of K, since now also ions (and more electrons) are created. This leads to the spontaneous formation of a double layer (DL) with a potential drop that exceeds  $V_i$ , and so this DL acts as a source of new charged particles

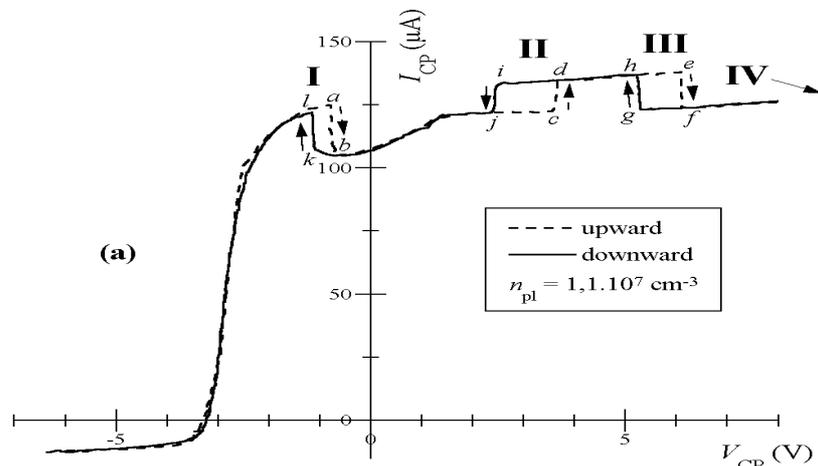


Fig. 1: Current-voltage characteristic of the CP at low density, showing three hysteretic jumps of the current (**I** – **III**). PRI-like oscillations appear not before jump **III**, and the real PRI has its onset for even higher values of  $V_{CP}$ , namely at **IV** (which in this figure is outside the range of the  $V_{CP}$ -scale).

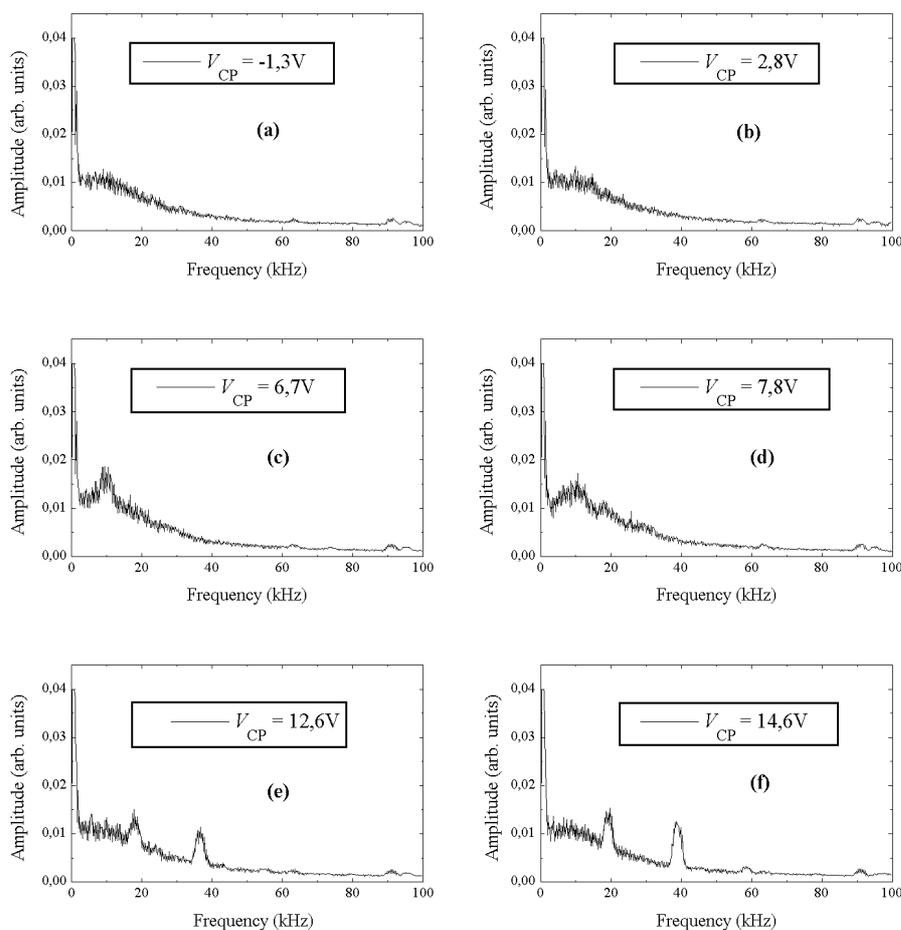


Fig. 2 (a-f): Spectra of the fluctuations superimposed on the CP current  $I_{CP}$ , taken at the indicated values of  $V_{CP}$  (partly outside the range of the  $V_{CP}$ -axis). We emphasise that the typical PRI is seen only in (e) and (f), whereas (c) and (d) are only incoherent PRI-like oscillations which nevertheless cause the current jump **III**.

**3. Contamination of the electrode surface:** The  $IV$ -trace of an electrode can also be strongly modified by a contamination of the electrode surface with plasma ions and residual gas particles. For Langmuir probes, this can lead to large errors in the determination of the plasma parameters. In the Innsbruck Q-machine the behaviour of various indirectly heated plane probes with a tungsten collector has been investigated [8]. In this case the background pressure was  $p \cong 10^{-6}$  mbar (corresponding to a particle flux of  $Z_R \cong 3 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ ) and the plasma density  $n_{pl} \cong 10^9 \text{ cm}^{-3}$  (corresponding to an ion flux of  $Z_K \cong 6 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ ).

Residual gases like  $\text{O}_2$  or  $\text{N}_2$  form covalent bonds with the probe surface and cause an increase of the work function  $W$ . On the other hand, a coverage by alkali atoms alone leads to the formation of chemisorbed complexes and reduces  $W$ . The changes  $\Delta W$  of  $W$  appear as shifts of the  $IV$ -trace along the  $V$ -axis (see Fig. 3). However, a continuous heating of a Langmuir probe in an alkali plasma, up to at least  $T \cong 550 \text{ K}$ , leads to a sufficient cleaning of the probe surface and enables a reliable determination of the change of the plasma potential and of the absolute values of the plasma density and the electron temperature. As the difference  $W_W - W_K$  is well known, the absolute value of the plasma potential can be estimated from an  $IV$ -trace of a probe completely covered by potassium. With increasing probe temperature, the cleaning of the probe surface starts by the evaporation of potassium and then proceeds with desorption reactions of K with loosely bound adsorbed residual gas atoms. Typical reactions are ( $\Delta H_f =$  enthalpy of formation):  $\text{K} + 2\text{O} \rightarrow \text{KO}_2$ ,  $\Delta H_f = -2,93 \text{ eV}$  and particularly  $\text{K} + \text{OH} \rightarrow \text{KOH}$ ,  $\Delta H_f = -4,41 \text{ eV}$ . However, the very first monolayer cannot be removed completely because of the high binding energies, and this leads to a permanent shift of the work function of about  $\Delta W \cong +1,5 \text{ eV}$ , which has to be taken into account in the measurements. The change of  $\Delta W$  stops for  $T > 600 \text{ K}$ , which indicates strongly bound residual gas atoms on the surface that could only be removed by heating it white red. Fig. 3 shows three typical  $IV$ -traces of an indirectly heatable probe isolated with a glass tube with and without heating [9].

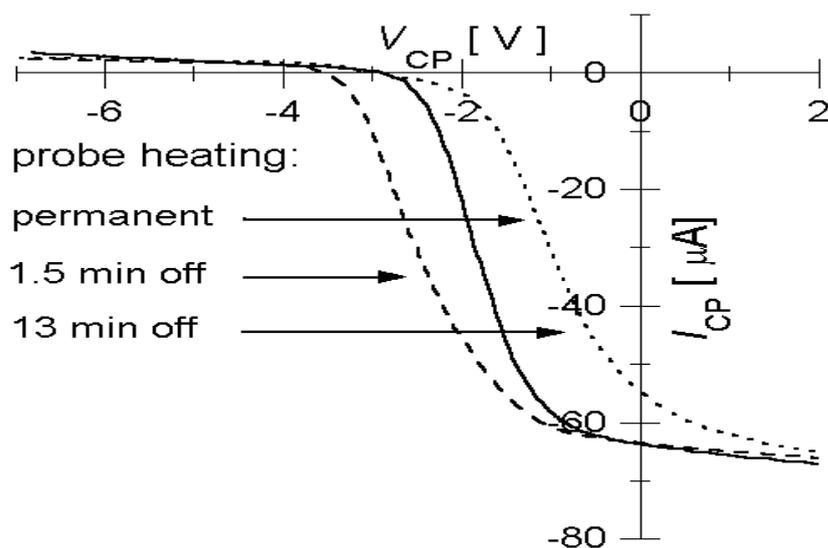


Fig. 3: Typical  $IV$ -traces of a heatable glass-isolated probe; solid line - clean probe during permanent heating, dashed line - 1.5 min after heating has been switched off and a pure K-coating has formed, dotted line - 13 min after heating has been switched off and a resistive layer of K and of compounds has formed.

Since any contamination of the probe surface shows itself by a horizontal shift of the  $IV$ -trace, the *calculated* plasma potential  $\Phi_{pl,c}$  is an excellent indicator for the cleanliness of the surface. So, Fig. 4 elucidates the effect of heating for a ceramic-isolated probe (open circles, dotted line) and a glass-isolated probe (solid squares, solid line) by showing the temporal evolution of  $\Phi_{pl,c}$ : At first the probe is heated and thus clean so that  $\Phi_{pl,c} \cong -1.3 \text{ V}$  which is a real-

istic value for our conditions. At  $t = 2$  min the heating is switched off and  $\Phi_{pl,c}$  starts to drop. This is a sign that the work function  $W$  of the probe surface drops because of a thin coating with K. For  $t \cong 7$  min,  $\Phi_{pl,c}$  starts to increase strongly, for  $t \cong 8$  min also the glass probe follows. Now the  $IV$ -traces become increasingly distorted due an inhomogeneous contamination by  $O_2$  and  $N_2$  and their compounds with K. This leads on one side to an increase of  $W$  and on the other side to a stretching of the  $IV$ -trace (Fig. 3, dotted line). For  $t = 9.3$  min for the ceramic probe, and for  $t = 13.3$  min for the glass probe, the heating is turned on again, and the contaminants start to desorb from the probe surface. After about 2 min for the ceramic probe, and after about 3 min for the glass tube, the original values for the plasma potential are almost reached again. For these thermal processes the glass tube lags behind because of the much lower heat conductivity of glass. Therefore it heats up more slowly, but needs also more time to cool down.

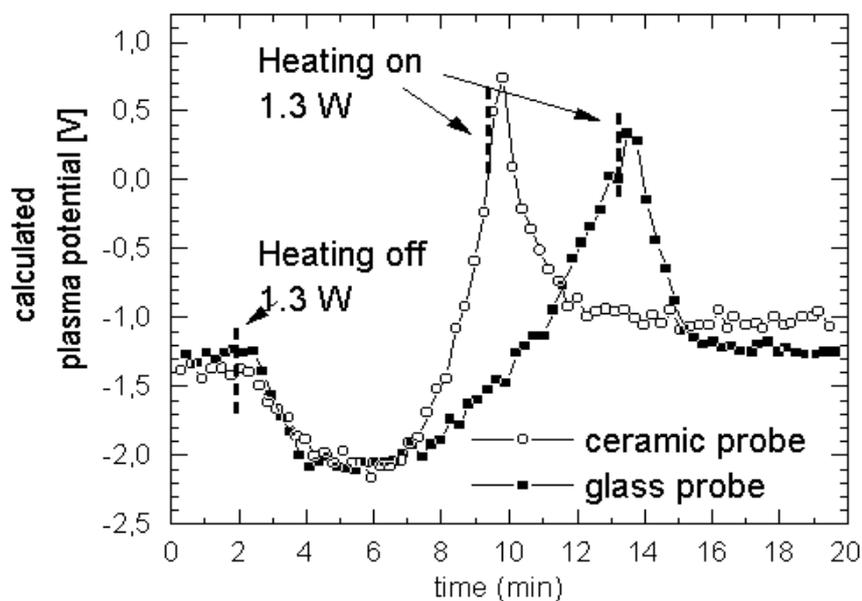


Fig. 4: Temporal evolution of the calculated values of the plasma potential of the ceramic probe and of the glass probe, as indicators for the cleanliness of the probe with and without heating (see below for further details). The thick vertical dashed lines indicate the times when the heating has been turned off and on again respectively. The heating of the ceramic probe has been turned on earlier.

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