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# On the Origin of Bistabilities in a DP Machine

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## 1. Introduction

Many systems in physical science and technology, but also in chemical and biological complexities, in which electric charge transport takes place, exhibit transitions between distinctly stable states. These usually appear as bistabilities, experimentally manifested by the presence of an S-shaped, respectively N-shaped **n**egative **d**ifferential **r**esistance (NDR). The physical origin of these effects is still among the most disputed subjects in nonlinear physics. It is known that in a plasma the S-type negative differential resistance is related to the appearance and disappearance of **c**omplex **s**pace **c**harge **c**onfigurations (CSCC) (e.g. anode double layers) [1,2], whereas the N-type negative differential resistance is related to the spatio-temporal dynamics of CSCC [3,4], or to the onset of some low-frequency instabilities [5].

In this paper we present experimental results concerning the bistable behaviour of the plasma of a DP-machine, subject to an external constraint. This bistability appears when a positively biased electrode E, immersed in the plasma, produces a local gradient of the kinetic electron energy. Under such conditions in front of the electrode a CSCC is formed, the consistence of which is ensured by a space charge **d**ouble **l**ayer (DL), able to maintain a potential drop that exceeds the ionisation potential of the neutrals present in the plasma. The intrinsic strongly nonlinear mechanism at the origin of the CSCC was already described earlier [6]. Acting as an internal source of charged particles, the spontaneous creation of the CSCC quickly reduces the internal resistance of the plasma so that the current collected by the electrode suddenly increases. Since the formation and decay of the CSCC sensitively depends on the current collected by the electrode, the plasma conductor shows a bifurcation between two stable conductive states at a critical value of the current. When the voltage at the positively biased electrode is in the right range for an S-shaped NDR, and if it is suitably connected to a system able to perform natural oscillations, the DP-machine works as a plasma oscillator. The frequency of the oscillations depends on the reactive circuit elements that form the system. These circuit elements can either be externally connected or can consist of the localised CSCC inside the DP-machine.

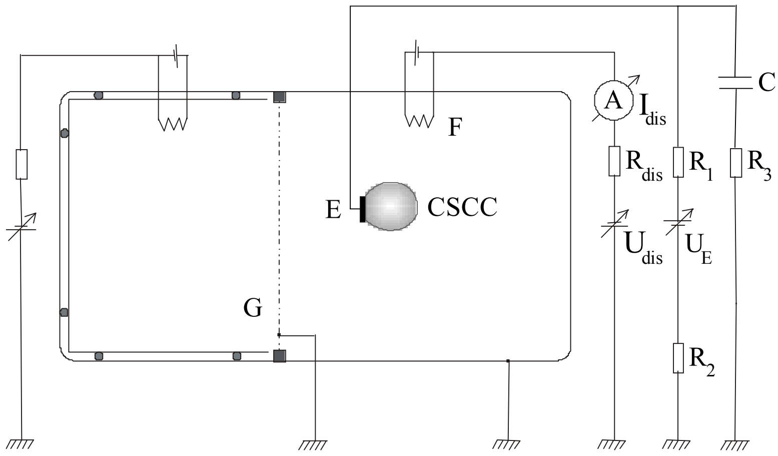


*Fig. 1: Experimental set-up of the Innsbruck DP-machine. G – grid, F – filament, $R_1$ = 500 Ω, $R_2$ = 10 Ω.*

## 2. Experimental results

The plasma created in the source chamber of the Innsbruck DP machine (Fig. 1) was driven away from thermal equilibrium by gradually increasing the voltage applied to a tantalum disk electrode E with 1 cm diameter. Fig. 2 shows the static *I-V* characteristic obtained under the following conditions: argon pressure $p = 5\times10^{-3}$ mbar, plasma density $n = 10^{11}$ cm$^{-3}$. By increasing *V* until the critical value corresponding to point **a** in the characteristic (Fig. 2) is attained, the current through the electrode jumps to a value corresponding to a new stable state (point **b** in the characteristic). After this jump, a quasi-spherical luminous CSCC, confined by an electrical DL, appears in front of E. By increasing *V* between **b** and **c**, the CSCC remains in a stable state. By decreasing the potential, the CSCC remains in its stable state for values of *V* smaller than those necessary for its formation (branch **b** – **d**). From point **d**, any small decrease of *V* will make the current to jump back to the lower stable branch of the characteristic (jump **d** – **e**). This type of behaviour corresponds to the S-type negative differential resistance of the plasma system.

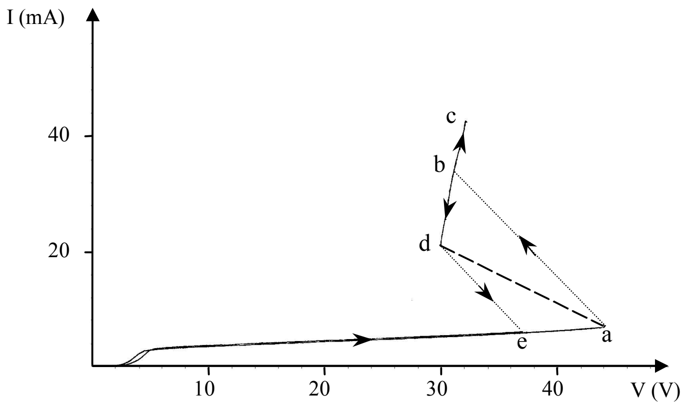


*Fig. 2: Static I-V characteristic obtained in DP-machine plasma.*

If we connect now an *RC* circuit, such that a capacitor will

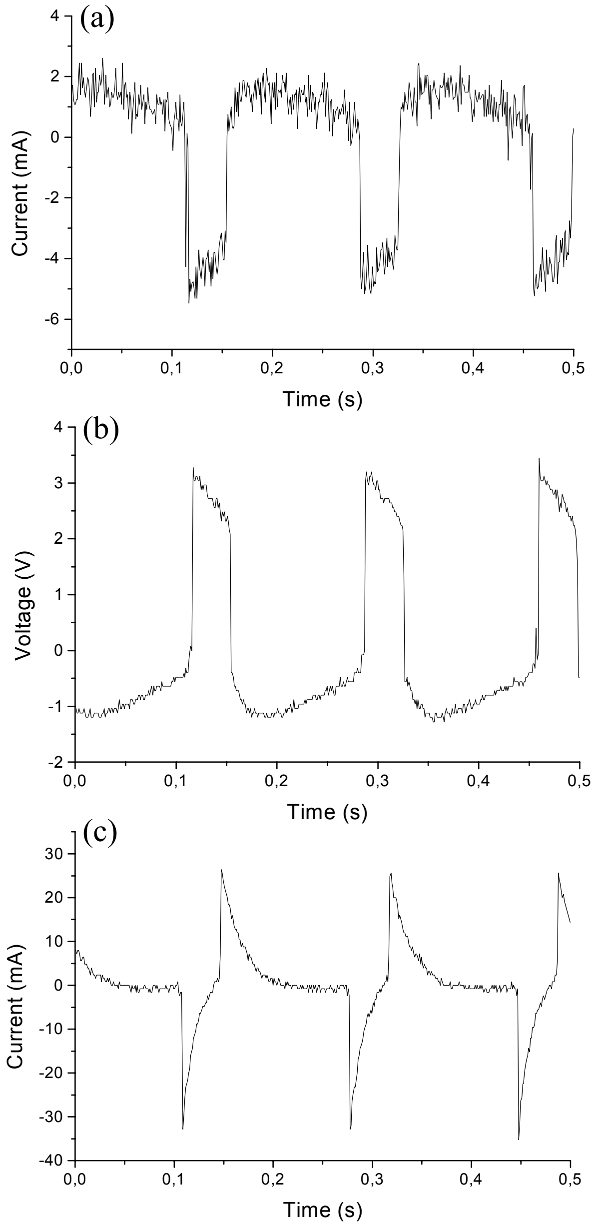


*Fig. 3: (a) Oscillation of the current in the external circuit; (b) Oscillations of the voltage across the plasma conductor; (c) Oscillations of the current in the RC branch of the circuit*

be in parallel with the plasma system (Fig. 1), we are able to trigger the formation and disruption of the CSCC, which causes oscillations of the current and voltage in the electrical circuit. The values of $C$ and $R_3$ were chosen in such a way that the period of oscillations was large enough to allow the establishment of a direct connection between the optical phenomena observed in front of E and the oscillations generated in the external circuit. Thus, for $R_3 = 1$ kΩ and $C = 64.9$ μF we obtain the current oscillations shown in Fig. 3a. To understand the physical phenomena, which take place here, we have simultaneously recorded also the oscillations of the voltage across the plasma conductor (Fig. 3b) and the oscillations of the current in the capacitor circuit branch (Fig. 3c). These oscillations appear as soon as the potential applied on E is large enough to initiate the formation of a CSCC (up to point **a** on the characteristic).

## 3. Discussion

After connecting the *RC* circuit, it becomes possible to trigger the current collected by E, and consequently also the CSCC formation and disruption, with a rhythm imposed by the charging and discharging processes of the capacitor *C*. The creation of the CSCC causes a sudden increase of the plasma conductivity, so that the current flowing to $R_1$ produces a big potential drop on it and a decrease of the voltage on E. In this conditions, the capacitor starts to discharge on plasma conductor and thereby maintains the CSCC for a while. When the voltage on $C$ reaches the critical value corresponding to point **d** on the characteristic, the CSCC disrupts, the conductivity of the plasma conductor decreases, so the voltage on $R_1$ decreases and the charging process of the capacitor starts again. When the voltage on $C$ reaches the critical value corresponding to point **a** in Fig. 2, the formation of the CSCC starts again. After this succession of stages, the processes are repeating, and the phenomenon becomes a periodical one. The period of these oscillations is determined by the values of the external circuit elements (capacitor and resistors), but also by the plasma conductor characteristics, like the conductivity of it, or the capacity of the DL confining the CSCC. The CSCC can continuously store energy in the DL electric field from external power supply and periodically release this energy into the plasma to sustain the oscillations. This permits the sudden transitions of the plasma system between the two stable states characterised by a different conductivity.

## 4. Conclusions

The experimental results reveal the presence of an S-type negative differential resistance in the static *I-V* characteristic, related to the generation and disruption of a CSCC in front of a positively biased electrode immersed in a DP machine plasma. We prove that under such conditions an *RC* circuit can initiate the intermittent appearance of the CSCC, which determines the plasma conductor to make periodic transitions between two stable state, with different conductivity.

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