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Ion Space Charge Structures-Formation and Properties: Experiment and Simulations

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Abstract

Experimental results and numerical simulation are presented on the formation and properties of the ion space charge structures in a DP machine. The plasma is produced solely in the source chamber, whence ions penetrate the separating grid into the target chamber, where they may form a positive space charge. The spatial distribution of the ion space charge and its temporal evolution during ion space charge instability were investigated for various boundary conditions and geometrical dimensions of the system. The boundary conditions are specified by the grid bias, which controls the ion energy and the anode potential of the target chamber, which may controls the number of ions in the space charge. This number is also controlled by plasma density in the source chamber and transparency of the separating grid and geometrical dimensions of the target chamber.

Keywords:

ion space charge, ion space charge instability, non-linear oscillations

1. Introduction

The formation of space charge is a frequent phenomenon in plasma physics, since a spatial separation between the particles (positive ions and electrons) can be a natural consequence of the kinetic properties of the particles, as e.g. in the case of ambipolar potentials or at the plasma solid interaction [1]. In other cases this separation is deliberately produced for special purposes, wich can be the production of a particle beam [2], or for electrostatic energetic analysis [3]. The purpose of this paper is to consider a simple structure like a diode in which the ion space charge forms [4]. The behavior of the space charge is investigated for (i) various boundary conditions, (ii) various geometrical dimensions of the system and (iii) various energies of the ions entering the diode. The experimental results are compared with those obtained by simulation using two-dimensional PDP-code [5]. Such a system has strong bearings e.g. one-grid system for extraction of large cross-section ion beam from the ion source [6], which is used for plasma heating by neutral and/or ion beam injection [7].

2. Experimental Device

The experiments were performed in the Innsbruck DP machine, which is presented in Fig. 1. It produces an unmagnetised plasma in a stainless steel cylinder of 44 cm diameter and 100 cm length, by a d.c. discharge in the source chamber (S). The argon pressure was 10^{-4} mbar and discharge voltage of 50V. The plasma density ranged between 2×10^{13} and 7×10^{14} m^{-3}. The argon ions have a temperature of about a 0.15 eV.

The ion space charge appeared in the target chamber (T) which is separated from the source chamber by a stainless steel grid (G). The grid

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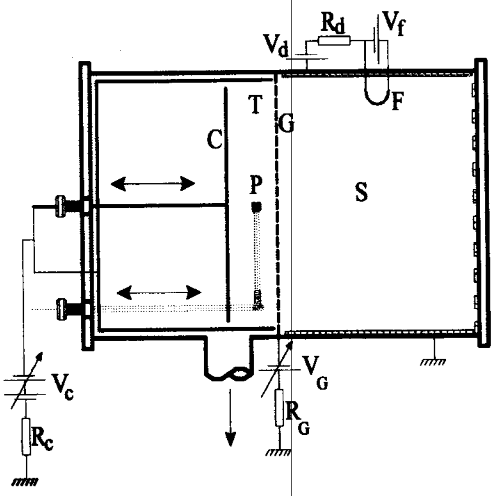

Fig. 1 Experimental set-up F-filament, S-Source, T-target, C-collector, P-plane probe

parameters are: 0.032 mm wire diameter, 0.064 mm distance between the wires (geometrical transparency T_g = 44% and the effective transparency T_{eff} = 37%) [8]. The grid bias (V_g) was varied between –50 and –300V. The length of the target chamber was varied between 3 mm and 200 mm using a large collector (C), which is axially movable but parallel to the separating grid [9]. A plane Langmuir probe (P) was used to measure the axial distribution of the ion current density in *T* in both steady state and time-variable regime.

3. Experimental Results and Discussions

The ion space charge is produced by letting ions flow from the source chamber to the target. For this purpose the separating grid was negatively biased in order to reflect electrons back to the source chamber and the length of the target chamber was larger as the thickness of the ion sheath around the grid. The thickness was estimated using Child-Langmuir law: $d = k\frac{V_G^{3/4}}{j^{1/2}}$ where k is a constant, and j is the density of the Bohm ion current [1].

Under our experimental conditions the Debye length was always larger as grid mesh size so that its effective transparency was constant as about 37%. The ion flux entering the target chamber was controlled by plasma density in the source chamber while grid bias allowed the control of their energy. For larger negative bias more energetic ions enter the target and maximum of the space charge is shifting away from the grid [9].

The easiest way to change the ion space charge structure and its position in space is by changing the collector bias (V_c) because, as was already show in [9], almost all ions are reflected and form a space charge in T, when the V_c is around plasma potential in S (around 1V). The ion space charge together with the grid sheath of S produce almost a symmetric potential well around G. Moreover, the ion space charge is concentrated in about 1 or 2 cm from the grid and its potential can be more positive than plasma potential of the source. Under these circumstances, ion oscillations can be observed the frequencies of which correspond to the ion transit time around the grid [10]. This is similar to the electron bouncing in so-called reflex ion source [11], and

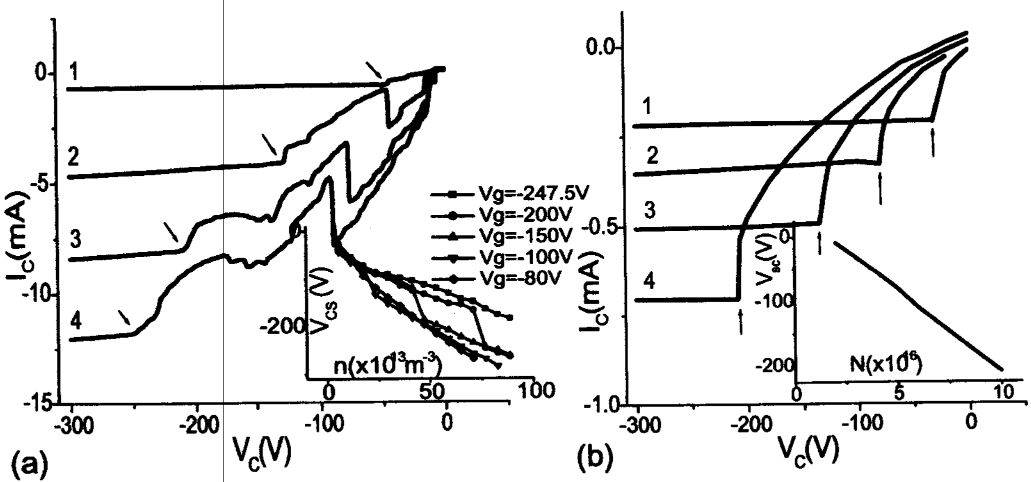

Fig. 2 Current-voltage characteristics of the collector a) experimental; b) numerical simulation and plasma density as parameter (1.7 × 10^{13} m^{-3} for 1, 5.7 × 10^{13} m^{-3} for 2, 9.7 × 10^{13} m^{-3} for 3 and 3.7 × 10^{14} m^{-3} for 4). Collector-grid distance of d = 9 cm, V_G = –150V. The arrows show the V_{CS} limit.

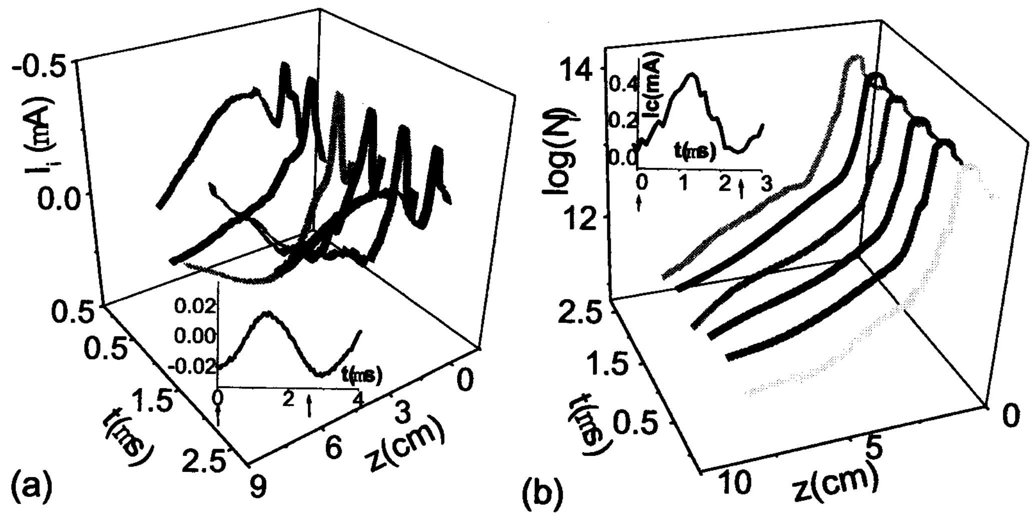

Fig. 3 Time-space diagrams for ion saturation current: a) measured by probe (biased –5V) and b) numerical simulation: V_c = 0V, V_G = –150V, n = 1.7 × 10^{14} m^{-3}

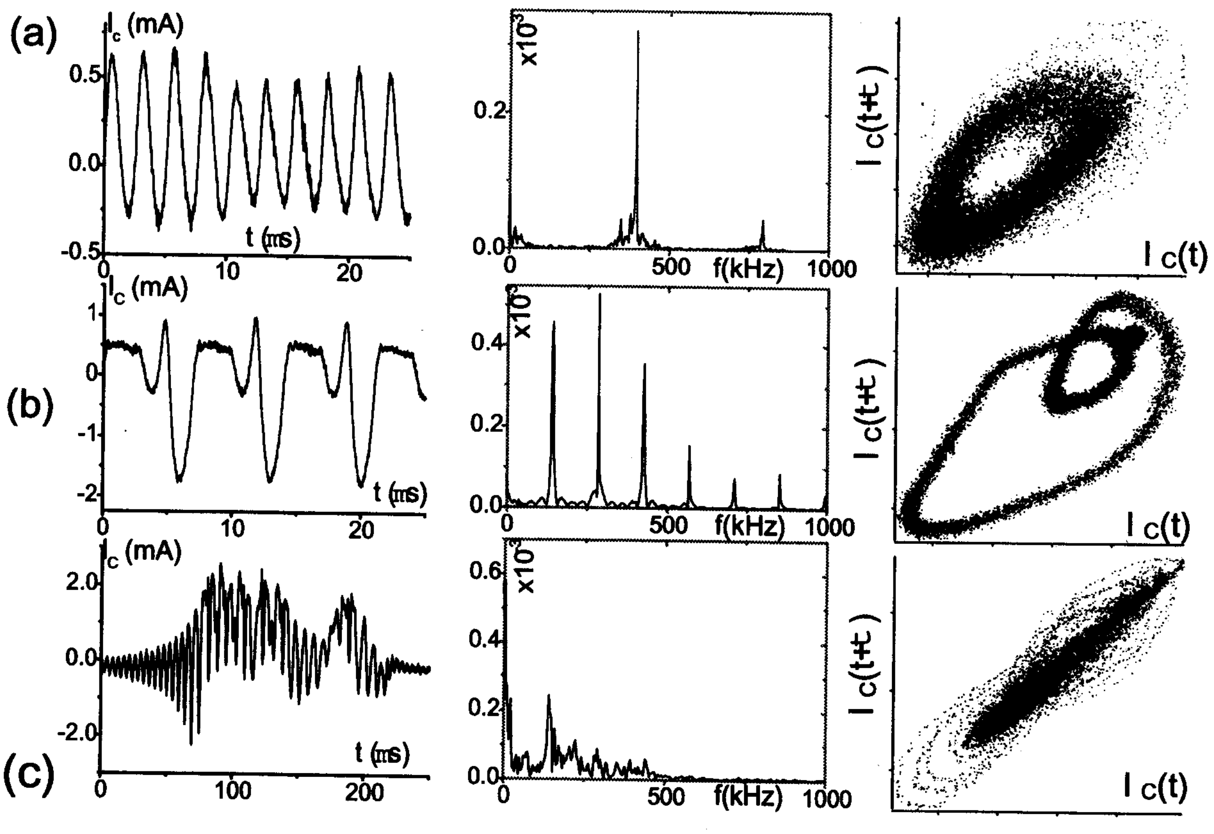

Fig. 4 Ion space charge fluctuation registered as current oscillation of the collector for d = 9 cm, V_G = –150V and V_c = –8V (a); V_c = –82V (b); V_c = –124V (c)

mechanism of the instability should be related manly to relationship between reflected ions from target and plasma potential in S than to the coupling of three ion beams that might reflected arise due to asymetry of the sheath potential [12].

In this space charge the ions are slowed down and thermalized so that they can be collected by the C as long as its potential is negative with respect to the potential of the space charge. In Fig. 2 the current voltage characteristic of the collector is presented with the plasma density in S as parameter. There is a remarkable qualitative agreement between experimental results (Fig. 2a) and those obtained by numerical simulation (Fig. 2b). Both results clearly show the limit of the collector bias, which corresponds to saturation current and to the decay of the ion space charge. The limit (V_{cs}) is labeled by arrows on each $I_c - V_c$ characteristic. Moreover, the dependence of the V_{cs} on the plasma density is presented in inserts of Figs. 2a and 2b, respectively. There is an almost linear dependence of the V_{cs} on plasma density, except a narrow parameter range. Moreover, this transition shifts towards more negative grid biases when the ion flux from the source increases (Fig. 2).

As long as the ion space charge is formed in T grid and collector currents can be registered (insert of Fig. 3). Both, the experimental results (Fig. 3a) and that of the numerical simulation (Fig. 3b), show the presence of the ion space charge in a distance of about 1 cm from G. Moreover, under certain experimental conditions (V_C = 0V, V_G = −150V and $n = 1.7 \times 10^{14}$ m^{-3}) the ion flux which leaves the space charge and is collected by the C shows large oscillations, appearing as a standing wave with half a wavelength, between G and C. This effect is very well visible in the experiments but less pronunced in the simulation. These oscillations are almost harmonics and have a small amplitude when the I_c is also small (Fig. 4a). Their behavior becomes strongly non-linear for incerasing I_c (Fig. 4b) and even shows high-amplitude intermittence close to the V_{cs}, before the decay of the ion space charge (Fig. 4c). Both, power spectrum and phase space for each oscillations of the Figs. 4a–c are also presented.

4. Conclusions

The experimental results and the numerical simulations presented allow the following conclusions:

1. A one grid system for ion extraction structure can be efficient as long as the collector voltage is above a certain threshold (V_{cs}). This threshold practically does not depend on the grid bias but its absolute value increases almost linearly with the ion flux which is extracted from the source.
2. The system is unstable as long as the ion space charge is formed near the extraction grid.
3. The characteristics of the instability are related mainly to ion transit time around the grid and relationship of reflected ions and plasma potential in S but they depend also on the geometry of the system and the boundary conditions.

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