Properties and control of anode double layer oscillations and related phenomena

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An experimental investigation is presented on oscillations excited by the dynamics of an anode double layer or fireball in a double plasma (DP) machine. The fireball is created by additional ionization processes in front of a small circular anode, which is inserted into the diffusive DP plasma and biased positively. An annular (ring) electrode, usually biased negatively, surrounds the anode. The extension of the ion sheath in front of this ring controls the anode current by varying the effective diameter of the anode during the fireball oscillations. The ring voltage affects not only the oscillation frequency of the anode current but also other characteristics of the instability. Related phenomena consisting of ion-acoustic waves and almost synchronous oscillations of the plasma potential in the chamber where the fireball is formed are also presented.

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I. INTRODUCTION

The first systematic investigations of the anode region of a hot cathode discharge, including the formation of a "ball of fire," were performed by Malter, Johnson, and Webster [1]; Webster, Johnson, and Malter [2]; Johnson and Webster [3]; and Johnson [4]. In these experiments, the gas pressure was of the order of one millibar, and a small cylindrical diode configuration with a diameter of about 1 cm was used. The transition from an anode sheath, known as the "anode glow mode," to a ball of fire mode and then to a Langmuir discharge mode was investigated [2,3]. Recently, similar experiments have been performed on the anode glow mode and the temperature limited mode in a large size hot cathode discharge, namely, a cylindrical structure of about 40 cm diameter, at low gas pressure (of the order of 10^{-3} mbar); for this purpose a multipolar confinement plasma system [5], similar to a so-called double plasma (DP) machine [6] or a triple plasma machine [7], was used.

The diffusion plasma of a DP machine was also used as "background plasma" in the case of the formation of anode double layers (ADL). ADLs are confining balls of fire or fireballs in front of an additional, usually plane, positively biased electrode inserted into one chamber of the DP machine. Fireballs are zones of higher plasma density, plasma potential, and luminosity. This phenomenon is due to additional localized excitation and ionization processes, and the plasma itself becomes strongly influenced by the DL formation [8–14]. Strictly speaking, in this case the system has to be considered as a combination of three active electrodes: the hot cathode, the large main anode (which is the electric ground), and the additional small electrode [15]. A detailed investigation has been made on the time evolution of the spatial distribution of the plasma parameters inside an ADL and the surrounding plasma during self-sustained ADL oscillations [8]. A strong correlation between the stability of an ADL and the temporal evolution of the plasma parameters was observed.

Similar properties have been observed in so-called fire-rod structures produced in a weak magnetized plasma system [16].

Recently, a new approach has been proposed for the phenomena related to the formation and the dynamics of an ADL starting from so-called self-organization processes in low temperature plasmas [14].

Here, we present experimental results on the possibility of the control of ADL oscillations using an additional ring electrode placed in front of the plane circular anode. Starting from the ADL formation, the frequency of the self-sustained oscillations and their quenching can be controlled by the bias of the ring electrode. Our results show that the anode current oscillations are accompanied by strong oscillations of the plasma potential in the chamber where the additional electrode is inserted. In addition, these ADL oscillations excite propagating ion-acoustic waves.

II. EXPERIMENTAL SETUP

The experiments have been carried out in two different devices: The first one is the Innsbruck DP machine presented in Fig. 1, where the cylindrical chamber is 90 cm long and has a diameter of 44 cm. A grid divides the vessel into two almost symmetric chambers. For our experiment a diffusive argon plasma was produced only in chamber 1 by a hot cathode discharge inside a magnetic multipole confinement between tungsten filaments and the cylindrical wall as main anode. The anode of chamber 1 was electrically grounded so that the plasma potential Φ_p in this chamber had a constant value of around $\Phi_p \cong +1.5$ V. The background pressure for the experiments was about 10^{-3} mbar. The typical plasma parameters used were an electron density $n=(1-5)\times 10^8$ cm^{-3} and a temperature of the almost thermalized electrons of $T_e = 1.5-2$ eV. Because, for our experiments,

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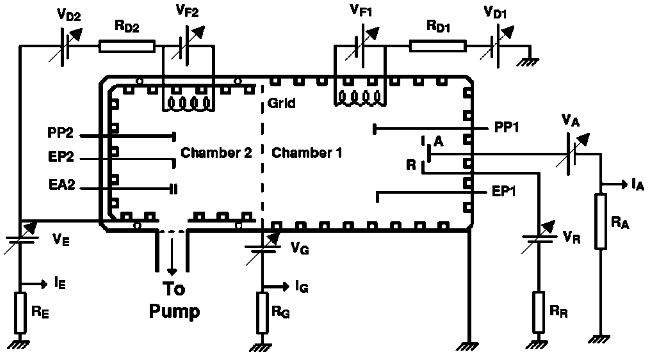

FIG. 1. Schematic of the Innsbruck DP machine; PP1 is the plane probe, EP1 is the emissive probe, **A** is the additional plane anode, and **R** is the ring-shaped electrode.

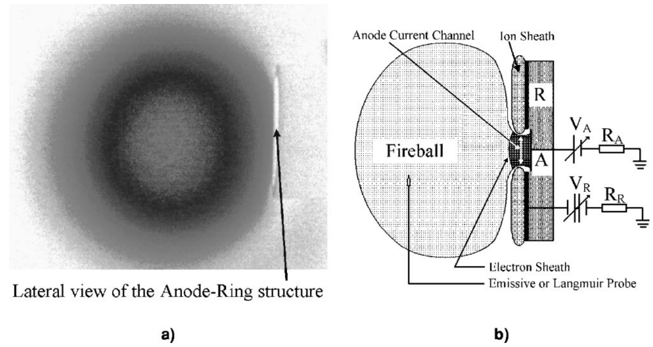

FIG. 2. (a) Single shot, 10-μs exposure photograph of the anode fireball recorded by a CCD camera during the maximum of the anode current [↓↓—Fig. 3(a)]; (b) Schematic of the anode fireball shape and of both ion and electron sheath formation in front of the ring-anode system.

we have used only chamber 1 we will refer to the DP machine as a single plasma machine. The plasma parameters and the results were the same if the separating grid was grounded or biased strongly negatively as it is usually the case in the DP mode for wave excitation in order to decouple the electrons of the plasmas of the two chambers [17].

The second device was a single plasma machine of the University of Iaşi. The cylindrical vessel has 30 cm diameter and 40 cm length. The parameters of the multipolar confinement argon plasma were approximately the same as in chamber 1 of the Innsbruck DP machine. Basically, in both devices the diffusive plasma is a result of a dc hot cathode discharge, and the potential distribution between the cathode and the anode corresponds to the ''temperature limited mode'' [1,5]. The single plasma machine was used to prove the experimental reproducibility and to investigate the effect of the separation grid of the DP machine on the anode oscillations.

In both devices, an additional plane tantalum electrode **A** (usually called the ''small anode **A**'' or simply ''anode **A**'') with a diameter of 1 cm was inserted. A ring-shaped electrode **R** of 2.5 cm external diameter and 1 cm inner diameter was mounted concentrically 0.2 mm in front of anode **A**. In our experiment **A** was positively biased (with $50 < V_A < 250$ V) with respect to the main grounded anode. By additional ionization processes in front of anode **A**, new plasma appears in the form of a fireball [8], confined by an ADL. The temporal evolution of this nonlinear plasma structure was investigated by means of a fast charge-coupled device (CCD) camera (exposure time 10 μs). The plasma parameters for both steady state and oscillating regimes were measured using a movable plane Langmuir probe (PP1), an emissive probe (EP1), and a box-car technique.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results reported here primarily refer to self-sustained anode oscillations and to a method of controlling the instability by the additional ring electrode biased with respect to the main anode. The second part reports on the effects of nonstationary ADLs and related phenomena in chamber 1.

A. Anode double layer oscillations

The first experiments have been performed in the Innsbruck DP machine (Fig. 1), but almost identical results were obtained in the single-plasma machine of the University in Iaşi. Argon plasma was produced only in chamber 1 using a discharge voltage $V_{D1} = -80 - -50$ V and a discharge current $I_{D1} = 10-40$ mA. For the sake of simplicity, from now on I_{D1} will be just denoted by I_D. This current, which flows between the filament and the main anode, is approximately proportional to the plasma density. Anode **A**, together with the ring electrode **R**, is inserted axially into chamber 1 at a distance of about 37 cm from the separating grid. A fireball appears when **A** is biased higher than about +100 V with respect to the main anode. Under these conditions, the mean free path for electron impact ionization processes is $\lambda \cong 1.6$ m [18], and thus much longer than the geometrical dimension of the localized fireball, which at its maximum extension has a diameter of 7 cm approximately [cf. Fig. 2(a)]. The ionization probability $P_i = (1 - e^{-x/\lambda}) \times 100\%$ [11] for this case (under approximately one-dimensional conditions) is about 4.3%. This value can be considered as a lower estimate of the additional ionization in the region of the ADL in a steady state regime.

The fireball is unstable and oscillates with a constant frequency in the range of tens of kHz. A typical time series of the anode current $I_A(t)$ is presented in Fig. 3(a). The oscillations are similar to those reported by Song, D'Angelo, and Merlino [8], but at an average current about ten times lower than in their experiment. The maximum current (labeled ↓↓) is about one order of magnitude larger than the minimum (labeled ↓) of I_A. The oscillations are characterized by a fast increase and a slower decay, thus showing typical characteristics of a relaxation oscillation. The two phenomena correspond to the formation of the fireball and to its disruption, respectively. The fast increase (↓→↓↓) occurs when the ADL appears and expands toward the chamber, and the slower decay (↓↓→↓↓↓) occurs when the density relaxes and the ADL disappears again.

Supplementary electrical and optical measurements were carried out in the single-plasma machine at the University of Iaşi, where results similar to those obtained in the DP ma-

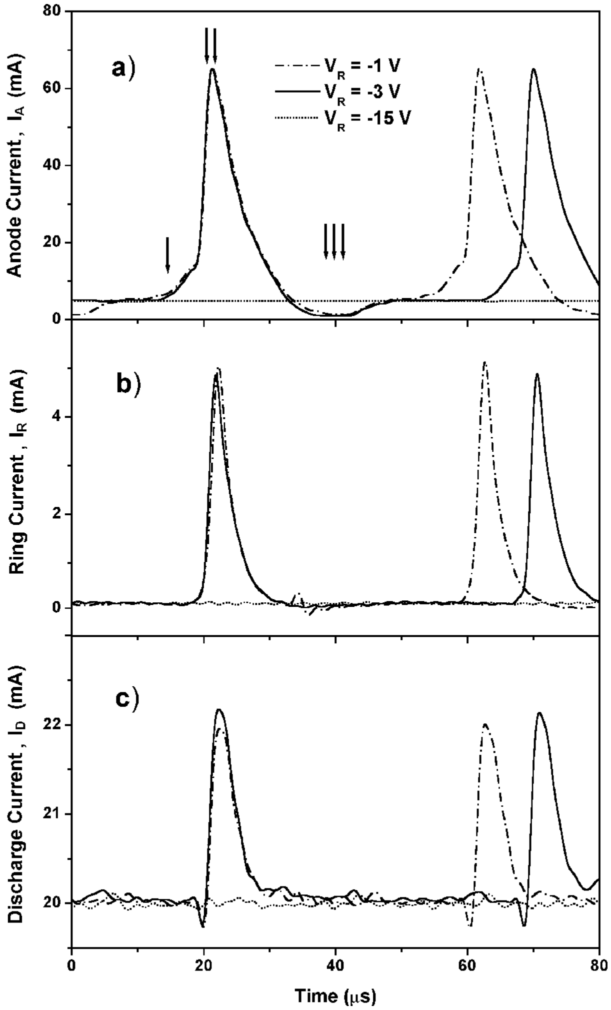

FIG. 3. Typical time series of the oscillations of (a) the anode current and (b) the ring current (ionic current) for different ring potentials; (c) time series of the plasma discharge current. $V_A = 145$ V, $p = 10^{-3}$ mbar, and $n = 1.5 \times 10^8$ cm^{-3}. For $V_R = -15$ V the ADL is not formed and the plasma is stationary.

chine of Innsbruck have been obtained. A fast recording camera shows that the anode current oscillations are indeed the result of the formation and the destruction of the ADL inside a range of about 7 cm from anode **A**, similar to an "on-off" discharge system. The lateral picture of the fireball [Fig. 2(a)] was acquired during the on state when the fireball was fully developed. During this time, the plasma parameters inside the fireball were $n_{eA} = 2.5 \times 10^9$ cm^{-3} and $T_{eA} = 5.6$ eV, whereas outside they were $n_e = 1.5 \times 10^8$ cm^{-3} and $T_e = 2.1$ eV.

For the floating ring **R** (or by removing it completely from the experiment), the anode current [Fig. 3(a)] and its oscillation frequency depend only on the anode voltage V_A and on the main plasma density, which is controlled by the discharge current I_D. Keeping the plasma density and V_A constant, the frequency of the anode current oscillations can easily be controlled by varying the bias V_R of the ring in a range of a few tens of volts around the plasma potential Φ_p (Fig. 4). The strongest influence of V_R occurs at negative values of the ring bias where the ring electrode collects an

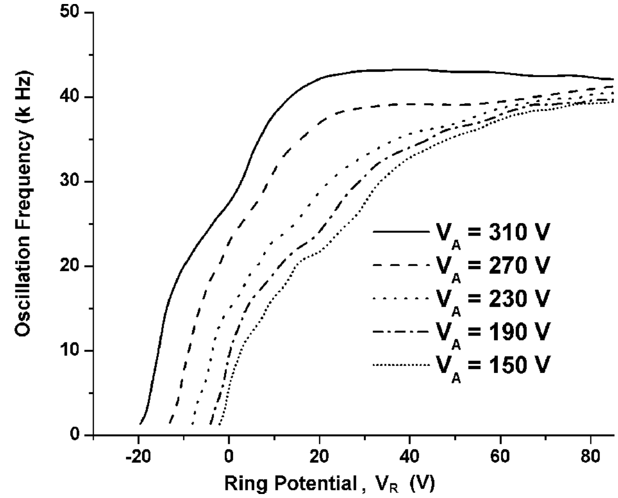

FIG. 4. Frequency of the anode current oscillation versus ring voltage for different anode voltages. The discharge current was $I_D = 20$ mA and $p = 10^{-3}$ mbar.

ion current. For decreasing ring voltage V_R [Fig. 3(a)], the rise time of I_A (during the ADL formation) is almost constant (↓→↓↓), whereas the duration of the slow decay of the anode current (↓↓→↓↓↓) increases and, consequently, the oscillation frequency decreases. Also the maximum of the anode current remains almost constant [compare the full line and the dash-dotted line in Fig. 3(a)]. Both, the ion current I_R collected by ring **R** [Fig. 3(b)] and the main discharge current I_D [Fig. 3(c)], oscillate almost in phase with the anode current I_A. During the oscillations, I_D [Fig. 3(c)] increases only by 10% compared to the steady state level, and therefore there is only a small increase in the main plasma density. But I_R is large during the oscillation maximum, since during this time a high-density anode plasma surrounds the ring. In spite of the fact that the surface area of the ring is about five times larger than the anode surface area, the ring current is about one order of magnitude smaller than the anode current. Moreover, for a high negative bias of the ring (e.g., $V_R = -15$ V) the anode oscillations are quenched, and thus the anode, the ring, and the main discharge currents attain their steady state values [dotted lines in Figs. 3(a)–3(c), respectively].

More information about the ADL oscillations can be obtained from their evolution during a temporal variation of the ring bias. The experimental results are presented in Fig. 5 for a linear variation of V_R [Fig. 5(a)]. The repetition frequency of the voltage ramp, which is applied to the ring, was much lower than the frequency of the anode oscillations. The time series of the anode oscillations can be followed in Figs. 5(b) and (c) for two different values of V_A but the same discharge current I_D. The following properties can be observed.

(i) The anode oscillations are quenched as long as the ring voltage is lower than a certain threshold labeled in Fig. 5(a) as $V_{R(\mathrm{th})}$.

(ii) The onset of the anode oscillations takes place when the ring bias is above this threshold, which depends on the plasma density and the anode potential.

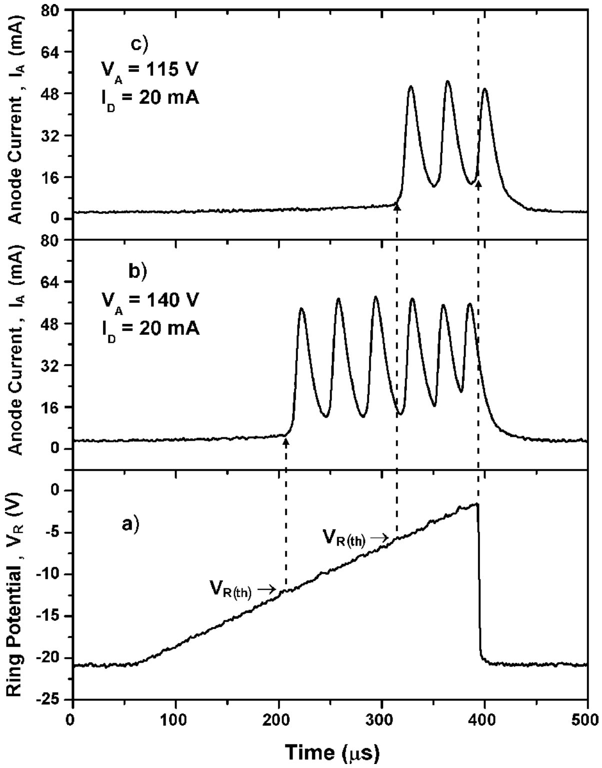

FIG. 5. Time series of the anode currents (b) and (c) as a response to the ramp voltage applied to the ring (a) for different anode voltages but the same plasma densities. I_D is the main discharge current, which is proportional to the plasma density. $V_{R(\mathrm{th})}$ represents the threshold of the ring bias for the onset of the ADL oscillations. $p=10^{-3}$ mbar.

(iii) The rise time of the anode instability is shorter than or at least equal to a quarter of the period of the anode oscillation.

(iv) With increasing ring voltage, the oscillation frequency increases (a result that is visible already from Fig. 4).

(v) The amplitude of the anode oscillations decreases with increasing ring voltage towards the plasma potential.

(vi) When the drop of the ring voltage occurs during the rising flank of the oscillation, still one complete period of the anode oscillation follows [Fig. 5(c)].

This latter result shows that the anode oscillations can also be produced as single cycles using a pulsed bias of the ring (Fig. 6). We observe that a pulse which is shorter than approximately the width at half maximum of one cycle and which raises the ring potential V_R from a negative value, where the ADL instability is suppressed, to a value $V_R > V_{R(\mathrm{th})}$ can excite just one cycle of the oscillation of I_A [Fig. 6(a)]. Moreover, the time between two successive oscillations of the anode current is long enough so that I_A can reach the steady state value.

Under these conditions the axial distribution of the plasma potential in front of the ring-anode structure was measured at different moments during one cycle of the anode current oscillation using a movable emissive probe [Fig. 6(b)]. We restrict ourselves here to emphasize some of the main features of this result, given as follows.

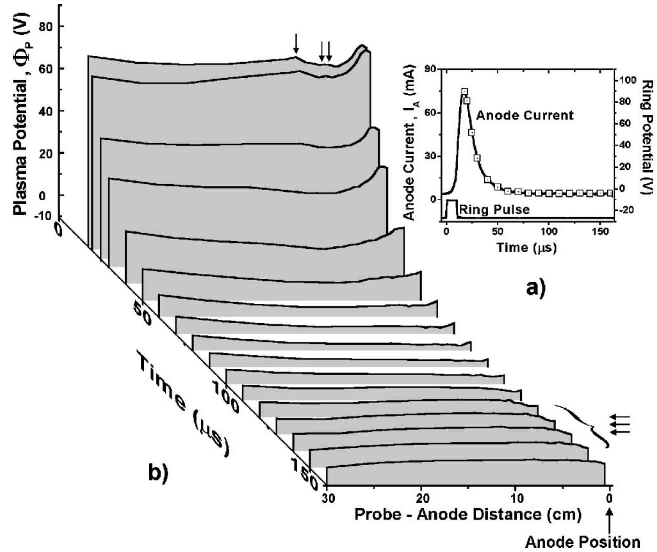

FIG. 6. (a) Time series of the anode current I_A triggered by a short pulse voltage applied to the ring electrode. (b) Axial distribution of the plasma potential Φ_p measured by the emissive probe at different instants of the anode oscillation. $p=10^{-3}$ mbar, $V_A=50$ V, and $I_D=20$ mA.

(i) In phase with the fast and strong increase of I_A, there is a strong increase of the plasma potential Φ_p (by a few tens of volts) all over the chamber.

(ii) The plasma potential is rather uniform except in a region of about 7 cm around the ring-anode system [labeled ↓ in Fig. 6(b)]. Usually, the presence of the electric probe in this region can strongly disturb the ADL so that we have not succeeded in achieving reliable time resolved data of the spatial distribution of the plasma potential in the range ↓ →↓↓. Consequently, we restricted the measurements up to a distance of about 1 cm in front of anode **A** and at about 2 μs after the maximum of the anode current. In this way we have obtained only the negative potential dip [labeled as ↓↓ Fig. 6(b)] in front of the ADL which is located close to the anode at a distance of 2 cm.

(iii) The fast increase of I_A and consequently of Φ_p are limited by the appearance of the negative dip in the axial profile of the plasma potential in front of the ADL [labeled as ↓↓ Fig. 6(b)]. This potential dip is of the order of a few volts so that it prevents the thermal electrons from the main chamber to enter the ADL. Consequently, the anode current I_A starts to decrease and the whole system relaxes towards the steady state parameters until a new oscillation cycle might start, being externally excited [as in Fig. 6(a)] or self-excited (as in Fig. 3).

The main DP discharge mode is temperature limited [1,5], and it remains so during the anode oscillations, so that the strong increase in the plasma potential does not significantly change the main discharge current [Fig. 3(c)]. The small anode **A** can be seen as a positively biased probe as long as additional excitation and ionization processes in front of it are negligible. But, during the ADL formation [branch ↓ →↓↓, Fig. 3(a)], the plasma region in front of anode **A** evolves into a fireball [3], which may expand up to about 7 cm in front of it. Moreover, the ADL acts as a virtual anode having a large area for collecting electrons (almost spherical with about 7 cm diameter), compared with the geometrical surface of anode **A** (a plane disk of 10 mm diameter). Consequently, both particle balance and energy balance are changed and the plasma potential of the main chamber tends to increase towards the potential V_A of the anode **A** [15]. An increase in the plasma potential in the main chamber does not significantly change the main discharge current I_D [Fig. 3(c)], but it reduces the potential difference between the small anode **A** and the plasma potential including the potential drop across the ADL. Moreover, the negative potential dip in front of the ADL [shown in Fig. 6(b)] can explain the limitation and even the decrease of the electron flux towards anode **A**. It also indicates that around the maximum of the anode current I_A, the ADL recedes close to the small anode **A** and diminishes continuously until its disappearance. Consequently, the decrease of the anode current I_A ends with the transition of the fireball mode into the probe mode, and the whole process repeats giving rise to the observed current oscillations.

The dependence of the ADL oscillations on the ring bias can be explained using a simple model taking into account the sheath formation in front of the ring and anode, respectively. To understand the complete scenario of sheath evolution in front of anode **A** and ring **R**, respectively, immersed in the plasma, we need to know the current densities $j_{A,R}$ through the plasma-electrode system and the potential differences V_{Ap} or V_{Rp} between the anode or the ring and the plasma potential Φ_p, respectively. Under collisionless conditions, the relationship between current density $j_{A,R}$ and $V_{Ap,Rp}$ can be approximated by the Child-Langmuir law [19]:

$$j_{A,R}=\frac{4}{9}\varepsilon_0\left(\frac{2e}{m_{e,i}}\right)^{1/2}\frac{V_{Ap,Rp}^{3/2}}{d_{A,R}^2}, \tag{1}$$

where ε_0 is the electric permittivity, e is the elementary charge, $m_{e,i}$ is the mass of the electron or ion, respectively, and $d_{A,R}$ is the thickness of the one-dimensional sheath formed between anode **A** or ring **R**, respectively, and the plasma.

Our system consists of two parts: anode **A**, which remains always positive with respect to the plasma potential, and ring **R**, which might be negative or positive with respect to Φ_p. The voltages of the ring electrode V_{Rp} and of the anode V_{Ap} with respect to Φ_p might change according to their biases and the temporal evolution of the plasma potential and the plasma density inside the anode region during the ADL oscillations. This is the reason why we have to analyze each sheath during both the steady state regime and the ADL oscillations.

1. Steady state regime

This regime is obtained either for a low positive anode bias (in our case $V_A<100$ V), or for a large positive bias of the anode, but a negative bias on the ring lower than $V_{R(\mathrm{th})}$.

In this case no ADL is present in front of the anode-ring system and the plasma of the anode region is rather uniform with the potential Φ_p of the order of 1–2 V with respect to the main anode. This fact can be easily observed from Fig. 6(b) (curves labeled ↓↓↓) which shows the axial distribution of the plasma potential inside the chamber late after relaxation of the anode current. Between the anode **A** and the unperturbed plasma region there is a potential drop

$$V_{Ap}=V_A-\Phi_p \tag{2}$$

of the order of 100 V so that the electron sheath thickness d_A is about 7 mm (upper dotted line Fig. 8). The ring electrode **R** is biased negatively with respect to the unperturbed plasma, and the potential drop across the ion sheath is

$$V_{Rp}=\Phi_p-V_R. \tag{3}$$

The thickness of this ion sheath in front of the ring also increases laterally with the negative bias so that the electron collecting channel in front of anode **A** is constricted with respect to its geometrical size. As a result, the electron current I_A to **A** decreases with increasing $|V_R|$ [Fig. 7(a)]. A similar effect was observed earlier in a Q-machine experiment where the collisionless approximation is better fulfilled [20]. The potential V_{Rp} might change from a very negative value (less than -100 V) up to a certain threshold $V_{Rp(\mathrm{th})}=\Phi_p-V_{R(\mathrm{th})}$, where the ADL instability is excited. Taking

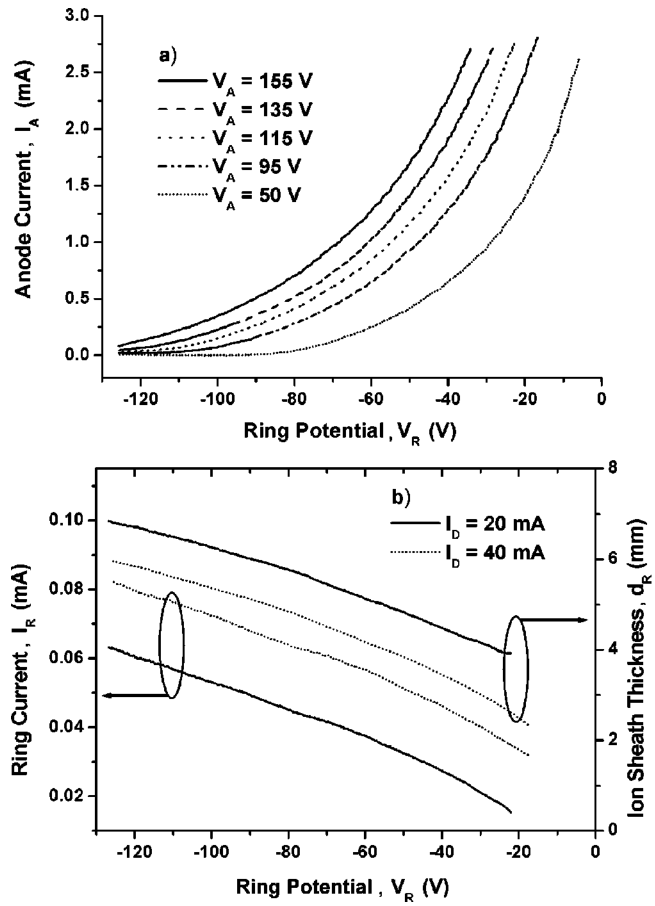

FIG. 7. (a) Dependence of the anode current I_A and (b) of the ring current I_R on the ring potential V_R together with the corresponding value of the ion sheath thickness d_R. For (a) $I_D=20$ mA and V_A is the parameter. For (b) there is no relation between I_R and V_A; I_R depends only on the discharge current.

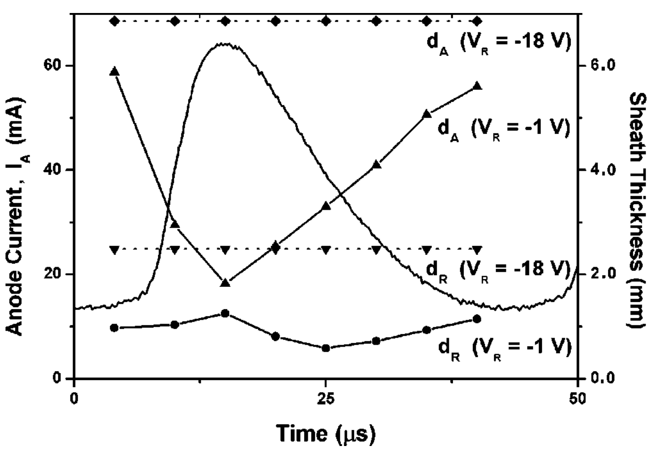

FIG. 8. Ring and anode sheaths thicknesses (d_R and d_A, respectively) for the steady state regime (dotted line) and the oscillatory regime (full line); $p=10^{-3}$ mbar, $V_A=90$ V, and $I_D=20$ mA.

into account the definition of $V_{R(\mathrm{th})}$ from Fig. 5, we see that the thickness of the ion sheath d_R between **R** and the unperturbed plasma may decrease from about 7 mm to about 2 mm [Fig. 7(b)].

2. Oscillatory regime

The oscillatory regime is attained for a large but constant positive potential of the anode and a constant negative potential of the ring when $V_R > V_{R(\mathrm{th})}$.

During the ADL oscillations the plasma potential in the anode region and in the entire chamber changes drastically, as presented in Fig. 6.

During the maxima of the anode oscillations [Fig. 3(a)], the plasma potential in the anode region (i.e., inside the fireball) rises to a few tens of volts [e.g., 80 V in Fig. 6(b)], and the plasma density also increases there. Between two maxima the plasma potential and the plasma density inside the same region are close to the plasma parameters in the main chamber. Consequently, the behavior of the sheath in front of each electrode has to be discussed separately at the maximum and the minimum of the anode current, respectively.

First, during the formation of an ADL, the thickness d_A of the electron sheath in front of anode **A** decreases from about 6 mm to about 2 mm (Fig. 8). This occurs because the anode current I_A increases by almost one order of magnitude [Fig. 3(a)], while the potential drop V_{Ap} between anode **A** and plasma may decrease by a value up to 50% [Fig. 6(b)]. Consequently, according to Eq. (2), d_A should decrease. Moreover, as will be seen later, the values of d_A might be even lower, taking into account that with increasing I_A the effective collecting area of the anode decreases. With decreasing anode current during the relaxation phase, both the plasma potential and the plasma density inside the ADL region approach the plasma parameters of the main chamber. Therefore, the potential drop across the electron sheath in front of anode **A** [Eq. (2)] increases, whereas the electron current decreases so that the thickness of the electron sheath increases from about 2 mm to about 6 mm.

The thickness d_R of the ion sheath in front of the ring electrode **R** varies slightly (less than 0.5 mm) (Fig. 8) with the time. This is because with increasing ring current [Fig. 3(b)], there is also a strong increase of the potential drop across the ion sheath [Fig. 6(b)]. During the relaxation both the ring current and the potential drop across the ion sheath decrease in such a way that according to Child-Langmuir's law [Eq. (1)] d_R remains almost constant. Consequently the relaxation period lasts until the electron flux towards anode **A** exceeds a certain limit, which corresponds to a new cycle of the ADL oscillation. The fact that the thickness of the ion sheath in front of ring **R** remains almost constant during the variation of I_A shows that the ring has a small or negligible influence during the oscillations. This is not the case when the ring potential is varied externally, so that the thickness of ion sheath can change the effective diameter of the collecting channel of the anode current, as was previously explained in the steady state situation.

The ring bias may also be positive with respect to the surrounding plasma. This causes an expansion of the electron-collecting channel, until it reaches the maximum diameter equal to the inner geometrical diameter of the ring. Under these conditions, the amplitude of the oscillation of I_A decreases and its frequency saturates around 45 kHz (Fig. 4).

We also found a dependence of the frequency of the I_A oscillations on the pressure of the background argon gas. This dependence is only indirect since the plasma density depends on the gas pressure. The operating conditions, including the pressure, were chosen in such a way that the ADL instability had a high oscillation amplitude. Under such conditions, by using simple circular plane anodes of various diameters instead of anode **A**, the relation between the anode area and the frequency of the oscillations was investigated. The diameters of the anodes inserted into chamber 1 of the DP machine were 6, 7, 8, and 9 mm. (Anode **A** of the ring-anode system has a geometrical diameter of 10 mm.) The amplitude and the shape of the anode current oscillations were compared using first the ring-anode system and then the simple plane anodes. The frequency was plotted in dependence on the ring voltage [Fig. 9(a)] and on the anode diameter [Fig. 9(b)] for two different plasma densities. From both measurements, we conclude that the frequency increases with the anode surface and saturates at a value which depends on the plasma density. We note that the main influence of the ring on the anode is to control the anode diameter.

At high plasma density ($I_D=40$ mA), the saturated frequency is almost the same for both cases [Figs. 9(a) and 9(b)]. At low plasma density ($I_D=20$ mA), the ring affects more strongly the anode plasma, and therefore the saturation frequency is different. This fact may suggest that the ring bias affects not only the size of the electron channel but also the plasma parameters at the ADL boundaries. Moreover, a qualitative relation between the period T of the anode oscillations and the anode surface area S can be established:

$$T \times S \cong \text{const.} \tag{4}$$

B. Phenomena in chamber 1 induced by the anode double layer oscillations

Propagating phenomena, induced by the dynamics of the ADL, were also investigated in chamber 1. The temporal

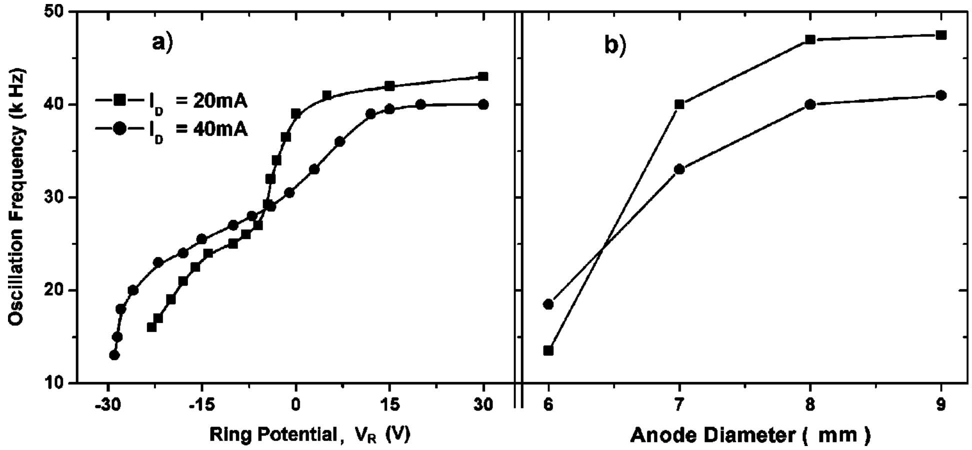

FIG. 9. (a) Frequency of the anode current oscillations versus ring voltage for two plasma densities. (b) Frequency of the anode current oscillations for four plane anodes of 6, 7, 8, and 9 mm diameter without the ring. For these measurements, the anode potential is $V_A = 160$ V and $p = 10^{-3}$ mbar.

evolutions of the axial profiles of the electron and ion saturation currents were measured by means of the Langmuir probe. Both from electrical and optical measurements we found that during its oscillation the fireball extends to a distance of about 7 cm from anode **A**. In order to investigate the evolution of the plasma parameters during one cycle of the ADL oscillation, we used a triggering experiment. On the ring a pulse was applied in order to open the channel only for a single ADL cycle, as in Fig. 6(a). The time between two pulses was long enough for the plasma to relax. Figure 10 shows the temporal evolution of the electron saturation current of the Langmuir probe PP1 for different axial positions, starting from anode **A** towards the grid, compared with the anode current I_A shown in Fig. 10(a).

Three phenomena, which have some particularities in common with the results of a previous investigation in a magnetized alkaline plasma, can be distinguished in Fig. 10 [21], and are described as follows.

(i) A decrease of the probe current in phase with a rapid increase of the anode current. This signal is due to the superposition of two effects. The first one can be associated to the direct-coupling effect between the probe and the ADL, which better should be called capacitive coupling effect [22]. The second effect is due to the fact that a realistic plane probe characteristic does not attain a real saturation current [23]. Therefore, with the plane probe being biased constantly at $V_{\mathrm{PP1}} = +90$ V, and in the presence of a strong amplitude of the oscillating plasma potential [Fig. 10(a)] all over chamber 1, the electron saturation current moves along the characteristic in the electron-collecting branch, giving rise to an apparent drop of the probe current. The propagating speed is in the range of an electron plasma wave.

(ii) A strong, almost in-phase increase of the probe current which follows the previous signal over a distance of about 7 cm from **A**, i.e., up to the distance where the ADL extends. It represents the local increase of the plasma density inside the ADL because of the additional ionization processes taking place there. Later, after the maximum the density relaxes simultaneously with the disappearance of the ADL.

(iii) An ion-acoustic wave which propagates from the edge of the ADL towards the separating grid of the DP machine during the minimum of the anode current. During the increase of I_A, the ADL develops in front of anode **A** simultaneously with the rise of the potential and the density. The ADL moves from the anode surface into the plasma until it stops approximately 7 cm from **A**. The resulting ion-acoustic perturbation is therefore a compressive one. The fact that ion-acoustic waves are excited at the boundary of the ADL is also confirmed in Fig. 11, where a linear extrapolation of the ion-acoustic wave signal [phenomenon (iii) shown in Fig. 10] shows that the wave is initiated at the same distance of about 7 cm from anode **A**. The linear dependence confirms aconstant velocity of the ion-acoustic

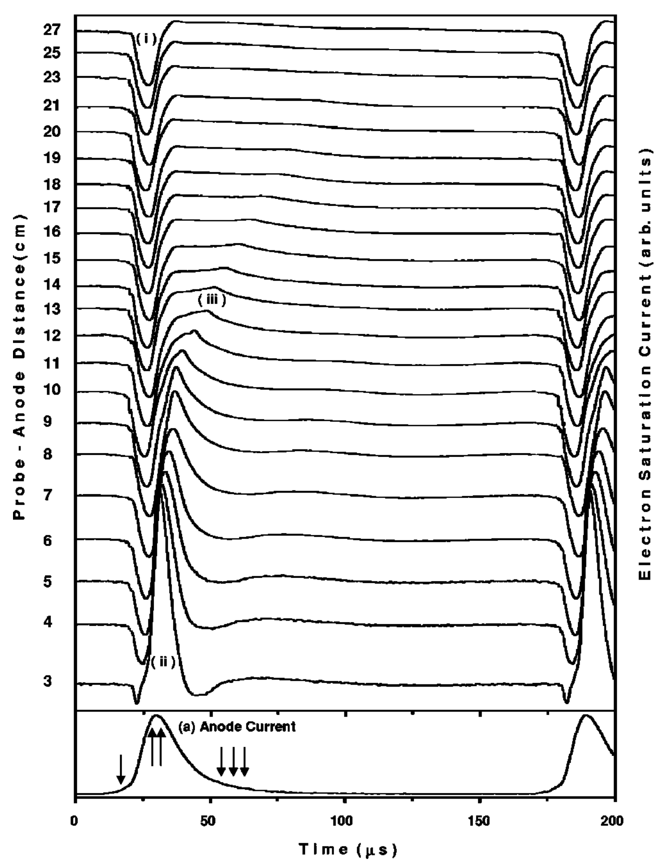

FIG. 10. Time series of the electron saturation current of the plane probe (bias +90 V) at different axial positions with respect to anode **A** in chamber 1, compared to the time series of the anode current $I_A(t)$ (a) $V_A = 150$ V, $p = 10^{-3}$ mbar, and $I_D = 20$ mA.

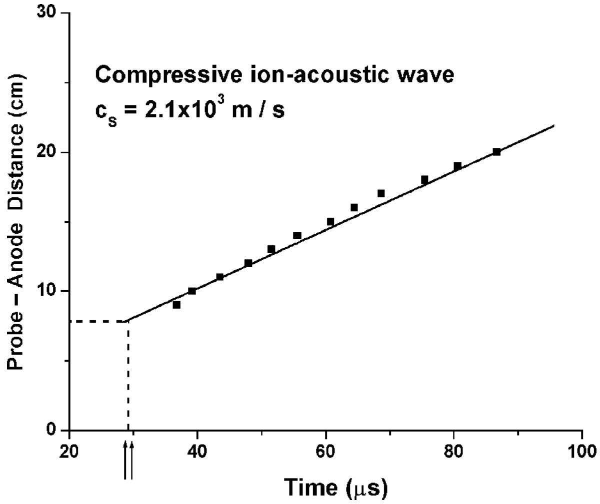

FIG. 11. Axial propagation of the compressive ion-acoustic signal in chamber 1 measured with PP1. The experimental points correspond to the electron saturation current measurement [phenomenon (iii) shown in Fig. 10]. The arrows ↑↑ mark the time where the anode current is maximum.

wave. The label ↑↑ in Fig. 11 corresponds to the point in time when the anode current I_A attains its maximum value.

The inherent dynamics of the fireball modify the main plasma properties. There is a strong correlation between the new plasma of the fireball and the main plasma of chamber 1.

IV. CONCLUSION

Our experimental results show that an unstable oscillating ADL forms in front of a positively biased additional small anode in the diffusion plasma of a DP machine, and that this ADL confines a localized zone of higher plasma density, plasma potential, and luminosity. This zone is called fireball. Some properties of the ADL oscillations, such as frequency and amplitude and their trigger and quenching, can be controlled by varying the voltage of a circular ring electrode situated in front of the anode. The main effect of the ring potential is to control the effective collecting area of the anode surface by changing the ring sheath thickness and its lateral extension. The frequency of the oscillations is found to be directly proportional to the anode surface. Moreover, the ADL produces a complex plasma response in chamber 1 of the machine. This response comprises a synchronous oscillation of the plasma potential in the chamber where the additional small anode is situated. The oscillations excite spherical compressive ion-acoustic waves during the fast phase of the ADL formation, which travel from the ADL during the minimum current of the anode. The probe measurements, their correlation with the ion acoustic wave, and the results of the CCD camera yield a more complete picture of the behavior of a fireball and of the development of the confining ADL.

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