Collisionless Instability of the Cathode Sheath in a Hollow-Cathode Discharge

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High-intensity periodic variations of the potential fall across the cathode sheath are observed in a low-pressure magnetic-field-free hollow-cathode discharge. These potential variations cause modulation of the discharge current, reaching a depth of almost 100%. Typical frequencies are tens of MHz, slightly lower than the ion plasma frequency near the cathode-sheath boundary and associated with the ion transit time through the sheath. The measured pressure dependence of the current threshold for the oscillations indicates that the mechanism of the instability is collisionless.

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We have observed intense rf current oscillations caused by cathode sheath instability in a magnetic-field-free low-pressure hollow-cathode discharge. The oscillation frequencies are associated with the ion transit time through the cathode sheath and are slightly lower than the ion plasma frequency ω_i at the sheath edge. The results infer that at each oscillation cycle the instability effects a collapse of the cathode-sheath voltage to the electron temperature level, followed by a reconstruction period to the nonoscillatory cathode-sheath voltage. This instability does exist contrary to some theoretical assertions about the general stability of the plasma sheath near a negative wall [1].

The high-frequency instability of the sheath-plasma resonance due to electron transit time effects is a well-known phenomenon [2–4]. The frequency of this resonance is close to the electron plasma frequency ω_e, and the instability occurs when the electron transit time through the sheath becomes comparable with the period $2\pi/\omega_e$ of the electron plasma oscillations. In this case the heavy ions do not follow the electrons, namely, the electrons oscillate in a fixed positive space-charge background of ions. A completely different situation exists in the lower-frequency oscillations observed in our experiments, since in this case the electrons can follow the moving ions. It seems that similar oscillations were noted by McClure [5] but they were not identified and investigated.

The experimental apparatus is shown in Fig. 1. We used a discharge tube composed of an open-ended cylindrical cathode, 10 cm long, having an inside diameter of 4.1 or 8.6 cm. Typically the anode was located at one end of the cathode cylinder. Changing of the anode shape, its diameter (0.5–5 cm), its location (see Fig. 1), or its material (Cu, Al, stainless steel) had no influence on the experimental results. These electrodes were mounted inside a glass vacuum vessel filled with He, Ne, or Ar. Typical operating pressures were between 5 mTorr and 1 Torr. The discharge was driven by a pulse generator with a pulse duration of 2 μs. A shunt capacitor, connected by short wires to the anode and the cathode, created a low-impedance path for the current oscillations. Above $\sim$200 pF its capacitance value had no influence on the frequency and amplitude of the oscillations. A smaller capacitance, or an inductance more than $\sim$40 nH in series to the anode, reduced the intensity of the oscillations but did not change the main frequency. Typical discharge currents I_a were between 5 and 120 A. The tube voltage V_a for He discharge varied correspondingly between 350 and 800 V. The cathode-fall voltage V_c, namely, the potential difference between the cathode and the plasma, was found to be independent of tube diameter and anode position. (The plasma potential was measured by a floating single probe.) Also V_c was found to be only weakly dependent on the pressure: Less than 50 V variations in V_c were recorded when the pressure was increased from 50 to 700 mTorr. The difference between V_a and V_c, which is the anode-fall voltage, was only about 50 V in the investigated current range. For Ne and Ar discharges the working pressure was in the range of 20–100 mTorr and 5–50 mTorr, respectively. The values of V_c for the three gases are compared in Table I for the case of $I_a = 8$ A.

The electron temperature and the spatial distribution of the plasma density were measured by both double and single movable probes. Both kinds of probes gave the same results which were further confirmed by the microwave cutoff method. Also, in order to measure the plasma density near the cathode-sheath edge, a separated small piece of the cathode surface served as a single

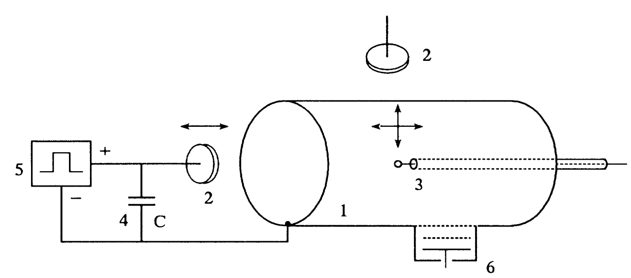

FIG. 1. Experimental apparatus. 1, cathode cylinder with 8.6 or 4.1 cm diameter; 2, movable anode; 3, movable probe (single or double); 4, shunt capacitor; 5, pulse generator; 6, electrostatic charged-particle analyzer.

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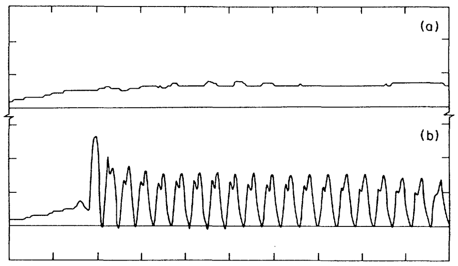

FIG. 2. Scope traces of discharge current. (a) Stable discharge (I_a=4.5 A); (b) with rf oscillation (I_a=7.5 A). Pressure 0.2 Torr He, cathode diameter 8.6 cm, $V_c \approx 350$ V, time base 100 ns/div, current 8 A/div.

probe. The plasma density n_e was found to be directly proportional to the discharge current I_a. Thus, for the 8.6-cm cathode with He, we obtained $n_e \approx 8\times10^{10} I_a$ cm^{-3} at the tube axis and $n_e \approx 1\times10^{10} I_a$ cm^{-3} near the cathode. For the 4.1-cm cathode, at the same discharge current I_a, the density was about 6 times larger at the axis and about 2.5 times larger at the vicinity of the cathode which is indeed close to the ratio of the areas of the two cathodes. The plasma density with Ne (Ar) was approximately 3 (4) times larger than that with He at the same I_a. The electron temperature T_e of the main plasma was approximately the same for all diameters, pressures, and discharge currents: $T_e \approx 7$–8 eV (He), $T_e \approx 6$–7 eV (Ne), and $T_e \approx 4$–5 eV (Ar).

The main phenomenon observed in the unstable hollow-cathode discharge is shown in Fig. 2, in which the scope traces of the total discharge current I_a are presented. Figure 2(a) shows a stable discharge current (below threshold) while in Fig. 2(b) the oscillatory current is recorded. Note the rapid startup of the oscillations, growing to the 100% modulation level at the very few first cycles.

Experimental evidence that the cathode-fall voltage collapsed to the electron temperature level during each oscillation cycle was obtained with an electrostatic charged-particle analyzer located at the cathode (Fig. 1), which measured separately the ion and electron currents hitting the cathode. Its 2-cm-diam input grid was part of the cathode surface. The analyzer operated either in ion collecting mode or in electron collecting mode. In Fig. 3(a) the ion current is presented in the absence of rf oscillations. In Fig. 4(a) the electron current collected by the analyzer is presented under the same conditions. One can see clearly that the electrons do not penetrate into the cathode sheath in the stable discharge, as expected. A completely different picture appears when the rf oscillations exist, as shown in Figs. 3(b) and 4(b) for the ion and electron analyzer currents, respectively (the discharge current was slightly above the threshold). Figures 3(c) and (4c) were obtained with a higher discharge current. From these figures one can clearly see that in certain moments the plasma electrons can penetrate into the cathode sheath up to the cathode wall. It means that in these moments the cathode-fall voltage is reduced to a few electron temperatures T_e, which is very small ($\sim$8 eV) compared to the typical 350-800 V of the stable discharge cathode fall. Note that the electrons reach the cathode surface in short spikes from zero level. This means that the time interval during which the cathode fall is sufficiently small to let electrons reach the cathode is very short compared to the oscillation period. Also

TABLE I. Measured and calculated oscillation frequencies, according to Eq. (1), for I_a=8 A and cathode diameter of 8.6 cm.

Gas type	V_c (V)	Frequency (MHz) Measured	Frequency (MHz) Calculated
He	360	24	23
Ne	310	21	19
Ar	250	17	15.5

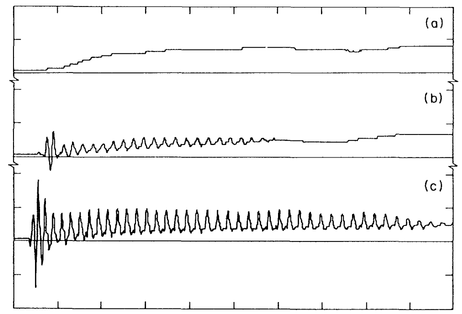

FIG. 3. Scope traces of electrostatic analyzer ion current. (a) Stable discharge (I_a=4.5 A); (b) slightly above threshold (I_a=7.5 A); (c) well above threshold (I_a=20 A). Pressure 0.2 Torr He, cathode diameter 8.6 cm, $V_c \approx 350$–400 V, time base 200 ns/div. Analyzer current is 10 mA/div for (a), 20 mA/div for (b), and 40 mA/div for (c).

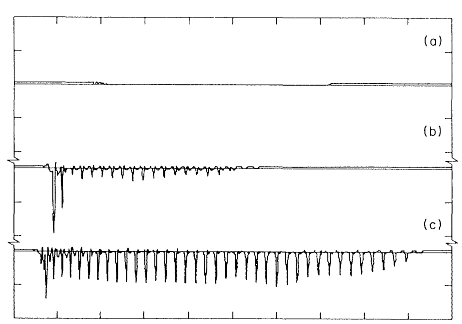

FIG. 4. Scope traces of electrostatic analyzer electron current. (a) Stable discharge (I_a=4.5 A); (b) slightly above threshold (I_a=7.5 A); (c) well above threshold (I_a=20 A). Pressure 0.2 Torr He, cathode diameter 8.6 cm, $V_c \approx 350$–400 V, time base 200 ns/div. Analyzer current is 10 mA/div for (a) and (b), and 20 mA/div for (c).

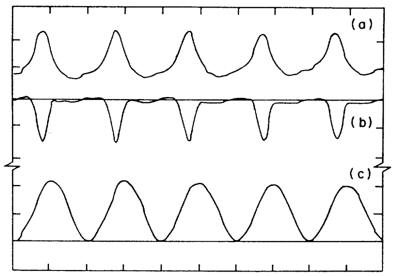

FIG. 5. Scope traces showing the phase relationship between (a) the ion current to the analyzer, (b) the electron current to the analyzer, and (c) the total discharge current I_a. Presure 0.2 Torr He, cathode diameter 8.6 cm, $V_c \approx 350$ V, $I_a = 12$ A, time base 20 ns/div. Current is 10 mA/div for (a) and (b), and 10 A/div for (c).

note that contrary to the electron current, the ion current does not fall to zero. This is because even when the sheath has collapsed (the cathode-fall voltage is very small) ions still reach the cathode due to their velocity prior to the collapse.

The phase relationship between the total discharge current, the ion current to the cathode, and the electron current to the cathode is presented in Fig. 5. Note that the electrons are light and fast particles whose transit time through the sheath is comparable to $1/\omega_e$ [2] and is much shorter than the period of the sheath oscillations. Thus the electrons do not feel any significant change in the field during their flight through the sheath. Because of this, the maximum of the electron current indicates the moment when the cathode-fall voltage is minimal. Therefore, as it is seen in Fig. 5, the maximum of the ion current corresponds to a minimum in the cathode-fall voltage. It is also seen that it is impossible to obtain an almost sinusoidal discharge current by combining the above electron and ion current (conductive current). Thus, an additional reactive current through the sheath must play a significant role.

The dependence of the oscillation frequency on the discharge current I_a for He is shown in Fig. 6 for two different cathode diameters, 4.1 and 8.6 cm. Since the plasma density increases either with the increase of discharge current or with the decrease of cathode diameter, we conclude that the oscillation frequency increases with plasma density. Note that at the same I_a the ratio of the oscillation frequencies for the two diameters is close to the ion plasma frequency ratio near the sheath edge.

The period of oscillations is associated with the ion transit time across the sheath. The large variations in the sheath voltage during the oscillation period complicates the calculation of this transit time τ. In order to provide some estimated bounds on the oscillation frequency, we consider two limiting cases: a full-voltage sheath and a collapsed sheath. For the full-voltage sheath one can obtain τ from the Child-Langmuir law [6]:

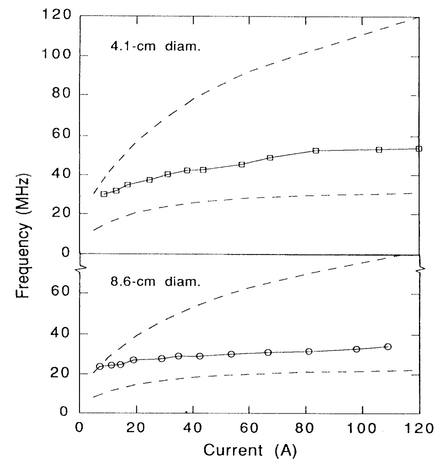

FIG. 6. Dependence of the oscillation frequency on discharge current for He (pressure 0.2 Torr). Dashed curves show estimated upper and lower bounds on the oscillation frequency $1/\tau$ (see text).

$$\tau = 3\left(\frac{eV_c}{kT_e}\right)^{1/4}\frac{1}{\omega_i}. \quad (1)$$

This equation should give reasonable results near threshold, where the cathode sheath is not significantly disturbed yet. The other limiting case can be obtained by calculating τ across the sheath under the lowest voltage conditions, namely, a fully collapsed sheath. In this case ion acceleration is negligible, and we can assume that the ions cross the sheath length d with the initial entrance velocity which they had before the collapse. This velocity is given by the Bohm criterion as $v_i = (kT_e/M_i)^{1/2}$, where M_i is the ion mass. The sheath length before the collapse is given by $d/\lambda_D = (eV_c/kT_e)^{3/4}$, where λ_D is the Debye length, so that

$$\tau = \frac{d}{v_i} = \left(\frac{eV_c}{kT_e}\right)^{3/4}\frac{1}{\omega_i}. \quad (2)$$

These two limiting cases for $1/\tau$ provide some bounds on the oscillation frequency. In Fig. 6 these bounds are compared with the measured frequencies. The upper bound corresponds to the full-voltage sheath [Eq. (1)] and the lower bound corresponds to the collapsed sheath [Eq. (2)].

The influence of gas type on the oscillation frequency is presented in Table I. These results were obtained with the same discharge current $I_a = 8$ A. This current value was chosen to be slightly above the threshold in order not to disturb significantly the cathode sheath. The measured voltages V_c and the expected values for the oscillation frequency according to Eq. (1) are given in Table I together with the measured frequencies. [Other plasma parameters needed for Eq. (1) have already been given before in the text.]

Contrary to the above frequency dependence, the

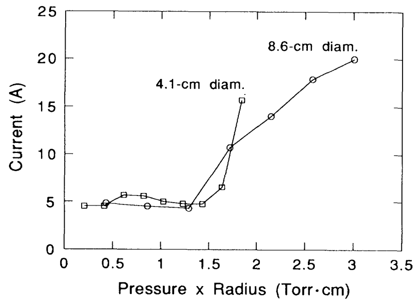

FIG. 7. Dependence of the threshold discharge current on pressure times cathode radius for He.

threshold conditions for oscillation exhibit a marked dependence on pressure. The threshold current for two cathode diameters is plotted in Fig. 7 vs PR, where P is the pressure and R is the cathode radius. Below $PR \approx 1.5$ Torr cm the threshold current is almost constant, independent of plasma density, pressure, and cathode diameter. (Note that at the same current there is a factor of ~ 6 between the plasma densities for the two diameters.) Thus the value of V_c at threshold is almost constant too. This means that oscillations would appear if the ion-neutral collision frequency ν_{in} is below a certain critical level and the cathode-fall voltage is above a value of ≈ 350 V. This voltage corresponds to a threshold current of ≈ 5 A (Fig. 7). Above the PR value of ≈ 1.5 Torr cm the threshold current rises steeply with pressure. Taking $\sigma_i \lesssim 4\times 10^{-15}$ cm^{-2} for the He ions cross section [7], and $v_i \approx 7\times 10^5$ cm/s for the ion velocity (assuming ion temperature value of $T_i \approx 1$ eV), one obtains $\nu_{in} \lesssim 21$ MHz for the 8.6-cm tube and $\nu_{in} \lesssim 50$ MHz for the 4.1-cm tube, at the pressures corresponding to $PR \approx 1.5$ Torr cm. In other words, the oscillations are attenuated when ν_{in} becomes comparable to the oscillation frequency. Furthermore, the oscillations cannot be caused by ionization and deionization processes because the plasma decay time τ_d is too long as can be seen from the following estimation: The recombination coefficient is $\beta < 10^{-7}$ cm^3/s [7] and $n_e \lesssim 5\times 10^{13}$ cm^{-3} (for the 4.1-cm tube and $I_a = 100$ A). Hence $\tau_d = (\beta n_e)^{-1} \gtrsim 200$ ns which is much larger than the oscillation period of about 20 ns under the same conditions. These results prove that collisions of charged particles with neutrals are detrimental to the instability, which should be evolving by a mechanism which is not related to collisions when $PR < 1.5$ Torr cm. It should be reasonable to regard such a mechanism as "collisionless."

The cathode-sheath disappearance could be caused by strong electron emission. In this case the ion space charge would be compensated by the emitted electron space charge. The condition for this is [8] $I_e \gtrsim (M/m)^{1/2} I_i$, where I_e is the emitted electron current from the cathode and I_i is the ion current from the plasma. However, in our case $I_e = \alpha I_i$; here $\alpha = 0.1$–0.5 [7] [α is the secondary emission coefficient, and $\alpha \ll (M/m)^{1/2}$].

Modeling of the experimental results may be approached qualitatively in two ways: (1) The oscillations may be due to transit time effects in the ion flux inside the cathode sheath. Ion inertia causes a phase shift between the ac voltage across the sheath and the ion current. Such a phase shift would lead to a negative sheath resistance if the phases of this current and voltage become opposite. According to Ref. [9] this would happen when the transit-time angle $\omega\tau$ is in the range between 2π and 3π (ω is the oscillation frequency close to ω_i). As follows from Eq. (1), $\omega_i \tau \approx 3(eV_c/kT_e)^{1/4}$. Inserting the measured values of T_e and V_c near the threshold, one obtains $\omega_i \tau \approx 2.7\pi$ independently of the plasma density and tube diameter. Experimental evidence for the negative resistance is seen in Fig. 5, namely, the ion current and the cathode-fall voltage are nearly in opposite phases. (2) The cathode-sheath instability may be explained alternatively by taking into account the possibility of fast heating of the bulk plasma electrons due to beam-plasma instability of the emitted electrons. This heating would change the sheath parameters [1] such as thickness, charge, and electric field spatial distributions. This, in turn, would change the parameters of the beam of emitted electrons heating the bulk plasma electrons. Such a cycle may create a positive feedback leading to the sheath instability. Obviously, the period of this cycle is directly related to the ion transit time through the sheath.

To conclude, we presented an experimental investigation of a new kind of instability in a hollow-cathode discharge. It was shown to be a collisionless instability of the cathode sheath, effecting a collapse of the sheath voltage and a modulation of almost 100% of the discharge current. The oscillation frequencies are related to the ion transit time through the sheath. Possible models were suggested but further theoretical investigation is needed.

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