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# Sharp transition between two regimes of operation of dc discharge with two anodes and thermionic emission from cathode

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In a dc discharge plasma with two anodes and thermionic emission from cathode, the two anodes are used for plasma control. The main anode is placed between the cathode and the other auxiliary anode has a circular opening for passing electron current from the cathode to the second anode. It is experimentally demonstrated that a plasma may exhibit a sudden transition between two quasi-stable conditions as one increases the cathode-electron current collected by the auxiliary anode through an aperture, i.e., hole, in the main anode. In one regime, a bright glowing "ball-shaped double layer" appears on the plasma side having a potential drop of 10–15 eV and concomitant ionization in the neighboring region attached to the opening. The second regime is characterized by a uniform potential profile in plasma and an absence of the ball-shaped double layer. The transition between these regimes is accompanied by a significant change in plasma properties, such as the electron energy distribution function (EEDF). Controlling the EEDF is a valuable capability in technological applications. Increasing the gas pressure leads to the elimination of the first regime for sufficiently high gas pressure, the threshold being a few Torr. The disappearance of a regime transition can be explained by invoking an EEDF transition, from being nonlocal at low pressure to becoming local at high pressure. Local EEDF is determined by local values of electric field. Nonlocal EEDF is determined by electric field values elsewhere, and the electron can travel without energy loss over a path much longer than the discharge dimension. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4876928]

## I. INTRODUCTION

Understanding the interaction between the plasma sheath and the contacting wall is important for predicting plasma kinetics and for controlling the electron energy distribution functions (EEDF) and other plasma properties for various applications where the plasma is volumetrically confined or is in contact with a solid interface.[1–8] Some new developments in this topic were reported in Refs. 9 and 10. It has been demonstrated[11] that the nonlocal nature of the EEDF in the presence of the sheath electric field can be used to distinguish different mutually, but weakly, interacting groups of electrons. Each group can be described and controlled separately, providing additional flexibility for controlling plasma properties. Furthermore, the interaction between one group and another plasma species or between one group and the plasma boundary can differ for each group and can provide expanded prospects for plasma control.[12]

In this paper, we experimentally demonstrate that plasma, having a nonlocal EEDF, that faces a boundary with a small opening may exhibit a sharp transition between two quasi-stable conditions. The kinetics associated with two populations of electrons in the presence of a conducting surface having a small opening (compared to the surface area) allows plasma to flow through the otherwise continuous, i.e., holeless, plasma midplane wall. One of the two populations consists of slow, thermal electrons with energy $\varepsilon_{e,thermal}$. The other population consists of energetic electrons with energy $\varepsilon_{e,nonthermal}$, where $\varepsilon_{e,nonthermal} \gg \varepsilon_{e,thermal}$. In such plasma, energetic electrons exhibit an almost free diffusion to the boundaries, while slow electrons are trapped by the potential well that forms at the plasma midplane. Increasing the gas pressure leads to disappearance of one of the regimes due to faster energy relaxation of the energetic electrons and because the EEDF becomes a local function of the electric field in the plasma.

It has been shown in Ref. 8 that the presence of even a small density of energetic electrons, which does not affect average electron energy, allows significantly enhanced control of plasma properties by biasing the plasma boundaries to a nonzero potential. The present paper demonstrates that the existence of a small opening in the wall gives an additional flexibility in the control of plasma parameters and, at certain conditions, as anode-collected cathode-electron current is increased, can provide a sudden transition between two stable states of the plasma due to the differences in the flow of two groups of electrons (energetic and slow) through the opening.

## II. EXPERIMENTAL SET-UP

The device configuration for reproducible investigation of the effects described above is shown schematically in Figs. 1 and 2, respectively. These experiments demonstrate the appearance of different operational regimes in plasmas characterized by nonlocal EEDF in the presence of a small opening at the plasma walls (boundaries).

 

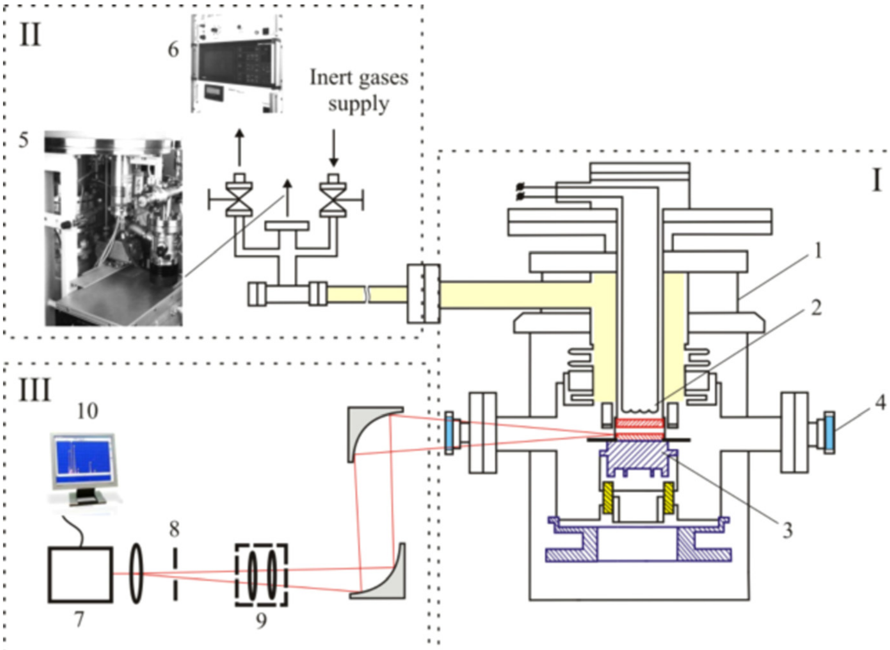


FIG. 1. Schematic diagram of the experimental set-up: vacuum camera (1), cathode unit (2), anode unit (3), sapphire inspection window (4), turbo-molecular pump (5), system of the mass-spectrometric analysis (6), monochromator (7), diaphragm (8), condenser (9), data acquisition and processing system (10).

The diagram of the experimental set-up in Fig. 1 is divided into three blocks. Block I includes the vacuum camera itself (1) with internal diameter of 160 mm and height of 0.5 m, the cathode (2) and anode (3) units, and the sapphire inspection windows (4) for the observation of the discharge glowing and conducting optical measurements.

Block II illustrates elements of the vacuum system. The vacuum is created by turbo-molecular pump (5). The vacuum system includes an automatic system of mass-spectrometric analysis (6). Noble gases are supplied using the precision-leak needle valve.

The optical block III consists of monochromator (7), diaphragm (8), condenser (9), and data acquisition and processing system (10). The optical measurements are based on the method of optical reabsorption.

The plasma discharge takes place between a grounded heated cathode (1) and a positively biased main anode (2) (Fig. 2). The cathode (1) is a disc with outer diameter of 1.0 cm. The outer diameter of the molybdenum anode (2), serving as the wall with an opening, is 3.0 cm in outer diameter and 0.2 cm in thickness. A molybdenum auxiliary anode (3) has an outer diameter of 3.0 cm. The separation between cathode and main anode is 0.8 cm and the separation between the main anode and auxiliary anode is 0.1 cm. A conical mesh electrode (9) restricts the discharge plasma in the radial direction. The conical electrode is electrically connected to the cathode and therefore also grounded. A flat one-sided movable tantalum probe with a diameter of 0.6 mm is introduced into the plasma for making measurements under different angles with respect to the discharge axis. The probe could also be used for measurements near the anode at cathode and auxiliary anode sides. The measurements were conducted in spectrally pure helium at a pressure in the range $1\,\mathrm{Torr} < p < 20\,\mathrm{Torr}$ with discharge current in the range $0.02\,\mathrm{A} < I <$ to 2 A.

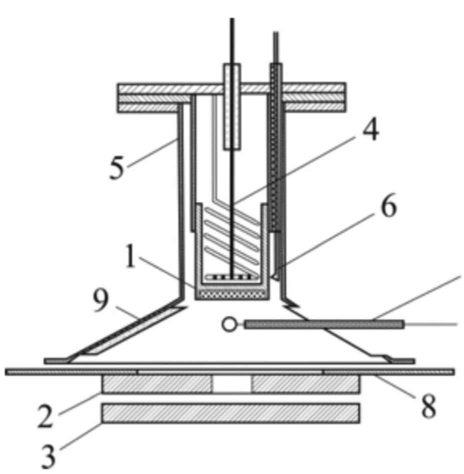


FIG. 2. Schematic diagram of experimental device: (1) cathode, (2) main anode, (3) auxiliary anode, (4) cathode heater, (5) thermal screen, (6) cathode micro-thermocouple, (7) flat one-sided probe, (8) $Al_2O_3$ isolation, and (9) conductive mesh cone (screen).

For the above conditions, the electron mean-free-path $\lambda_e$ is less than 1 mm, which is much smaller than the characteristic plasma dimension $L = 8$ mm and, thus the plasma is collisional. In the lower end of the above pressure range, the elastic-collision electron-energy-relaxation length $\lambda$ is approximately 40 mm which is greater than $L$, thus the EEDF is considered nonlocal. This makes possible the existence of two different and independent groups of electrons. Energetic electrons are created due to the acceleration of the electrons emitted from the heated cathode in the near-cathode sheath and, in at least some parts of the discharge volume, have energies higher than atom ionization potentials. Thermal electrons arise due to inelastic processes in the plasma.

Increasing gas pressure in the range of interest can shorted the energy relaxation length (increase energy relaxation of energetic electrons) and result in gradual transition to the local EEDF in the plasma. For the pressure of 5 Torr, the parameter $\lambda$ is approximately 8 mm which is equal to $L$.

Therefore for higher pressure, the EEDF is expected to be local.

Note also that for the device that is shown in Fig. 1, the area of the opening $S_{op}$ is small (0.44%) relative to the area of the anode.

## III. EXPERIMENTAL: EXISTENCE OF TWO PLASMA REGIMES

Fig. 3 presents typical *IV*-traces of the cathode-main anode gap obtained for the helium pressure of 1 Torr. Each curve was obtained with fixed auxiliary anode current.

A current stabilizer regulating the auxiliary anode voltage was used to hold the auxiliary anode current fixed. The *IV*-traces were found to have two distinct sets of curves (denoted as "diffuse regime" and "constricted regime"), with the exception of the case having zero auxiliary anode current. When the main anode voltage is sufficiently high, the *IV*-trace corresponds to a curve from the diffuse-regime set of curves. In the diffuse regime, the plasma glow is distributed somewhat homogeneously over the discharge volume. This regime has been studied in more detail and modeled in Ref. 13. Decreasing the main anode voltage leads to a situation where the plasma changes abruptly to visibly to the different condition associated with the constricted regime. In the constricted regime, the glow in the main part of the discharge gap is absent, but there is a bright, tear-drop-shaped glow in close proximity to the anode opening. Increasing the voltage leads to the opposite transition. The threshold for this back transition is typically higher than the forward transition threshold in anode potential. Due to this hysteresis effect, two values of the current may be possible at some potential and the discharge may be bi-stable. Fig. 4 demonstrates the glow schematically for the two modes.

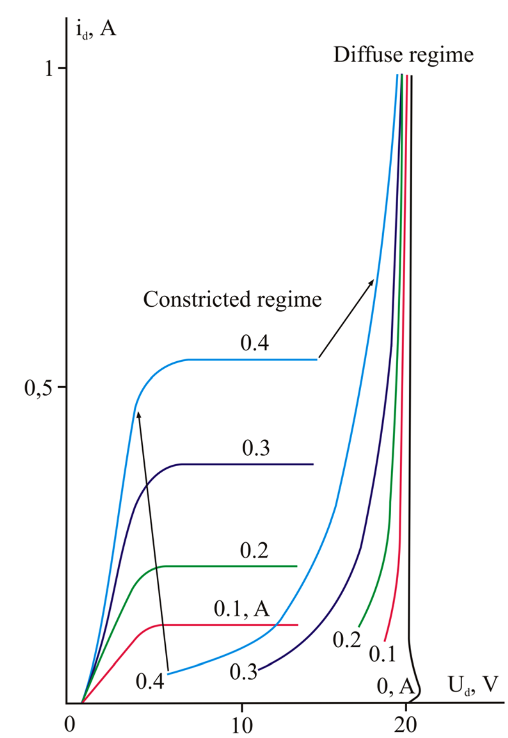


FIG. 3. IV-traces of the cathode-anode gap. The label near each curve indicates auxiliary anode current. The transition between diffuse and constricted regimes takes place when the anode potential is lowered past a certain threshold. Opposite transition takes place at a different threshold value of anode potential. Helium gas pressure is 1 Torr.

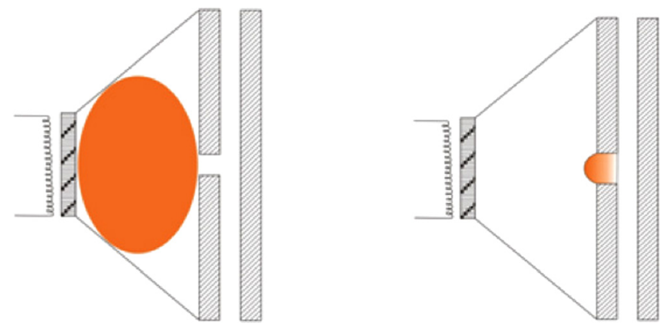

FIG. 4. Illustration of the difference between the glow associated with the discharge modes: Diffuse-glow mode (left) and constricted-glow mode (right) of the discharge.

During the transition, all plasma parameters, including slow electron density and temperature, energetic electron density and energy, and ratio between slow and energetic electron densities, change suddenly. An example of the changing axial plasma potential during this transition is shown in Fig. 5 (curves 1 and 3). Curve 3 (corresponding to diffuse regime) shows a somewhat homogeneous axial potential distribution, in contrast to curve 1 (corresponding to constricted regime), which shows an abrupt potential increase near the opening. This sharp potential increase spatially coincides with intensive light emission and takes the form of a ball.

Fig. 6 gives an example of measurements of second derivatives of the probe current with respect to the probe potentials in the plasma between cathode and main anode and near the main anode from the sides of cathode and auxiliary anode. Two groups of electrons, each corresponding to a maximum in the second derivative profile, are clearly seen in the plasma between cathode and main anode. The

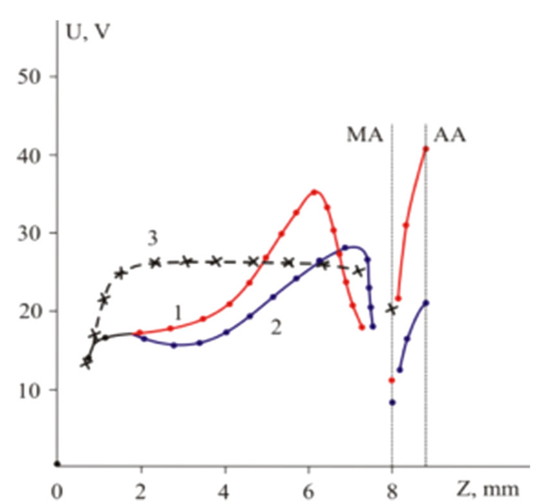


FIG. 5. Axial behavior of the plasma potential. Z is the axis of symmetry of the device going from cathode to auxiliary anode (Z = 0 at the cathode). Curves shown are for the case of pressures of 3 Torr (curve (1) corresponds to regime II and curve (3) corresponds to regime I) and 7 Torr ($I_a = 0.2$ A and $I_d = 0.2$ A (2)). MA and AA schematically show the main and auxiliary anodes. Dots and crosses show experimental points.

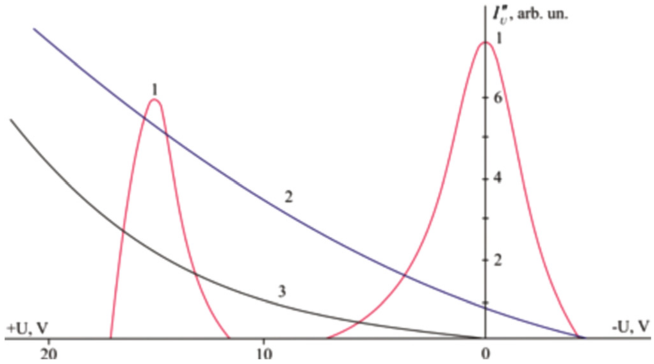


FIG. 6. Second derivatives of the probe current with respect to the probe potentials $dI/dV$ in the plasma between cathode and main anode (1). $d^2I/dV^2$ in the vicinity of the main anode at the cathode (2) and auxiliary anode (3) sides. Helium gas pressure is 3 Torr, $I_a = 0.4$ A, $I_d = 0.2$ A.

measurements demonstrate that the energy of the energetic electrons is approximately equal to the plasma potential $V_p$ at the points of measurement ($\varepsilon_{e,nonthermal} \approx eV_p$, where $e$ is the electron charge), indicating that energetic electrons are created by the cathode emission and acceleration by the plasma potential. Unfortunately, the measurements near the main anode (curves (2) and (3)) are not conclusive and cannot provide information about EEDF. Note that in constricted regime the anode can be used as a large wall probe for the measuring the energetic electrons.[14,15] In this case, the diffusive probe theory can be used.

Figures 7–9 show similar IV traces obtained at different values of gas pressure (4, 7, and 19 Torr). For the pressure of 4 Torr, there are two regimes are still visible, but they are less pronounced. For higher pressures, the second regime practically disappears. This behavior is connected to the transition between nonlocal EEDF and local EEDF in plasma. As can be seen from Fig. 5 for the pressure of 7 Torr, the maximum near the main anode is still visible but less pronounced. Increasing the gas pressure makes the axial potential behavior in the plasma more homogeneous.

Note, also, that for some regimes, IV traces have negative differential resistance (negative derivative in *IV* trace).

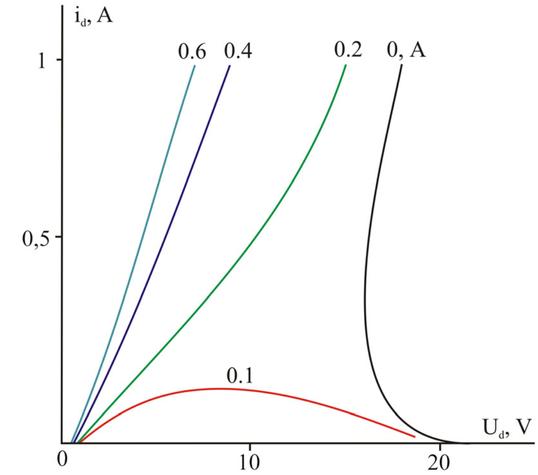


FIG. 8. IV traces of the cathode-anode gap. The label near each curve indicates auxiliary anode current. Helium gas pressure is 7 Torr.

For those regimes, the discharges may be unstable and may exhibit plasma oscillations and instabilities. Sometimes, auxiliary anodes can be helpful for suppressing such self oscillations.[10]

## IV. DISCUSSION

The qualitative explanation of the existence, for lower pressure, of two branches of IV traces (Fig. 3) in terms of the self oscillating transition between nonlocal EEDF and local EEDF follows. In diffuse regime, the main anode current is supplied mostly by slow electrons and depends exponentially on the main anode voltage. Slower electrons, having higher density, can also provide substantial electron current to and through the opening and ultimately to the auxiliary anode. The absence of significant electric field strength in the opening volume allows for this volume to be populated by electrons and ions from the plasma. The presence of plasma in the opening volume results in the discharge plasma being effectively screened from the electrostatic potential of the auxiliary anode and results in the generation of the required

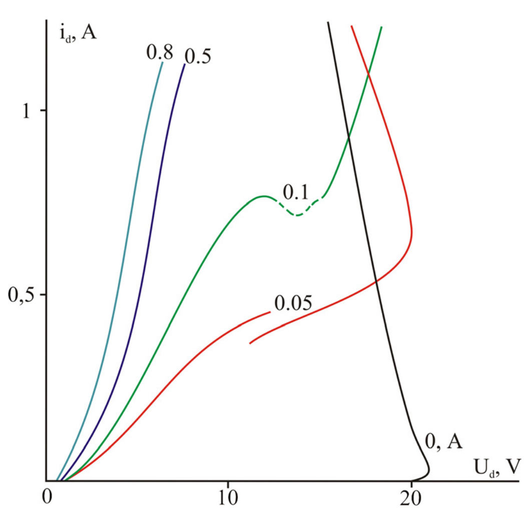


FIG. 7. IV traces of the cathode-anode gap. The label near each curve indicates auxiliary anode current. Helium gas pressure is 4 Torr.

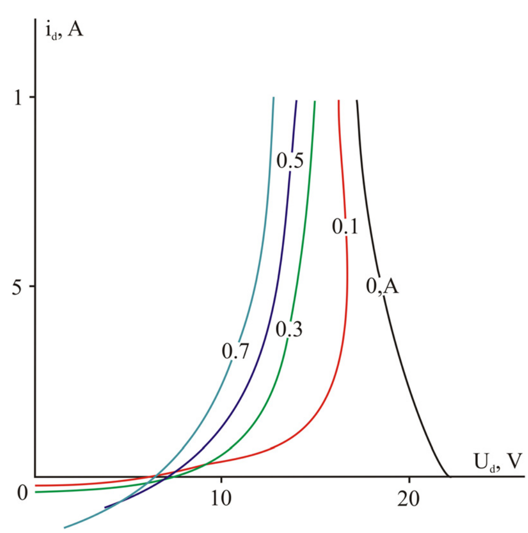


FIG. 9. IV traces of the cathode-anode gap. The label near each curve indicates auxiliary anode current. Helium gas pressure is 19 Torr.

current through the opening. Increasing the negative potential of the main anode may lead to the emergence and/or expansion of the sheath in the opening and, in this case, the effective opening area for the auxiliary current channel $S_{op}^{eff}$, which is normally somewhat smaller than $S_{op}$, may become smaller with increasing potential of the negative main anode. The reduction of the main anode potential may require increasing the electric field in the opening for conservation of the current from plasma through the opening. As the main anode potential decreases further and the electric field in the opening increases, the electric field in the opening becomes large enough to remove almost all ions from the opening and the current through the opening cannot be adequately supplied, as the plasma in the opening has insufficient density. Then electric field from the auxiliary anode penetrates further into the plasma through the opening. This situation is consistent with a simple model described in details in Ref. 13 that predicts the discontinuity of the discharge for sufficiently low main anode potential.

In experiments when the current cannot be sustained, the auxiliary current stabilizer increases the auxiliary anode voltage, causing the electric field to penetrate the discharge plasma through the opening (as no plasma screening) and provides the additional production of charged particles in plasma near the opening needed for the discharge to jump to constricted regime. The simple model from Ref. 13 does not predict such a transition will occur. In contrast to the constricted discharges like,[16,17] where plasma is produced on both sides of the constricted part of the discharge and inside the opening, the presence of an auxiliary anode just near the anode does not allow for plasma generation near the auxiliary anode. As a result, and because there is insignificant ion production near the auxiliary anode, it is impossible to populate the volume of the opening with electrons from one side and ions from another side of the opening. Instead, the electric field produces a group of energetic electrons that are able to generate a relatively dense plasma by ionizing atoms in a relatively small, tear-drop-shaped volume outside the opening. This provides the required current to the opening. The electric field inside the opening remains low while supplying the required current and while populating the opening volume with ions and electrons. Plasma generation in the relatively small volume outside the opening can create enough ions and slow electrons to populate both the entire plasma volume and the opening volume and requires a weak electric field in the opening volume to get ions to flow to the opening. Experiments demonstrate that in regime II there is no plasma generation in the entire volume, except in the small, tear-shaped volume near the opening, and energy of the energetic electrons in most of the plasma volume becomes lower than the first ionization level of atoms.[12] An attempt to simulate this effect was performed in the kinetic model described in Ref. 18. However, the absence of participation of metastable atoms in the model reactions could provide only a qualitative description of the effect, showing very different plasma potential profiles in the plasma volume. The presence of metastable atoms leads to production of several groups of nonlocal electrons and could be described in more complicated models. Increasing the gas pressure leads to effective energy loss by energetic electrons, smoothing and eventually making the above effects vanish, as seen in Figs. 5–7.

The effects discussed in this paper may be similar to the effects in anode spots.[19–21] Such is the case if the anode spots are connected to an inhomogeneous distribution of anode current over the anode surface. It may mean that, in different points of the anode, the conditions for diffuse and constricted regimes are valid at the same time. Then, the device described in this paper may be a convenient instrument for anode spots studies.

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