Nonlocal particle loss effects on the electron kinetics in a direct current helium diffusion-controlled positive column

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The electron energy distribution function (EEDF) in a positive column of low-pressure and discharge current is determined not only by the local collision processes and the axial electric field action, but also by the transport phenomenon, the radial ambipolar diffusion due to the gradient of plasma density. Thus, to completely determine the EEDF, the Boltzmann equation including radial inhomogeneity terms has to be solved. The present work proposes a simplified method to account for the radial inhomogeneity, when the electron kinetics in the central part of the positive column can be reduced to be one energy-dimensional. The radial diffusion of electrons is taken into account via a wall loss term. A greatly simplified kinetic equation is obtained and its numerical solutions agree well with the EEDF determined from Langmuir probe measurements in a helium dc discharge positive column. Also, a comparison of the present method with local and nonlocal approach theories is made. A discrepancy is observed, especially at high energies, where either local or nonlocal approach theories predict too-large values of EEDF. © *1997 American Institute of Physics.* [S1070-664X(97)02504-4]

I. INTRODUCTION

Recent achievements in computational technique have allowed more complete self-consistent models to describe the behavior of plasma devices.[1,2] In particular, some 2-D (two-dimensional) kinetic models for a diffusion-controlled positive column of dc discharge have been recently proposed.[3,4] However, the development of approximate models is still useful, since such models might provide more physical insight, as well as fast computations.

The basic task in studying a diffusion-controlled positive column is to describe the spatially dependent kinetics of the electrons. To do this the 2-D Boltzmann equation must be solved. A great simplification of this problem has been achieved by the so-called nonlocal approach method originated by Bernstein and Holstein[5] and later developed by Tsendin.[6] The method takes into account the spatial inhomogeneity of the EEDF (electron energy distribution function) through the total electron energy distribution, regarded, up to a small first order correction, as a homogeneous one. By averaging over the cross section of the positive column, the spatial inhomogeneity terms in the kinetic equation vanish for bounded electrons and are neglected for free ones, thus a reduction of the electron kinetics to a one energy-dimension has being achieved. Since the first order correction to the EEDF (spatially dependent) remains unsolved, the method cannot account for the net outward-directed flux of electrons and their loss at the wall. The nonlocal approach can be applied to sufficiently low-pressure discharge plasmas when the electron energy relaxation length exceeds the typical dimensions of spatial inhomogeneity.

For high pressure, the EEDF on the axis of plasma column can be obtained by a type of local approximation. The EEDF is determined only by the local axial electric field and the pressure, as obtained in dc and rf discharges.[7,8] A comprehensive review of the foundation of both the local and nonlocal approaches has been recently done by Kortshagen *et al.*[9]

Considering two energy levels, ε_1, at which excitation begins to take place, and ε_2 ($\varepsilon_2 > \varepsilon_1$), beyond which electrons can reach the wall, Tsendin and Golubovskii[10] solved analytically the spatially averaged electron kinetic equation for bounded electrons and a type of radial diffusion equation for free electrons. Due to the electron loss to the wall, an additional cooling of the EEDF at high energies ($\varepsilon > \varepsilon_2$) was found, with the solution showing two knee points, at energies ε_1, and ε_2, respectively.

Recently, the nonlocal kinetic model has been verified by comparing its solution with the numerical one of a 2-D kinetic model for an argon plasma column.[11] Good quantitative agreement was obtained for neutral particle density up to $N_0 = 5 \times 10^{21}$ m (about 0.15 Torr). There still, however, remains a range of intermediate pressures where neither the local nor the nonlocal approach approximation can appropriately describe the positive column.

The nonlocal character of the electron kinetics in the dc positive column is found also in the theoretical investigation of Uhrlandt and Winkler.[12] They solved the inhomogeneous kinetic equation in the two-term Legendre expansion of the EEDF approximation, using the radial ambipolar potential and the axial electric field taken from the experiment. The radial flow of electrons has been appropriately described by the radial anisotropic component of the EEDF. Due to the electron radial flow to the wall allowed in the model, a steeper decrease of the EEDF at high energies compared with the nonlocal approach approximation result was found.

A self-consistent 2-D kinetic model for a plasma column in He–Hg (He/Hg = 93/7) including the electron loss to the wall was recently proposed by Hartig and Kushner.[3] However, the boundary condition at the wall does not take into

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account the effect of electron reflection on the space charge formed at plasma boundary. Their results show a knee point in the EEDF on the center of the plasma column at an energy corresponding to the radial ambipolar potential.

A self-consistent model of the dc positive column in inert gases that take into account the wall loss of particles was recently proposed.[13] The electrons of the energies exceeding the radial barrier of potential were assumed to diffuse freely towards the wall. From the particle and energy balance equations and the equality of the electron radial current to the wall with the ion one, the axial electric field and the radial profile of potential were found in a self-consistent manner.

The present work proposes an approximate method to account for the effect of radial inhomogeneity on the electron kinetics of the central part of the plasma column. Since high-energy electrons diffuse towards the wall, where they are lost through recombination, the radial inhomogeneity terms in the kinetic equation are approximated by a sink of electron terms expressed by the wall loss frequency, with the electron kinetics thus being reduced to one energy-dimensional. Theoretical solutions of the local and nonlocal approximate models and the present method are compared with the experimental results obtained from Langmuir probe measurements in the dc helium positive column at pressures ranging between 0.4 and 0.9 Torr.

II. THEORETICAL MODEL

A widely used theoretical method for obtaining the EEDF in weakly ionized gases is to solve the Boltzmann equation in approximation of two terms of Legendre polynomial expansion. Taking into account the radial terms corresponding to the profiles of plasma density and ambipolar electric field, the following equation is obtained for the isotropic part of EEDF:[14]

$$\frac{2e}{3m_e}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{u^{3/2}}{\nu_m}\frac{\partial f}{\partial r}\right)-\frac{u^{3/2}}{\nu_m}\frac{1}{r}\frac{\partial}{\partial r}\left(rE_r\frac{\partial f}{\partial u}\right)\right]+\frac{\partial}{\partial u}\left(\frac{2m_e}{M_a}u^{3/2}\nu_m f\right)+\frac{2e}{3m_e}\frac{\partial}{\partial u}\left[-\frac{u^{3/2}}{\nu_m}E_r\frac{\partial f}{\partial r}+\frac{u^{3/2}}{\nu_m}(E_r^2+E_z^2)\frac{\partial f}{\partial u}\right]=S(f)|_{\text{exc.,ioniz.}}. \tag{1}$$

Here $f(r,u)u^{1/2}$ is the isotropic part of EEDF normalized by the electron density: $n_e(r)=\int_0^\infty f(r,u)du$, u is the electron kinetic energy: $u=m_e v^2/(2e)$, E_z and E_r are the axial and the radial components of electric field, and ν_m is the electron-neutral collision frequency for momentum transfer given by: $\nu_m(u)=N_0 q_m(u)\sqrt{2eu/m_e}$, where q_m is the electron-neutral momentum transfer cross section. $S(f)$ is the collision term which describes the loss or gain of electrons due to inelastic collisions (excitations and ionization),

$$S(f(u,r))_{\text{exc.,ioniz.}}=\sum_{k(\text{exc.,ioniz.})}[\nu_k(u)f(u,r)u^{1/2}-\nu_k(u+u_k)f(u+u_k)(u+u_k)^{1/2}], \tag{2}$$

evaluating $\nu_k(u)$ as $\nu_k(u)=N_0 q_k(u)\sqrt{2eu/m_e}$, where $q_k(u)$ and u_k are the electron-neutral cross sections and the energetic thresholds for the inelastic processes k.

Since at high pressure the terms accounting for the radial diffusion on the central part of column are much smaller than others in Eq. (1), they can be neglected, the local approximation being applicable. On the other hand, at low pressure, when the energy relaxation length is much larger than the column radius, the nonlocal approach method can be used. The EEDF can be obtained by solving Eq. (1) averaged on the cross section of positive column. As the result the radial term drops out and the following equation is obtained:

$$\frac{2e}{3m_e}\frac{d}{d\varepsilon}\left[\frac{\overline{\varepsilon^{3/2}}}{\nu_m(\varepsilon)}E_z^2\frac{df(\varepsilon)}{d\varepsilon}+\frac{3m_e}{M_a}\overline{\varepsilon^{3/2}\nu_m(\varepsilon)f(\varepsilon)}\right]=\overline{S(f(\varepsilon))}_{\text{exc.,ioniz.}}. \tag{3}$$

The overlined terms are averaged according to the formula: $\overline{a(\varepsilon)}=2/R\int_0^{r(\varepsilon)}a(\varepsilon+V(r))rdr$, where ε is the total electron energy that corresponds to the kinetic energy on the axis of the positive column since $V(0)=0$, $r(\varepsilon)$ is the turning point defined from $u(r(\varepsilon))=\varepsilon+V(r)=0$ and $V(r)$ is ambipolar potential

In the present work, another approximate method is proposed which accounts for the effect of particle diffusion and their loss at the discharge tube wall on the electron kinetics in the central part of positive column. The following assumptions are made: (1) The plasma column can be divided into its central part, where n_e and $\mathbf{E}(E_z, E_r)$ are rather uniform, and the radial part, where they are varied to their wall boundary values; (2) low-energy electrons are produced mainly in the central part by ionization or excitation collisions, and they are accelerated along E_z until they have gained enough energy to perform other inelastic collisions or to escape to the tube wall; (3) for the central part, the spatial inhomogeneity terms in Eq. (1) can be replaced by a negative source term, $\nu_w(u)f(u)u^{1/2}$, by taking account of the nonlocal effect resulting from the radial diffusion of electrons and their loss by recombination at the wall, where $\nu_w(u)$ stands for the electron wall loss frequency. Thus, Eq. (1) becomes:

$$\frac{2e}{3m_e}\frac{d}{du}\left[\frac{u^{3/2E_z^2}}{\nu_m(u)}\frac{df(u)}{du}+\frac{3m_e}{M_a}u^{3/2}\nu_m(u)f(u)\right]=S(f(u))|_{\text{exc.,ioniz.}}+\nu_w(u)f(u)u^{1/2}. \tag{4}$$

Thus, if $\nu_w(u)$ can be estimated, $f(u)$, which is the EEDF for the central part, is given by Eq. (4). A formula for $\nu_w(u)$ can be found considering the radial profiles of n_e and $V(r)$, which is related to E_r as $E_r=-(1/e)(\partial V/\partial r)$. The potential barrier formed by $V(r)$ and the space charge near the wall are schematically drawn in Fig. 1. There is a threshold energy, u_w, which is determined by the minimum energy required for electrons to overcome the ambipolar potential barrier, u_a, and the wall space charge field barrier, u_b. Electrons with energy lower then u_w are reflected by the electric field towards the center, so that they cannot reach the wall. The bounded electrons are assumed to have a very long life time, $\tau_w(u)$, and $\nu_w(u)$ equal to zero:

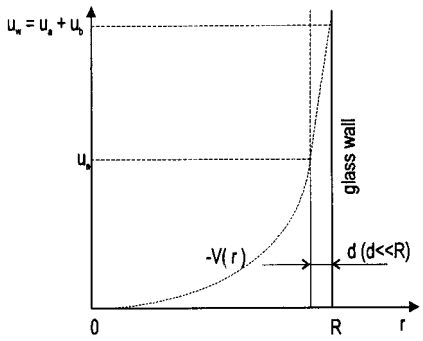

FIG. 1. Sketch of the ambipolar and wall space charge potential energy barrier (d = width of wall space charge). The potential energy is assumed to be zero at the center.

$$\nu_w(u)=1/\tau_w(u)=0, \quad \text{for } u<u_w. \tag{5}$$

In order to find $\nu_w(u)$ for free electrons, their radial flux density is estimated as:

$$\Gamma_e(u,r)=-\frac{2}{3}\frac{eu^{3/2}}{m_e\nu_m(u)}\left(\frac{\partial f}{\partial r}\right)-\frac{2}{3}\frac{eu^{3/2}}{m_e\nu_m(u)}\left(\frac{\partial f}{\partial u}\right)E_r$$
$$=w(u,r)u^{1/2}f(u,r). \tag{6}$$

Then, the following expression for the electron radial diffusion velocity, $w(u,r)$, is deduced:

$$w(u,r)=-\frac{2}{3}\frac{eu}{m_e\nu_m(u)}\left(\frac{\partial f}{\partial r}+E_r\frac{\partial f}{\partial u}\right)\cdot\frac{1}{f}. \tag{7}$$

If the distribution function of total electron energy is assumed to be homogeneous[9,15] according to Eq. (6), neither radial flow nor loss of electrons at the wall is allowed. Indeed, on the basis of the energy conservation law, $u(r)=u(0)+V(r)$, the kinetic energy, $u(r)$, becomes a spatially dependent variable and the total energy, which is the kinetic energy on the column axis, $u=u(0)$, becomes the independent variable. Then the drift component of $w(u,r)$ is opposite but equal to the diffusion one, so that $w(u,r)=0$. The nonlocal approach may hold for bounded electrons, where electrons are confined by $V(r)$ and they move without inelastic collisions, but it cannot hold for free electrons where a net flow of electrons is yielded towards the wall and inelastic collisions play a role. The electron escape time to the wall is the sum of the diffusion time, $\tau_{\text{diff.}}$, and the time, $\tau_{\text{esc.}}$, required for electrons near the wall to enter into the escape cone, which is the cone determined in velocity space under the condition for the electron energy corresponding to movement in the radial direction to exceed the potential barrier formed by the wall space charge.[10,11] $\tau_{\text{esc.}}$ can be written as:

$$\tau_{\text{esc.}}=\frac{4\pi}{\delta\Omega}\left(\frac{1}{\nu_m}\right)=\frac{2}{1+\sqrt{u_b/u}}\frac{1}{\nu_m}. \tag{8}$$

Since in a dc He positive column at pressure greater than 0.1 Torr, $\tau_{\text{diff.}}\gg\tau_{\text{esc.}}$, ν_w can be approximated as $\tau_{\text{diff.}}^{-1}$, where $\tau_{\text{diff.}}=R/w(u)$. The velocity $w(u)$ is obtained by averaging Eq. (7) over the cross section of the positive column as: $w(u)=(2/R^2)\int_0^R w(u,r)dr$, where $u=u(0)$. To compute $w(u)$, it is worthwhile to introduce the radial diffusion length and the effective electron temperature in Eq. (7) as spatially independent parameters:

$$\frac{1}{f(u,r)}\frac{\partial f(u,r)}{\partial r}=-\frac{1}{\Lambda(u)} \quad (a),$$
$$\frac{1}{f(u,r)}\frac{\partial f(u,r)}{\partial u}=-\frac{1}{T(u)} \quad (b). \tag{9}$$

Assuming parabolic $V(r)$ and $\nu_m(u)$ to be constant, the following formula for the averaged radial diffusion velocity is obtained:

$$w(u)=\frac{2e}{3m_e\nu_m R}\left[\chi(u-u_a/2)-\frac{4\theta}{3}(u-3u_a/5)\right], \tag{10}$$

where $\chi=R/\Lambda$ and $\theta=u_a/T$. Equation (10) easily deduces a relation of $\nu_w(u)=w(u)/R$. The parameters u_a, u_b, χ and θ can be computed taking into account the ion movement. The electric force exerted on electrons by E_r should balance that due to the kinetic pressure gradient, i.e., $u_a\sim T_b$, where T_b is the low-energy or bounded electron temperature. The potential barrier due to space charge near the wall can be computed by equating the Bohm ion current with the thermal electron one at the plasma edge.[16] Thus the value u_b is determined using the effective high-energy electron temperature, T_t, as $u_b=T_t[3.3+0.5\ \ln(m_{\text{He}}/m_{\text{H}})]$, where m_{He} and m_{H} are He and H atomic masses, respectively. The value of parameter χ depends on the radial profile of plasma density of interest.

III. RESULTS AND DISCUSSION

The measurements were performed in a striation-free dc He positive column of 2 cm radius and 50 cm length at pressure ranged between 0.4 Torr and 0.9 Torr. To detect the EEDF and the plasma potential, a single Langmuir probe, movable in the radial direction, was used. The probe was made from a 0.15 mm diameter tungsten wire that was glass-coated except for the 2 mm active probe length. Another probe installed 15 cm away from the former was used only for measurement of the axial electric field. Each probe characteristic was acquired in 2.5 ms as 2048 words of 12 bits resolution, the probe current signal being averaged 20 times to improve the signal-to-noise ratio. The signal was smoothed using a smoothing technique based on a convolution of the data with a four data points half-width Gaussian error distribution function.[17] The first and the second derivatives were obtained by a method using the minimum square fitting of a sequence of 60 data, which correspond to 1.5 V biasing voltage interval, with a third-order polynomial function. The EEDF was determined using the well-known Druyvesteyn formula:[18]

$$f(u)u^{1/2}\big|_{u=e(V_s-V_p)}=\frac{2}{e^2A_p}\sqrt{\frac{2m_e(V_s-V_p)}{e}}\left(\frac{d^2I_p}{dV_p^2}\right), \tag{11}$$

where V_s is the plasma potential, V_p is the probe biasing potential and A_p is the probe surface area. V_s was identified as the probe voltage at which the second derivative of probe

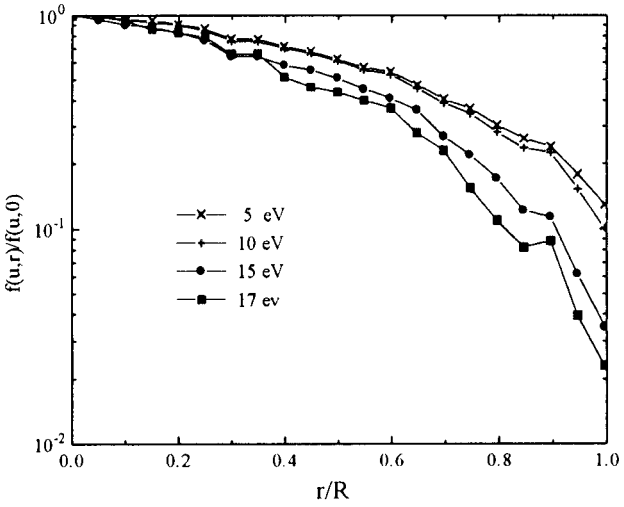

FIG. 2. Radial profile of $f(u,r)$ at four values of u (p = 0.85 Torr, I_d=150 mA). The radius of the central part of the column was taken at $0.5R$.

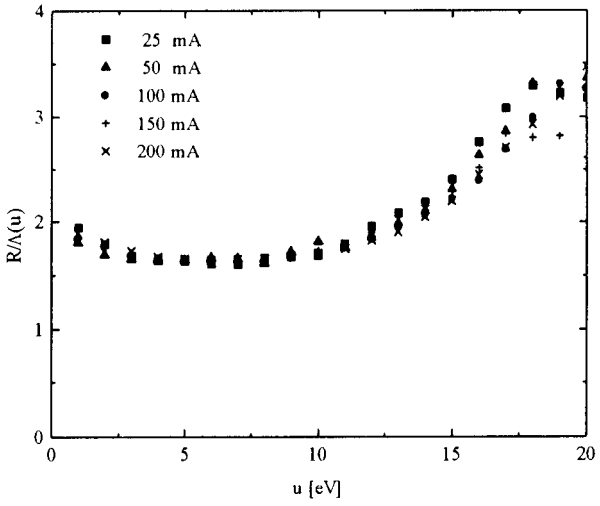

FIG. 3. Dependence of R/Λ on u for the central part of the plasma column (p = 0.85 Torr).

current passes through zero. A 0.4 eV resolution of the EEDF is estimated within a dynamic range of 25 eV. Taking into account the level of noise in the Langmuir probe current data, a noise level around 10^{-4} in the normalized EEPF data has been estimated so that results at energies larger than 22 eV [Fig. 5(a) below] or 23.5 eV [Fig. 5(b)] are disregarded.

In order to get an image of the difference between the bounded electron diffusion and free electron one, the radial profiles of $f(u,r)u^{1/2}$ for some kinetic energies are depicted in Fig. 2. Due to the confinement of low-energy electrons in the electric field, a much steeper decrease in high-energy electron density, compared to the low-energy one, is observed. Since there are a large number of low-energy electrons compared to the high-energy ones, the profile of $n_e(r)$ is determined roughly by the low-energy electrons, and thus by $V(r)$. Also, due to the electron repulsive wall space charge field, $n_e(r)$ at the wall boundary is about one tenth of its center value, a fact that is in discordance with the zero Bessel function profile. If the radial profile of a certain energy electron population is characterized by $\Lambda(u)$, then $\Lambda(u)$ for high energies must be smaller than those for low energies. This result is shown in Fig. 3, where $R/\Lambda(u)$ averaged on the central part of the positive column is represented as a function of u. The central part was taken as satisfying $E_r < E_z$ as well as a weak dependence of $\Lambda(u)$ on r. An almost constant value of $R/\Lambda(u)$ is observed at low energies whereas it increases at high energies. Also, a slight dependence of $\Lambda(u)$ on the discharge current is noticed only at high energies.

A 3-D (three-dimensional) representation of EEDF as a function of total electron energy, ε, is given in Fig. 4. A weak spatial dependence of the low-energy electron distribution in the central part is noticed. This means that the total energy electron distribution at low energies can be regarded as a homogeneous one there. Thus, according to Eq. (7), $w(u,r)$ becomes zero at low energies as predicted. This does not hold for high energies where a radial decrease in the total energy electron distribution is observed and a net flow of electrons towards the discharge tube wall is expected. Also, an additional cooling of distribution at energies that exceed a threshold energy around 17 eV is observed.

In Figs. 5, the local [Eq. (1) without radial inhomogeneity terms], the nonlocal [Eq. (3)], the present method [Eq. (4)] solutions and measured EEPF are compared. The parameters needed for computing the electron wall loss term in Eq. (4) and averaged coefficients of Eq. (3) (u_a, u_b, χ and θ) were taken from the experiment. u_b was regarded as the floating potential of the probe located near the wall and Λ as its averaged value on the central part. The inelastic collision processes taken into account in computing of $S(f)$ are excitations from ground states to the excited 2^1S, 2^3S, 2^1P and 2^3P levels and ionization.[19] The local approximation theory predicts larger values of EEPF in a high-energy tail compared with the experimental or numerical solution of Eq. (4). The nonlocal approach method predicts even a greater EEPF in the high-energy tail because electron wall loss is neglected. Also, the collision terms in Eq. (3) are diminished by averaging, so that a smaller decreasing rate of the EEDF in the high-energy tail is predicted by the nonlocal approach

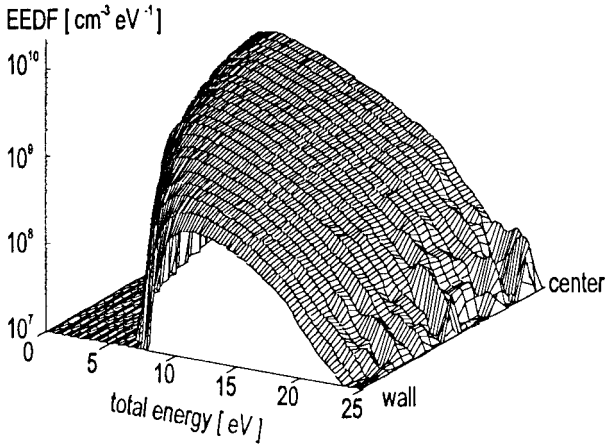

FIG. 4. Spatial dependence of EEDF (p = 0.85 Torr, I_d=150 mA).

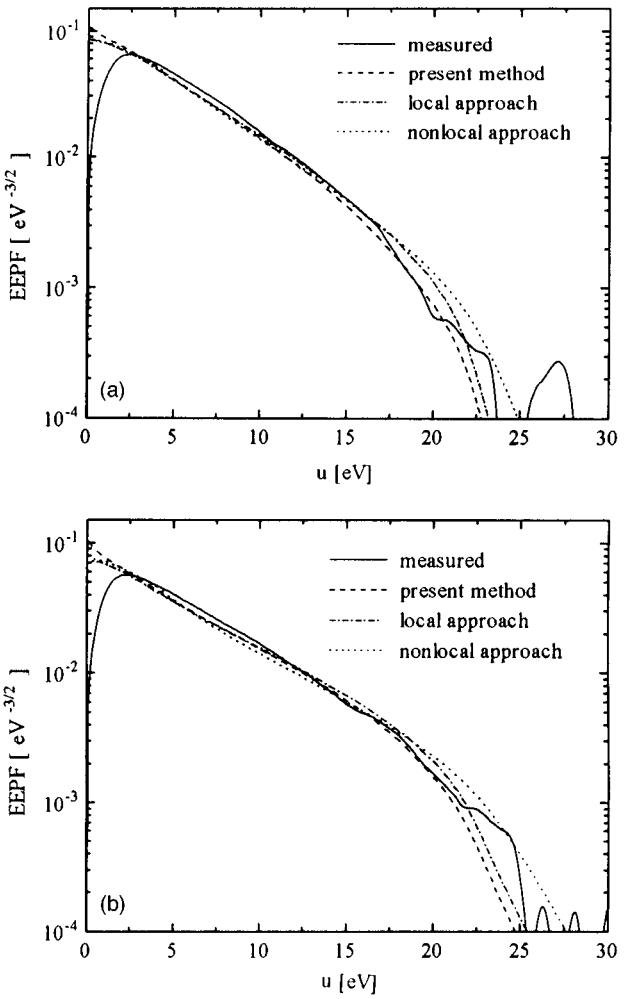

FIG. 5. Comparison of the measured EEPF with the numerical solutions of Eq. (1) without radial terms (local approach), Eq. (3) (nonlocal approach) and Eq. (4) (present method). (a) $p = 0.85$ Torr, $I_d = 150$ mA, $R = 2$ cm, $E_z = 2.7$ V/cm, $u_a = 7.6$ eV, $u_b = 9$ eV, $\chi = R/\Lambda = 2.8$, $\theta = u_a/T = 1.7$; (b) $p = 0.46$ Torr, $I_d = 150$ mA, $R = 2$ cm, $E_z = 2.32$ V/cm, $u_a = 8.7$ eV, $u_b = 9.5$ eV, $\chi = 2.4$, $\theta = 1.5$.

theory. Due to the coupling between high-energy and low-energy electrons, the differences in slope of distribution occurred even at low energies. Quantitative results concerning the electron temperature and the mean energy for the central part are given in Table I. The electron temperatures were computed from the slope of the EEPF for four intervals of energy, the errors in their experimental values being evaluated around 1% for $T_{(5-10)}$, 5% for $T_{(10-15)}$ and 15% for $T_{(15-20)}$. There is a good agreement of the electron temperatures determined from measured EEPF with those computed using the solution of Eq. (4). Due to the electron wall loss term in Eq. (4), lower electron temperatures at high-energy (15–25 eV) are predicted compared with the local approximation or nonlocal approach. Discrepancies between electron mean energy values resulting for the experiment and the model may be due in part to an overestimation of the experimental value. The local and nonlocal approximation solutions show only a knee point at the first excitation energy, where the cooling depends only on the loss of high-energy electrons by the inelastic collision, while the measured EEPF

TABLE I. Comparison between experimental, present method, local approach and nonlocal approach results. Electron temperatures are corresponding to four energy intervals (5–10 eV, 10–15 eV, 15–20 eV and 20–25 eV). $\overline{\varepsilon}$ is mean electron energy. (a) $p = 0.85$ Torr, $I_d = 150$ mA, $R = 2$ cm, $E_z = 2.7$ V/cm $u_a = 7.6$ eV, $u_b = 9$ eV, $\chi = 2.8$, $\theta = 1.7$; (b) $p = 0.46$ Torr, $I_d = 150$ mA, $R = 2$ cm, $E_z = 2.32$ V/cm, $u_a = 8.7$ eV, $u_b = 9.5$ eV, $\chi = 2.4$, $\theta = 1.5$.

	Results	T_{5-10} (eV)	T_{10-15} (eV)	T_{15-20} (eV)	T_{20-25} (eV)	ε
(a)	experimental	4.72	4.35	2.6	⋯	6.7
	present method	4.73	4.19	2.89	1.1	6.3
	local appr.	5.02	4.65	3.38	1.13	6.68
	nonlocal appr.	4.58	4.55	3.82	1.85	6.49
(b)	experimental	5.72	5.24	3.9	⋯	7.8
	present method	5.88	5.56	3.7	1.66	7.22
	local appr.	6.17	6.0	4.34	1.74	7.63
	nonlocal appr.	4.95	5.82	5.03	2.78	7.29

and the present method solution show a first knee point at an energy around 17 eV [Fig. 5(a)] and 18 eV [Fig. 5(b)].

In Fig. 6, a 3-D representation of the EEPF variation to the radial direction is given. The spatial variation of EEPF can be qualitatively understood as a shift of the distribution towards lower kinetic energies with $-V(r)$. Thus, knowing the distribution on the center and $V(r)$, the EEPF variation in the radial direction can be roughly estimated.

IV. CONCLUSION

The present work provides experimental evidence of the role played by the wall loss of high-energy electrons in the electron kinetics of the He dc discharge positive column. Also, a theoretical approach accounting for the wall loss effect on the electron kinetics in the central part of the plasma column is developed. The effect of the net outward-directed flow of high-energy electrons and their loss at the wall on the electron kinetics at the central part of the plasma column is approximated by a wall loss term that is added to the local kinetic equation. The wall loss of electrons is treated in a similar manner as the inelastic collision losses, the wall loss frequency of electrons being approximated by the invert of the diffusion time from the center to the wall. The low-energy electrons are trapped in the radial potential well and

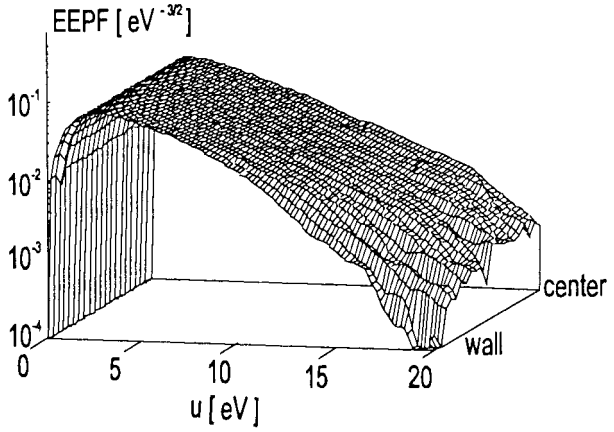

FIG. 6. Spatial dependence of EEPF ($p = 0.85$ Torr, $I_d = 150$ mA).

their net radial flow is assumed to be zero. The radial flow of high-energy electrons and their loss at the wall cause an additional cooling of the EEDF for energies that exceed the barrier formed by the ambipolar and wall space charge fields. For a positive column at pressure ranging between 0.4 and 0.9 Torr, the free electron threshold energy was found to be less than the first He excitation energy. At lower pressure (around 0.1 Torr) the electron distribution is spread towards high energies due to the high values of E_z/p, and thus a higher threshold energy is expected. However, some ambiguity in determining the barrier formed by the radial potential well still remains due to the experimental difficulties, i.e., the plasma distortion causes some errors in determining the ambipolar potential, and the Langmuir probe measurements close to the wall allow a finite spatial resolution equal with probe length. Despite these experimental difficulties and the simplicity of the theoretical model, the experimental results agree well with the theoretical ones.

Due to the diffusion and to the axial electric field action, an electron flow in energy space is formed. High-energy electrons can be lost in two ways: Through the inelastic collisions with gas particles, in which they ''jump'' from high to low energy and their number in configurative space is conserved, and through the diffusion and the recombination at the wall. The particle loss mechanism controls the high-energy electron density and thus affects the ionization and excitation rates. The low- and high-energy parts of electron distribution are coupled through diffusion and collisions, so that taking into account of the wall loss will affect the whole distribution. Since the theoretical model does not take into account the inward-directed radial flow formed by the acceleration in E_r of low-energy electrons yielded in the radial part of the column through inelastic collisions, Eq. (4) does not satisfy the particle conservation law, and the particle loss rate exceeds the production one.

Comparison with the local approximation and nonlocal approach solutions has shown discrepancies in the high-energy tail, where either the local or nonlocal approaches predict too-large values. Since basic assumptions of the nonlocal approach make it inappropriate to account for the radial flow of electrons and their loss at the wall, this method should be used only for bounded electrons. However, further experimental and theoretical investigations will be necessary to fully clarify the applicability of the nonlocal approach method. Since at the intermediate range of pressure (around 1 Torr) at which the approximation methods, the local approximation and the nonlocal approach have failed to provide the EEDF, the method proposed here may give a good approximation of the electron kinetics of dc diffusion-controlled positive column.

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