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Plasma parameters in a multidipole plasma system

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Abstract. Plasma potential and electron number densities and electron temperatures under bi-Maxwellian approximation for electron distribution function of the multidipole argon plasma source system were measured for a gas pressure ranging between 10^{-4} and 10^{-3} mbar and an anode-cathode voltage ranging between 40 and 120 V but a constant discharge current intensity. The first group, as ultimate or cold electrons and main electron plasma population, results by trapping of the slow electrons produced by ionisation process due to primary-neutral collisions. The trapping process is produced by potential well due to positive plasma potential with respect to the anode so that electron temperature of the ultimate electrons does not depend on both the gas pressure and discharge voltage. The second group, as secondary or hot electrons, results as degrading process of the primaries and their number density increases while their temperature decreases with the increase of both the gas pressure and discharge voltage.

PACS. 52.50.Dg Plasma sources – 52.80.Tn Other gas discharges – 52.40.Hf Plasma-wall interactions; boundary layer effects; plasma sheaths

1 Introduction

Since the so called "double plasma" machine (DP) has been proposed as an alternative device for low temperature almost collisionless and unmagnetised plasma [1,2], a large variety of experiments were performed either for fundamental or applied phenomena in plasma physics. An important improvement, with respect to the efficiency of the plasma confinement, was realised by multipolar system proposed by Limpaecher and Mac Kenzie [3]. The same principle for plasma production was also used in so called triple plasma machine for unmagnetised [4] or magnetised [5] plasma system.

However, in spite of the great number of problems studied by multipolar plasma system, its equilibrium is not yet well understood. The basic features of such plasmas are related to the relatively high electronic density but their complexity made different authors to study only some aspects as: spatial profiles of the plasma density [6] and electron density dependence on magnetic multipole wall configuration [7], particles loss mechanism by cusp structure [8,9] or the general mechanism of the discharge [10].

However, it is generally accepted that at the lower limit of the gas pressure (less than about 10^{-4} mbar), where the discharge is still in operation, there are three groups of electrons. They were primarily named, by Boyd and Twiddy, for a hot cathode discharge as: (i) primary, (ii) secondary and (iii) ultimate electrons [11]. The primary group is formed as a mono-energetic one due to the acceleration of the filament electrons into the cathodic sheath and it is always considered as a very small fraction with respect to other two groups [10]. In general it is also accepted that ionisation of the gas atoms due to their collisions with primary electrons may produce the other two groups of electrons but their behaviour as bi-Maxwellian distribution it is not yet well understood. Moreover, the two groups of electrons have been named differently by the authors. For instance, the group of secondary electrons has been named as hot electrons [4], while the group of ultimate has been named as main group [4] or cold electrons [12].

Rather detailed results have already been obtained about dependence of both density and temperature of these two groups of electrons *versus* gas pressure and discharge current intensity in unmagnetised plasma region of a multipolar plasma system [4,12]. The plasma parameters were measured using classical semilogarithmic plot of the Langmuir probe characteristic. A more reliable technique was realised by Hansen *et al.* [5] using a fully automatic computer acquisition and evaluation system for electrostatic probes in a magnetised collisionless plasma region of a multipolar plasma system. Basically the method is a direct fitting of the Langmuir characteristic, which was originally used by Cellarius *et al.* [13] for a bi-Maxwellian distribution function. This time the algorithm is based on the Laframboise model [14] taking special measure for choosing of the initial value and fitting procedures including ion component of the probe current.

In this paper the attention is paid to the plasma diagnoses of the unmagnetised Ar plasma of a multipolar

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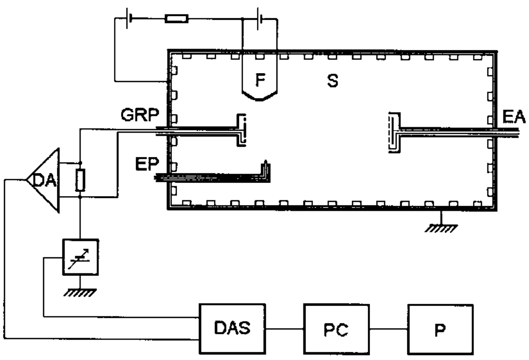

Fig. 1. Experimental set-up. F: Filament cathode, S: source chamber, GRP: guard ring plane probe, EP: emissive probe, EA: electrostatic analyser, DAS: data acquisition system, PC: personal computer, P: printer.

system, in which the electron density and temperature and plasma potential are measured versus gas pressure and anode-cathode potential but a rather constant discharge current intensity. The range of the gas pressure was between 10^{-4} and 10^{-3} mbar where both Maxwellian groups of electrons are well developed. Anode-cathode potential ($U_{\rm AK}$) was varied between 40 V and 120 V so that the energy of the primary electrons was in the range of a monotone increasing of the ionisation cross-section of the electron-neutral collisions for argon atoms with electron kinetic energy [15]. In this way information's about evolving of the bi-Maxwellian electron distribution function can be obtained as result of the primary-neutral collisions. The electron parameters as number densities and temperatures were measured by the new method proposed recently by Ruscanu *et al.* for bi-Maxwellian electron distribution function [16,17] and developed by Stamate *et al.* for primary electrons [18] and negative ions [19,20].

2 Experimental set-up and experimental procedure

The experiments were performed in the "Alexandru Ioan Cuza" University multipolar system (Fig. 1). A DC discharge produces the argon plasma for a pressure of 10^{-4} to 10^{-3} mbar. in a nonmagnetic stainless-steel cylinder (26 cm diameter and 65 cm long) as anode and a tungsten filaments (F) – (wire 0.3 mm in diameter and 50 mm length) as the cathode. The chamber wall is electrically grounded. Multidipole magnets ($B_{\rm max} \approx 1.1$ kG) of line cusp type are mounted for plasma confinement at the wall vessel. The rows of permanent magnets, each row having 10 mm thickness and 30 mm width, were fixed along the generatrix inside of the anode cylinder at about 40 mm each other. The maximum B field between rows was about 480 gauss and decreases rapidly, in the chamber, so that at about 45 mm from the wall, the magnetic field is negligible.

Both the emissive probe (EP) and the electrostatic analyser (EA) were used in order to measure the plasma potential in addition to a guard ring plane probe (GRP) which was used for probe measurements of both the electron number density and temperature.

The GRP consists of a plane circular Langmuir probe made of tantalum plate of 1.2 mm diameter and a plane guard ring of 3 mm external diameter and 1.4 inner diameter. Both the plane probe and plane guard ring, respectively, were fixed concentric, in the same plane and electrically insulated by each other with ceramic cement. The GRP surface was, first of all, mechanically polished and then chemically cleaned but, before any new registration of the probe characteristics, an additional cleaning was realised by ion bombardment.

The EP consists of a tantalum wire (diameter 0.1 mm) loop (total length about 2 mm) fixed at the end of two cooper wires (0.5 mm diameter each) placed in a twin slot ceramic tube. The EA is a simple construction of about 10 mm plane stainless steel grid (mesh size 10 wire/mm and 48% transparency) placed at about 0.5 mm distance but insulated from a plane collector (stainless steel disk). The grid was biased negatively to reflect electrons and the collector bias was changed around plasma potential in order to obtain the ion current of the collector.

In order to minimise the influence of the primary electrons on the probe characteristics [18] the filament was placed along the axis of the chamber at about 10 cm from the end flange and the GRP also on the axis at about 25 cm from the filament and facing the opposite end flange. The EP and EA where placed symmetrically with respect to the GRP out of axis at about 5 cm.

Data acquisition system (DAS) with two differential inputs was selected in order to register and process the probe characteristics.

The experimental procedure comprises two parts, the first related to the global parameters of the DC discharge and the second to the probe method.

2.1 Measurement of the global parameters of the discharge

As it was already specified, the main purpose of this paper is to present the experimental data on plasma parameters of a multidipole system with respect to gas pressure and anode-cathode potential. In this view, the cathode temperature was kept constant using an appropriate heating system of the filament with a control of the heating current ($I_{\rm f}$). Typical current ($I_{\rm AK}$)-voltage ($U_{\rm AK}$) characteristics of the discharge are presented in Figure 2 with the $I_{\rm f}$ as a parameter. These characteristics show the experimental conditions in which the discharge current intensity is limited by filament-cathode temperature. In that case the flux of the primary electrons is almost constant and only their energy can be modified by the change of the $U_{\rm AK}$. The experimental conditions were selected so that by changing the $U_{\rm AK}$ the discharge current stays almost constant or it may change less than 40% when the $U_{\rm AK}$ might increase 3 times! Such a situation can be realised, for instance, in our experimental conditions, as long as the $I_{\rm f}$ is smaller than 2.35 A. In this case, some conclusions can be obtained about the evolving of the bi-Maxwellian

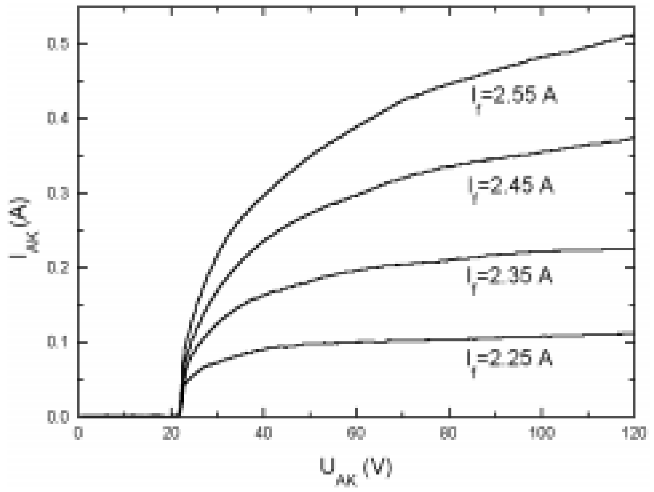

Fig. 2. Discharge current intensity $I_{\rm AK}$ *versus* anode-cathode voltage $U_{\rm AK}$ and filament heating current intensity $I_{\rm f}$ as parameter, $p = 2 \times 10^{-4}$ mbar.

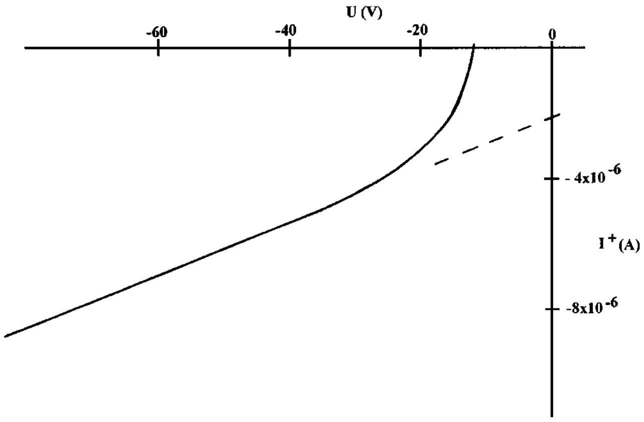

Fig. 3. Typical characteristics of the ion saturation current of the GRP.

EDF on the discharge voltage $U_{\rm AK}$. That because the $U_{\rm AK}$ is the main parameter through which the primary electrons gain their energy but, non-linear phenomena such as inelastic electron-atom collisions and possible phenomena of electron beam-plasma interactions [21], determine a rather complicated mechanism for both the generation of a bi-Maxwellian distribution function and the dependence of its parameters on both the discharge voltage and gas pressure.

2.2 The probe method

The theoretical background and related errors about the plane probe characteristic under bi-Maxwellian approximation have been presented elsewhere [16,17].

Main analytical relations [16] for electron temperatures of two groups of electrons are:

$$T_1 = \frac{e}{k}\frac{B - \sqrt{B^2 - 4C}}{2C} \text{ and } T_2 = \frac{e}{k}\frac{B + \sqrt{B^2 - 4C}}{2C} \quad (1)$$

and for electron number densities, respectively:

$$n_1 = \frac{1}{eA}\sqrt{\frac{2\pi m}{kT_1}}\frac{I'(V_{\rm p}) - \dfrac{e}{kT_2}I(V_{\rm p})}{\dfrac{e}{k}\left(\dfrac{1}{T_1} - \dfrac{1}{T_2}\right)}$$

$$\text{and } n_2 = \frac{1}{eA}\sqrt{\frac{2\pi m}{kT_2}}\frac{\dfrac{e}{kT_1}I(V_{\rm p}) - I'(V_{\rm p})}{\dfrac{e}{k}\left(\dfrac{1}{T_1} - \dfrac{1}{T_2}\right)} \quad (2)$$

where e and m are the charge and mass of the electron and k the Boltzman constant and A the area of the plane probe.

The B is the slope of the linear dependence of the semilogarithmic characteristic of the "test function" [18] and C is given by [16]:

$$\frac{BI' - I''}{I} = C$$

where the function $I = I(U)$ is the electron current of the probe under bi-Maxwellian approximation. It corresponds to:

$$I(U) = n_1 eA\sqrt{\frac{KT_1}{2\pi m}}\exp\left[\frac{e(U - V_{\rm p})}{kT_1}\right] + n_2 eA\sqrt{\frac{kT_2}{2\pi m}}\exp\left[\frac{e(U - V_{\rm p})}{kT_2}\right]. \quad (3)$$

The I' and I'' are the first and second derivatives of the electron characteristic (3).

In order to use relations (1, 2) for finding the fundamental plasma parameters it is primarily necessary to obtain both the electron characteristic $I(U)$ of the probe and the plasma potential.

The first, each characteristic of the probe was digitised with 12-bit resolution after averaging 300 times. From these characteristics the electron component $I(U)$ was recovered using a linear extrapolation of the ion saturation current. The typical behaviour of ion saturation region of the probe characteristic is presented in Figure 3. Its slope is less as 10^{-7} A/V and taking into account the presence of the quard ring, this linear dependence is mainly due to contribution of the primary electrons than the edge effect of the ion sheath [18]. The isotropic population of the primaries has a mean energy of the order of $eU_{\rm m}$ which in the experiment was between 40 and 120 eV. Moreover, the ion component of the probe current is about four order of magnitude smaller than the electron component.

The method is based on the first $I' = {\rm d}I(U)/{\rm d}U$ and the second $I'' = {\rm d}^2I(U)/{\rm d}U^2$ derivatives of the electron characteristics $I(U)$ given by (3). As a result, after recovering of the $I(U)$ a numerical programme was used to obtain the first and the second derivatives of the electron component of the probe characteristic.

The second important part was to find the plasma potential. This is a rather difficult task [22] especially when bi-Maxwellian EDF is involved [5] and some ambiguities might come into sight in both defining and locating of the plasma potential from the experimental probe characteristic.

From theoretical point of view both first and second derivatives of the function (3) may indicate clearly the plasma potential but, because experimentally there is a rather smooth transmission from retarding electronic part to the electron saturation current of the probe, even for the GRP, it is on open question where the plasma potential can be located. The problem was analysed by different authors [22,23] and recently by Hansen *et al.* [5]. Following the former analysis we have observed, for the most cases, a constant difference of about 0.3 V between the maximum of the second derivative and its first zero value or maximum of the first derivative.

Moreover, an other variable difference, but smaller as 0.4 V, has been observed between the point where the second derivative crosses zero and the point given by classical method of intersection of the linear part of semilogarithmic characteristic of the electron current of the probe and the electron saturation of the probe. Because of that, both emissive probe and ion electrostatic analyser were used.

Unfortunately both methods includes also some errors which may become important in some circumstances. Thus, the emissive probe disturbs, locally, plasma parameters because of the electron emission. As a result the upper knee of the characteristic, which is supposed to give the plasma potential, shifts towards more positive value than any other value measured by simple probe. This shift increases with decreasing of plasma density and may grow up to 0.4 V. The electrostatic analyser needs a negative bias grid and this bias cause, locally, a shift of the plasma potential towards more negative value then those obtained by the plane probe. This shift depends on both plasma density and grid bias and may reach up to 1 V. In such circumstances the plasma potential was taken as the probe potential where the second derivative of the electron current characteristic crosses zero [22].

According to the new method of processing of the probe characteristic, the main test for bi-Maxwellian approximation of the electron distribution function is the linear dependencies of the logarithm of the test function [18]. The slope (B) of the linear part of the semilogarithmic characteristic of the test function and the value (C) are used in order to work out with relations (1, 2). A detailed analysis of the data obtained by the new method in comparison with those obtained by the standard method based on the semilogarithmic plot of the probe characteristic [4,12] have shown that the differences between the plasma parameters obtained by these methods can be larger as 50% for the temperature of the secondary or hot electrons and 100% for the number density of the ultimate or cold electrons, respectively [17].

A direct verification of the plasma parameters obtained by these two methods is presented, as an example, in Figure 4, in which the experimental electron

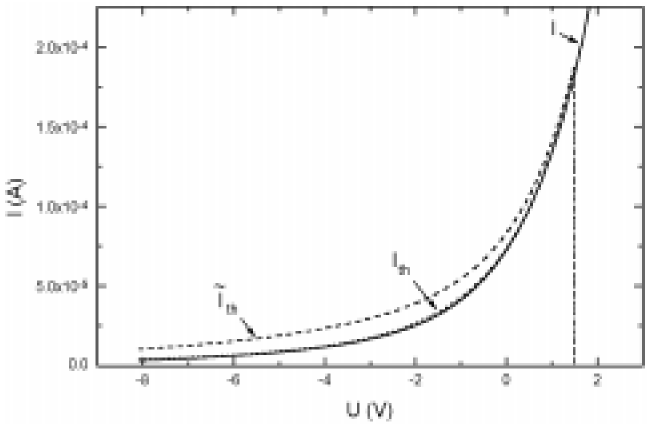

Fig. 4. The experimental electron probe characteristic (solid curve I) together with the computed characteristics $I_{\rm th}$ (dotted curve) using the plasma parameters given by the new analytical method and the computed characteristic $\tilde{I}_{\rm th}$ (dashed curve) respectively obtained by using plasma parameters given by the classical method of the semilogarithmic plot.

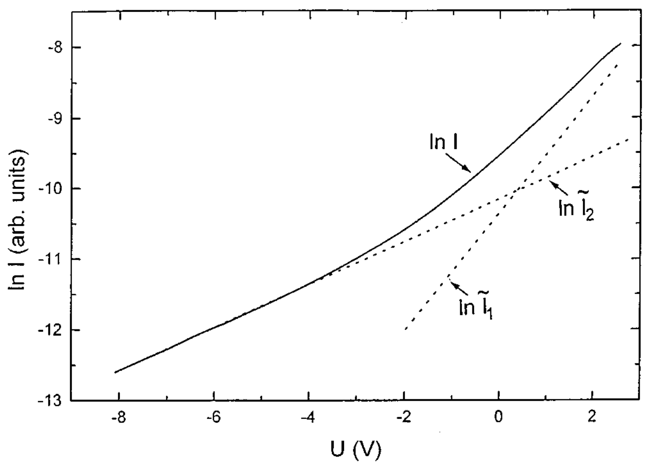

Fig. 5. The experimental semilogarithmic characteristics ln$I$ (solid line) together with ln$\tilde{I}_2$ and ln$\tilde{I}_1$ where $\tilde{I}_2$ and $\tilde{I}_1$ ($= I - \tilde{I}_2$) are the electron current intensities of the probe given by the secondary or hot electrons and ultimate or cold electrons, respectively.

characteristic of the probe (curve I) is compared with the "theoretical" characteristics ($I_{\rm th}$ and $\tilde{I}_{\rm th}$) obtained by using function (3). The curve labelled $I_{\rm th}$ was obtained using plasma parameters ($n_1 = 2.2 \times 10^{15}$ m^{-3}, $n_2 = 1.7 \times 10^{14}$ m^{-3}, $T_1 = 1.6$ eV, $T_2 = 7.0$ eV) given by relations (1, 2) of the new method, while the curve $\tilde{I}_{\rm th}$ was obtained using plasma parameters ($\tilde{n}_1 = 0.8 \times 10^{15}$ m^{-3}, $\tilde{n}_2 = 1.3 \times 10^{15}$ m^{-3}, $T_1 = 1.5$ eV, $T_2 = 3.2$ eV) given by the classical semilogarithmic plot (Fig. 5). It is obvious that the plasma parameters obtained by analytical relations (1, 2) fit far better the experimental characteristic compared with the plasma parameters obtained by the so called classical method of the semilogarithmic plot of the electron current of the probe.

In this paper all plasma parameters have been obtained by this new analytical method. Each experimental point is a result of a statistic over more then 10 probe characteristics so that the corresponding standard deviation is presented too.

3 Experimental results and discussions

Hassal and Allen in a recent paper [4] present the results about the dependence of the plasma parameters, as electron number densities and temperatures of the both groups of electrons of a bi-Maxwellian distribution function, *versus* discharge current and gas pressure. In general, electron number densities exhibit an almost linear dependence *versus* discharge current, a result that was also reported by other studies.

This time attention has been paid for finding the dependence of the plasma parameters, under bi-Maxwellian approximation of the EDF, *versus* gas pressure, in the most sensitive range from 10^{-4} to 10^{-3} mbar, and anode-cathode potential, but for an almost constant discharge current intensity. Consequently, information's can be obtained about the degrading process of the monokinetic character of the primary electrons and generation and evolving of the bi-Maxwellian distribution function with respect to the energy of the primaries. Moreover, the influence of the neutral gas pressure on the leak of the plasma in a cusp geometry of the multidipole device can, at least be qualitatively, observed.

It is obvious that the plasma parameters as plasma potential, the EDF, electron and ion temperatures and plasma density in a steady state regime are the result of self-consistent problem where the equilibrium must be considered between production and loss of the plasma particles. In a multipolar DC discharge system, as was mentioned, plasma is produced manly by ionisation processes due to collisions between primary electrons and neutrals. These processes take place in the whole plasma volume but manly near the wall of the discharge [6,24]. Plasma particles loss is not yet a process fully understood because the ion-electron recombination in the plasma volume is a rather negligible process so surface recombination has to be considered. In the most cases there are no free floating surfaces (except the probes and filaments shaft) but the active ones as the cathode and the anode, respectively. The cathode is a hot filament, which produces the primary electrons, and it has a negligible area to be considered as an important ion collector. The most difficult problem is related to the anode. The large surface of the anode might explain the positive value of the plasma potential because of the large electron losses by its circuit. But, the presence of the cusp magnetic field produced by row permanent magnets, has a strong influence on the flux of both kinds of plasma particles: electrons and ions, respectively, in that region.

Detailed analysis made by Hershkowitz *et al.* [25] or Knorr and Merlino [26] have shown that such cusp structure, in presence of a neutral gas background and with fast primary electrons, the leak width is of the order of a hybrid widths $2\sqrt{a_i a_c}$, where a_i, a_c are the ion and electron Larmor radii, respectively. This fact may limits the

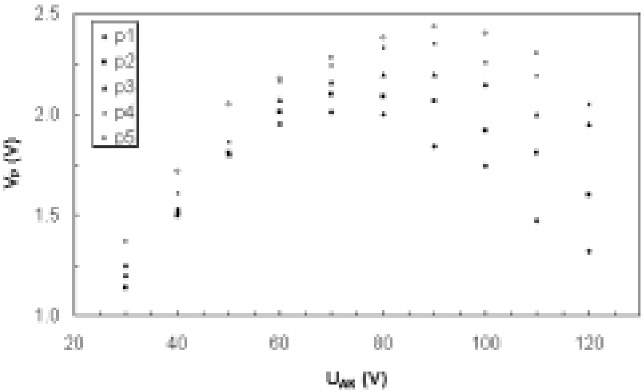

Fig. 6. Plasma potential V_p *versus* anode-cathode potential U_{AK} and gas pressure as a parameter $p_1 = 10^{-4}$ mbar, $p_2 = 2 \times 10^{-4}$ mbar, $p_3 = 4 \times 10^{-4}$ mbar, $p_4 = 6 \times 10^{-4}$ mbar, $p_5 = 8 \times 10^{-4}$ mbar.

effective area of the collecting anode but still the electron loss is important so that the plasma potential becomes positive with respect to the anode. Dependence of the plasma potential on the energy of the primary electrons, having the argon neutral gas pressure as parameter, is presented in Figure 6. In this case the filament current was 2.35 A. So, taking into account the current-voltage characteristics of Figure 2, the increase of the plasma potential with the increase of the U_{AK} up to about 70 V, for $p = 10^{-4}$ mbar, might be explained by the increase of the density of the primary electrons which inhibit the diffusion of plasma electrons towards anode [26]. But, the decrease of the plasma potential with further increase of the U_{AK} has to be explained because, above about 70 V the discharge current becomes constant. Moreover, the maximum of plasma potential with respect to the U_{AK} increases from about 1.8 V to 2.4 V and shifts towards larger value with the increase of the neutral gas pressure.

This result shows that, very probable, the leak process might have a more complicated dependence on both the gas pressure and the energy of the primary electrons than the hybrid width model predicts. The plasma potential might also depend on other parameters as anode coating with insulating layer and magnet outgassing [3].

The main results are shown in Figure 7 where the dependence of the electron temperatures (left column) and of the electron number densities (right column) of the both groups of electrons, are presented *versus* discharge voltage U_{AK}. The heating current of the filament ($I_f = 2.35$ A) was constant but different gas pressure as: 10^{-4} mbar (Fig. 6a), 2×10^{-4} mbar (Fig. 6b), 4×10^{-4} mbar (Fig. 6c), 6×10^{-4} mbar (Fig. 6d) and 8×10^{-4} mbar (Fig. 6e), respectively.

It is obvious that the temperature (T_1) of the ultimate electrons does not depend on both gas pressure and discharge voltage. Its value is around 1.2 eV. The number density n_1 of these electrons is also rather independent of the gas pressure, but it depends on the discharge current intensity. Taking into account the discharge current-voltage characteristics in Figure 2 and the dependence

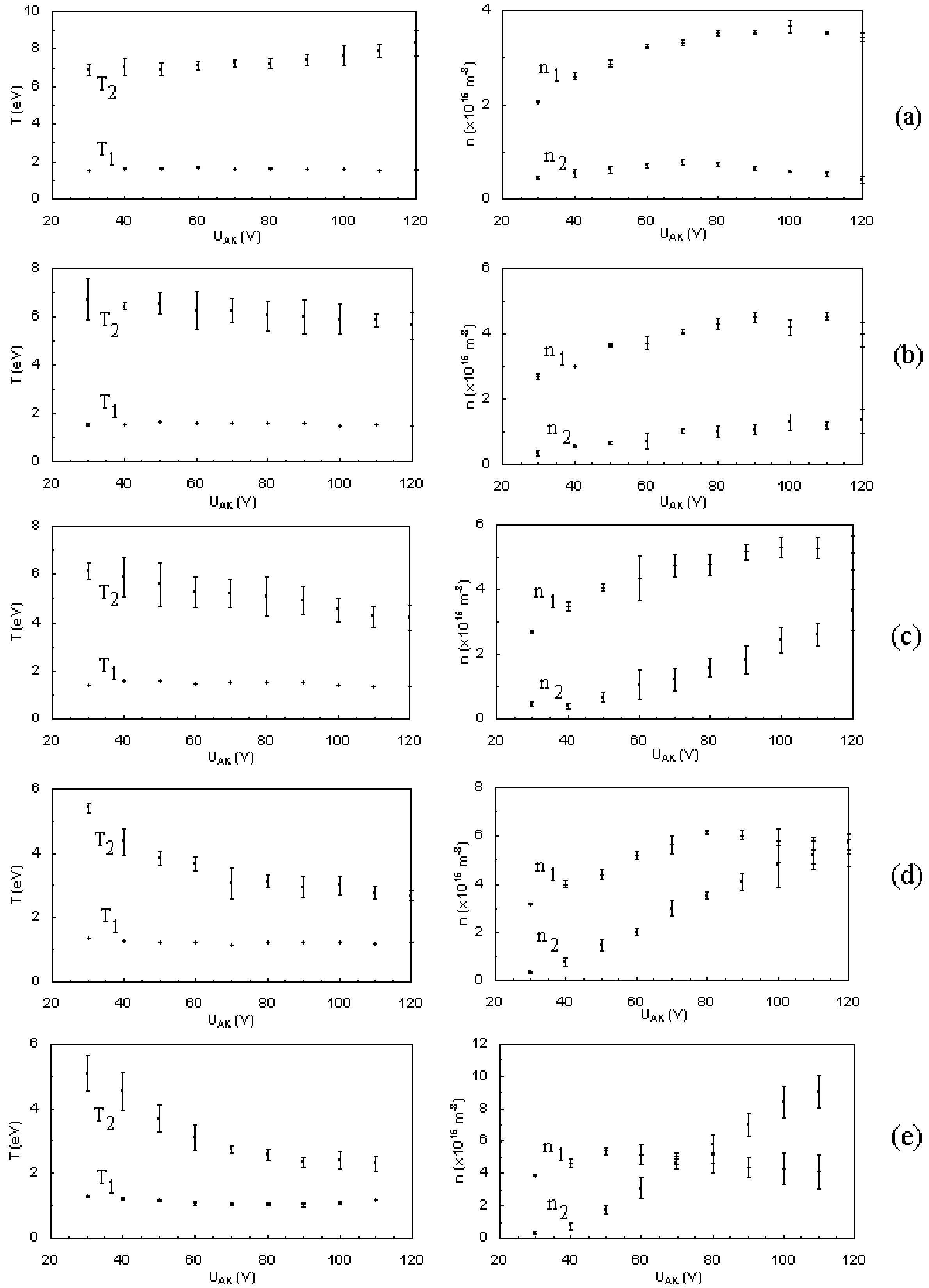

Fig. 7. Electron temperatures (T_1 for ultimate or cold electrons and T_2 for secondary or hot electrons) – left column – and electron number densities (n_1 and n_2 with similar meaning of subscripts) – right column – *versus* discharge potential U_{AK} and gas pressure as parameters; $p = 10^{-4}$ mbar (a), 2×10^{-4} mbar (b), 4×10^{-4} mbar (c), 6×10^{-4} mbar (d) and 8×10^{-4} mbar (e), respectively.

of the density of the ultimates on the U_{AK}, we may find previous results [4] which shows that the n_1 increases also almost linearly with the discharge current intensity. These results can be explained through the fact that the ultimate electrons come mainly from the direct ionisation of the atoms and/or metastables due to inelastic collisions with primary and, eventually, the secondary electrons, respectively as step ionisation process. The ultimate electrons are practically entirely electrostaticaly trapped in the potential well produced by positive plasma potential, which is larger as 1 V with respect to the anode. They may only undergo elastic collisions with neutral atoms of argon, although these collisions are also less probable because of Ramsauer effect.

The secondary or hot electrons behave differently. Their temperature and number density depend on both the gas pressure and the discharge voltage. The increase of the gas pressure both the electron temperature decreases and the number density increases in a rather complicated manner related to the discharge voltage. Thus, at the lower limit of the pressure (10^{-4} mbar, Fig. 7a) both temperature T_2 and the number density n_2 of the secondary electrons are almost not dependent on the U_{AK}. They represent about 10% from the total electron population. But, the increase of the gas pressure towards 10^{-3} mbar, the electron temperature T_2 decreases, *e.g.* from 7 eV to about 3 eV for $U_{AK} = 60$ V. The same parameter T_2 decreases also with the increase of the U_{AK} for higher gas pressure. Moreover, the rate dT_2/dU_{AK} increases with the increase of the gas pressure from about 0.01 eV/V at 2×10^{-4} mbar to about 0.06 eV/V at 8×10^{-4} mbar. This fact proves the origin of the secondary electrons as degrading primary electrons because with the increase of the gas pressure the primary electrons undergo more inelastic collisions and so their diffusion in the energy space increases with the number of the collisions. Moreover, the decrease of the electron temperature with the increase of the U_{AK} can be explained. So, with the increase of the U_{AK}, the energy of the primary electrons increases and taking into account that the ionisation cross-section [15] and the ionisation probabilities through electron-atom collisions increase with the energy of the primary electrons, the thermalisation of the electrons can be enhanced.

The same elementary processes and their dependence on both gas nature and the energy of the electrons can explain the dependence of the electron number density n_2 on both gas pressure and the U_{AK}. So, with the increase of the gas pressure, the primary electrons experience more collisions and more secondary electrons are produced for a constant U_{AK}, while with the increase of the U_{AK}, the primary electrons undergo also more collisions because the collision cross-section increases and as a result the number of the secondary electrons increases too. Moreover, with the decrease of their temperature T_2 both the Larmor radius and leak width decrease so that the loss of the secondary electrons decreases and the n_2 may also increase with the increase of the gas pressure. These processes lead to the fact that towards 10^{-3} mbar, the temperature T_2 of the secondary electrons reaches almost the temperature T_1 of the ultimate and their number density becomes comparable with that of the ultimate too. At the limit, for a gas pressure larger than about 10^{-3} mbar, it is very probable to find only one group of electrons with a Maxwellian distribution function.

4 Conclusions

In the multipolar DC discharge plasma and argon pressure between 10^{-4} and 10^{-3} mbar besides primary electrons there are also two Maxwellian groups of electrons named as ultimate and secondary, respectively. Both the temperature and number density of the former group (ultimate) are almost independent of the gas pressure and discharge voltage. The latter group (secondary) is very sensitive with respect to both gas pressure and discharge voltage. The temperature of the secondary electrons decreases while the number density increases with the increase of both the gas pressure and the discharge voltage.

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