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A STUDY OF TRANSITORY PROCESSES IN A DC CYLINDRICAL PULSED HELIUM PLASMA

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In this paper we analyse the creation and decay processes in a cylindrical dc helium plasma whose length is greater than its diameter. The ionization front velocity is studied. From the temporal evolution of the plasma electron density and temperature during the creation and decay processes, we determined the characteristic times of these magnitudes in both processes. The mechanism which controls the decay process was identified that permits us, firstly, to determine the recombination and ambipolar diffusion coefficients and, secondly, to establish the variation of the momentum transfer cross section for an electron-neutral collision with the electron temperature. The diagnostic techniques used are based on the I—V probe characteristics.

INTRODUCTION

The study of the plasma transitory processes in tubes whose length is greater han their diameter is a matter of interest to many workers because of the mportance of this type of devices in plasma chemistry, lasers, etc. [1], [2].

A matter of great scientific interest is the study of the pulsed plasmas because t helps us analyse the response time, the stability and reproducibility of the bove devices.

At present, a good classification of the characteristic stabilization times of the ery important plasma magnitudes does not exist. That is why a full discharge ime evolution theory does not exist. The object of this work is to present an nalysis that tends systematize the transitory processes in a dc cylindrical pulsed Ielium plasma.

In Section I. the theoretical considerations of the creation and decay process-s are present. The study of the creation process includes the ionization front elocity and the density and temperature stabilization times. Next, the decay lasma process is studied by means of an analysis of the time evolution of the lasma parameters. From this evolution the ambipolar diffusion and ion-elec-on recombination coefficients and the momentum transfer cross section were btained.

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In Section II, the experimental set-up used and the results obtained are shown. The paper concludes with a summary and conclusions.

I. THEORETICAL CONSIDERATIONS

I.1. Creation Process

The creation process in a cylindrical tube begins with the gas ionization in a region near the active electrode, propagating the ionization front along the tube with the velocity v_f, [3]. For a fixed discharge tube and gas, the velocity v_f depends on the gas pressure and the dc pulse amplitude that originates the plasma [4].

In these cylindrical dc discharges, the voltage signal which is propagated originates the evolution of the electron density and temperature toward the stationary values. For each one of these parameters a characteristic stabilization time can be defined as the time interval spent between the beginning of the pulse and time when the stationary value is reached. The time intervals t_{cn} and t_{ct} for reaching the saturated values of the number density and the electron temperature, respectively, are generally different and are functions of the gas pressure and the dc pulse amplitude, for each tube and gas used. The knowledge of v_f, t_{cn} and t_{ct} will give us a full understanding of the creation and stabilization plasma process.

Theoretically it can be verified that the ionization front velocity is related to the stationary electron density, n_s, by the equation [4]:

$$v_f = \sigma(p, V_0)\, \alpha(E)\, v_d(E)\, n_s \tag{1}$$

with

$$E = V_0/L_0 \tag{2}$$

where α is the ionization coefficient, v_d the electron drift velocity, V_0 the dc pulse amplitude and p the gas pressure. The parameters σ and L_0 for the tube and gas used are

$$L_0 = 0.13\,\mathrm{m} \tag{3}$$

$$\sigma = k V_0^{-2}$$

with

$$k(10^{-16}\,\mathrm{m}^4\,\mathrm{Volt}^2) = \begin{cases} 1.13, & p \leq 333\,\mathrm{Pa} \\ 0.48, & 333 < p \leq 533\,\mathrm{Pa} \\ 0.37, & p > 533\,\mathrm{Pa} \end{cases} \tag{4}$$

I.2. Decay Process

When the pulse is off, charge losses occur due, for the rare gases, to the ambipolar diffusion and the ion-electron recombination. Therefore, the electron density evolution equation is

$$\frac{\partial n_e}{\partial t} = D \nabla^2 n_e - \beta n_e^2 \tag{5}$$

where D is the ambipolar diffusion coefficient and β is the ion-electron recombination coefficient.

If the ambipolar diffusion is the principal mechanism of the loss charge, the solution of eq. (5) for a cylindrical geometry is

$$n_e = n_0 \exp(-t/\tau_d) \tag{6}$$

with

$$\frac{r_0}{(D\tau_d)^{1/2}} = 2.405 \tag{7}$$

where r_0 is the tube radius and $n_0 = n_e(t = 0)$.

When the principal process of the charge losses is the ion-electron recombination, the solution of eq. (5) is:

$$1/n_e = 1/n_0 + \beta t\,. \tag{8}$$

The eqs. (6) and (8) allow us to determine the transport coefficients D and β, respectively, with the knowledge of the electron density evolution in the range where each process is predominant.

If it is supposed that the electron-neutral collision frequency is practically not dependent on the electron temperature, the time evolution of the electron temperature during the decay process can be expressed as [5]:

$$T_e - T_g = (T_{e0} - T_g) \exp(-t/\tau) \tag{9}$$

where T_g is the gas temperature ($T_g = 300\,\mathrm{K}$), τ is the characteristic time for the electron cooling and $T_{e0} = T_e\,(t = 0)$.

The parameter τ is related with the momentum transfer cross section for the electron-neutral collision, σ_{en} by the expression (6):

$$\sigma_{en} = 3.1 \times 10^{-21} \frac{M}{2m_e} \left(\frac{\pi m_e}{8kT_e}\right)^{1/2} \frac{1}{\tau p} \tag{10}$$

where M and m_e are the ion and the electron massses, respectively, and k is the Boltzmann constant.

Similarly as in the creation process it is possible to define the characteristic extinction times for the electron density and temperature, t_{Dn} and t_{Dt}, respectively, as the time interval spent between the beginning of the afterglow and the time necessary to reach 10% of the maximum value. The knowledge of these times permit us to compare the evolution of the electron density and temperature in the creation and the decay processes.

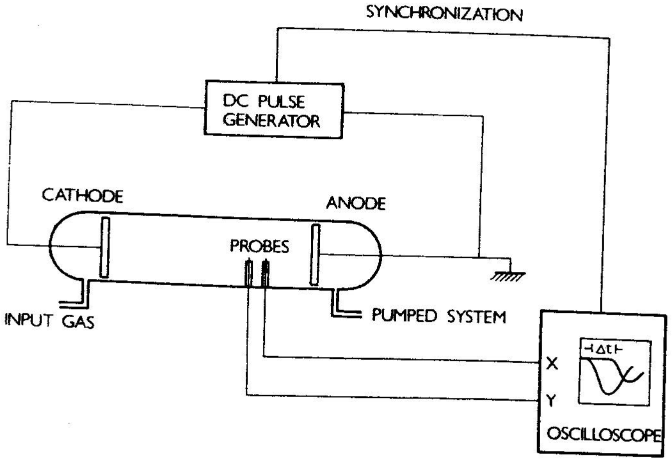

Fig. 1. Experimental set-up for the study of the ionization front velocity

II. EXPERIMENTAL SET-UP AND RESULTS

The experiments were performed in a cylindrical Pyrex glass tube 4 cm in diameter. Two circular stainless steel electrodes with a diameter 3.8 cm and separated by a distance of 25 cm were used to obtain the breakdown of gas, in this case Helium. A COBER '605 commercial model with an average power output of 360 W and a pulse width and repetition pulse frequency (PRF) continually adjustable (50 ns to 1 ms and 10 Hz to 1 MHz, respectively) was used as the dc pulse generator. Small tungsten filaments were used as probes (50 μm in diameter and 3 mm long).

In order to guarantee, firstly, the extinction of the plasma created by a pulse before the following comes and secondly to assure a sufficient dc pulse width so that the plasma reaches the stationary state, the PRF and the pulse width were set at 50 Hz and 100 μs, respectively.

In Figure 1 the experimental set-up used for the measuring of the ionization front velocity is shown. The measuring of this parameter is based on the detection of the delay time, Δt, from the onset of the ionization front to two probes separated by a distance $\Delta z = 2$ cm, 20 cm being the distance of the cathode-first probe.

The electron temperature and density at each fixed time are obtained from the I—V probe characteristic [7] and the I^2—V probe characteristic [8]. The experimental set-up used to obtain them is shown in Figure 2. A delay line permits us to fixe the time, with respect to the pulse on or pulse off (for the creation and decay processes, respectively), so that a memory oscilloscope will sample the collected probe current for several bias values [9].

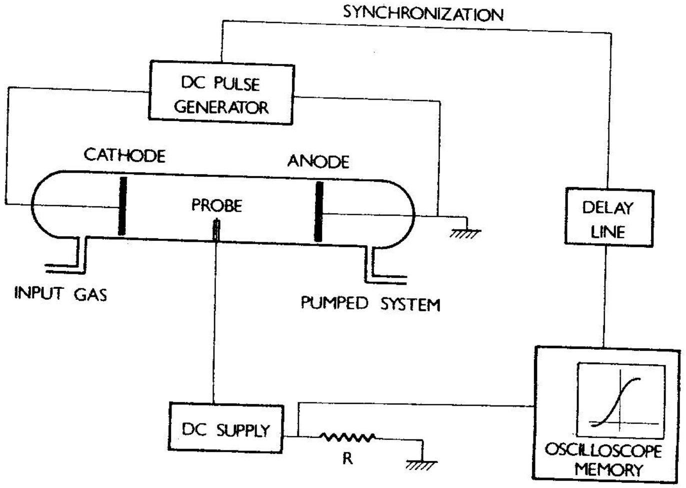

Fig. 2. Experimental set-up used for obtaining the I—V probe characteristics.

II.1. Creation Process

Figures 3 and 4 show the v_f variation as a function of the gas pressure and the dc pulse amplitude. The solid line corresponds to the theoretical results obtained with the eq. (1). As can be seen in Figure 3, there exists a gas pressure for which v_f is a maximum. This behaviour has been detected equally in discharges produced by surface waves [10].

Figures 5 and 6 show the time evolution of the electron density and temperature for several gas pressures a fixed dc pulse amplitude. From this it is possible to obtain the stabilization times defined in Section I. The variation of these times is shown in Figure 7. As can be seen, there exists a gas pressure for which these times has minimal values. This pressure is approximately the same for which the ionization front velocity has a maximum. Also, it can be seen that

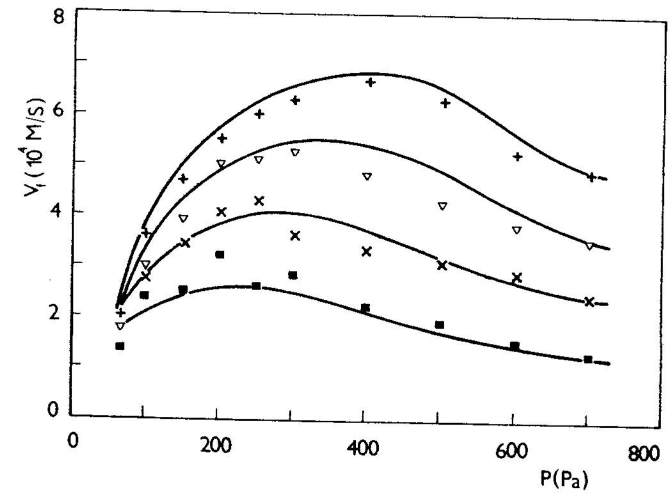

Fig. 3. Theoretical (solid line) and experimental results for the ionization front velocity as a function of the gas pressure for several dc pulse amplitude: 1300 V (+); 1100 V (▽); 900 V (×); 700 V (■).

the electron temperature was stabilized at 15—20 μs before the electron density. Figure 8 shows the t_{cn} and t_{cT} variation as a function of the dc pulse amplitude, for a fixed gas pressure.

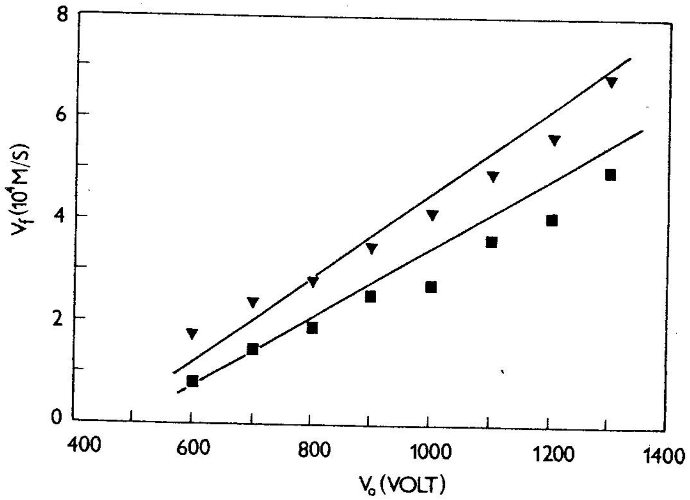

Fig. 4. Theoretical (solid line) and experimental results for the ionization front velocity as a function of the dc pulse amplitude for two different gas pressures: 400 Pa (▼); 700 Pa (■).

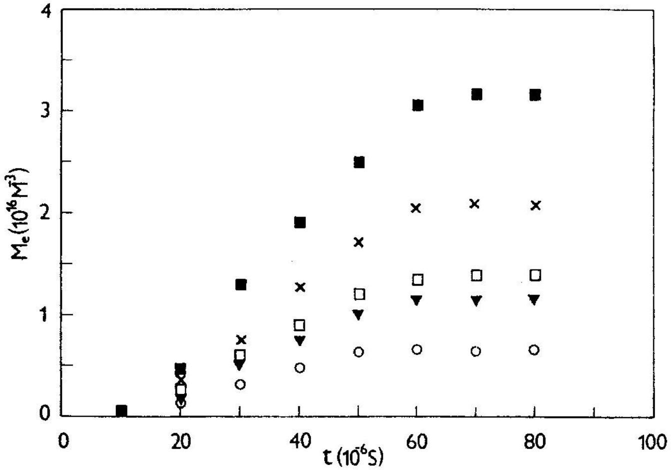

Fig. 5. Experimental results for the electron density time evolution during the creation process for a dc pulse amplitude of 900 Volt and several gas pressures: 600 Pa (■); 500 Pa (×); 400 Pa (□); 350 Pa (▼); 300 Pa (○).

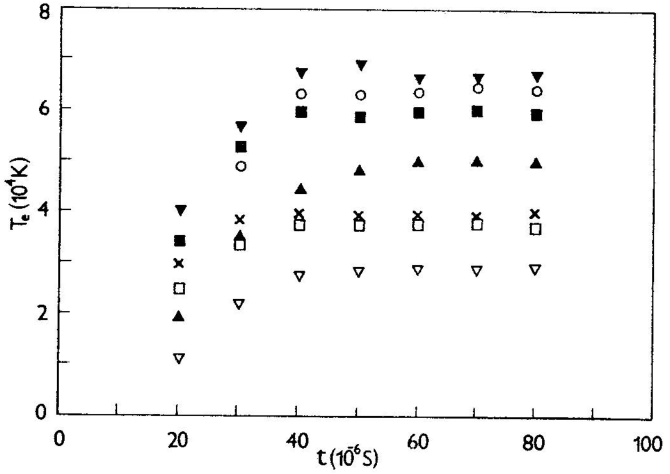

Fig. 6. Experimental results for the electron temperature time evolution during the creation process for a dc pulse amplitude of 900 Volt and several gas pressures: 600 Pa (□); 500 Pa (○); 400 Pa (▼); 350 Pa (■); 300 Pa (×); 200 Pa (□); 150 Pa (▽).

II.2. Decay process

Figure 9 shows the electron density time evolution for set conditions. The corresponding functions $1/n_e$ and Ln n_e for these conditions are shown in Figure 10. In an initial interval of, approximately, 2 ms, the mechanism controlling the decay process was the ion-electron recombination. From 4 ms on approximately, the decay mechanism was the ambipolar diffusion. Between 2—4 ms both processes are present. The strong electron density variation (nearly 85%) was

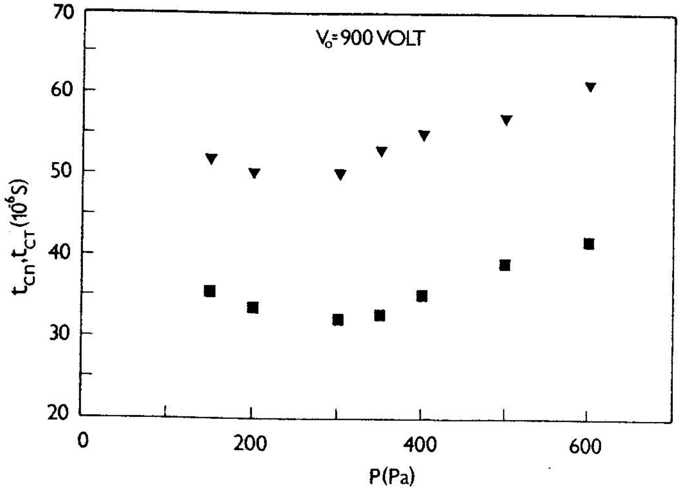

Fig. 7. Experimental results for the electron density and temperature stabilization times as a function of the gas pressure, for a fixed value of the dc pulse amplitude: t_{cn} (▼); t_{cT} (■).

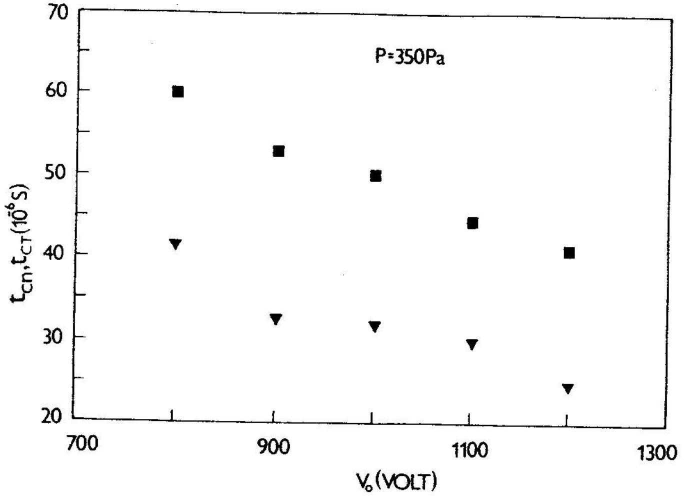

Fig. 8. Experimental results for the electron density and temperature stabilization times as a function of the dc pulse amplitude for a fixed value of the gas pressure: t_{cn} (■); t_{cT} (▼).

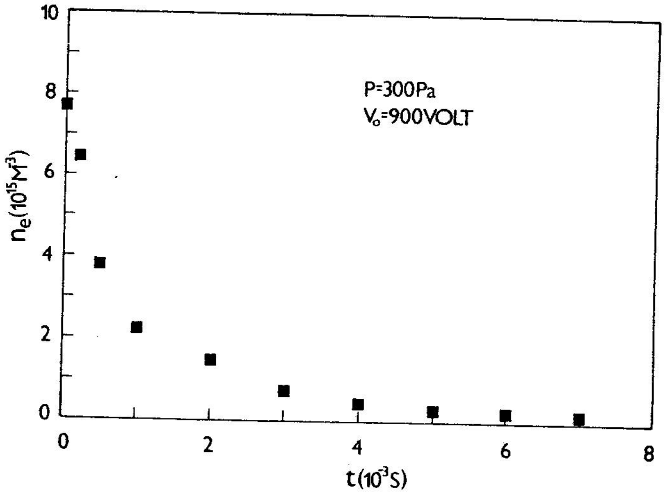

Fig. 9. Experimental results for the electron density time evolution during the decay process for fixed values of the dc pulse amplitude and the gas pressure.

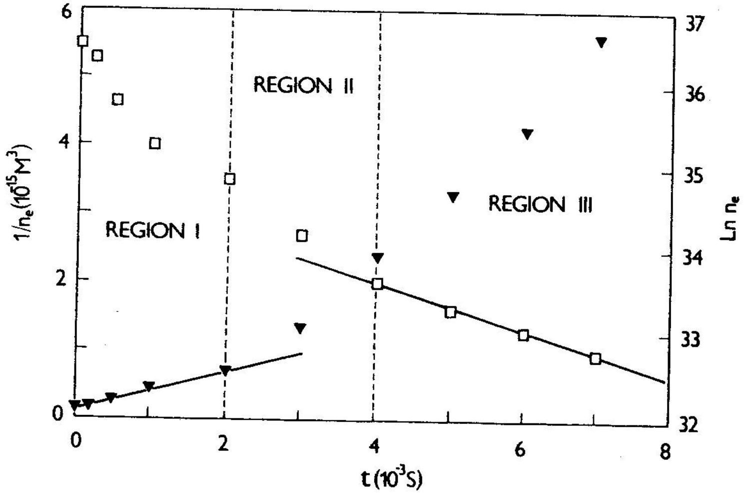

Fig. 10. Time evolution of the functions $1/n_e$ and Ln n_e during the decay processes for fixed values of the dc pulse amplitude and the gas pressure.

produced in the small time interval during which the ion-electron recombination was predominant.

From figures similar to Figure 10 and eqs. (6) and (8) it is possible to obtain the values for D and β coefficients, respectively. Table I shows the values of these coefficients as a function of the gas pressure and the dc pulse amplitude. Figure 11 show the product pD as a function of p. As can be seen, this relation is linear, as reported in other gases [2].

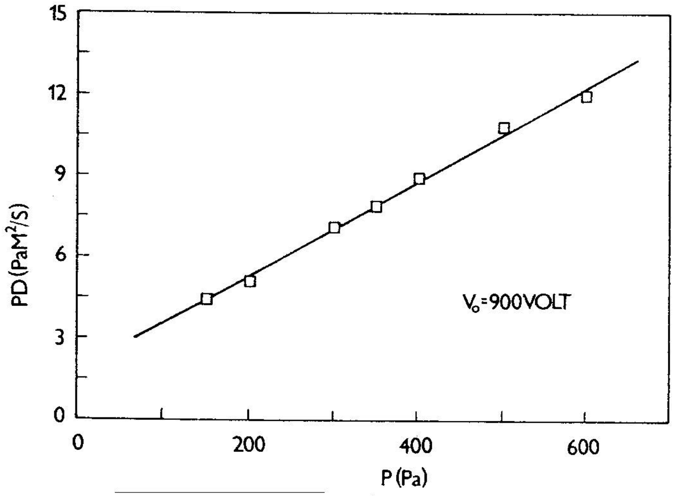

Fig. 11. The function pD as a function of the gas pressure for a fixed value of the dc pulse amplitude.

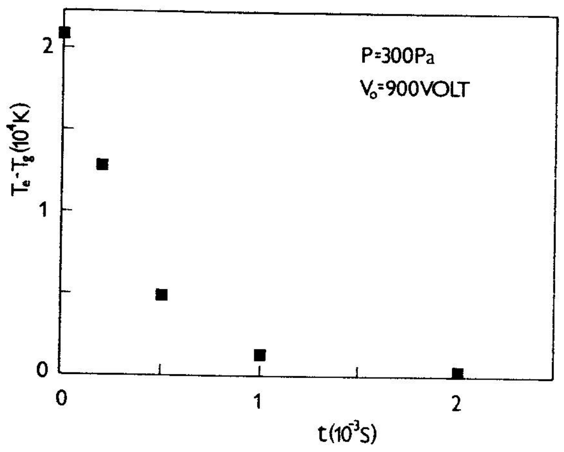

Fig. 12. Experimental results for the electron temperature time evolution during the decay process for fixed values of the dc pulse amplitude and the gas pressure.

Table I

Experimental results of the ion-electron recombination and ambipolar diffusion coefficients

Table Ia ($V_0 = 900$ Volt)

p (Pa)	β (10^{-13} m^3/s)	D (10^{-4} m^2/s)
150	4.7	298
200	4.2	257
300	2.8	238
350	2.2	227
400	2.0	224
500	1.7	216
600	1.0	200

Table Ib ($p = 200$ Pa)

V_0 (Volt)	β (10^{-13} m^3/s)	D (10^{-4} m^2/s)
800	6.3	276
900	4.2	257
1000	3.6	236
1100	2.8	214
1200	1.9	192

Table II

Experimental results of the gas pressure variation of the characteristic time for the electron cooling, for a fixed value of the dc pulse amplitude

$V_0 = 900$ V

p (Pa)	150	200	300	350	400	500	600
τ (10^{-3} s)	0.725	0.531	0.344	0.254	0.222	0.171	0.141

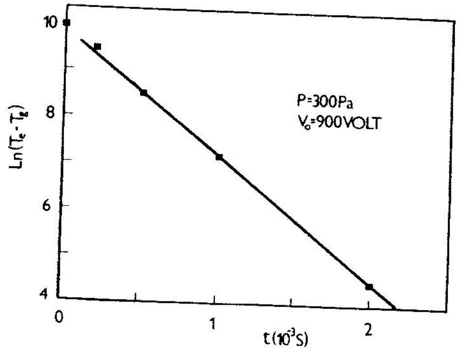

Fig. 13. Time evolution of the function $\mathrm{Ln}(T_e - T_g)$ during the decay process for fixed values of the dc pulse amplitude and the gas pressure.

Figures 12 and 13 show the $T_e - T_g$ and $\mathrm{Ln}(T_e - T_g)$ time variations for set conditions. According to eq. (9), the function $\mathrm{Ln}(T_e - T_g)$ is linear and, consequently, from this it is possible to determine the parameter τ and from eq. (10), the momentum transfer cross section variation with the electron temperature. The electron temperature drop was produced in the time interval when the predominant decay mechanism was the ion-electron recombination. Table II shows the τ-variation with the pressure. As can be seen, τ decreases when p increases.

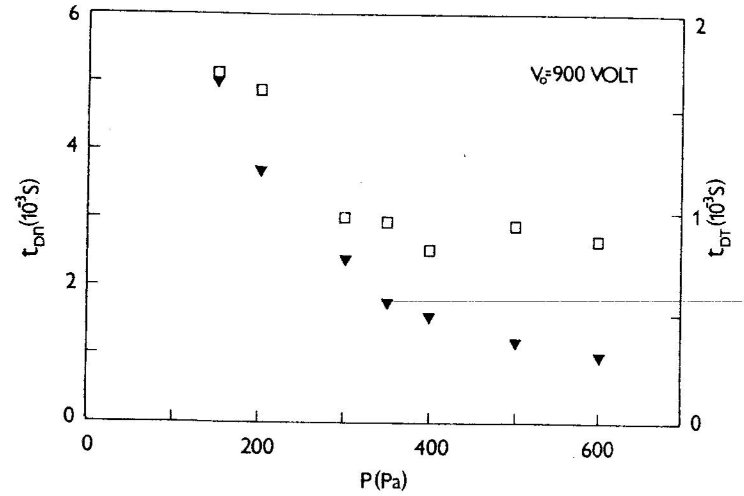

Fig. 14. Experimental results of the electron density and temperature decay times as a function of the gas pressure, for a fixed value of the dc pulse amplitude: t_{Dn} (□); t_{DT} (▼).

Figure 14 shows the electron density and temperature extinction times, defined in Section I, as a function of the gas pressure. Similarly as in the creation process, t_{DT} is less than t_{Dn}, and, as can be seen, both times decrease when p increases. It is necessary to remark that, as expected, in the gas pressure range studied, no variation of these times with the dc pulse amplitude has been observed.

CONCLUSIONS

In this paper we analyse the creation and decay processes in a cylindrical dc helium plasma whose length is greater than its diameter.

The study of the creation process was found by the analysis of the ionization front velocity. Next, the electron density and temperature time evolution is studied. It has been found that the electron temperature is stabilized approximately 20 μs after the electron density, in consequence during this time interval the electron density increases whereas the electron temperature is constant.

The electron density decay process, controlled by two different mechanisms, has been determined. The recombination of the ion-electron controlled the decay process during the 0—2 ms time interval. From 4 ms the decay process is controlled by the ambipolar diffusion and, during the interval between 2 and 4 ms both mechanism are present. It is necessary consider that the electron density decreases, fundamentally, in the time interval during which ion-electron recombination is predominant and that, during this time interval, the electron temperature decreases to, practically, the gas temperature. Analogously to the creation process the decay temperature time is less than the decay density time. It is found that the electron temperature decay is an exponential function with a tempering time of two ms, approximately.

From the electrons density and temperature time evolution it has been possible to determine the ion-electron recombination and ambipolar diffusion coefficients and the momentum transfer cross section for the electron-neutral collision, respectively.

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ИЗУЧЕНИЕ ПРОЦЕССОВ В ТРАНЗИСТОРАХ, ПОМЕЩЕННЫХ В ПРОСТРАНСТВО ЦИЛИНДРИЧЕСКОЙ ФОРМЫ С ПУЛЬСИРУЮЩЕЙ ГЕЛИЕВОЙ ПЛАЗМОЙ ПОСТОЯННОГО ТОКА

В работе приводится анализ процессов рождения и распада, протекающих в пространстве цилиндрической формы с гелиевой плазмой, причем длина цилиндра больше его диаметра. При этом изучалась скорость фронта ионизации. На основе временного расвития плотности электронной плазмы были определены характеристические времена этой величины в обоих процессах. Установлен механизм, который управляет процессами распада, и это возволило определить как рекомбинацию, так и изменение поперечного сечения, являющегося функцией переданного испульса, при столкновениях электронов с нейтральными атомами в зависимости от электронной температуры. Использованные методы диагностики основывались на зондирующих вольт-амперных характеристиках.