acta phys. slov. 26 (1976), No.3

TIME DEVELOPMENT OF ELECTRON TEMPERATURE IN THE PLASMA OF A SPARK DISCHARGE

ELENA BREŽNÁ*, ŠTEFAN VEIS*, Bratislava

In this work the electron temperature in the spark channel plasma and in the phase of its decay due to cooling, has been determined. For measurements we made use of spectroscopic diagnostic methods, modified in such a way as to permit the observation of the time development of individual plasma parameters. The subject of the study was a spark originating in the air at atmospheric pressure. The influence of the parameters of the outer electric circuit of the spark discharge upon the time development of the electron temperature has been investigated. Thus the validity of a partial local thermodynamic equilibrium in the spark discharge plasma has been experimentally proved.

I. INTRODUCTION

One of the important parameters of the spark discharge plasma is the temperature of the electrons. For its determination it is possible to make use of advantageously of spectroscopic diagnostic methods. In their application, however, it is necessary to realize that some of these methods assume the validity of a local thermodynamic equilibrium in the plasma.

Criteria for the possibility of using the model of the local thermodynamic equilibrium (further LTE) in the spark discharge plasma, taking into account time changes and space inhomogeneity, have been discussed in detail in paper [1].

It has been shown that although the LTE model is otherwise acceptable even in the spark discharge plasma, it need not always refer to a complete LTE in the case of a spark discharge originating in the air.

In spectroscopic diagnostic methods founded on the presence of LTE in the plasma it is therefore imperative to make a careful selection od spectral lines, because the population of not all energy levels in the case of a partial LTE is described by Boltzmann's distribution.

* Katedra experimentálnej fyziky PFUK Mlynská dolina, 816 31 BRATISLAVA, Czechoslovakia.

II. MEASUREMENT METHODS AND DESCRIPTION OF EXPERIMENT

If in the plasma there is a sufficiently high value of electron density, which in the case of the spark discharge is fulfilled ($N_e \approx 10^{17}$ cm^{-3}, [2, 3]), then it is possible to conclude that the electron velocity distribution is Maxwellian, and we can ascribe a meaning to the local temperature of electrons.

Assuming that the plasma is in a state of a complete LTE, the density of the excited particles is connected with the temperature according to Botzmann's distribution law. In the case of the spark channel plasma the excitation is characterized by the electron temperature T_e [1].

The electron temperature determination, assuming the validity of the LTE, has been performed from the measured relative intensities of the spectral lines, from the known transition probabilities (resp. of the oscillator forces), from statistical weights, and excitation energy, according to the relation

$$\frac{I_{mn}}{I_{kl}} = \frac{g_m}{g_k}\frac{\nu_{mn}}{\nu_{kl}}\frac{A_{mn}}{A_{kl}} e^{-(\chi_m - \chi_k)/kT_e}. \qquad (1)$$

In Eq. (1) I_{mn}, I_{kl} represent the intensities of the spectral lines; g_m, g_k statistical weights; A_{mn}, A_{kl} transition probabilities; χ_m, χ_k excitation energies of each particular energy level; ν_{mn}, ν_{kl} the frequencies corresponding to the individual transitions; k the Boltzmann's constant; T_e electron temperature.

In view of the fact that the temperature had been determined from a relatively large number of pairs of lines, and moreover the time development of the electron temperature had been investigated, the calculation of electron temperatures from Eq. (1) was numerically realized on a TESLA 200 computer.

For the observation of the time development of the electron temperature an apparatus had been built that enables us to register the time evaluation of the spark discharge spectra. This apparatus is schematically illustrated in Fig. 1. The light of

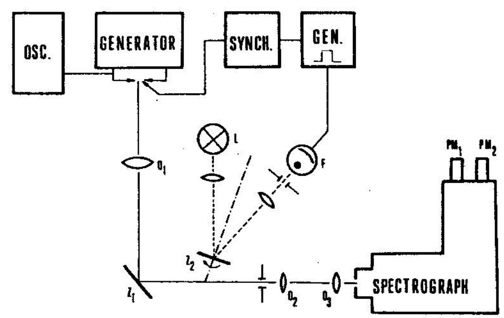

Fig. 1. Scheme of the measuring equipment.

the auxiliary lamp L falls upon the rotary mirror Z_2, from which it is reflected to the photo-electric tube F. The impulses from the photo-tube, amplified and formed into right angles, open the trigger circuit SYNCH. On the output of the trigger circuit a steep impulse is obtained with an amplitude of ≈ 1 μs, by which the firing of the spark is synchronized. The synchronizing impulse is led to the auxiliary electrode of a triple electrode air spark gap. With the other two electrodes a high voltage (8—12 kV) from Feussner's spark generator is connected. The spark image is formed up on the entrance slit of the spectrograph by the fixed mirror Z_1, and the spectrum is registered with the help of photo-multipliers.

The advantage of an equipment working in this manner for the registration of the time development of the spark discharge spectra is the possibility of alternating the method of resolution by means of photo-multipliers with the method of a rotary mirror and a photographic plate. A detailed description of the apparatus and its function is to be found in [4].

III. EXPERIMENTAL RESULTS AND DISCUSSION

Experimentally the temperature of the electrons in the plasma of the spark discharge originating in air at atmospheric pressure was determined in its channel stage and in the phase of its decay due to cooling, while individual measurements were taken in the axis of the discharge channel. For investigation purposes this region was delimitated by means of a diaphragm.

For the measurement of the spectral line intensity the time development of the profiles of 12 spectral lines of singly ionized nitrogen NII ($\lambda = 5666.63$ Å; 5535.36 Å; 5495.70 Å; 5179.52 Å; 5045.10 Å; 5005.15 Å; 4621.39 Å; 4613.87 Å; 4607.16 Å; 4601.48 Å; 3995.00 Å; 3919.00 Å), of two spectral lines of neutral nitrogen NI ($\lambda = 4935.03$ Å; 4151.46 Å), of two lines of doubly ionized nitrogen NIII ($\lambda = 4514.89$ Å; 4103.37 Å), seven lines of singly ionized oxygen OII ($\lambda = 4941.02$ Å; 4414.89 Å; 4366.91 Å; 4121.48 Å; 4085.12 Å; 4075.87 Å; 3973.27 Å); of two lines of neutral oxygen OI ($\lambda = 4368.30$ Å; 3947.35 Å), of four lines of doubly ionized oxygen OIII ($\lambda = 3754.67$ Å; 3707.24 Å; 3702.75 Å; 3638.70 Å) were registered.

Since the lines NI, NIII, OI, OIII had weak total intensities, it was possible to use for the determination of the electron temperature only the lines NII, OII. From the lines mentioned upon line NII $\lambda = 3919.00$ Å line OII $\lambda = 3919.29$ Å is superposed, which, however, has but a slight intensity, and it can therefore be assumed that it does not influence the total intensity of line NII $\lambda = 3919.00$ Å. In the vincinity of line NII $\lambda = 5005.10$ Å there lie the lines NII $\lambda = 5007.32$ Å, NII $\lambda = 5002.70$ Å; near the line NII $\lambda = 4607.16$ Å there lies the weak line OII $\lambda = 4609.42$ Å.

The resolving power of the grid spectrograph ZEISS PGS-2, which has been

made use of, and of the photo-multipliers, was so high that it allowed clearly to distinguish the above mentioned spectral lines from one another.

In the case of the lines OII the situation was less favourable, because here it was not possible to use the line OII $\lambda = 4121.48$ Å for temperature calculation, because its profile overlapped the lines OII $\lambda = 4120.55$ Å, OII $\lambda = 4120.27$ Å.

The transition probabilities, respectively the oscillator forces of the lines under investigation, taken over from paper [5], the energies of excitation of the upper energy levels [6], and the statistical weight values, are to be found in Table 1. The energy level scheme of the investigated spectral lines is in Figs. 2, 3.

Table 1

Element	λ [Å]	χ_m [eV]	$10^{-8}\times A_{mn}$ [s^{-1}]	g_m	g_n	f_{nm}	log ($g_n f_{nm}$)
NII	5666.63	20.65	0.423	5	3	0.339	0.008
NII	5535.36	27.71	0.56	9	7	0.334	0.368
NII	5495.70	23.40	0.298	5	5	0.135	−0.171
NII	5179.52	30.37	0.83	9	7	0.429	0.478
NII	5045.10	20.94	0.410	3	5	0.094	−0.328
NII	5005.15	27.95	0.064	5	5	0.0242	−0.92
NII	5005.15	23.13	1.22	9	7	0.588	0.614
NII	4621.39	21.14	0.90	1	3	0.096	−0.54
NII	4613.87	21.14	0.196	3	3	0.063	−0.73
NII	4607.16	21.14	0.340	3	1	0.325	−0.488
NII	4601.48	21.15	0.270	5	3	0.143	−0.368
NII	3995.00	21.59	1.58	5	3	0.63	0.276
NII	3919.00	23.56	1.00	3	3	0.231	−0.160
OII	4941.12	29.06	0.83	4	2	0.61	0.083
OII	4414.91	26.24	1.15	6	4	0.50	0.305
OII	4366.90	25.83	0.50	4	6	0.096	−0.239
OII	4121.48	28.83	0.93	2	2	0.237	−0.324
OII	4085.12	28.68	0.478	6	6	0.120	−0.144
OII	4075.87	28.70	1.98	10	8	0.62	0.69
OII	3973.26	26.50	1.27	4	4	0.300	0.080

The intensity time development of all the spectral lines mentioned was registered in various régimes of the spark discharge electric circuit (See Table 2).

Since for the total intensities of spectral lines there applies

$$I_{total} = \int_{line} I_\lambda \, d\lambda \,, \qquad (2)$$

these (after the elimination of the continuous background and calibration of the apparatus in view of the different spectral sensitivities of photo-multipiers) were determined by the graphic integration method.

The determining of temperature from the relative intensities of the spectral lines of singly ionized nitrogen and oxygen led to two diverse values in the time development on the electron temperature (Fig. 4, 5). Taking into account the lines with the energy differences of the upper levels $\Delta\chi \approx 3$ eV, there was obtained a time development (Fig. 4, curve a), which is in agreement with the time development of the temperature of the spark discharge channel calculated according to the theoretical relation (Fig. 4, 5, curve b), derived by Braginsi[7] (on the assump-

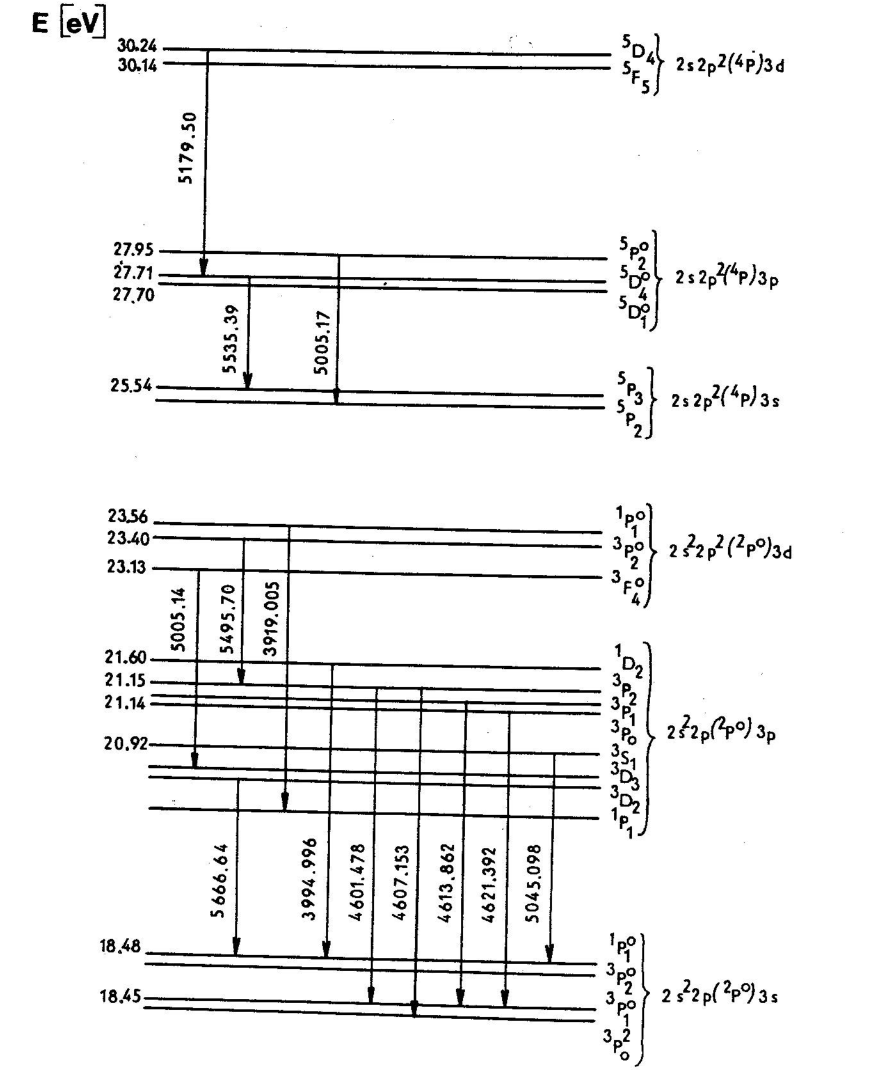

Fig. 2. Schematic energy level diagram of the investigated lines of singly ionized nitrogen NII.

Table 2

Regime	U [kV]	C [pF]	L [mH]
1	8	3000	0.012
2	8	6000	0.012
3	10.6	1500	0.012
4	10.6	3000	0.012
5	10.6	6000	0.012
6	10.6	6000	0.08
7	12	6000	0.012

tion that $T_e = T_a$), according to which $T = \alpha \varrho_0^{1/14}(It^{-3/4})^{2/7}$. ($T$ is stated in eV, I in kA, t in µs, $\alpha = 3.5-4$, ϱ_0 for air $\approx 1.3\times10^{-3}$ gcm^{-3}).

For the lines in which $\Delta\chi \approx 7$ eV a considerably higher electron temperature was obtained (Fig. 5, curve a), which is no more in agreement with the theory cited. And because in the method of determination of temperature from the relative intensities of spectral lines the error in the determined temperatures may attain as high a value as ≈ 30 %, it is relatively difficult to ascertain the origin of this discrepancy.

One of the possible explanations appears to be that in the plasma of the spark

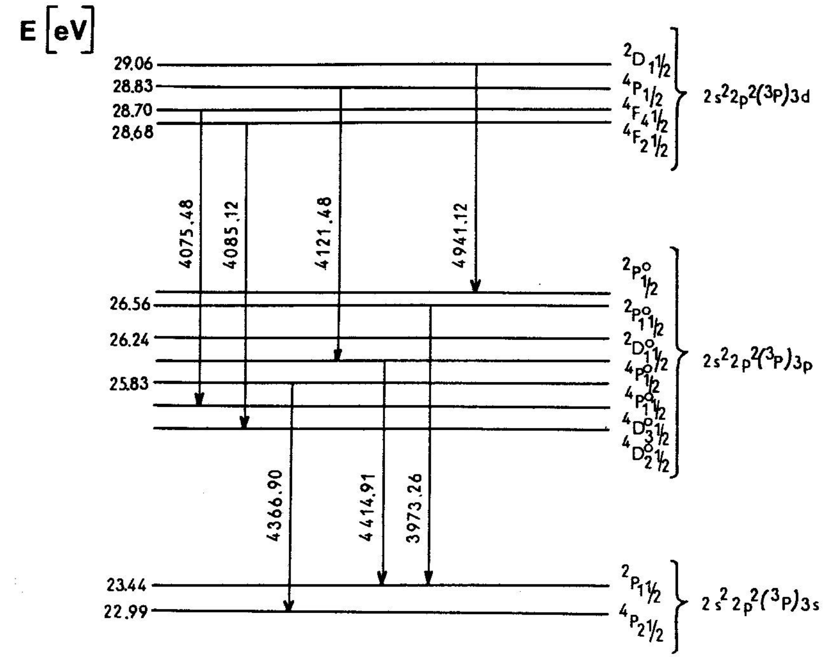

Fig. 3. Schematic energy level diagram of the investigated lines of singly ionized oxygen OII.

discharge originating in air there is in reality no question of a complete LTE, i.e. Boltzmann's law does not describe the population of all the energy levels, and for the determination of the electron temperature, therefore, it is not possible to use any two arbitrary spectral lines. In Rel. (1) for the ratio of intensities, by which, in essence, the electron temperature is stated, only the difference of the energies of the upper energy levels explicitly stands out. It is necessary, however, to take into account that when deriving this relation, a complete LTE, i.e. the validity of Boltzmann's distribution for all levels, the lower levels of transition included, is assumed. And it is just this fact that it is necessary to have in view when selecting suitable spectral lines if the calculation is expected to give a correct value of the electron temperature.

When we compare the results we have obtained with other experimental works in this sphere, one can come to the following conclusions: There are relatively few papers in which the electron temperature in the plasma of a spark discharge originating in air is determined from the lines of nitrogen or oxygen. In most cases there is question of a spark discharge in hydrogen [2, 8, 9], where the existence of

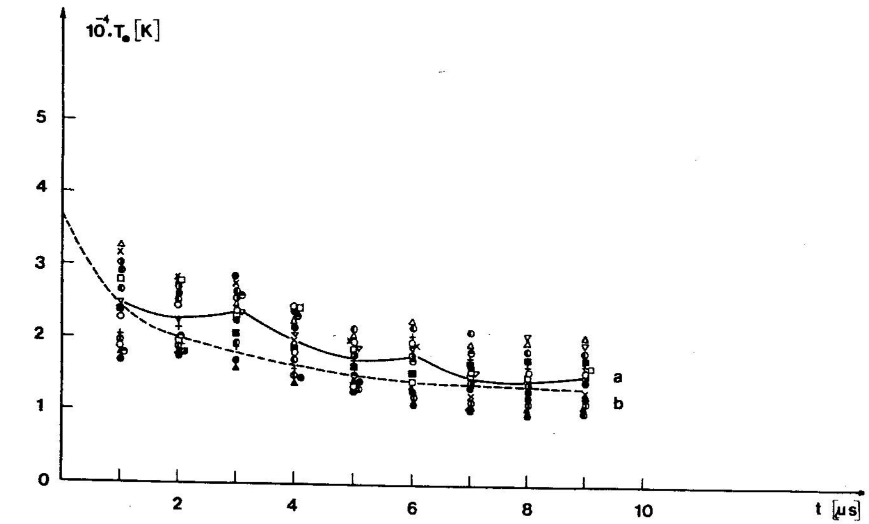

Fig. 4. Time development of the electron temperature in the plasma of the spark discharge originating in air. Curve a) experimentally obtained from the measured relative-intensities of spectral lines of NII, OII, in which the difference of higher level energies $\Delta\chi \approx 3$ eV. o OII 4941 Å/OII 4366 Å, ▲ OII 4941 Å/OII 3973 Å, △ OII 4366 Å/OII 4075 Å, ● OII 3973 Å: OII 4075 Å, ◑ NII 5666 Å/NII 3919 Å,□ NII 5495 Å/NII 4601 Å, ◒ NII 5666 Å/NII 3995 Å, ◓ NII 5495 Å/NII 4621 Å, ● NII 5495 Å: NII 4613 Å, + NII 5495 Å/NII 5005 Å(χ_m=23.13 eV), ▿ NII 5045 Å/NII 3919 Å, ■ NII 4621 Å/NII 3919 Å, ○ NII 4613 Å: NII 3919 Å, × NII 3995 Å/NII 3919 Å, ◐ NII 4601 Å/ /NII 3919 Å. b) From calculation according to [7]. Régime: U=10.6 kV, C=6000 pF, L=0.012 mH.

LTE is not as problematic as it is in that of nitrogen or oxygen, there being a sufficiently high value of electron density in hydrogen plasma to fulfil the criterion of LTE.

On the other hand the time development of the electron temperature in a spark discharge originating in air has been obtained by other authors (for instance [10, 11]) by methods different from the one used in our experiment. In the works mentioned above, the electron temperature had been determined from diverse pairs of spectral lines NII (3—5 pairs), the spectrum of the spark being registered upon a photographic plate without time evaluation. It was evident that the differences in the temperature obtained, calculated from various line pairs, are within the boundaries of incorrectnesses due to the used method. Therefore for the time development of the electron temperature only one line couple had been made use of. (Note: The maximum temperature in the plasma of the channel of the spark discharge burning in air was estimated by some authors [10—12] to have the value $T \approx 25000$ K—40000 K).

In our work, on the other hand, the temperature time development has been performed with all the possible spectral line couples NII, OII enumerated in the

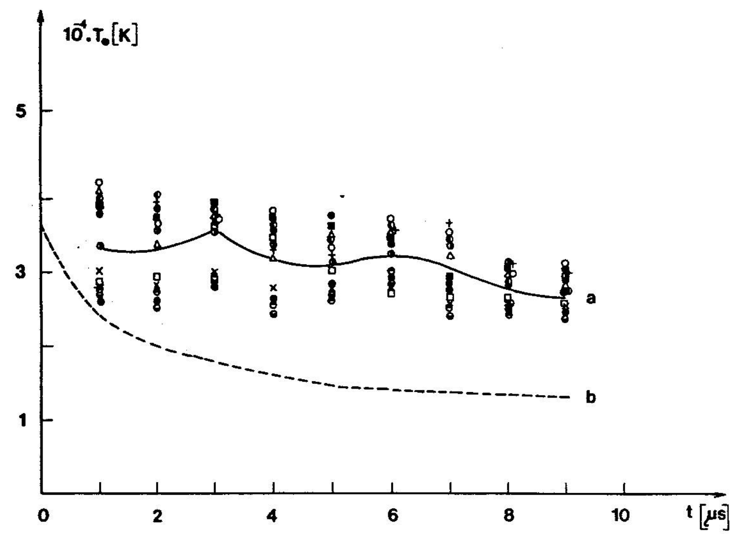

Fig. 5. Time development of the electron temperature in the plasma of the spark discharge originating in air. Curve a) experimentally obtained from the measured relative intensities of spectral lines NII, in which the differences of higher level energies $\Delta\chi \approx 7$ eV. o NII 5535 Å/NII 5045 Å, △ NII 5535 Å: NII 4621 Å, × NII 5666 Å/NII 5005 Å (χ_m = 27.95 eV), ● NII 5535 Å/NII 4613 Å, ◐ NII 5535 Å/NII 4601 Å, ◑ NII 5495 Å: NII 5179 Å, + NII 5179 Å/NII 4621 Å, ⊠ NII 5045 Å/NII 5005 Å × × (χ_m = 27.95 eV), ◓ NII 3995 Å/NII 5005 Å (χ_m = 27.95 eV), ◒ NII 4607 Å/NII 5005 Å (χ_m = = 27.95 eV), □ NII 5179 Å/NII 3919 Å, ■ NII 5179 Å/NII 3995 Å. b) From calculation according to [7]. Regime: U = 10.6 kV, C = 6000 pF, L = 0.012 mH.

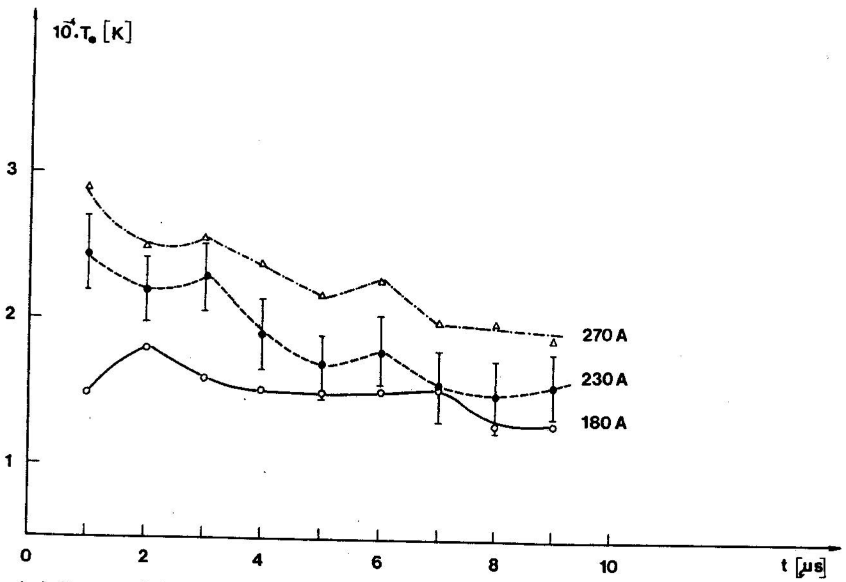

Fig. 6. Influence of the current intensity on the time development of the electron temperature in the spark discharge plasma.

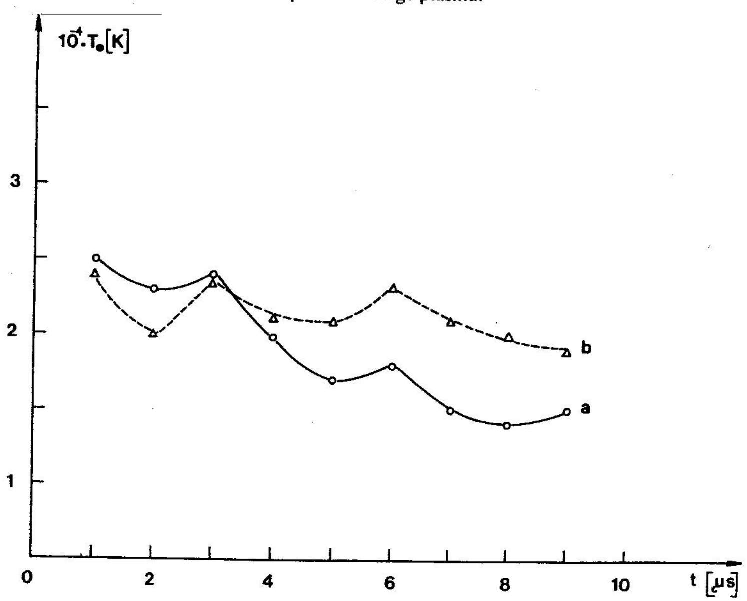

Fig. 7. Dependence of the time development of the electron temperature on the capacity of the outer electric circuit. $U = 10.6$ kV, $L = 0.12$ mH, a) $C = 6000$ pF, b) $C = 3000$ pF.

introduction to this paragraph. The electron temperature value T_e at a given time, has been obtained as an arithmetical average of the results of individual measurements. (See Figs. 4, 5).

In this manner we studied also the influence of the outer electric circuit parameters of the spark (the influences of voltage, current, inductivity and capacity) upon the time development of the electron temperature. The electron temperature was determined from the lines in which the energy differences of the upper levels were $\Delta\chi \sim 3$ eV. The results obtained are illustrated in Figs. 6—8. Even if it is clear at first sight that by a change of the parameters of the outer circuit of the spark the entire character of the spectrum undergoes a change (See Figs. 9—11), in the conformity with papers [11, 13], it is possible to conclude that the change of the parameters of the spark discharge has no essential influence upon the time development of the electron temperature in the later phases of duration of the discharge.

The relative error of the temperature determined from the ratio of the spectral line intensities is

$$\frac{\Delta T_e}{T_e} = \frac{kT_e}{\Delta\chi} \frac{\Delta(I_1/I_2)}{I_1/I_2} \qquad (3)$$

which for a temperature $T_e \approx 25000$ K, $\Delta\chi \approx 3$ eV, and the errors in the determination of intensities ≈ 10 %, gives the value $\approx \pm 2000$ K.

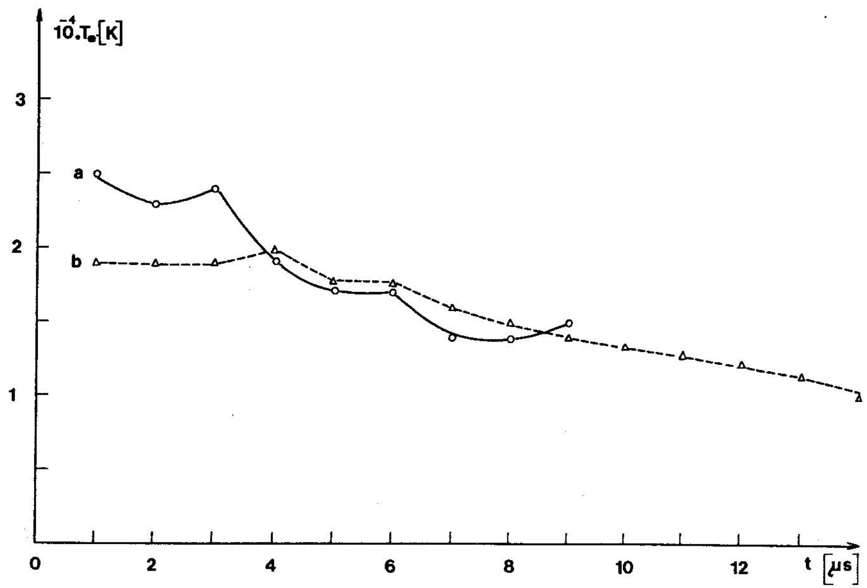

Fig. 8. Influence of the change of induction on the outer electric circuit on the time development of the electron temperature in the spark discharge plasma.

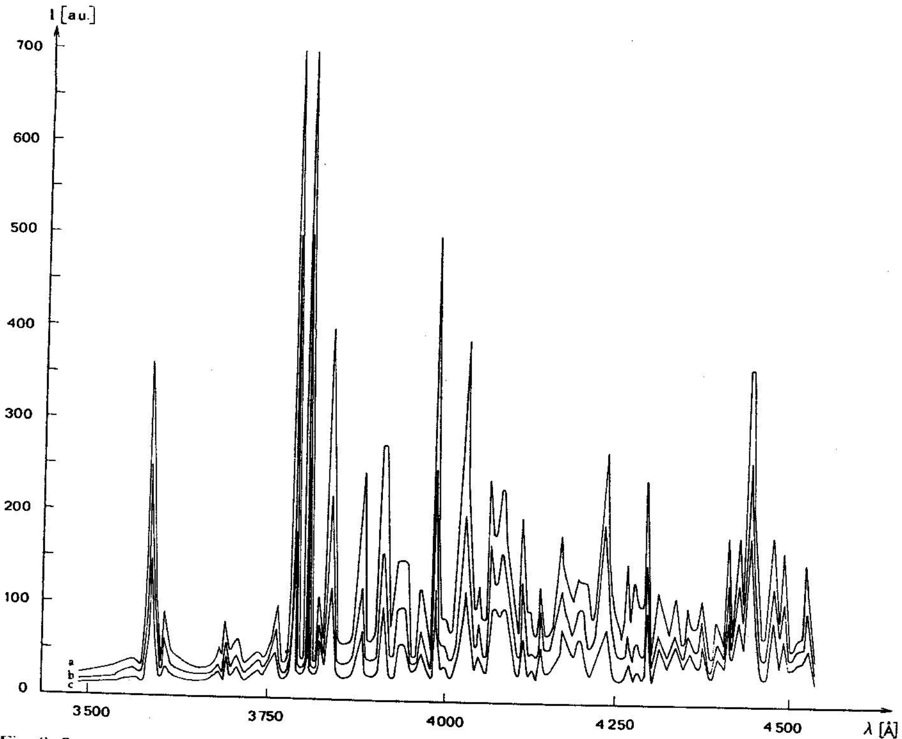

Fig. 9. Spectrum of the spark discharge originating in air at a pressure of 1 atm. registered with the help of photomultipliers at various time phases of discharge. a) $t = 1$ μs, b) $t = 3$ μs, c) $t = 6$ μs. Regime: $U = 10.6$ kV, $C = 6000$ pF, $L = 0.012$ mH.

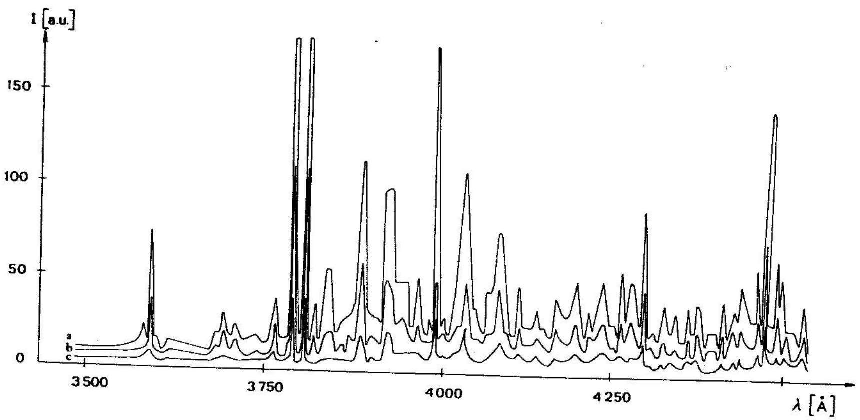

Fig. 10. Spectrum of the spark discharge air at a pressure of 1 atm. registered with the help of photo-multipliers at various time phases of the discharge. a) $t = 1$ μs, b) $t = 3$ μs, c) $t = 6$ μs. Regime: $U = 8$ kV, $L = 0.012$ mH, $C = 6000$ pF.

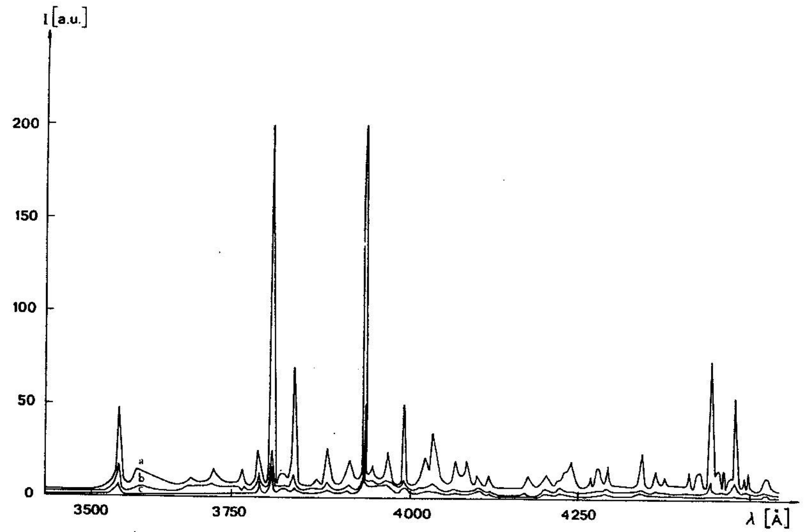

Fig. 11. Spectrum of the spark discharge in air at a pressure of 1 atm. registered with the help of photo-multipliers at various time phases of the spark discharge. a) $t = 1$ μs, b) $t = 3$ μs, c) $t = 6$ μs. Regime: $U = 10.6$ kV, $L = 0.08$ mH, $C = 6000$ pF.

Analogically it is possible to evaluate the error brought into the determined values of the electron temperatures by insufficiently known transition probabilities. With the help of approximative methods it is possible at present to express the transition probabilities with a ≈ 20 % accuracy, which in the determined temperatures represents the value of ≈ 4000 K.

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Received May 27th, 1975