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TIME DEVELOPMENT OF THE PARAMETERS OF EXPLODING WIRE PLASMA1)

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In this paper we present the results of the time development of the parameters of plasma originating from the explosion of copper wire in the air under atmospheric pressure obtained by means of spectroscopic diagnostic methods. We have determined the time development of the optical thickness of the plasma, the density and temperature of the electrons.

ВРЕМЕННАЯ ЗАВИСИМОСТЬ ПАРАМЕТРОВ ПЛАЗМЫ ВЗРЫВАЮЩЕЙСЯ МЕДНОЙ ПРОВОЛОКИ

В данной работе приведены результаты временной зависимости параметров плазмы, источноком которой служит взрыв медной проволоки в воздухе при атмосферном давлении, полученные при помощи методов спектроскопической диагностики. При этом определены временная зависимость оптической толщины плазмы и плотность, а также температура электронов.

I. INTRODUCTION

The plasma of the exploding wire represents a formation in which the parameters vary in time and space very rapidly and as a consequence the character of the plasma emission in each phase of its development varies, too. In the first stage, when the plasma is optically opaque, it is possible to observe an intensive continuum approaching the radiation of an absolutely black body. In the process of the development of the discharge the optical thickness of the plasma declines and the continuum passes into the radiation of the spectral lines. In the last stages of the discharge the plasma is practically thin [1], [2], [3].

Hence we determined from the line spectrum the basic parameters of the plasma of the exploding wire both for the stages of its final optical thickness and for optically thin layers, too.

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II. TEMPERATURE, DENSITY OF ELECTRONS AND OPTICAL THICKNESS OF THE EXPLODING WIRE PLASMA

A character feature of the plasma of a considerable optical thickness is the presence of spectral lines, the profiles of which are deformed as a consequence of the self-absorption of radiation.

In a case of thin sort the method elaborated by Bartels [4], [5] for determining the temperature of the plasma in a state of local thermodynamic equilibrium (LTE) contains in the following the expression of the intensity I_ν at the maximum of the selfreversing spectral line

$$I_\nu = \frac{2h\nu^3}{c^2} e^{-h\nu/kT_m} M Y_{\max}(p). \tag{1}$$

In relation (1) T_m is the maximum temperature in the direction of the observation. The function M describes the degree of nonhomogeneity of the plasma column. According to [4] in the first approximation for the neutral atom and the singly charged ion lines broadened as a result of Stark's effect there applies

$$M = \left(\frac{E_n + \chi_0/2}{E_m + \chi_0/2}\right)^{1/2}, \tag{2}$$

where

$$\frac{kT_m}{E_n + \chi_0/2} \ll 1. \tag{3}$$

In relation (2) and (3) E_n, E_m is the excitation energy of the lower, respectively the upper level of transition, χ_0 is the energy of ionization.

$Y_{\max}(p) = Y_{\max}(\hat{\tau}_0, p)$ corresponds to the maximum value of the function $Y(\tau_0(\nu), p)$ describing the influence of the optical thickness upon the measured intensity

$$Y(\tau_0(\nu), p) = \exp(-\tau_0/2)\{\tau_0(1-p)/2 + p \operatorname{sh}(\tau_0/2) + \\ + 1/\sqrt{p} \operatorname{sh}(\tau_0\sqrt{p/2})\}, \tag{4}$$

where

$$p = \frac{6}{\pi} \operatorname{arc\,tg} \frac{M^2}{(1+2M^2)^{1/2}}. \tag{5}$$

$\hat{\tau}_0$ is the optical thickness in the maximum of the self-reversed line.

The time development of the profiles of the spectral lines proved that the lines in the initial stages of the discharge are self-reversed. For the determination of temperature in these phases expression (1) has been used. In our experiments we did not have intensity standards with a sufficiently high temperature which would have enabled us to determine the absolute value of the intensity of the spectral line. Therefore we made use of the fact that in the LTE plasma the temperature determined from all the spectral lines should be the same. We applied relation (1) to two spectral lines and from the ratio of their intensities we determined the temperature

$$T = \frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2} \frac{hc}{k} \frac{1}{\ln \dfrac{I_1\lambda_1^3(MY_{\max})_2}{I_2\lambda_2^3(MY_{\max})_1}}, \tag{6}$$

where λ_1, λ_2 are the wave lengths of the spectral lines studied, I_1, I_2 the maximum intensities.

The values of function M and $Y_{\max}$ have been determined from relations (2) and (4) and for the investigated lines Cu I are shown in Table 1.

Table 1

λ [nm]	M	p	$Y_{\max}$	$\hat{\tau}_0$
501.661	0.890	0.784	0.92	3.6
510.554	0.827	0.799	0.90	3.6
570.021	0.847	0.823	0.90	3.6
578.213	0.848	0.824	0.90	3.6

In the later time-phase, where the spectral lines did not manifest any self-reversal and where the optical thickness was small for the determination of the temperature of the plasma, we made use of relation (7) — assuming the existence of LTE — shown in [6].

$$T = \frac{E_1 - E_2}{k \ln \dfrac{g_1 f_1 I_2 \lambda_2^3}{g_2 f_2 I_1 \lambda_1^3}} \tag{7}$$

where E_1 and E_2 are the excitation energies of the upper levels of transitions; g_1, g_2 the corresponding statistical weights; f_1, f_2 the oscillator strengths.

The values of g, f are from papers [3], [7]. The presence of LTE in the plasma of the exploding Cu wire in the air was verified in [8].

The density of electrons in each time phase has been determined on the basis of the well-known Stark's constants C_4 from the relation shown in [9]

$$\gamma = 11.37 C_4^{2/3} v^{1/3} N_e, \tag{9}$$

where $\gamma = 2\pi\Delta\nu$ and $\Delta\nu$ is the width of the line at half intensity (in s^{-1}), v the

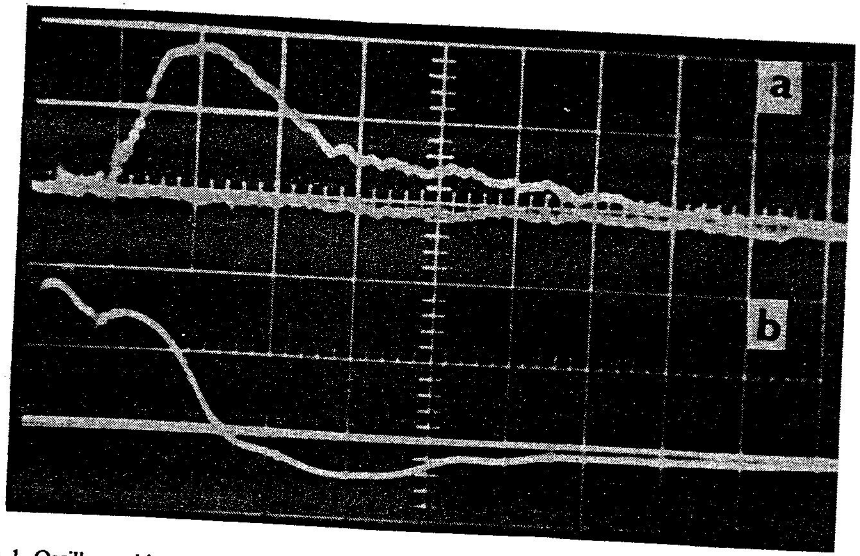

Fig. 1. Oscillographic record from the photomultiplier a) intensity of radiation in the spectral line, b) current passing through the exploding wire — reference signal (Basic time 20 μs/cm).

relative velocity of interacting particles. The value of the constant C_4 has been taken from [10].

From the course of the dependence of the optical thickness upon the distances from the centre of the line obtained by graphical methods [4], [5] from the function $Y(\tau_0(\nu), p)$ and/or by an equivalent numerical method we obtained the value of the optical thickness of the far-distant part of the profiles of spectral lines, which practically corresponds to the thickness in the continuum.

III. EXPERIMENTAL RESULTS AND DISCUSSION

We reproduced the time development of the exploding Cu wire plasma spectra (the length of the wire $l = 4.2 \times 10^{-2}$ m and diameter $\Phi = 2.5 \times 10^{-4}$ m) by means of a three-prism spectrograph ISP-51 with a camera UF-90, a lightguide and photomultiplier with a double-beam oscilloscope. The explosion of the wire was realized in the air at atmospheric pressure. The apparatus used is described in detail in [8], [11]. From the oscillographic records (Fig. 1) the time dependencies of the profiles of the spectral lines Cu I with wave lengths $\lambda = 578.2$ nm, $\lambda = 570.0$ nm, $\lambda = 510.6$ nm, $\lambda = 501.7$ nm, $\lambda = 448.0$ nm have been compiled.

The profiles obtained showed that the spectral lines in the initial stages manifest self-reversal due to a great optical thickness in the centre of the line ($\tau_0 \approx 15$); in the later phases the profiles of the lines do not show any deformation at all. (The typical course is shown in Fig. 2). Exceptions being line $\lambda = 510.6$ nm which shows a self-reversal during the entire time of the duration of the discharge and line $\lambda = 448.0$ nm which manifests no phenomenon of this kind whatsoever. The fact that in this latter case we do not observe any self-absorption can be due to the errors in the measurement of the intensity. These errors are caused by the low intensity of the said line when compared with the continuous background of the initial stages of the discharge.

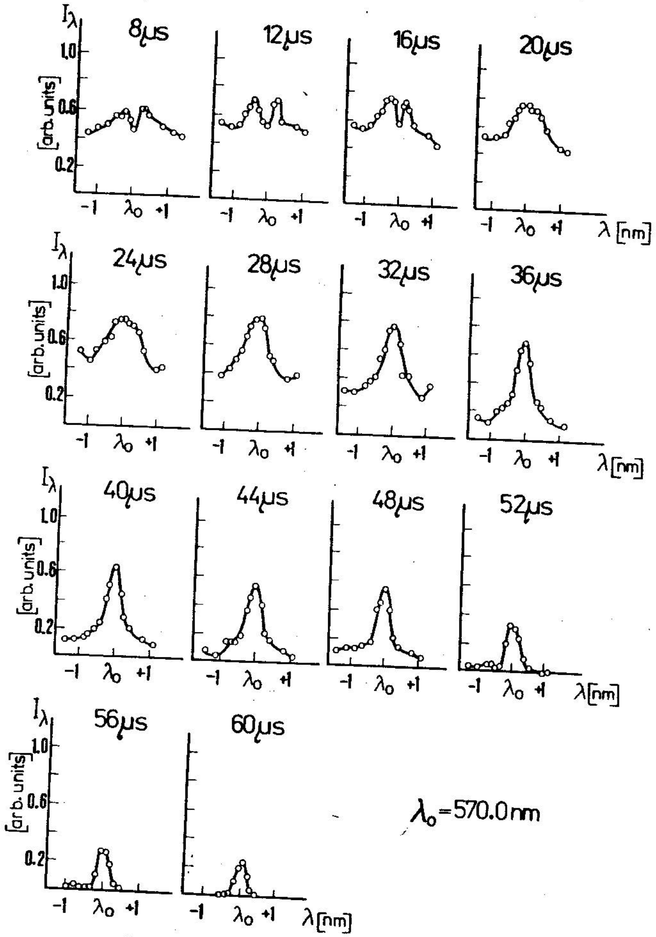

Fig. 2. Time development of the spectral line profile $\lambda = 570.0$ nm.

The time dependencies of the temperature, the density of the electrons and the optical thickness of the continuum are set forth in Fig. 3.

When comparing the individual parameters of the plasma in Fig. 3 with the course of the current, we come to the following conclusions: — during the first 20 μs the current is high and presents a quasi-stationary regime; — the maxima of the temperature and of the density of the electrons occur simultaneously; — the optical thickness of the continuum during the first 20 μs preserves its constant value $\tau_c = 0.9$.

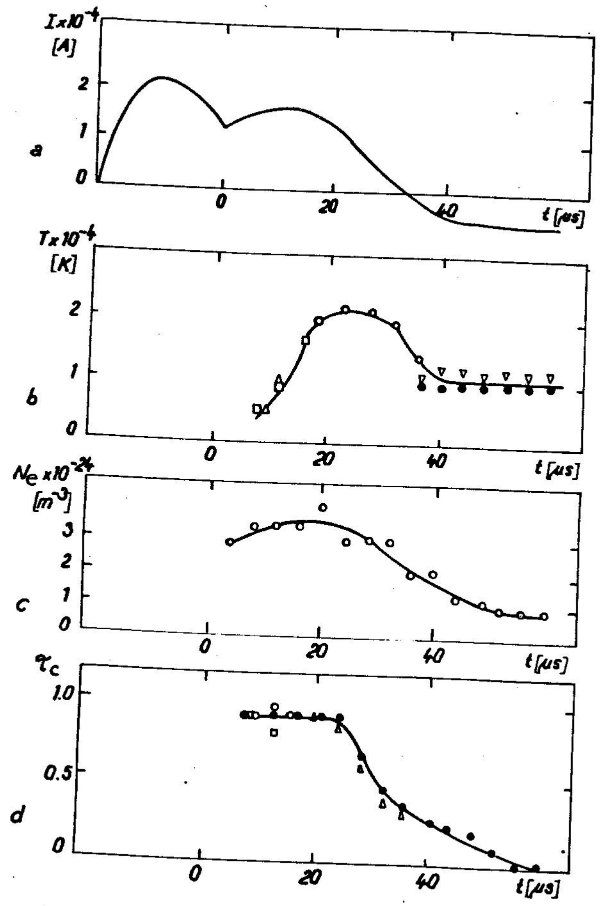

Fig. 3. Dependence of a) current, b) temperature, c) density of electrons, d) optical thickness of continuum on time. Time $t = 0$ at the moment of breakdown (i.e. current minima).

In the further stage there follows a rapid decrease of the current which testifies to a considerable drop in the supply of energy to the discharge. The dense plasma formation decays and it manifests itself in the decrease of the values of the plasma parameters. The fact that the decrease in temperature and concentration later ceases (at about 40 μs) is caused by the reincrease of the current in the second half-period.

The error in the determination of temperature and the electron densities in the intervale 0—20 μs is relatively high ≈50 %, due to the uncertainty in the small differencies of the intensities. Later the error decreases to 20 %. The error in the determination of the optical thickness of the background is 10—20 %. It is necessary to remark that the electron density is determined from single independently formed lines out of the lines of Cu, where Stark's constants are known ($\lambda = 448.0$ nm).

The temperature and electron density values obtained experimentally were in good agreement with paper [1] (Ag-wire, $T_e = 3 \times 10^4$ K, $N_e = 4 - 0.5 \times 10^{24}$ m^{-3}). In paper [3] the time-space development of the temperature and density of the electrons of the Cu and Mg wires is given. As the authors did not have the values of Stark's constants for the Cu lines, the density of the electrons had been determined from the lines of Mg. The results concerning temperature were, however, higher, (up to 6×10^4 K). The density of the electrons was determined for the later stages of the discharge only ($t > 60$ μs the length of the first halfperiod being 60 μs) and the values obtained were found to be lower than $N_e \approx 4 \times 10^{23}$ m^{-3}.

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