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Invited lecture

ON THE ELECTRON TEMPERATURE MEASUREMENTS IN A MEDIUM ELECTRON DENSITY PLASMAS

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Abstract – This paper reports the results of the spectroscopic electron temperature (T_e) measurements in plasmas with electron densities ranging $(0.3 - 1.4)\cdot 10^{17}$ cm^{-3}. The results of T_e measurements obtained from various spectroscopic methods are mutually compared and discussed in relation to the condition for partial local thermodynamic equilibrium (PLTE). For the cases when the application of the spectroscopic techniques for T_e measurements can not be justified on the bases of PLTE criterion, new method for determination of plasma electron temperature is proposed and tested.

Measurements of plasma parameters, electron temperature and electron density were performed in a low pressure pulsed arc in helium and argon with small admixture of nitrogen or oxygen whose ions were used as thermometric species. The electron densities were determined from the width of the He II P_α 468.6 nm line.

1. INTRODUCTION

The plasma electron temperature T_e is one of the most important parameters used for plasma modeling, in opacity calculations, plasma line broadening studies etc. The most popular nonperturbative spectroscopic techniques for T_e determination involve absolute and/or relative line intensity measurements. The plasma electron temperature determined in this way is sometimes referred as an excitation temperature. If one excludes corona equilibrium from further considerations, the common for all line-intensity spectroscopic techniques is requirement of thermal equilibrium i.e. the Boltzmann distribution of the population of energy levels involved in the procedure of T_e measurements. Since most of laboratory plasmas are not in complete thermodynamic equilibrium the Boltzmann distribution of energy levels population is achieved only above certain energy level whose principal quantum number depends upon electron density, spectroscopic charge number Z and the electron temperature, see e.g. Griem, 1964; 1997; Stokes, 1971. Here, we exclude from further considerations the influence of strong gradients and fast time changing plasmas, see Griem, 1964; 1997.

In many cases when T_e measurements have to be performed it is difficult to select spectral lines in the accessible spectral region, which originate from the energy levels populated in accordance with the Boltzmann distribution. In addition, for these lines reliable atomic data should be available. All these requirements frequently limit the applications of spectroscopic methods fur T_e measurements.

In this paper the method for plasma electron temperature measurement using spectral lines originating from the energy levels not fulfilling PLTE criterion is described. This method is applied and tested for temperature measurements in a plasma of a low pressure pulsed arc in helium.

2. DESCRIPTION OF THE METHOD

The validity criteria for PLTE and consequently determination of the conditions for application spectroscopic methods for T_e measurements are extensively discussed by Griem, 1964; 1997 and Drawin, 1975. Simple formula (Griem, 1964) derived for the steady state plasma (applicable also to slow time varying plasmas) may be used to estimate the importance of emitter characteristics for estimation of PLTE criterion

$$N_e \geq 7\times10^{18}\frac{Z^6}{n^{17/2}}\sqrt{\frac{kT_e}{E_H}} \tag{1}$$

where N_e is plasma electron density in cm^{-3} units, Z - spectroscopic ion charge, n - principal quantum number, T_e plasma electron temperature and E_H – hydrogen ionization energy. Although the fulfillment of above PLTE criterion is essential for the application of spectroscopic techniques and this was discussed in many plasma spectroscopy textbooks, see e.g. Griem, 1964; 1997; Drawin, 1975; Lochte-Holtgreven, 1968, some authors measure T_e assuming but not proving fulfillment of PLTE criterion.

Whenever spectral lines of consecutive stages of ionization of a single element in plasma spectrum appear several spectroscopic methods may be used to determine T_e. Apart from the Boltzmann plot of relative line intensities for each ionization stage, the lines of two consecutive stages of ionization may be used for T_e measurements also. To apply this method one has to measure plasma electron density and the ionization equilibrium is required. For more details see Griem, 1964; 1997.

In the cases when, according to PLTE criterion, Eq. (1), none of the discussed spectroscopic techniques may be applied, we propose method which may be used for T_e determination from the results of standard spectroscopic methods applied to non-PLTE conditions. The proposed method requires at least two T_e measurements from the spectral lines belonging to two consecutive ionization stages of the same element. Since PLTE criterion, Eq. (1) is not fulfilled measured electron temperatures are erroneous. The difference from the correct T_e is related to the deviation from the criterion expressed by Eq. (1). So in this case incorrect T_e values can be used in an extrapolation procedure to derive correct (or true) plasma T_e^c using linear fit through ($\ln(N_e^c/N_e)$, $\ln T_e$) points or exponential fit through ($\ln(N_e^c/N_e)$, T_e) points where N_e^c is calculated from Eq.(1). Thus the extrapolated value T_e^c is obtained for $\ln(N_e^c/N_e)=0$. Each N_e^c comes out from the condition of the fulfillment of PLTE criterion. Eq. (1), for appropriate T_e, N_e, Z and n. Therefore the proposed procedure for T_e^c determination requires independent N_e measurements. An illustration of the described method for T_e^c determination is presented in Fig. 1.

Furthermore the whole procedure may be iterated by using $T_e^{c,\,1}$ obtained in the first step into the system of equations (1), to calculate new N_e^c values which are further used to evaluate new set of ($\ln(N_e^c/N_e)$, $\ln T_e$) data points. The extrapolation of this new set of points gives $T_e^{c,\,2}$ value and so on. The iterations can be repeated until required precision of the iterative method is achieved. In our case the temperatures T_e^c obtained from the first and the last iterations differ no more than 3%.

Here, we draw attention to an important assumption made by applying spectroscopic methods for non-LTE conditions. Namely only Boltzmann distribution of energy levels population gives straight line of the Boltzmann plot. Numerous experimental measurements performed within this experiment showed for non-LTE conditions that Boltzmann plots may be, within experimental uncertainty, approximated with the straight line. So we assumed that, if energy levels are overpopulated or underpopulated in comparison with LTE distribution, they still have an analytical form of the Boltzmann distribution. This assumption will be further discussed in relation to the experimental results.

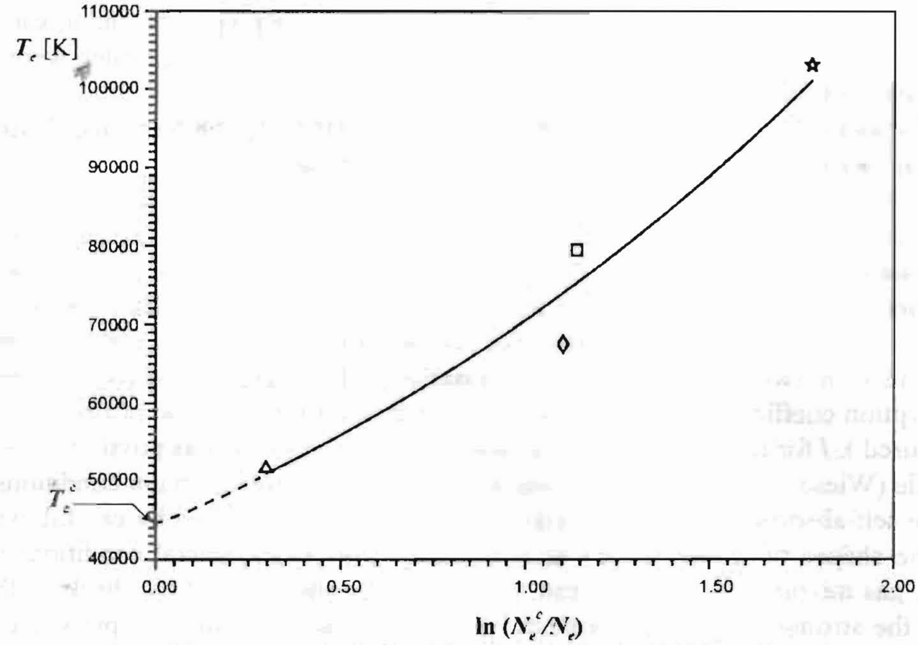

Figure 1. Sample of the extrapolation fit through (ln(N_e^c/N_e), T_e) points gives T_e^c=44360 K for ln(N_e^c/N_e)=0. Four (ln(N_e^c/N_e), T_e) points on this plot are calculated from relative intensities of O III lines (Δ), O III and O IV lines (◊), O IV lines (□), O IV and O V lines (☆), radiated from helium-oxygen plasma for t=6 μs, see Figure 4.

3. EXPERIMENT

The light source was a low pressure pulsed arc with quartz discharge tube 10 mm internal diameter. The distance between aluminum electrodes was 161 mm and 3 mm diameter holes were located at the center of both electrodes to allow end-on plasma observations. The central part around the pulsed arc axis was imaged 1 : 1 onto the entrance slit of the 1 m monochromator by means of the concave 1 m focal length, focusing mirror. A 30 mm diaphragm placed in front of the focusing mirror ensures that light comes from the narrow cone about the arc axis, see Fig.2. The monochromator with inverse linear dispersion 0.833 nm/mm in the first order of the diffraction grating was equipped with the photomultiplier tube (PMT) and a stepping motor. Signals from the PMT were led to a digital storage oscilloscope, which was triggered by the voltage pulse from the Rogowski coil induced by the current pulse through the discharge tube. The experiments are performed in He-N_2, He-O_2, Ar-N_2 and Ar-O_2 gas mixtures. The discharge in the experiments was driven by a 15.2 μF low inductance capacitor charged to 3 kV (14.5 kA peak current) and fired by an ignitron. Greatest care was taken to find the optimum conditions with the negligible line self-absorption. The ratios N_2 : He = N_2 : Ar = 2 : 98 and O_2 : He = O_2 : Ar = 1 : 99 were determined after a number of experiments in which N_2 and O_2 were diluted gradually until strong spectral line intensities of N and O ions were found proportional to the concentration of N_2 and O_2 in the gas mixture. During the spectral line recording continuous flow of gas mixture was maintained at a pressure of about 3 Torr. The stepping motor and oscilloscope were controlled by a personal computer, which was also used for data acquisition. Recordings of spectral line shapes were performed shot by shot. At each wavelength position of the monochromator the digital oscilloscope recorded time evolution and decay of the plasma radiation. Eight such signals were averaged at each wavelength. To construct the line profiles these averaged signals at different wavelengths and at various times of the plasma existence were used. In all experiments spectral line profiles were recorded with the instrumental half widths of 0.0168 nm.

For electron density measurements width of the He II P_α 468.6 nm line (Büscher et al, 1996) was used. Our main concern in the electron-density measurements was a possible presence of self-absorption of the He II P_α line, which may distort the line profile. This would result in erroneous reading of the line width, which would introduce an error in the electron-density measurements. In order to determine the optical thickness of the investigated lines we have introduced in the discharge an additional movable electrode (Kobilarov et al, 1981). By placing the movable electrode (10 mm thick) at two different positions and by recording the line profiles from two plasma lengths, it is possible to determine $k_\lambda l$, where k_λ is the spectral line absorption coefficient and l is the plasma length along the direction of observation. Since the measured $k_\lambda l$ for the He II P_α line was always smaller than 1 it was possible to recover the line profile (Wiese, 1965). Great care was also taken to find the optimum conditions with the negligible self-absorption of the investigated lines. This was achieved by careful examination of the line shapes of N and O ions as a function of the experimental conditions (total gas pressure, gas mixture composition, and capacitor bank energy), and by checking the optical depth of the strongest lines by measuring the intensity ratios within multiplets, see Konjević and Wiese, 1976, and comparing them with theoretical predictions (Wiese et al, 1996).

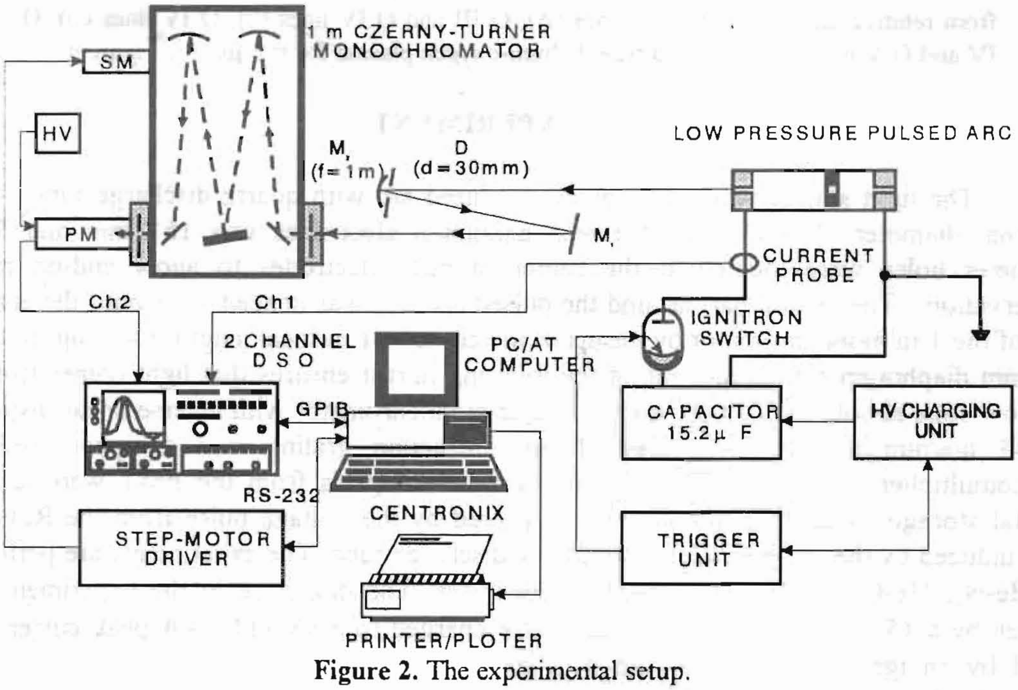

Figure 2. The experimental setup.

The axial electron temperatures were determined in He-N$_2$ mixture from the Boltzmann plots of the relative intensities of: N II 399.500, 463.054, 444.703, 480.329 nm; N III 409.736, 410.339, 463.413, 464.064 nm; N IV 347.872, 348.300, 374.754, 405.776 nm; also from the relative intensities of two lines: N II 463.054

and N III 409.736 nm; N III 409.736 and N IV 405.776 nm; N IV 405.776 and N V 460.374 nm.

The axial electron temperatures were determined in He-O_2 mixture from the Boltzmann plots of the relative intensities of: O III 375.470, 375.988, 370.727, 371.509 nm; O IV 306.343, 307.160, 340.123, 341.169 nm; also from the relative intensities of two lines: O III 375.988 and O IV 341.169 nm; O IV 341.169 and O V 278.699 nm.

Transition probabilities and other atomic data, needed for determination of plasma electron temperatures were taken from Wiese et al, 1996.

The spectral response of the photomultiplier-monochromator system was calibrated against a standard coiled-coil quartz iodine lamp.

4. RESULTS AND DISCUSSION

Helium-nitrogen plasma

As a consequence of relatively low plasma electron density in our experiment, only electron temperatures evaluated from N II lines were derived under condition described by expression (1). All other T_e measured from the lines of higher ionization stages of nitrogen were determined without PLTE criterion, Eq.(1) fulfilled so they are incorrect. The electron temperatures evaluated from the Boltzmann plot of N III lines, see Fig.3, are the closest to the correct value, T_e^c , because N_e is only about 50% smaller than the one estimated from Eq.(1). Other electron temperatures derived from the lines of higher nitrogen ions show larger deviation from T_e^c. This is in qualitative agreement with Z dependence of the Eq.(1). The results in Fig.3 show that the overestimation of the correct plasma electron temperatures is proportional to the deviation from the PLTE criterion. The dashed curve in Fig.3 represents T_e^c values calculated by the extrapolation method interpolated by qubic spline. There is good agreement between T_e^c values (dashed curve in Fig.3) and plasma electron temperatures derived from the Boltzmann plot of N II lines.

Helium-oxygen plasma

The helium-oxygen experiment was performed under same discharge conditions as the preceding one (see 3. Experiment). The results are presented in Fig.4. Unfortunately, PLTE criterion, Eq.(1), is not fulfilled for any observed transition of O III, O IV and O V used for temperature measurements. By applying the extrapolation method plasma electron temperature, T_e^c, was determined (see also example in Fig.1) and presented as a dashed curve in Fig.4. As one would expect for the same discharge conditions used in both experiments the part of T_e^c curve, which describes plasma electron temperature decay, see Fig.4, looks like an extension of T_e^c curve in helium-nitrogen mixture, see Fig.3.

From the comparison of T_e obtained using different ions of a single element as thermometric species, see Figs.1, 3, 4, it is interesting to notice that measured T_e from one ionization stage to another differs less than one would expect from the

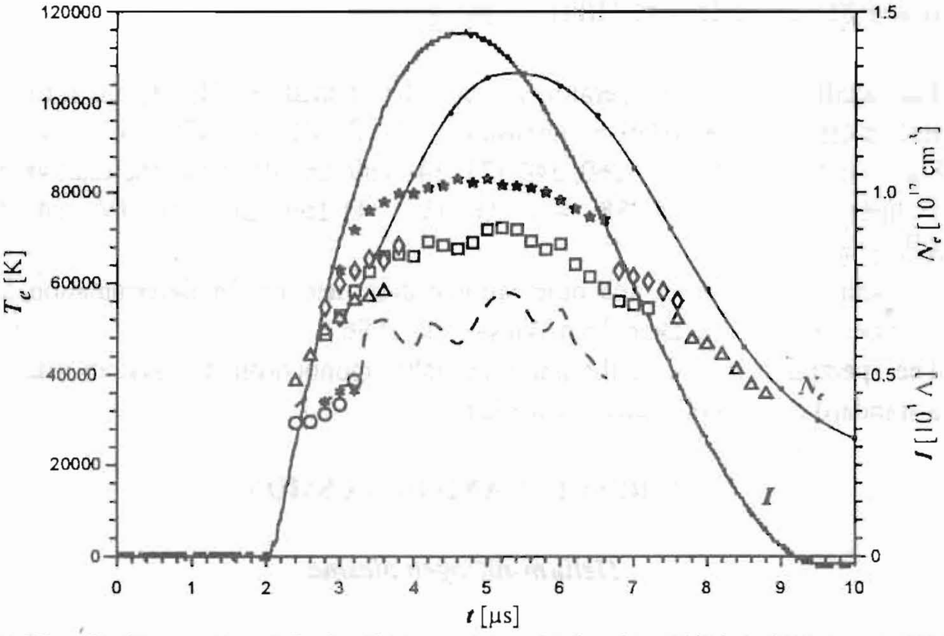

Figure 3. The discharge current I, the electron concentration N_e and the electron temperatures T_e measured from the relative intensities of nitrogen ion spectral lines in helium-nitrogen plasma experiment: N II lines (O), N II and N III (✱), N III lines (Δ), N III and N IV lines (◊), N IV lines (□), N IV and N V lines (☆). Dashed curve presents T_e^c values calculated by the extrapolation method and interpolated by qubic spline.

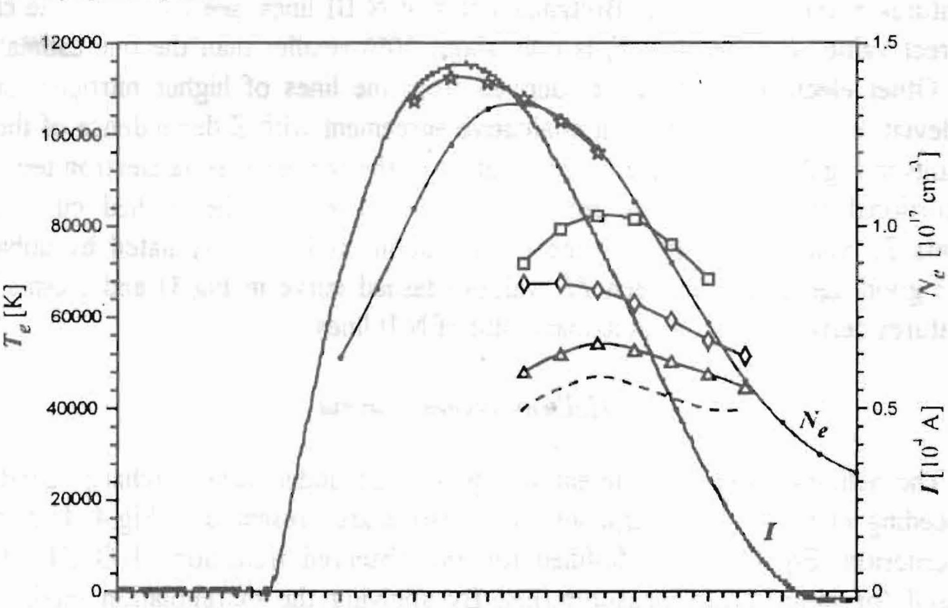

Figure 4. The discharge current I, the electron concentration N_e and the electron temperatures T_e measured from the relative intensities of oxygen ion spectral lines in helium-oxygen plasma experiment: O III lines (Δ), O III and O IV lines (◊), O IV lines (□), O IV and O V lines (☆). Dashed curve presents T_e^c values calculated by the extrapolation method and interpolated by qubic spline.

corresponding change of PLTE N_e evaluated from Eq.(1). Here one should mention that all lines taken for T_e measurements are from n = 3 (3s-3p and 3p-3d transitions). Another interesting result is a good agreement (approximately within 10%) between temperatures obtained from the lines of two consecutive stages of ionization and from the Boltzmann plot of the lines from upper ionization stage. For both methods N_e^c values in Figs.1, 3, 4 are calculated from Eq.(1) using same Z and n. This result suggests that the criterion for application of two ionization stages method for T_e measurements should be relaxed.

Finally one can notice in both experiments, see Figs.1, 3, 4 that whenever PLTE criterion is not fulfilled measured plasma T_e is always higher than correct value. T_e^c. This may be explained by overpopulation of the energy levels involved in T_e measurements.

Argon-nitrogen and argon-oxygen plasmas

The argon-nitrogen and argon-oxygen experiments were performed under the same discharge conditions as the helium-nitrogen and helium-oxygen experiments respectively. Only difference is that helium is replaced by argon in gas mixtures. The results are presented in Figs.5 and 6. Relative intensities of singly and doubly ionized nitrogen and oxygen are detected only. Self-absorption of recorded nitrogen line shapes are detected in region 3-9 [μs] in the argon-nitrogen experiment (see Fig.5). In the argon-oxygen experiment, self-absorption of oxygen line shapes was present in region 7-8 [μs] (see Fig.6). Plasma electron temperatures, determined by using the methods of relative line intensities, obtained from self-absorbed line intensities are incorrect in above mentioned time regions. Transition from region of self-absorption to region without self-absorption is characterized by changing the T_e trend, see 9[μs] on Fig.5 and 8 [μs] on Fig.6. New method for determination of plasma electron temperature was not applied in these two experiments, because the T_e obtained by using methods of relative intensities which not fulfilled PLTE criterion are close to true T_e obtained from Boltzmann plots of N II (9-10 [μs]) and O II (8-10 [μs]) lines which satisfied PLTE criterion.

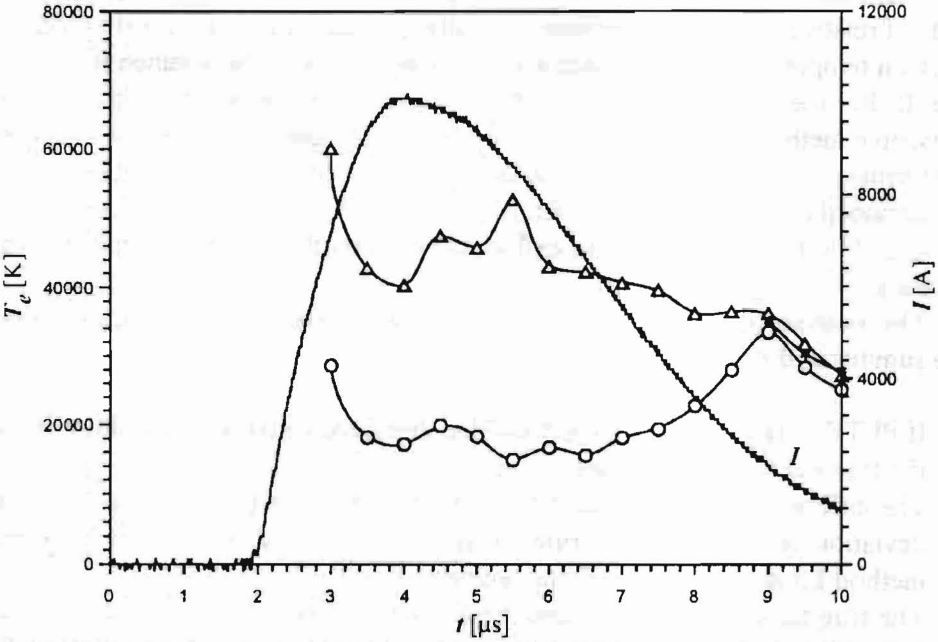

Figure 5. The discharge current I, the electron temperatures T_e measured from the relative intensities of nitrogen ion spectral lines in argon-nitrogen plasma experiment: N II lines (O), N II and N III (✱), N III lines (Δ).

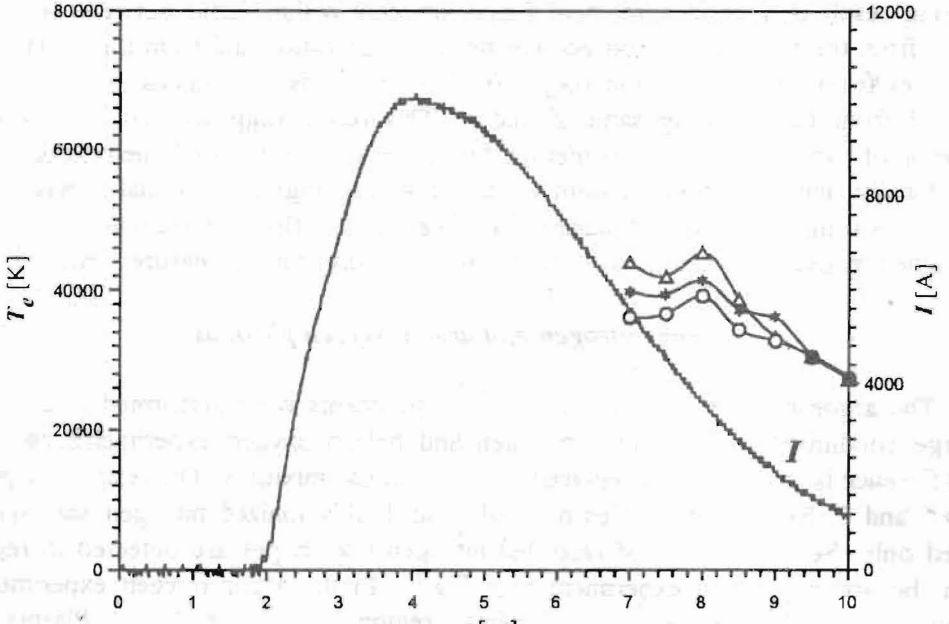

Figure 6. The discharge current I, the electron temperatures T_e measured from the relative intensities of nitrogen ion spectral lines in argon-oxygen plasma experiment: O II lines (O), O II and O III (∗), O III lines (Δ).

5. SUMMARY

The medium electron density plasma generated in a low pressure pulsed arc in helium with admixtures of nitrogen and oxygen was used to demonstrate the possibility of proposed extrapolation method for plasma electron temperature T_e^c measurements. The spectroscopic methods of relative spectral line intensities of nitrogen and oxygen ions were used to measure the electron temperature T_e. The plasma electron density, N_e, is determined from the width of the He II P_α line. According to the PLTE criterion expressed by Eq.(1) none of the spectroscopic methods can be used with the lines of nitrogen or oxygen ions for temperature measurements). The only exception was the Boltzmann plot technique applied to N II lines. It was demonstrated however, that temperatures obtained without fulfillment of the PLTE criterion, Eq.(1) may be used with an extrapolation method to determine true plasma electron temperature.

The analysis of the results of systematic plasma electron temperature measurements may be summarized as follows:

I. If PLTE criterion, Eq.(1), is not fulfilled measured electron temperature is higher than the true electron temperature.

II. The difference between measured and true electron temperature is proportional to the deviation from PLTE criterion. This proportionality is used in an extrapolation method for determination of true temperature.

III. The true temperature determined from the PLTE Boltzmann plot of spectral lines of ion with the charge Z is lower than the temperature of $Z+1$ ion derived from non-PLTE Boltzmann plot for about 20%. If the method of two subsequent stages of ionization is used difference between true and measured temperatures applied to the same pair of ions is smaller for about 10%. These two factors may be applied to any other consecutive ionization stages to predict approximate overestimation of the true temperature. It is necessary only to estimate the ionization stage with fulfilled PLTE criterion for unchanged principal quantum number *n*.

At the end one should mention that the preceding conclusions are derived from the data obtained in a limited range of electron densities and temperatures and therefore any extrapolation outside of this range of plasma parameters should be done with great precautions. Similar experiments at different plasma conditions would be very desirable.

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