Determination of spatially-resolved electron temperature in nanosecond pulsed longitudinal discharges

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Abstract. Using the results for the time- and spatially-averaged electron temperature, which were previously obtained by the line-ratio method of optical emission spectroscopy for several metal halide vapour lasers excited in nanosecond pulsed longitudinal discharge and analytically solving steady-state heat conduction equation for electrons as well, radial distribution of electron temperature, i.e. spatially-resolved electron temperature, is obtained.

Keywords: gas discharge, heat conduction, gas temperature, electron temperature, optical emission spectroscopy.

1. Introduction

One of the main fundamental and relevant problems in plasma physics is the determination of main plasma parameters, namely gas and electron temperatures, electron density, etc. It is very important for gas-discharge laser physics, gaseous discharges, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy and plasma in general. Electron temperature determines thoroughly the characteristics constants for elastic and inelastic electron-atom and electron-ion collisions, as well as three-body electron-ion recombination [1-4]. In particular for gas discharge lasers the electron temperature directly influences on the formation of the inversion population with the abovementioned processes or indirectly through heavy particles’ interaction, such as asymmetric charge transfer, Penning ionization, etc. Widely applied methods for the electron temperature measurement include the use of a Langmuir probe and laser Thomson scattering, which are inapplicable to nanosecond pulsed longitudinal discharges (NPLDs) used in our experiments. In the literature there are several models, which predict, among the other parameters, values of electron temperature with considerable variation, and furthermore there is no overlap [1-6].

Under conditions of Local Thermodynamic Equilibrium (LTE) measurement of relative intensities of some He and Ne spectral lines, originating from different upper levels, enabled us to experimentally...
determine the electron temperature, which was spatially- and time-averaged in a NPLD in He, Ne and Ne-He mixtures, because spatial- and time-averaged relative intensities were measured [7-9]. Though the experimentally determined electron temperature was averaged over the time, our results, which were well accepted in gas-discharge plasma society, established line-ratio method in our research activity as a powerful source of knowledge, confirmed its applicability for NPLDs and suggested its further development and refinement. Unfortunately, time-resolved spectral investigation through devices equipped with photomultiplier are prohibited for the discharge period of NPLDs, because of the noise from high-power electrical pulses and the steep rise of voltage and current pulses of TV.s\(^{-1}\) and GA.s\(^{-1}\). For the discharge period, i.e. electrical power pulse period, spectral signal and noise were definitely equal, i.e. the signal remained the same using shutter in front of the spectrometer slit. That is why time-resolved electron temperature was determined in NPLD for the afterglow period only [9]. Average values of the electron temperature were also found for the afterglow period by mathematically averaging the time-resolved electron temperature over the time [9].

Unfortunately, despite the tremendous efforts, determination of radial electron temperature distribution, i.e. spatially-resolved electron temperature, encounters some insuperable obstacles for NPLDs because of the low signal and unavoidable excessive noise from the photomultiplier, i.e. low signal-noise ratio. Assuming that the electron temperature varies only in the radial direction and using the experimental results obtained for the time- and spatially-averaged electron temperature, a simple method based on analytical solution of the steady-state heat conduction equation for electrons is presented in this paper for uniform and non-uniform power input.

2. Experimental setup

Schematic diagrams of the two used discharge tubes, which are typical for the deep ultraviolet (DUV) Cu⁺ Ne-CuBr laser and the middle infrared (MIR) He-(Ne)-SrBr₂ laser, are shown in figure 1 (a) and (b), respectively. The first basic tube (a) with an 11.8-mm inside diameter and a 15-mm outside diameter is made of fused quartz. A ceramic insert, confining the active zone, with an inside diameter of 7.1 mm, an 11.2-mm outside diameter and a length of 100 cm is coaxially sleeved in the basic tube. The CuBr powder is placed in seven quartz side-arm reservoirs, which are externally heated.

![Figure 1 (a) and (b). Construction of the two gas-discharge tubes studied.](image)

The reservoir and quartz tube temperature is measured by thermocouples. The second basic tube (b) with a 71.5 mm inside diameter and a 76 mm outside diameter is made of fused quartz. A ceramic insert, confining the active zone, with a 30.5 mm inside diameter, a 38.5 mm outside diameter and a
length of 98 cm is coaxially sleeved in the basic tube. The SrBr₂ powder is placed inside the ceramic tube along its length. The necessary vapour pressure for laser oscillation is obtained by discharge heating; i.e. the discharge operates in a self-heating regime. The discharge tube is wrapped by a layer of fibrous insulation and its thickness depends on the power input in the discharge. The temperature at the quartz tube surface is also measured by a thermocouple. The electrodes of both tubes are made of porous copper with a special design preventing them from contamination by CuBr, SrBr₂ and Br₂.

The investigated NPLDs discharges are excited by an electrical pulsed scheme with interacting circuits (IC scheme). The IC excitation of the CuBr lasers, operating on the copper atom and ion transitions, was described in details in [3, 10]. The switch T is a hydrogen thyratron TGI 1000/25. The capacitors (C₁,…,C₄), forming a capacitor bank (CB) are of the low-inductance KV1-3 type. Their capacitance is experimentally optimized for achieving of maximal output laser parameters. The capacitor bank is charged from a high voltage (HV) rectifier. The pulsed excitation scheme could deliver voltage and current pulses with an amplitude up to 25 kV and 500 A, respectively, an excitation pulse duration of 50–300 ns, and a pulse repetition frequency of 5–30 kHz. Varying the four capacitors, as well as the matching inductor L, the amplitude, waveform and duration of the pulses of the discharge current and the tube voltage, as well as the phase shift between them, could be manageably changed and controlled. In this way, appropriate discharge conditions for different excitation processes, such as electron impact excitation, charge transfer, Penning ionization, and etc., were found and hence output parameters of various metal atom and ion lasers were increased from 35% up to two times in comparison with the frequently used electrical pulsed excitation schemes [3, 10].

The spectral investigation is made, using a Bentham M300 spectrometer equipped with two 1800 groove/mm holographic gratings and a DH-2 photo-multiplier. The spontaneous emission pulses are displayed on a Tektronix 2455A oscilloscope with a 20 MHz cutoff filter.

3. Experimental and theoretical results

3.1. Experimental determination of electron temperature spatial- and time-averaged

Under LTE conditions a measurement of the averaged relative intensity ratio of two lines, originating from different upper levels \( i \) and \( j \), enabled us to experimentally determine the electron temperature \( T_e \) in NPLD in He, Ne and Ne-He mixtures, using the following relative intensity ratio, Boltzmann relation for the relative equilibrium populations of the two upper levels and the expression derived from them:

\[
\frac{I_i}{I_j} = \frac{\lambda_i n_i A_i}{\lambda_j n_j A_j} = \frac{n_i}{n_j} e^{\frac{E_j - E_i}{k_b T_e}},
\]

\[
T_e = \frac{(E_j - E_i)}{k_b} \ln \left( \frac{I_i g_i A_i}{I_j g_j A_j} \right)^{-1}
\]

where \( \lambda_i \) and \( \lambda_j \) are the wavelength of the measured transitions from levels \( i \) and \( j \), \( A_i \) and \( A_j \) are the transition probabilities (spontaneous rate coefficients) for the measured transitions from levels \( i \) and \( j \), \( n_i \) and \( n_j \) are the populations in levels \( i \) and \( j \), \( g_i \) and \( g_j \) are the statistical weights (degeneracies of levels \( i \) and \( j \)), and \( E_i \) and \( E_j \) are the energies of levels \( i \) and \( j \), \( k_b \) is the Boltzmann constant. The use of Boltzmann’s law was also justified in our previous studies [7-9]. Discharge conditions, such as discharge tube with construction and sizes described above, buffer gas or buffer-gas mixture with the corresponding pressure, and \( T_{e,exp} \) obtained experimentally, are summarized in table 1 [7-9].

3.2. Theoretical determination of electron temperature spatial-resolved and time-averaged

As is mentioned above, experimental determination of radial distribution of electron temperature with measurement of relative intensity ratio of two spectral lines for NPLDs is not possible due to some insuperable obstacles encountered, namely low signal and unavoidable noise from high-power electrical pulses in the kHz range, secondary electrical pulses in the MHz region and rise time of voltage and current pulses of TV.s⁻¹ and GA.s⁻¹. In order to obtain electron temperature distribution in the discharge zone, the following steady-state heat conduction equation:

\[\text{heat conduction equation} \]
Table 1. Discharge conditions used as input data.

| Discharge tube          | Buffer gas or buffer-gas mixture | Pressure (Torr) | $T_{e}^{exp}$ (eV) |
|-------------------------|----------------------------------|----------------|-------------------|
| First discharge tube    | He                               | 10             | 0.59              |
| First discharge tube    | Ne                               | 16.7           | 0.48              |
| Second discharge tube   | He                               | 45             | 0.49              |
| Second discharge tube   | Ne-He                            | 2.5-42.5       | 0.80              |
| Second discharge tube   | Ne-He                            | 5-40           | 0.68              |
| Second discharge tube   | Ne-He                            | 10-35          | 0.61              |
| Second discharge tube   | Ne-He                            | 15-30          | 0.78              |

\[
\text{div}(k_e \text{grad} T_e) + \xi q_v = 0
\]  
for electrons is firstly solved for uniform power input, where $k_e$ is electronic thermal conductivity of the electron gas and $\xi q_v$ is electric power density deposited for electrons heating. Using Wiedemann-Franz law for electronic thermal conductivity $\frac{k_e}{\sigma} = cT_e$, where $\sigma$ is specific electrical conductivity, $c = \frac{\pi^2}{3} \left( \frac{k_b}{e} \right)^2$ is constant quantity, $k_b$ is the Boltzmann constant, and $e$ is the electron charge.

Assuming that $\sigma$ is independent of the spatial coordinates and has a value $\overline{\sigma}$, the steady-state heat conduction equation is transformed to the given equation:

\[
\text{div}(T_e \text{grad} T_e) = -\frac{\xi q_v}{c \overline{\sigma}}
\]  
The equation (3) is of the kind, which is typical steady-state heat conduction equation:

\[
\text{div}(k \text{grad} T) + Q_v = 0
\]  
where the dependence of the thermal conductivity $k$ has the form $k = B T^a$. Under assumption that temperature varies only in the radial direction equation (4) assumes the following form:

\[
\frac{1}{r} \frac{d}{dr} \left( r k \frac{dT}{dr} \right) + Q_v = 0
\]

It is well-known [7-9] that the equation (5) has the following analytical solution for gas discharge zone with radius $R$:

\[
T(r) = \left[ T_w^{a+1} + \frac{(a+1)Q_v}{4B} (R^2 - r^2) \right]^{\frac{1}{a+1}}
\]

considering the following boundary conditions: $\left. \frac{dT}{dr} \right|_{r=0} = 0$, $\left. T \right|_{r=R} = T_w$

For the case of equation (3), it is obvious that $B = 1$, $a = 1$, and $T_w = 0$, i.e. the kinetic energy of electrons for $r = R$ is zero as a first approximation. In this way, the solution of (3) has the form for the discharge zone:

\[
T_e(r) = \frac{1}{2} \frac{\xi q_v}{c \overline{\sigma}} \sqrt{R^2 - r^2}
\]

where the constant $\xi$ remained to be obtained. The spatially-average electron temperature in the discharge zone is found by mathematically averaging the solution (7) in the discharge zone over the radius and is made equal to the experimentally determined electron temperature $T_{e}^{exp}$ (see table 1), i.e. $\overline{T_e} = T_{e}^{exp}$. After mathematical processing the following radial electron temperature distribution is obtained:
\[ T_e (r) = 4 \frac{T_{e \text{exp}}}{\pi R} \sqrt{R^2 - r^2} \] (8)

Radial distributions of electron temperature in the discharge zone are shown in figure 2 for NPLD in He-CuBr and Ne-CuBr mixtures.

[Figure 2. Radial distributions of electron temperature for NPLD in He-CuBr and Ne-CuBr mixtures.]

Radial distributions of electron temperature in the discharge zone are presented in figure 3 for NPLD in pure He of 45 Torr and Ne-He mixtures with additives of neon of 5, 10 and 15 Torr maintaining the total mixture pressure of 45 Torr constant. The used average input power is also shown in the figure.

[Figure 3. Radial distributions of electron temperature in NPLD in He- and Ne-He mixtures.]
A comparison is made between radial electron temperature distributions for electrical power density independent of radial coordinate and electrical power density, which depends on the radius with polynomial profile of the second degree. The discrepancy is less than $10^{-5}$ eV and is impossible to be presented in a figure.

4. Conclusions

Using the results obtained for the spatially and time-averaged electron temperature by the line-ratio method of optical emission spectroscopy and analytically solving steady-state heat conduction equation for electrons as well, radial distribution of electron temperature, i.e. spatially-resolved electron temperature, is obtained for NPLD in various gas mixtures. The results obtained, though simplified, enable us to undertake development of numerical 2D model $(r, t)$ for determination of spatially- and time-resolved electron temperature in NPLD exciting DUV Cu$^+$ Ne-CuBr laser and other powerful gas-discharge lasers.

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