Determination of space-time resolved electron temperature in nanosecond pulsed longitudinal discharge in various noble gases and discharge tube constructions

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Abstract. Using our results obtained by the analytical solution of the steady-state heat conduction equation for electrons and deriving a new thermal conductivity, 2D \((r, t)\) numerical solution of nonstationary heat conduction, an equation for electrons is found for nanosecond pulsed longitudinal discharge in helium for two different pressures and in neon.

1. Introduction

One of the main fundamental and extremely relevant problems in plasma physics is the determination of the 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. The electron temperature determines thoroughly the characteristic constants for elastic and inelastic electron-atom and electron-ion collisions, as well as the three-body electron-ion recombination \([1, 2]\). In particular for gas discharge lasers, the electron temperature directly influences the formation of the population inversion with the abovementioned processes or indirectly through heavy particles’ interaction, such as asymmetric charge transfer, Penning ionization, etc. Determining the electron temperature will be of benefit for theoretical optimization of gas-discharge lasers by self-consistent or simplified kinetic models. The widely applied methods for the electron temperature measurement include the use of a Langmuir probe and laser Thomson scattering, which are inapplicable to the nanosecond pulsed longitudinal discharges (NPLDs) used in our experiments. There exist in the literature several years-consuming models, which predict, among the other parameters, the electron temperature values with considerable variation, and, furthermore, there is no overlap.

Under the conditions of a local thermodynamic equilibrium (LTE), measurement of the relative intensities of some He and Ne spectral lines, originating from different upper levels, enabled us to determine experimentally the electron temperature in a NPLD in He, Ne and Ne-He mixtures, using the relative intensity ratio, Boltzmann relation for the relative equilibrium populations of the two upper levels and the expression derived from them. This electron temperature was space-time
averaged, because space-time averaged relative intensities were measured [3-5]. In spite of the fact that the previous results were space-time averaged, the technique of line-ratio measurement of the temperatures proved to be applicable to NPLDs and to provide a wealth of information on those discharges with further refinement.

Unfortunately, time-resolved spectral investigation using devices equipped by a photomultiplier are prohibited for the discharge period of NPLDs, because of the noise from the 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. the electrical power pulse period, the spectral signal and the noise were definitely equal, i.e. the signal remained the same using a shutter in front of the spectrometer slit. That is why the time-resolved electron temperature was determined in a NPLD for the afterglow period only [5]. Moreover, despite the tremendous efforts, determination of the radial electron temperature distribution, i.e. the space-resolved electron temperature, also encounters some insuperable obstacles for NPLDs, because of the low signal and the unavoidable excessive noise from the photomultiplier due to the high-power electrical pulses in the kHz range, the secondary electrical pulses in the MHz region and the steep rise in the voltage and discharge current of TV.s^{-1} and GA.s^{-1} (white noise), i.e. a low signal-to-noise ratio.

Assuming that the electron temperature varied only in the radial direction and using the experimental results obtained for the space-time averaged electron temperature, a simple method based on the analytical solution of the steady-state heat conduction equation for electrons was developed for uniform and non-uniform power input in NPLD in He, Ne and Ne-He mixtures [6]. The electronic thermal conductivity was determined from the Wiedemann-Franz law 

\[ \frac{k_e}{\sigma} = cT_e \]

for plasma physics, where \( \sigma \) is the specific electrical conductivity, \( c = \frac{\pi^2 k_b^2}{3} \left( \frac{k_b e}{e} \right)^2 \) is a constant, \( k_b \) is the Boltzmann constant, and \( e \) is the electron charge, and assuming that \( \sigma \) is independent of the spatial coordinates and had a value of \( \sigma \). The discharge conditions, such as discharge tubes with special construction and corresponding sizes, buffer gas or buffer-gas mixture at the corresponding pressures, were optimal for laser oscillation in the deep ultraviolet (DUV), and in the near and middle infrared (NIR and MIR) spectral ranges. A comparison was made between the radial electron temperature distributions for an electrical power density independent of the radial coordinate and electrical power density that depends on the radius with a polynomial profile of the second degree. The discrepancy was less than 1×10^{-5} eV and was impossible to be presented in a figure. These results, although satisfactory, enabled us to obtain the electric power density deposited for electrons heating and the initial and boundary conditions for the next advance in our research presented in this paper, namely numerical solution of the nonstationary heat conduction equation for electrons in axial symmetry, i.e. determination of the radial and time dependence of the electron temperature in the NPLDs investigated.

2. Experimental setup
A schematic diagram of the first discharge tube, which is typical for the powerful DUV Cu+ Ne-CuBr and the NIR Cu+ He-CuBr lasers, is shown in figure 1 (a). The basic tube 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.

Schematic diagram of the second discharge tube, which is typical for the high-power MIR He- SrBr2 laser, is presented in figure 1 (b). The basic tube 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 temperature at the quartz tube surface is measured by a thermocouple. The investigated NPLDs are excited by an electrical scheme with interacting circuits (IC scheme) described in detail in [2]. Electric power density $\xi q_V$ deposited for electrons heating was 2.0 W cm$^{-3}$ for the first discharge tube (DUV Cu$^+$ Ne-CuBr and NIR Cu$^+$ He-CuBr lasers) and 0.2 W cm$^{-3}$ for the second discharge tube (MIR He-SrBr$_2$ laser), as was found in [6].

![Figure 1](image1.png)

**Figure 1.** Discharge tube construction used for: (a) DUV Cu$^+$ Ne-CuBr and NIR Cu$^+$ He-CuBr lasers; (b) MIR Sr He-SrBr$_2$ laser.

### 3. Theoretical results and discussion

The following nonstationary heat conduction equation is solved:

$$c_p \rho \frac{\partial T_e}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r k_e(T_e) \frac{\partial T_e}{\partial r} \right) + \xi q_V, \quad 0 \leq r \leq R, \quad 0 \leq t \leq T$$

under the initial conditions

$$T_e(r,0) = T_e^0(r) = \left[ T_e(R,t)^{1+a} + \frac{1+a}{4B} q_V (R^2 - r^2) \right]^{\frac{1}{1+a}}$$

and boundary condition

$$\lim_{r \to 0} r k_e(T_e) \frac{\partial T_e}{\partial r} = 0. \quad (3)$$

The second boundary condition $T_e(R,0)$, together with the discharge zone radii $R$ and some required thermodynamic properties are presented in table 1. The excitation pulse duration $T_1$ is set at 140 ns for the NPLDs studied. The period between the excitation pulses $T$ is 50 µs at a pulse repetition rate of 20 kHz.

Our preliminary results from the computer simulation show that the electronic thermal conductivity derived from the Wiedemann-Franz law does not reflect the physical reality for the nonstationary electron temperature. This is why, a power index scanning was undertaken for the thermal conductivity in the allometric form, i.e. $k_e = B.T_e^a$, which was widely used for the analytical solution of the stationary heat conduction equation. The results are presented in figure 2.

Using the new thermal conductivity obtained through the power index scanning, theoretical determination of radius- and time-resolved electron temperature is made for the three cases shown in table 1.
Table 1. \( c_p \) – specific heat capacity, \( \rho \) – gas density, \( R \) – discharge radius, \( T_e(R,0) \) – second boundary condition.

| Lasers                     | Buffer gas       | \( c_p \) (J/kgK\(^{-1}\)) | \( \rho \) (kg/m\(^3\)) | \( R \) (mm) | \( T_e(R,0) \) (K) |
|----------------------------|------------------|-------------------------------|--------------------------|--------------|------------------|
| DUV Cu\(^+\) Ne-CuBr laser | Ne (16.7 Torr)   | 1300                          | 9,525.10\(^{+3}\)        | 3.55         | 880              |
| NIR Cu\(^+\) He-CuBr laser | He (10 Torr)     | 5200                          | 1,131.10\(^{+3}\)        | 3.55         | 880              |
| MIR Sr He-SrBr\(_2\) laser | He (45 Torr)     | 5200                          | 3,395.10\(^{+3}\)        | 15.25        | 1240             |

The time-resolved electron temperature for different radial distances is shown in figure 3 in NPLD in Ne (a) and He (b) buffer gases at pressures of 16.7 Torr and 10 Torr, respectively.

The time-resolved electron temperature for different radial distances is shown in figure 4 in NPLD in He (45 Torr) buffer gas.

The results obtained are in a fair agreement with the self-consistent models developed for NPLD in Ne-Cu and Ne-CuBr lasers [1, 2], as well as to a certain extent with the time-resolved space-averaged electron temperature presented in figure 5, which was obtained by time-resolved measurement of the electrical discharge parameters, such as tube voltage and discharge current [7].

Figure 3. Time dependence of the electron temperature in NPLD in Ne (a) and He (b) used for excitation of DUV and NIR Cu\(^+\) lasers, respectively, for different radial distances.

Figure 4. Time dependence of the electron temperature in NPLD in He used for excitation of MIR Sr He-SrBr\(_2\) laser for different radial distances.

Figure 5. Electron temperature experimentally and theoretically determined in NPLD in Ne (16.7 Torr) used for excitation of a DUV Cu\(^+\) Ne-CuBr laser.
4. Conclusions
Using results obtained by the analytical solution of the steady-state heat conduction equation for electrons and determining new thermal conductivity with one-parameter scanning procedure, 2D \((r, t)\) model is developed through a numerical method and MATLAB software for determination of spacetime resolved electron temperature in NPLDs used for excitation of the high-power DUV Cu⁺ Ne-CuBr, NIR Cu⁺ He-CuBr, the MIR Sr He-SrBr₂ lasers and the DUV Cu⁺ Ne-CuBr laser.

The discrepancy seen in figure 5 between the experimental results [7] and the new theoretical results are maybe due to the approximation of an uniform excitation pulse over the time. Simulations with time-dependent excitation pulses are in progress.

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