# Study of a stationary surface-wave sustained neon plasma column at atmospheric pressure

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**Abstract**

A spectroscopic study of a neon surface wave plasma column at atmospheric pressure under steady-state conditions has been carried out. The gas and electron temperature, the electron density, and the absolute population of the excited states, including the metastable and resonant levels, were measured under different conditions of power and gas flow. The results show that we are dealing with a two temperature (2T) discharge whose excitation kinetics is controlled by electron collisions (electron excitation kinetics). A partial Saha equilibrium is reached by no excited level and the plasma present an ionizing character very far from the Local Thermodynamic Equilibrium (LTE). This situation contrasts with the argon plasma created under the same conditions where the upper levels remain in LTE.

## 1. Introduction

The interest in studying the high frequency (HF) plasmas ($\omega/2\pi$ > 1MHz), especially surface-wave sustained discharges, has grown significantly in recent years by virtue of the major application of this type of discharge in a number of scientific and technological fields such as analytical chemistry, spectroscopy and surface processing [1]. The most salient features of HF plasmas are high flexibility, ease of handling and the ability to obtain them under broad ranges of experimental conditions [1]. In the last years, a significant amount of theoretical and experimental work has been conducted on the behavior of this type of plasma at atmospheric pressure [2-5]. However, the majority of these works focus their attention in helium and argon plasmas while there is no experimental study about the complete characterization of neon plasmas.

## 2. Experimental arrangement and diagnostic methods

The surface-wave sustained plasma columns studied were generated by using a *surfaguide* device [6], which allows microwave energy (2.45 GHz) to be coupled to the discharge. We have varied the absorbed microwave powers from 50 to 250 W. Neon discharges were produced within quartz capillary tubes of 2.5-mm inner diameter. The discharge gas is 99.99% pure neon, flowing at 0.5 l/min and coming out into the room through the open end of the discharge tube.

The gas temperature was considered equal to the rotational temperature $T_{rot}$ obtained of the rotational spectrum for the $Q_1$ branches of the (0-0) of the OH radical, which resulted from the dissociation of water traces present in the plasma gas.

The electron temperature was derived from the relative intensity of an isolated line $I$ to its neighboring continuum $\varepsilon_c$ through the expression

$$\frac{I}{\varepsilon_c} = \left(\frac{3\sqrt{3}h^4}{4e^6}\right)\left(\frac{c^3\varepsilon_0^3}{k}\right)\frac{A_{pq}g_p}{Z^+}\frac{\lambda}{T_e\xi}\exp\left(\frac{E_{ion}}{kT_e} - \frac{E_p}{kT_{exc}}\right) \quad (1)$$

where $\xi$ is the free-bound Gaunt factor, $Z^+$ the partition function of singly ionized atoms, $E_{ion}$ the ionization potential of neon, $A_{pq}$ the coefficient for spontaneous emission from level $p$ to level $q$, $\lambda$ the wavelength of the corresponding transition, $g_p$ the statistical weight of the level $p$, $E_p$ the energy of the level $p$, and $T_{exc}$ the excitation temperature that relates the population of the level $p$ with that of the ground state

The absolute populations of the different atomic levels $n_p$ were determined from measurements of the intensity $I_p$ of the spectral lines corresponding to atomic transitions starting at each specific level using the following expression:

$$I_p = \frac{hc}{4\pi}\frac{A_{pq}n_p}{\lambda} \quad (2)$$

where $A_{pq}$ is the coefficient for spontaneous emission from level $p$ to level $q$, and $\lambda$ the wavelength of the corresponding transition.

The density of atoms in the ground state is determined from the equation for the ideal gas:

$$P = n_1 k T_{gas} \quad (3)$$

where the pressure $P$ is 1 atm and $T_g$ is the previously calculated gas temperature.

The population of Ne($^3P_0$) and Ne($^3P_1$) states was obtained using self-absorption techniques [5]. In using this method, the ratio of the total intensities of two partially self-absorbed lines emitted by the discharge is measured. Both lines end at the same level whose population we aim to determine.

The electron density, $n_e$, was determined from the Stark broadening of the $H_\beta$ line (Hydrogen Balmer series line). The hydrogen is present in the discharge as an impurity.

## 3. Results and discussion

Figure 1 shows the axial gas and electron temperature profiles obtained for the different surface-wave plasma columns studied. As can be seen, these profiles were practically constant. Also, the electron temperature was much higher than the gas temperature ($T_e >> T_{gas}$) which indicates that the discharge is clearly a *2T* plasma. We can also note that the values of $T_e$ in the SWD neon columns are higher (~ 50 %) than those obtained for the argon columns at the same experimental conditions ($\approx 7000\,\mathrm{K}$) while the gas temperature values are very close. This fact can be explained taking into account the higher ionization potential of neon yielding a value of the electron density less than the argon one as was commented above. Since it is necessary much energy from the electric field to ionize the neon and the electron number per volume unit is lower, we can expect the free electrons to be more energetic and consequently a higher electron temperature.

Figure 2 shows the axial profiles of electron density for the surface-wave sustained plasma columns studied as well as those corresponding to helium and neon plasmas. The slope of the density profile, $dn_e / dz$, is directly related with the electron-atom collision frequency for the momentum transfer $v$ and inversely related with the discharge tube radius $a$. Thus, in argon plasmas, $dn_e / dz$ remains practically constant varying $a$ because of the radial contraction. This contrasts with the case of neon and helium plasmas which present no contraction at atmospheric pressure.

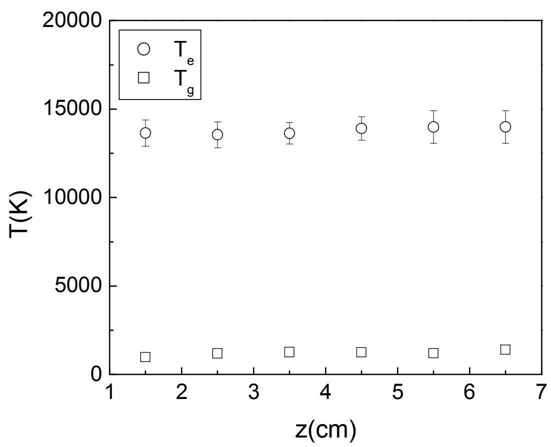


**Figure 1:** Measured gas and electron temperature as function of axial position for the different plasma column studied.

From the present results of electron density and temperature, we have obtained that the frequency, $\upsilon$, for elastic electron-atom collisions in the neon discharge was $\upsilon / \omega = 5$ and the power, $\theta$, absorbed per electron from the electric field was $\theta = 5.2\,\mathrm{pW}$. These results indicate that neon plasmas present an intermediate excitation kinetic between helium and argon.

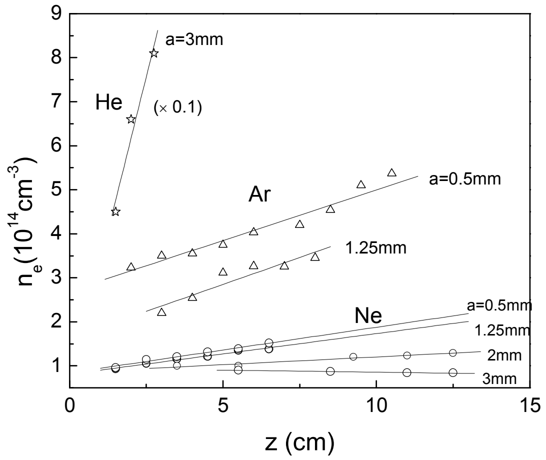


**Figure 2:** Electron density profiles as function of axial positions in helium, argon and argon plasmas.

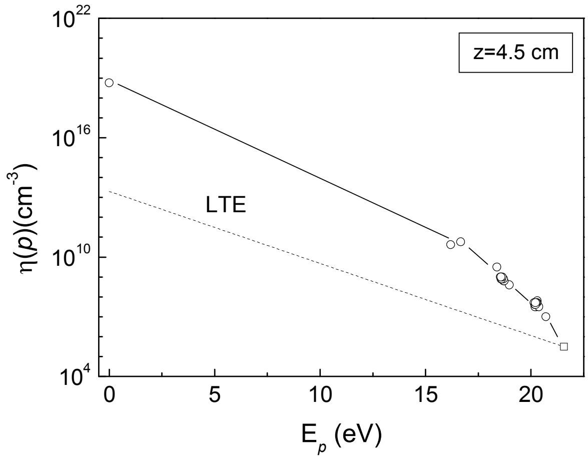


**Figure 3:** ASDF at z = 4.5 cm measured by the absolute intensity technique.

Figure 3 shows the Boltzmann-plot of excited neon atoms obtained at a given axial position of the column. The plot also includes the points corresponding to the ground state and metastable and resonant levels as well as the Saha point of the ionization level. The Saha distribution is also depicted in this ASDF representation. The overpopulation of the excited states respecting to the Saha distribution shows clearly the ionizing character of the neon plasma columns. As can be seen, no measured level is in Saha equilibrium and the departure from the equilibrium of the plasma is very high.

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