Measuring the electron density in plasmas from the difference of Lorentzian part of the widths of two Balmer series hydrogen lines

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ABSTRACT

We present an alternative Optical Emission Spectroscopy method to measure the plasma electron density from the difference of widths of two Balmer series hydrogen lines (H_α and H_β), especially convenient for non-thermal plasmas since using this method, there is no need of knowing neither the gas temperature or the van der Waals contribution to the Lorentzian part of the line. In this paper it has been assumed that the part of full width at half maximum due to Stark broadening can be determined with the approximation of Lorentzian line shape. The method has been applied to the determination of the electron density in an argon microwave-induced plasma maintained at atmospheric pressure, and comparison with the results obtained using other diagnostic methods has been done.

Keywords: Plasma spectroscopy, microwave discharges, electron density, atomic spectral lines, atomic emission spectroscopy.

INTRODUCTION

Plasmas are physically and chemically active media, and they have been successfully employed in numerous fields of Science and Technology. In the last years the interest in studying and using *non-thermal plasmas* (also referred to as non-equilibrium or cold plasmas) has significantly grown. These plasmas are characterized by a large difference in the electron temperature relative to those of the ions and neutrals (gas temperature). Because of the small mass of electrons, they can be easily accelerated under the influence of an electric field. Thus, in non-thermal plasmas the electrons can reach temperatures of 10000 K up to 250000 K (1–20 eV), while the gas temperature can remain as low as room temperature.

Non-thermal plasmas are considered as a very promising technology due to their non-equilibrium properties, namely, their low power requirement and their capability to induce physical and chemical reactions within gases at relatively low temperatures. Non-thermal plasmas are being employed currently in a large variety of applications including gas detoxification, materials processing (thin film deposition, surface functionalization…), plasma catalysis, elemental analysis, treatment of liquids (water) with plasma, sterilization...[1-6].

The electron density (n_e) is a plasma characteristic parameter related to its ability to induce reactions. It is one of the parameters determining the plasma reactivity, so knowing its value in technological applications could be crucial.

Optical Emission Spectroscopy (OES) techniques based on the analysis of Balmer series hydrogen lines are commonly employed for electron density determination of plasmas sustained at atmospheric pressure [7-14], because their high line shape sensitivity (linear Stark effect) on the microfield induced by charged particles (electrons and ions) surrounding the emitter (H). In several cases, the Stark broadened parts of H_α

and H_β Balmer series hydrogen line profiles can be approximated to a Lorentz function [8,11,13] and, as a consequence, the experimental shapes of these lines can be assumed as a Voigt function. Recent works have shown that even when this approximation applies care should be paid when determining the Stark broadening of Balmer series hydrogen lines (even for the H_β line, considered as the most adequate one) through deconvolution of experimental profile by fitting with a Voigt function for non-thermal plasmas with low gas temperatures [9, 10]. In these cases, the so called van der Waals broadening (related to the *plasma gas temperature*, T_g) becomes important giving rise to a non-negligible Lorentzian contribution. For these cases, the electron density determination is conditioned to know the value of T_g.

In this paper, we present an alternative method to measure the electron density using the Lorentzian part of the widths of two Balmer series hydrogen lines (H_α and H_β). When using this method, prior knowledge of the van der Waals contribution or the gas temperature is not necessary, so although the method is also valid for thermal plasmas, it is particularly convenient for non-thermal ones. We applied it to the determination of the electron density of an argon microwave plasma sustained at atmospheric pressure. Comparison with the results obtained using other diagnostic methods based on the use of Stark broadening of H_α or H_β [9, 10, 12] has been done.

METHOD

The shape of the atomic spectral lines emitted by plasmas generated at pressures higher than 100 Torr is the result of different broadening mechanisms. The *van der Waals broadening* is due to dipole moment induced by neutral atom perturbers in the instantaneous oscillating electric field of the excited emitter atom [15] and generates line profiles with a Lorentzian form. *Doppler broadening* (due to the movement of emitter atoms) and the *instrumental broadening* (determined by the device used for the plasma radiation registration) give line shapes with a Gaussian form. Finally, the *Stark broadening* (due to collisions of the emitter atom with the surrounding charged particles), as a rule, has not a simple Lorentzian or Gaussian line shape. However, as stated in the recent review of Bruggeman and Brandenburg [8] about the state of art of plasma diagnostics on atmospheric pressure plasmas, in several cases Stark broadened part of the line profile is assumed to have a Lorentzian shape (which is not always true, especially for large electron densities). In this way, Konjevic and co-workers in [11] consider that assumption as a good approximation of the Stark broadening of H_α and H_β lines for electron densities of the order of 10^{14} cm^{-3} and above. Stehlé and co-workers in [16,17] have also found that in absence of ion microfield, Stark profile of hydrogenic spectral lines can be approximated by a single Lorentzian function, and they even have obtained a simple analytical expression for the Stark widths of these lines. As a consequence, for all these cases the experimental shapes of H_α and H_β lines can be assumed as a Voigt function resulting from the convolution of a Gaussian profile with a Lorentzian profile [8].

For plasmas with gas temperature and electron density values relatively high, Stark broadening dominates the Lorentzian part of the H_α and H_β profiles, being the van der Waals contribution negligible (see Tables I and II). On the other hand, for plasmas with gas temperature below 5000 K, both van der Waals and Stark broadenings have a relatively strong contribution to the Lorentzian part of the line profile [10], as shown in Tables I and II. In this way, for an argon plasma at atmospheric pressure with a typical electron density n_e of $5 \cdot 10^{14}$ cm^{-3} and gas temperature T_g around 2000 K, not considering the van der Waals broadening leads to a Stark broadening overestimation for H_α and H_β lines of a 70% and 22%, respectively, and to a resulting overestimation of n_e. This overestimation could reach until 500% for gas temperatures of 500 K.

Under the experimental conditions abovementioned (electron densities of the order of 10^{14} cm^{-3} and above) the full width at half maximum (FWHM) of the Lorentzian profile for H_α and H_β lines, w_L, could be written as follows

$$w_L^{H_\alpha}(T_e, n_e, T_g, \mu_r) = w_S^{H_\alpha}(T_e, n_e, \mu_r) + w_W^{H_\alpha}(T_{gas}) \tag{1}$$

$$w_L^{H_\beta}(T_e, n_e, T_g, \mu_r) = w_S^{H_\beta}(T_e, n_e, \mu_r) + w_W^{H_\beta}(T_{gas}) \tag{2}$$

being w_s and w_w the FWHM due to the Stark and van der Waals broadenings, respectively, T_e the plasma electron temperature and μ_r a fictitious reduced mass of the pair H-pertubed atom, defined later. Calculation of the electron density using some of these lines is then conditioned to know the value of the gas temperature which makes possible to subtract the van the Waals contribution [9, 10].

In order to circumvent this difficulty, we propose an alternative method based on the fact that H_α and H_β lines have a very similar value of van der Waals broadening. For an argon plasma the FWHM for the van der Waals broadening of H_α and H_β lines can be written in terms of the gas temperature as [10]

$$w_W^{H_\alpha}(T_g) = 18.67C \Big/ T_g^{\frac{7}{10}} \; (\cdot 10^9 \,\mathrm{nm}) \tag{3}$$

$$w_W^{H_\beta}(T_g) = 17.97C \Big/ T_g^{\frac{7}{10}} \; (\cdot 10^9 \,\mathrm{nm}) \tag{4}$$

where C is given by $C = \left(\alpha^{2/5} P / \mu^{3/10}\right)$ being α the polarizability of the perturbed atom given in cm^3, P the pressure measured in atm, T_g measured in K and μ the reduced mass of the H-perturbed atom pair.

For a typical gas temperature of 1000 K, the difference between van der Waals broadenings $R(T_g)$ is less than 5 %. So, the difference between the H_β and H_α Lorentzian widths can be then considered as not depending on the van der Waals ones:

$$\begin{aligned} w_L^{H_\beta}\left(T_e, n_e, T_g, \mu_r\right) - w_L^{H_\alpha}\left(T_e, n_e, T_g, \mu_r\right) &= w_S^{H_\beta}\left(T_e, n_e, \mu_r\right) - w_S^{H_\alpha}\left(T_e, n_e, \mu_r\right) + R(T_g) \\ &\approx f\left(T_e, n_e, \mu_r\right) \end{aligned} \tag{5}$$

The Computer Simulation (CS) model proposed by Gigosos *et al.* [18] enables to calculate the theoretical Stark broadenings of H_α and H_β emission lines. This is a computational model including the effects of the ion dynamic (so the relative movement between emitter-ion pair with a reduced mass μ) with non-equilibrium conditions existing in non-thermal plasmas through a *fictitious reduced mass* of this pair, $\mu_r = \mu\, T_e/T_{gas}$.

In the present work, using the theoretical results of this CS model the values of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ have been calculated for several conditions of electron density, electron temperature and fictitious reduced mass (see Figs. 1 and 2). Theses figures show the weak dependence of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ on T_e and fictitious reduced mass for electron densities in the range between 10^{14} and 10^{16} cm^{-3}. So for this electron density range we can rewrite Eq. 5 as:

$$w_L^{H_\beta}(T_e, n_e, T_g, \mu_r) - w_L^{H_\alpha}(T_e, n_e, T_g, \mu_r) \approx f(n_e) \tag{6}$$

The curves depicted in Figures 3 and 4 represent the theoretical dependence of $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ on electron density for electron densities in the ranges from 1 to 10·(10^{14} cm^{-3}) and from 1 to 10 ·(10^{15} cm^{-3}), respectively, for T_e = 5000 K and μ_r = 4.0. By measuring experimentally the difference $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ and considering these theoretical curves (or similar ones calculated for other specific values of T_e and μ_r), the electron density in the plasma could be determined.

Moreover, for each range of electron density the theoretical relationship between $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ and n_e has been approximated to a simple equation (see Figs. 3 and 4) given by

$$n_e \approx 185 \cdot 10^{14} \left(w_L^{H_\beta} - w_L^{H\alpha}\right)^{3/2} \ (\mathrm{cm}^{-3}) \tag{7}$$

for n_e in the order of 10^{14} cm^{-3}, and

$$n_e \approx 168 \cdot 10^{15} \left(w_L^{H_\beta} - w_L^{H\alpha}\right)^{3/2} (\mathrm{cm}^{-3}) \tag{8}$$

for n_e in the order of 10^{15} cm^{-3}, being w expressed in nm in both cases. These equations have been obtained from the exponential fit of the values represented in Figs. 3 and 4, respectively (from the central point of each figure).

Equations (7) and (8) apply for a range of electron temperature between 5000-15000 K, offering in this way an easy and useful tool to make a quick calculation of the electron density in non-thermal plasmas with electron density values of the order of 10^{14} cm^{-3} and above.

ELECTRON DENSITY OF A MICROWAVE PLASMA SUSTAINED AT ATMOSPHERIC PRESSURE

Experimental set up

We have applied this method to measure the electron density in an argon microwave (2.45 GHz) induced plasma at atmospheric pressure generated inside a quartz tube of 1.5-4 mm of inner and outer diameter, respectively, using a *surfaguide* device [19], with powers ranging from 100 to 250 W. Movable plunger and stubs permitted the impedance matching so that the best energy coupling could be achieved, making the power reflected back to the generator (P_r) negligible (< 5%). The argon flow rate was set at 0.5 slm and adjusted with a calibrated mass flow controller.

Surfaguide launched an electromagnetic surface-wave (linked to the plasma-dielectric interface) that delivered the energy needed for creating and sustaining the plasma column (Surface Wave-sustained Discharge, SWD). The power flux of the surface-wave, and hence the electron density, decreased longitudinally as the wave moved away from the surfaguide until a final axial position, where the electron density was equal to the critical value, n_c.

Light emission from the plasma was analyzed by using a Czerny-Turner type spectrometer of 1 m focal length equipped with a 2400 grooves/mm holographic grating and a photomultiplier (spectral output interval of 200-800 mm) as a detector. The light emitted by the plasma was side-on collected using an optical fiber at different axial positions along the plasma column (z = 4, 6, 8, 10 and 12 cm measured from the end of the column). A UV-VIS collimating beam probe was coupled to the optical fiber giving a 0º-45º of field of view and 3mm of aperture.

Spectra recorded allowed to identify the different species existing in the corresponding plasma region. In these spectra, besides atomic argon lines, H_α and H_β

lines could be identified because hydrogen was present in the plasma as an impurity of the gas feeding the discharge. The instrumental broadening (measured for the conditions in which these lines were recorded) was 0.03 nm.

Measurements of light absorption have shown that the plasma studied can be considered as optically thin for all Ar I lines detected (even for Ar I 794.81 nm line with a oscillator strength $f = 0.56$) in the direction of observation chosen (transversally) [20-21]. On the other hand, Santiago et al in [22] have shown that in argon plasma columns similar to that studied in the present paper H_α and H_β lines are not affected by self-absorption when they are measured either transversally (length of observation 1 mm) or axially (length of observation 75 mm), and conclude that even H_α could be employed to measure electron density in plasma columns generated in tubes of diameter bigger than 1 mm.

For n_e determination, H_α and H_β emission lines were recorded three times at each plasma axial position z. The Lorentzian contribution to the whole broadening in each case, was obtained using a commercial process of deconvolution (Peak-Fitting module, Microcal Origin©), based on the Leverberg-Marquardt non-linear least squares algorithm. Because dispersion was lower than 2%, the error of each measurement was considered as equal to its deviation.

Approximation of Lorentzian profile for Stark broadening

In this paper it has been assumed that the part of full width at half maximum due to Stark broadening, can be determined with the approximation of Lorentzian line shape. This means that even if Stark broadening contribution to the total line shape cannot be approximated by Lorentzian profile(due mainly to the ion broadening, which introduces asymmetry and it is most important in line wings), the Stark broadening contribution to the central part of the profile, important for FWHM determination, can still be considered as Lorentzian. This assumption was also used by Konjevic et al in [11] and Parigger et al in [13].

In order to support this assumption, although they are not in the scope of this paper, some profile simulations for H_α and H_β lines were performed.

Figures 5 and 6 represent experimental profiles recorded for H_β and H_α lines (under some specific experimental conditions) and simulated profiles obtained considering: (i) a Gaussian profile of 0.03 nm corresponding to the instrumental profile measured and Doppler profile (calculated from the gas temperature measured T_g = 1380 ± 120 K); (ii) a Lorentzian profile of 0.039 nm corresponding to van der Waals broadening (calculated also from the gas temperature measured) and both (iii-a) a Stark profile assumed Lorentzian shaped and (iii-b) the Gigosos et al. Stark profiles [18], all leading to the best fitting.

As shown in Fig. 5, simulation of the H_β profile considering a Lorentzian approximation for the Stark broadening reproduces quite acceptably the experimental profile. On the other hand, as shown in Fig. 6, good fittings were also found for the H_α using Lorentzian shape assumption of its Stark profile.

Finally, the value of electron densities found from profile simulations of H_β and H_α lines using Lorentzian assumptions for Stark broadenings are consistent to each other (being both equal to $2.3 \cdot 10^{14}$ cm^{-3} in this particular case), which supports that both assumptions could be considered as a good approach.

Results

Table III shows the values of Lorentzian widths obtained from H_α and H_β line profiles measured at different plasma axial positions following a deconvolution procedure (using Microcal Origin code). This table also includes the values of electron density determined from both the eq. (7) and the $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ vs. n_e curve represented in Fig. 3 for a value of electron temperature equal to 5000 K (typical value for the plasma studied [10,20,23,24]) and a fictitious reduced mass equal to 4. Figure 7 shows an example of n_e determination from $w_L^{H_\beta} - w_L^{H_\alpha} = f(n_e)$ theoretical curve at z = 4 cm plasma position. As it can be verified, the values of n_e obtained using eq. (7) and $w_L^{H_\beta} - w_L^{H_\alpha} = f(n_e)$ curve were quite similar.

The Lorentzian widths of H_α and H_β line profiles were also measured by fixing the Gaussian part (for a value of T_g = 1380 ± 120 K, typical in the plasmas studied) of the Voigt function as suggested by Konjevic et al. in Ref. [11]. As also shown in Table III, no significant differences were observed, what justify the validity of the deconvolution procedure proposed in this paper (which not needs prior knowledge of T_g).

It should be pointed out that, although this method is based on the use of a difference of two widths $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$, in the range of electron densities from $1.0 \cdot 10^{14}$ to 10^{16} cm^{-3} proposed, this difference ranged between ~ 0.03 nm and 0.7 nm (see Figs. 3 and 4). Particularly, for electron densities in the order of 10^{15} cm^{-3} this difference always overpasses 0.15 nm, being much larger than Gaussian contribution (instrumental and Doppler) to the profile width (= 0.026 nm ~ 0.03 nm). Thus, reliability of the method improves for the highest values of electron density. Low values of Gaussian contribution (low gas temperatures, good spectral resolution of the optical system) also help to improve consistency of the method.

As seen in Table IV, all these results are in good agreement with those obtained using CS model for H_α and H_β lines [10], considering that Stark broadening results in a Lorentz profile, and extracting from the whole Lorentzian width the van der Waals contribution (for T_g = 1380 ± 120 K). On the contrary, when this contribution was not considered, the values of electron densities obtained were overestimated, as already shown by Luque et al. and Yubero et al. [9, 10].

Recently, Ivkovic et al. [12] have proposed a method for electron density determination based on the use of the wavelength separation between characteristics peaks of H_β Stark profile, $\Delta\lambda_{PS}$. They have derived different approximate formula allowing n_e calculation from $\Delta\lambda_{PS}$ and show that this *peak separation* (PS) *method* is reliable for electron density diagnostic in plasmas with a relatively large electron density ($\Delta\lambda_{PS}$>0.03 nm), even in the presence of considerable self-absorption. The method also offers a useful tool to evaluate self-absorption of H_β line profile.

When other broadening mechanisms (such as Doppler and instrumental ones) are present, a reduction of the peak separation takes place and at low n_e (for $\Delta\lambda_{PS}$ values smaller than 0.03 nm) the characteristic dip between peaks reduces [12] becoming sometimes undetectable (even though the plasma is observed with a high resolution spectrometer).

We have estimated the electron density using the PS method for those cases where $\Delta\lambda_{PS}$ measured was higher to 0.03 nm (corresponding to z = 10 and z = 12 cm cases, see Table IV), and a good agreement with the values obtained using other methods was found. Furthermore, a quick calculation of self absorption for H_β line profile following Ivkovic et al [12] recommendation, i.e. using the ratio of n_e determined from H_β using CS model and from peak separation, shows that this phenomenon can be considered as negligible in these cases.

Finally, we have determined the Stark broadening of the Ar I 603.2 nm line using the values of electron density obtained from this new method (Table III), and we have compared this result to the theoretical value of this parameter given by Christova *et al.*

[25] in 2005 and Dimitrijevic *et al*. [26] in 2007. Since the dependence of Stark FWHM is linear with n_e for the electron density range of interest, the Stark FWHM for a value of electron density of 10^{14} cm^{-3} can be scaled to other electron density by multiplying with n_e (cm^{-3}) / (10^{14} cm^{-3}), so that the Lorentzian width of an atomic spectral line can be written as (see e.g. Ref. 25-27)

$$w_L\left(T_e, n_e, T_g\right) = w_S\left(T_e\right) n_e\left(\cdot 10^{-14}\right) + w_w\left(T_g\right) \tag{9}$$

where $w_s(T_e)$ is the Stark FWHM for a value of electron density of 10^{14} cm^{-3} and $w_w(T_g)$ is the van der Waals broadening. Due to the gas temperature (so $w_w(T_g)$) is unchangeable throughout the z-position of the plasma [27], the value of the Stark parameter of an atomic line can be obtained from the representation of the Lorentzian width of this line versus the electron density value at different axial positions of the plasma column. In this way, the slope and the intercept are equal to the Stark width (w_s) and the van der Waals (w_w) width respectively (see Fig. 8), namely the w_L-value on the ordinate is equal to $w_s + w_w$.

From the slope of this representation, a Stark FWHM of 2.45 ± 0.09 pm was obtained for Ar I 603.2 nm line ($n_e = 10^{14}$ cm^{-3}). The theoretical values of this parameter published in [25] and [26] were 2.43 pm and 1.57 pm, respectively. Also, from the intercept the gas temperature was estimated [27]. A value of about $T_g \sim 900$ K was obtained, being a typical value for this type plasma [10,20,23,24].

CONCLUSSIONS

In this work, an alternative method to measure the electron density from the difference of Lorentzian widths of two Balmer series hydrogen lines (H_α and H_β), especially convenient for non-thermal plasmas, has been presented. When using this method, previous measurement of the gas temperature (so van der Waals contribution to the Lorentzian part of the line profile) is not required.

The method applies to plasmas in which the Stark profile of H_α and H_β lines profiles can be approximated to a Lorentz function and, as a consequence, the experimental shapes of these lines can be assumed as a Voigt function. Thus, two Lorentzian contributions are taken into account, corresponding to both van der Waals and Stark broadenings.

As H_α and H_β lines have a very similar value of van der Waals broadenings, the difference between the H_β and H_α Lorentzian widths can be then considered as not depending on the van der Waals or T_{gas}, and being equal to the difference between their Stark broadenings. The Computer Simulation (CS) model proposed by Gigosos *et al.* also shows a weak dependency of this difference on T_e and fictitious reduced mass for electron densities in the range between 10^{14} and 10^{16} cm^{-3}. As a consequence, the difference between the H_β and H_α Lorentzian widths only depends on electron density for this range of experimental conditions. Calculating this curves, and measuring experimentally $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$, electron density could be calculated.

We have applied this method to the determination of the electron density in a non-thermal microwave-induced plasma at atmospheric pressure, obtaining results in good agreement with previous ones obtained using H_α and H_β Stark broadenings, and CS Model.

Finally, comparison between the values of the Stark broadening of the Ar I 603.2 nm line experimentally obtained using the electron density estimated from the new method, and the theoretical value of this broadening calculated by Christova *et al.* in Ref. [25] and Dimitrijevic *et al.* in Ref.[26], was done.

ACKNOWLEDGMENTS

The authors wish to acknowledge to *Física de Plasmas: Diagnosis, Modelos y Aplicaciones (FQM 136)* research group for their funding and technical support. Authors are also grateful to Isabel Santiago for her valuable discussions during the preparation of this manuscript.

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Figure captions

Figure 1. CS model dependence of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ on n_e for $\mu_r = 4$ and different values of T_e.

Figure 2. CS model dependence of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ on n_e for T_e = 5000 K and different values of μ_r.

Figure 3. Representation of $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ vs. n_e for $\mu_r = 4$ and T_e = 5000 K (given by both CS model and Eq. (7)).

Figure 4. Representation of $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ vs. n_e for $\mu_r = 4$ and T_e = 5000 K (given by both CS model and Eq. (8)).

Figure 5. Experimental and simulated profiles for H_β line (z = 10 cm).

Figure 6. Experimental and simulated profiles for $H\alpha$ line (z = 10 cm).

Figure 7. Calculation of n_e from the $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ vs. n_e curve (z = 4 cm).

Figure 8. Lorentzian broadening of Ar I 603.2 nm line versus n_e.

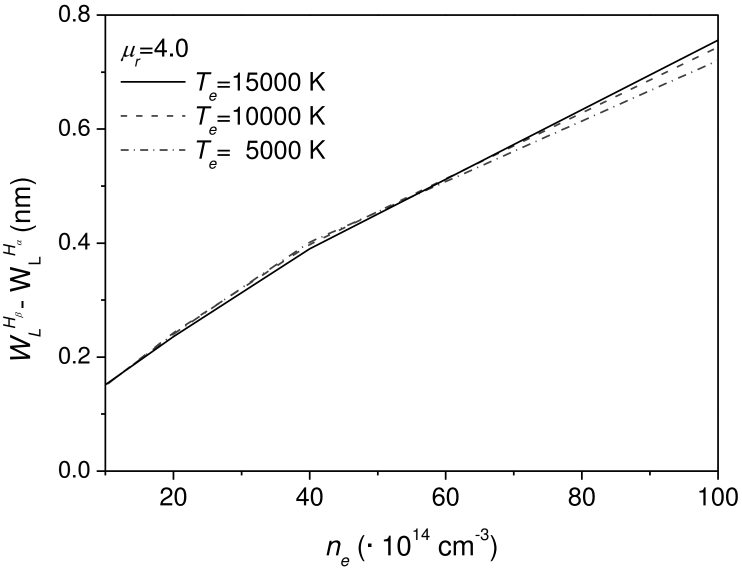

Figure 1. Yubero et al.

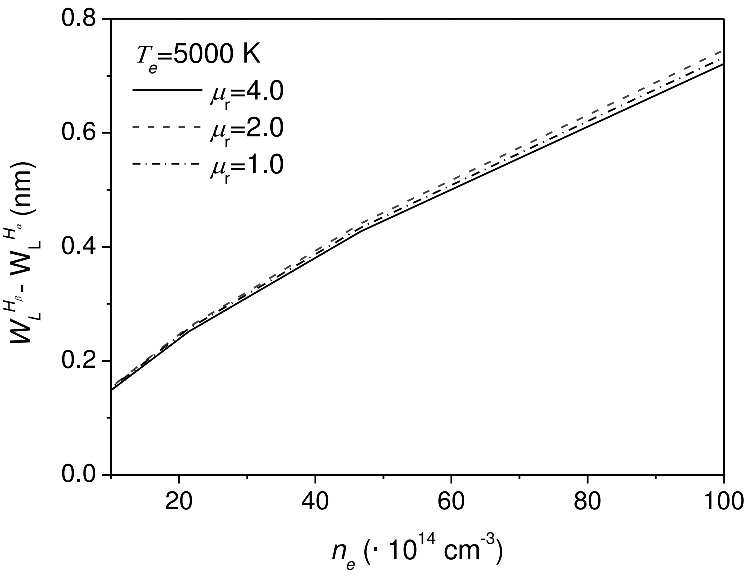

Figure 2. Yubero et al.

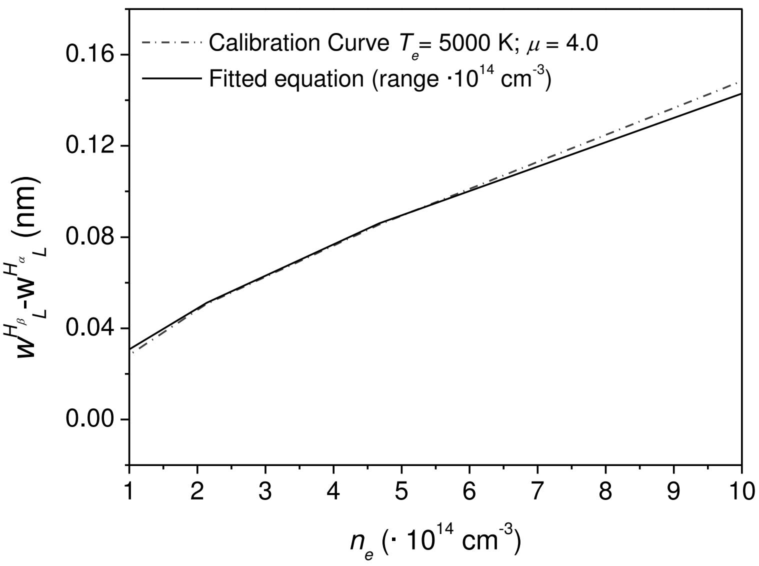

Figure 3. Yubero et al.

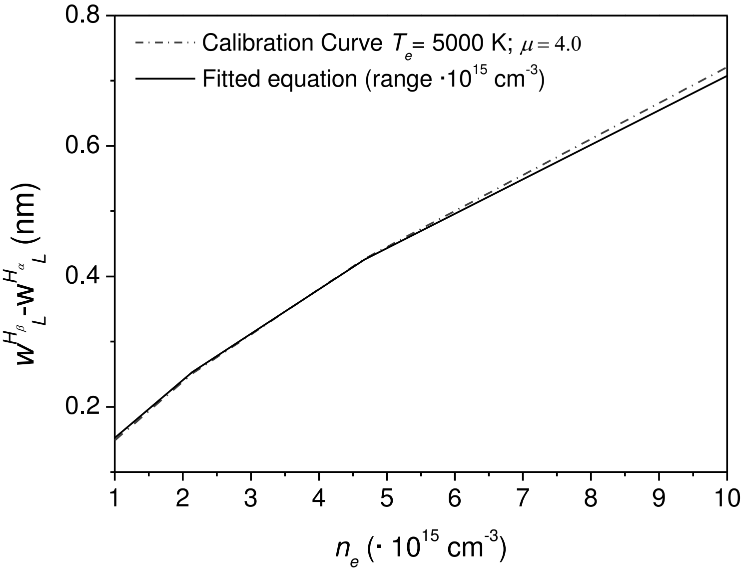

Figure 4. Yubero et al.

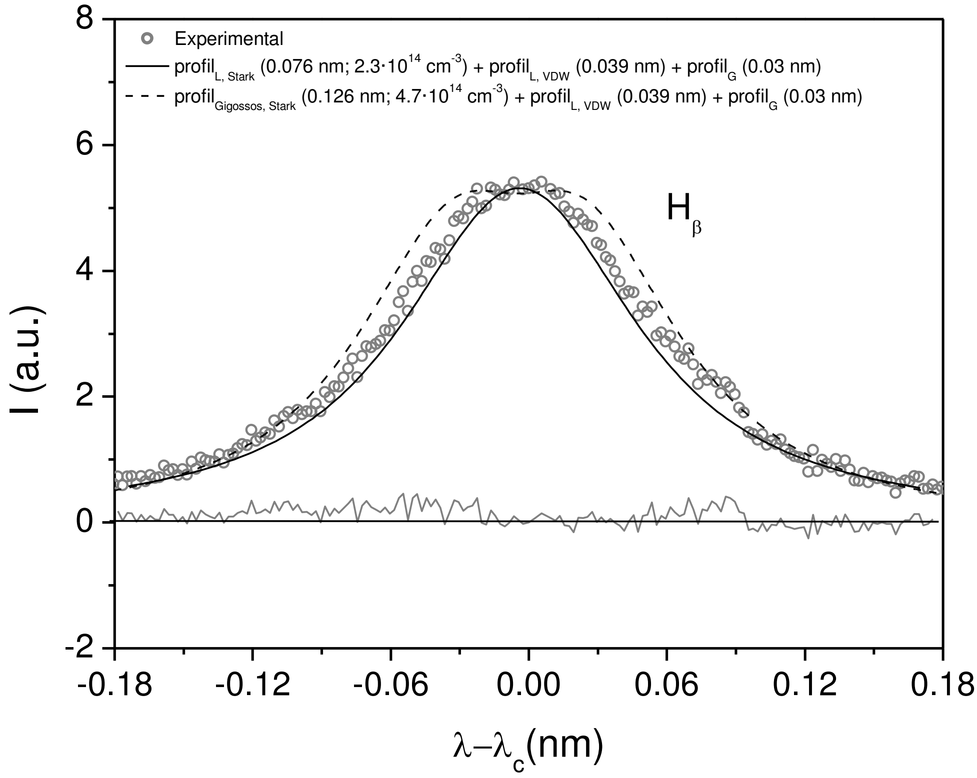

Figure 5. Yubero et al.

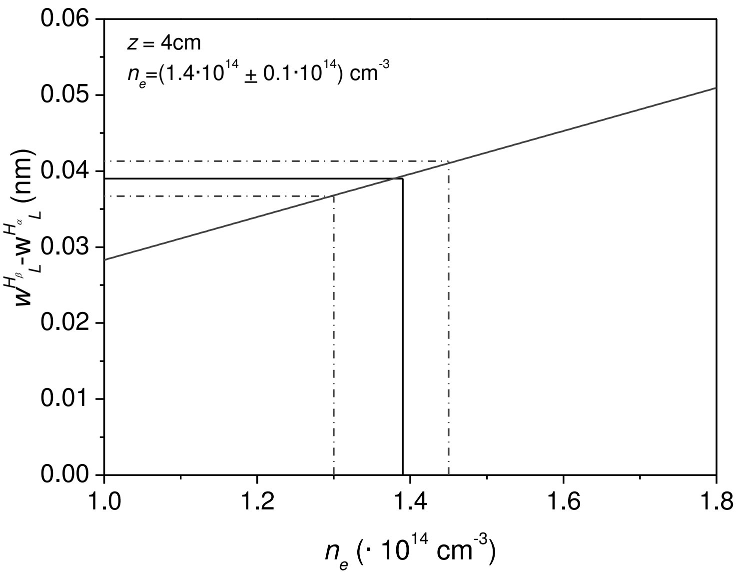

Figure 7. Yubero et al.

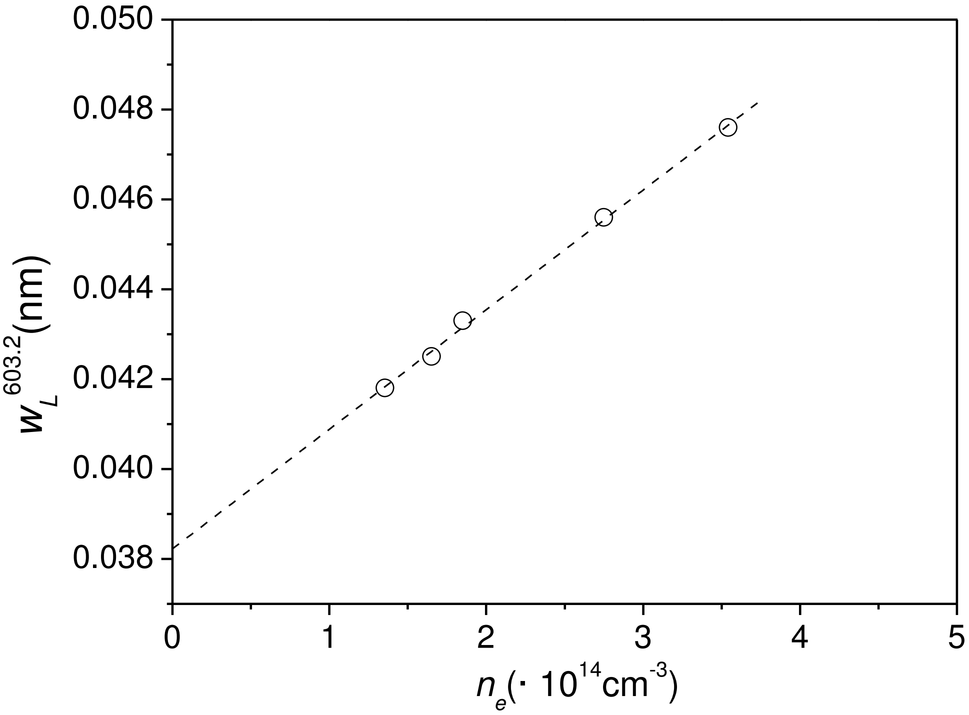

Figure 8. Yubero et al.

T_g	$w_W^{H_\alpha}$ (nm)	$w_W^{H_\beta}$ (nm)
500	0.0740	0.0712
800	0.0533	0.0513
1000	0.0456	0.0438
1500	0.0343	0.0330
2000	0.0280	0.0270
2500	0.0240	0.0231
3000	0.0211	0.0203
3500	0.0189	0.0182
5000	0.0148	0.0142
7500	0.0111	0.0107
10000	0.0091	0.0088
15000	0.0069	0.0066

Table I. Van der Waals broadenings of H_α and H_β lines for different gas temperatures.

n_e (cm^{-3})	T_e (K)	$w_S^{H_\alpha}$ (nm)	$w_S^{H_\beta}$ (nm)
$(1\text{-}10)\cdot 10^{14}$	5000-15000	0.014-0.064	0.042-0.217
$(1\text{-}10)\cdot 10^{15}$		0.058-0.246	0.210-0.997

Table II. Stark broadenings of H_α and H_β lines for different ranges of electron density.

z (cm)	$w_L^{H_\alpha}$ (nm)		$w_L^{H_\beta}$ (nm)		n_e (x10^{14} cm^{-3}) Curve	n_e (x10^{14} cm^{-3}) Eq. (7)
	This work	Ref [11]	This work	Ref [11]		
4	0.055 ± 0.002	0.058 ± 0.009	0.094 ± 0.001	0.091 ± 0.012	1.4 ± 0.1	1.42 ± 0.18
6	0.0565 ± 0.0012	0.059 ± 0.008	0.101 ± 0.001	0.092 ± 0.015	1.68 ± 0.08	1.74 ± 0.13
8	0.0580 ± 0.0011	0.061 ± 0.008	0.106 ± 0.001	0.101 ± 0.015	1.92 ± 0.09	1.95 ± 0.12
10	0.0615 ± 0.0011	0.066 ± 0.009	0.124 ± 0.001	0.117 ± 0.016	2.77 ± 0.12	2.9 ± 0.14
12	0.0634 ± 0.0015	0.068 ± 0.011	0.137 ± 0.002	0.128 ± 0.018	3.5 ± 0.2	3.7 ± 0.3

Table III. Lorentzian widths measured for H_α and H_β lines and electron densities obtained from the method proposed in this paper.

z (cm)	n_e (H_α) ($\cdot 10^{14}$ cm^{-3}) (considering *ww*)	n_e (H_β) ($\cdot 10^{14}$ cm^{-3}) (considering *ww*)	n_e (H_α) ($\cdot 10^{14}$ cm^{-3}) (not considering *ww*)	n_e (H_β) ($\cdot 10^{14}$ cm^{-3}) (not considering *ww*)	n_e (H_β) ($\cdot 10^{14}$ cm^{-3}) *PS method*
4	1.6 ± 0.3	1.51 ± 0.06	8.3 ± 0.6	3.01 ± 0.06	-
6	1.91 ± 0.23	2.10 ± 0.07	8.7 ± 0.4	3.36 ± 0.06	-
8	2.2 ± 0.2	2.43 ± 0.06	9.1 ± 0.3	3.61 ± 0.05	-
10	2.65 ± 0.15	2.73 ± 0.05	10.1 ± 0.3	4.50 ± 0.05	2.8 ± 0.6
12	3.10 ± 0.22	3.63 ± 0.08	10.7 ± 0.5	5.12 ± 0.11	3.2 ± 0.6

Table IV. Electron densities obtained using other methods based on the use of Stark broadening of H_α and H_β [8, 9, 12].