Experimental characterization of the Hβ-line profiles in microwave-produced plasmas at atmospheric pressure

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Abstract. An experimental study on the asymmetry of the Balmer Hβ profile in plasmas produced by microwaves at atmospheric pressure is presented. The study is based on the definition of several functions and parameters that quantify the asymmetry and different shape aspects of the profile. The study shows the experimental dependence of these characteristics on the electron density and control parameters such as the gas flow and the hydrogen admixture ratio. The possible use of these newly introduced profile characteristics to plasma diagnosis is discussed.

1. Introduction

The broadening, shifts and asymmetries of spectral lines emitted by plasmas have been widely studied in the past [1,2]. The spectral line studied most extensively in the past is the Hβ line of the hydrogen Balmer series especially in relation with its function in plasma diagnosis. Most of the experimental and theoretical studies on the asymmetry of the hydrogen spectral lines has been made up for plasmas with electron densities equal or higher than 1023 m-3 [3,4,5] for which one expects this asymmetry to be appreciable. The objective of this work is the study and characterization of the Stark asymmetry and dip formation of the line Hβ at lower electron densities, i.e. in the order of 1021 m-3, and to investigate whether the behaviour of the asymmetry and dip-formation follows a tendency that is consistent with the plasma characteristics. This could point towards new possibilities for plasma diagnosis and might give guidelines for the future theory formation.

2. Characterizing the asymmetry of Hβ profiles

In Figure 1 the most relevant features of the Hβ line is shown. The asymmetry of the Hβ line has been described in several studies (a good and early example is that of Wiese [2]) in a qualitative way the blue peak is higher than the red one, while the red wing is higher than the blue one. Moreover, it is generally accepted that the asymmetry of the profile becomes higher when the electron density is
increased. To make the asymmetry in the profile quantitative, relevant definitions of line aspects have to be introduced. The zero position of the intensity, i.e. the background level has been determined by adjusting the profile wings to an expression of the type $I \propto (\lambda - \lambda_0)^{-5/2}$ [1]. The height of the line is given by $I_{\text{max}}$, the average maximum of the blue and red peak intensities. The width of the line is described by the full-width at half-maximum (FWHM) where the role of the maximum is played by $I_{\text{max}}$. The central position $\lambda_c$ of the $H_\beta$ line is now defined as the centre of this FWHM (cf. Figure 1). We can now introduce functions that quantify the line asymmetry for the line profile for which we have used the following expressions (cf. [3]):

\begin{align}
A_1(\Delta \lambda) &= \frac{I_r(\Delta \lambda) - I_b(\Delta \lambda)}{I_r(\Delta \lambda) + I_b(\Delta \lambda)} \\
A_2(I) &= \frac{\Delta \lambda_r(I) - \Delta \lambda_b(I)}{\Delta \lambda_r(I) + \Delta \lambda_b(I)} \\
A_3(I) &= \frac{\Delta \lambda_r(I) - \Delta \lambda_b(I)}{2}
\end{align}

where $I_r(\Delta \lambda)$ and $I_b(\Delta \lambda)$ are respectively the intensities of the red and blue wings of the profile at a certain displacement $\Delta \lambda$ with respect to the central wavelength, while $\Delta \lambda_r(I)$ and $\Delta \lambda_b(I)$ represent the spectral position of these red and blue sides at a given intensity $I$. From the definitions it follows that the functions $A_1(\Delta \lambda)$ and $A_2(I)$ are dimensionless, while the function $A_3(I)$ has the unit of wavelength; moreover the following equalities are fulfilled: $A_1(\Delta \lambda_{1/2}) = A_2(I_{\text{max}}/2) = A_3(I_{\text{max}}/2) = 0$, $\Delta \lambda_{1/2}$ being the full-width at half-maximum (FWHM).

This study reports on the measurements of $H_\beta$ lines emitted by the TIA plasma (the Torche à Injection Axiale is a device in use for the production of atmospheric plasmas [6]). With this axial injection torch microwave energy with a power of 1000 W at 2.45 GHz has been coupled into an Ar atmospheric flow in which different amounts of hydrogen gas are introduced. The measurement where taken at a fixed axial position of 1 mm above the nozzle’s tip. A detailed description of this setup can be found in [7,8]. In the range of electron densities existing in our plasma ($10^{20}$ m$^{-3}$ – $10^{21}$ m$^{-3}$), the asymmetry of the $H_\beta$ profiles due to the Stark effect is weak. Therefore it is necessary to keep other possible asymmetry sources in mind. The instrumental asymmetry introduced by the optical setup has been calibrated and eliminated of the experimental profiles. The thermal Doppler and van der Waals broadenings are symmetrical and do not introduce asymmetry. The self-absorption is worthless since the $H_\beta$ line is optically thin in our plasma. The internal structure (inhomogeneities) in the observed plasma zone could be of certain importance, but at present these preliminary results show the presence of Stark asymmetry in plasma with electron density of the order of $10^{21}$ m$^{-3}$, even disregarding this structural detail.

![Figure 1. Main characteristic features of the $H_\beta$ line profile: full width at half-maximum (FWHM), spectral separation between dip peaks or full width peak-to-peak (FWPP), intensity difference between peaks, dip depth, dip position.](image-url)
3. Results and discussion

3.1. Influence of the electron density on the asymmetry functions

In figures 2, 3 and 4 the three asymmetry functions corresponding to four Hβ profiles at different electron densities are depicted for the Ar TIA plasma. The experimental settings are a power of 1000 W, an Ar flow of 5 L/min and a concentration of H2 in the range of 2 % – 17 %. The general tendency is that increasing the hydrogen admixture ratio reduces the electron density. The values of electron density are calculated using the FWHM-Stark broadening of the Hβ lines and the computational results provided by Gigosos et al [9]. The relative error for the electron density calculated in this work remains less than 10 %. These figures show the asymmetry-functions give a clear response to the variation of $n_e$ and that they follow a coherent behavior (the asymmetry increases with the electron density) in the wings of the profiles ($I < 0.5I_{max}$ and $\Delta \lambda < 0.5\Delta \lambda_{1/2}$). It can be seen that $A_1(\Delta \lambda)$ is much more irregular that the other two. Also, that the wing-side of the $A_2(I)$ is less sensitive to $n_e$-variations than the function $A_3(I)$.

![Figure 2](image-url)

**Figure 2.** Function of asymmetry $A_1(\Delta \lambda)$ of the Hβ profile at 5 L/min of Ar flow, 1000 W of HF power and different electron density values.

![Figure 3](image-url)

**Figure 3.** Function of asymmetry $A_2(I)$ of the Hβ profile at 5 L/min of Ar flow, 1000 W of HF power and different electron density values.

![Figure 4](image-url)

**Figure 4.** Function of asymmetry $A_3(I)$ of the Hβ profile at 5 L/min of Ar flow, 1000 W of HF power and different electron density values.

3.2. Influence of the gas flow in the asymmetry functions

The internal structure of the plasma flame provided by the TIA strongly depends on the gas flow and it’s well known fact that the line shape is affected by the presence of gradients in the discharge and therefore the gas flow could affect the asymmetry and shape of Hβ. This has been studied further using the next set of figures that were obtained for 5 L/min and 1 L/min of Ar flow. In figures 5 and 6 we show the central valley and the corresponding $A_3(I)$ function with an H2 concentration chosen to kept electron density constant. In figures 7 and 8 the concentration of H2 has been kept constant.
and 7 show how the dip changes when the flow is decreased from a normal asymmetry to an inverse or anomalous asymmetry in which the red peak is higher than the blue one. In figures 6 and 8 the corresponding $A_3(I)$ functions show how the anomaly in the asymmetry for the case of lower flow also alters the spectral form of the whole profile from 60 % of $I_{\text{max}}$ up. A possible explanation is that the reduction in the gas flow affects the internal structure of the plasma introducing higher inhomogeneities.

![Figure 5](image_url) **Figure 5.** Detail of the central valley at two different gas flux, 5 L/min and 1 L/min, maintaining the electron density = $1.7\times10^{21}$ m$^{-3}$.

![Figure 6](image_url) **Figure 6.** Asymmetry function $A_3(I)$ at two different gas flux, 5 L/min and 1 L/min, maintaining the electron density = $1.7\times10^{21}$ m$^{-3}$.

![Figure 7](image_url) **Figure 7.** Detail of the central valley at two different gas flux, 5 L/min and 1 L/min, maintaining the $\text{H}_2$ concentration = 5 %.

![Figure 8](image_url) **Figure 8.** Asymmetry function $A_3(I)$ at two different gas flux, 5 L/min and 1 L/min, maintaining the $\text{H}_2$ concentration = 5 %.

3.3. Specific characterization of the $H_\beta$ dip shape

In this section other specific parameters have to be constructed in order to study the central valley of $H_\beta$. The measurements were done at 1000 W of HF power, changing the concentration of hydrogen from 17 % (lower electron density) to 2 % (higher electron density) in plasmas generated with Ar flows of 5 L/min and 2.5 L/min.
3.3.1. Spectral separation between peaks (full-width peak-to-peak, FWPP) and dip depth (DD)

The values of $FWPP = \lambda_{rp} - \lambda_{bp}$ and $DD$ (normalized to the maximum of intensity: $(I_{\text{max}} - I_{\text{dip}}) \times 100/I_{\text{max}}$) by themselves do not provide any direct information about the asymmetry, however they provide information of the shape and the H$_β$ line structure as the spectral distance between peaks and the dip depth are directly related to the internal distribution or separation of the line-components. In figures 9 and 10 the values obtained for these two parameters as a function of the electron density are depicted. It is shown that these parameters follow an increasing dependence on the electron density which is less pronounced when the gas flux is higher.

![Figure 9](image1.png)  
**Figure 9.** Experimental values of the $FWPP$ as a function of the electron density for 5 L/min and 2.5 L/min of Ar flow and 1000 W of HF power.

![Figure 10](image2.png)  
**Figure 10.** Experimental values of the $DD$ as a function of the electron density for 5 L/min and 2.5 L/min of Ar flow and 1000 W of HF power.

3.3.2. Intensity difference between peaks (PID) and spectral dip position (DP)

Next, we introduce the values of $PID$ (normalized to the maximum intensity: $(I_{bp} - I_{rp}) \times 100/I_{\text{max}}$) and $DP$ (normalized to the $FWPP$: $(\lambda_{dip} - \lambda_{bp}) \times 100/(\lambda_{rp} - \lambda_{bp})$). These parameters give us direct information on the asymmetry in the central valley since they compare characteristic of the blue and

![Figure 11](image3.png)  
**Figure 11.** Experimental values of the $PID$ as a function of the electron density for 5 L/min and 2.5 L/min of Ar flow and 1000 W of HF power.

![Figure 12](image4.png)  
**Figure 12.** Experimental values of the $PID$ as a function of the electron density for 5 L/min and 2.5 L/min of Ar flow and 1000 W of HF power.
red sides of the dip. The normal asymmetry of the Hβ line is that blue peak is more intense than the red one \((PID > 0\%)\) and that the dip is closer to the red peak \((DP > 50\%)\). Figures 11 and 12 show the experimental values of \(PID\) and \(DP\). These last two parameters show a much larger scatter; thus they do not follow a clear tendency as a function of the electron density. The influence of the internal structure fluctuation is then appreciable in this representation, and could explain the great dispersion of the points, particularly the appearance of some negative values concerning the anomalous or inverse asymmetry (under the dashed line).

4. Conclusions

In this experimental study, the asymmetry concerning the spectral profiles of the Balmer Hβ line has been experimentally characterized in high-pressure, microwave plasmas produced by the TIA device in which the electron density reaches a value of \(10^{21}\) m\(^{-3}\), which implies a considerably lower value than in previous characterizations \(10^{23}\) m\(^{-3}\) or higher. The asymmetry has been studied with the help of some asymmetry functions for the flanks of the profile, including the wings. It has been shown how the asymmetry of the profiles increases with the electron density in the discharge, which is coherent with the known behavior for the studied line. With respect to the gas flux influence, is detected that at low enough gas flux strange or anomalous values of the asymmetry have been measured for which the red side of the profile is more intense than the blue one.

For the central valley or dip, specific functions charactering its shape have been used. The spectral distance between peaks, \(FWPP\), and the dip depth, \(DD\), exhibit a clear and bare increasing (quasi-linear) dependence on the electron density, less pronounced at a higher gas flux. The other two functions giving direct information about the central valley asymmetry i.e. the difference of intensity between peaks, \(PID\), and the spectral position of the dip, \(DP\), are significantly affected by the fluctuations in the plasma. In some cases, when the gas flux drops enough, it can end up inverting the normal tendency of the profile asymmetry, giving rise to the so-called anomalous asymmetry in which the blue peak of the Hβ is less intense than the red one.

From a practical point of view, the \(FWPP\) and \(DD\) seem to be good candidates for the determination of the electron density since their \(n_e\)-dependence shows almost no scatter.

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