

## POLYDIAGNOSTIC STUDY ON A SURFATRON PLASMA AT ATMOSPHERIC PRESSURE

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### Introduction and experimental setup

In this paper, spectroscopic measurements performed on a microwave induced plasma (MIP), created by a surfatron, are presented. The plasma is generated at atmospheric pressure using Ar as the main gas; H<sub>2</sub> is introduced as an additive (0%-3%). A poly-diagnostic study is applied at different plasma conditions. The poly-diagnostic refers to a procedure, that the same plasma quantity is measured for the same plasma conditions and locations, using more than one method quasi-simultaneously. The aim of the present study is to compare and calibrate different passive and active spectroscopic techniques in a similar way as it was done in [1] for the case of low pressure surfatron plasma.

Electromagnetic waves are generated in a Muegge magnetron which operates with maximum power of 300 W. The frequency of the microwaves is fixed at 2.45 GHz. The microwaves are coupled into the plasma via the launcher device surfatron [2]. The plasma is contained inside a capillary quartz tube through which the surface waves propagate sustaining the discharge. Approximately 1cm after the surfatron's gap the tube finishes and the plasma expands in the open air at atmospheric pressure. This results in flame-like plasma similar to those obtained in the microwave plasma torch (MPT) or axial injection torch (TIA, *Torche à Injection Axiale*). The diagnosis takes place 1mm after the end of the tube at three plasma conditions: pure Ar and 74 W of applied power, Ar + 0.3% of H<sub>2</sub> and 88 W, and Ar + 0.3% of H<sub>2</sub> and 57 W power.

### Active spectroscopy

Two active laser techniques are applied, Rayleigh Scattering (RS) and Thomson Scattering (TS). The detection setup used for both techniques is described in detail in [3]. The only difference is that in order to measure the TS signal first the RS signal must be filtered out with the help of the triple grating spectrograph (TGS). These active methods are used to measure the gas temperature,  $T_g$ , (via RS) and the electron density and temperature,  $n_e$  and  $T_e$ , (via TS).

Both methods give results with good precision and with spatial resolution, which allow us to obtain the radial profiles of the magnitudes and to determine the diameter of the plasma. In figure 1, the radial profiles of  $n_e$  and  $T_g$  are shown. It is observed that the introduction of  $H_2$  reduces the values of electron density and gas temperature. The radial results for  $n_e$  (figure 1a) show how the plasma becomes smaller and with a sharper profile with the addition of  $H_2$ . The radial results for  $T_g$  (figure 1b) show a wider profile with a smoother decay with and without impurities. The TS measurements were repeated at different laser powers in order to study possible plasma perturbations. While the values of  $n_e$  were constant for any laser power, the values of  $T_e$  showed an increase around 50% for the laser power used during the measurements. The electron heating due to inverse bremsstrahlung in the surroundings of an ion has been calculated and it is smaller than 3% [4], what is in contradiction with the experimental observations. A possible explanation lays on a more important role of the electron-atoms interactions for the case of atmospheric plasmas. This effect would not be of great importance for the cases of low pressure surfatron [3] where the atom density is much lower and no electron heating has been detected during TS experiments.

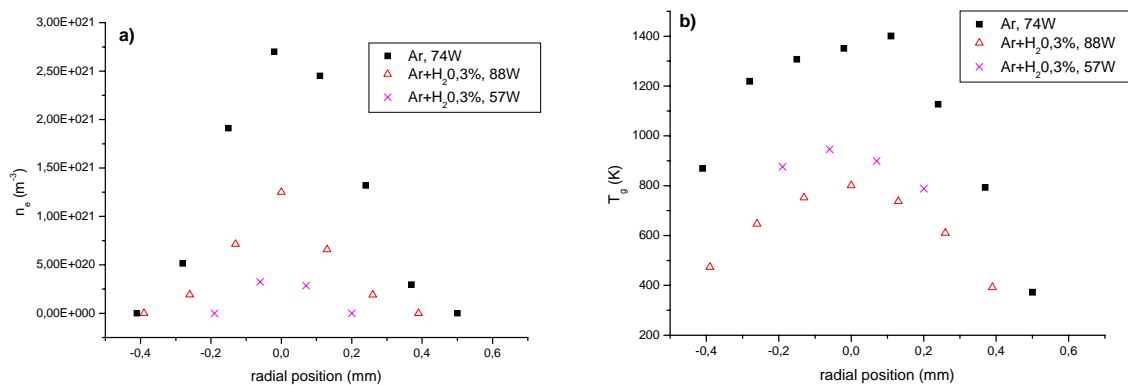


Figure 1: radial profiles of  $n_e$  (a) and  $T_g$  (b) for the different plasma conditions. The plasma diameter obtained is 0.63mm for the condition of pure Ar, 0.4mm for the case of 0.3% of  $H_2$  and 88 W, and 0.23 mm for the case of 0.3% of  $H_2$  and 57 W.

### Stark broadening

The detection setup used for the passive spectroscopic techniques is described in detail in [1]. This detection setup is based on a double Echelle monochromator (DEMON) that provides high resolution spectrums with a small instrumental broadening. Stark broadening measurements have been carried out for the  $H_\beta$  line of the Balmer series of hydrogen to obtain the value of  $n_e$ . The Doppler and van der Waals contributions to the line broadening are calculated for the gas temperature obtained with the RS measurements, the instrumental contribution is obtained from calibration measurements. Once these contributions are

deconvoluted from the experimental line profile  $n_e$  is obtained with the help of the computer simulations of Gigosos et al [5].

### **Absolute Intensity Measurements**

In [6] a method is introduced for the determination of  $T_e$  as a (weak) function of  $n_e$ . It is based on the combination of passive spectroscopy, absolute intensity measurements of Ar lines, and a Collisional Radiative Model (CRM). The CRM supports the interpretation of the measurements and accounts for the influence of the departure from equilibrium on the density of the excited states.

In [7] a method is introduced for the determination of  $n_e$  as a function of  $T_e$ . This method, denoted by Absolute Continuum Intensity (ACI) measurements, is based on the absolute value of the continuum radiation. It is applied to argon plasmas with a low degree of ionization so that extra attention had to be paid to the continuum radiation as originated by electron-atom collisions.

In [8] the method of the Absolute Intensity Measurement (AIM) is presented for the first time. The AIM is a new method that combines the absolute measurements of spectral lines and the continuum radiation emitted by strongly ionizing argon plasmas in an iterative procedure to obtain simultaneously  $T_e$  and  $n_e$ .

### **Results and discussion**

In table 1, the results obtained with passive methods (Stark broadening and AIM) and active laser spectroscopy (TS and RS) are presented. The results shown in table 1 for TS and RS measurements are obtained integrating the signal coming from all the radial positions.

There is good agreement between the  $n_e$  results obtained with TS and those obtained with the Stark broadening of the line  $H_\beta$ , thus proves the quality and precision of both methods under the present plasma conditions. For lower electron densities there is a deviation due to a decreasing of the Stark contribution to the total line broadening, this makes the deconvolution more complicate and introduces the error. On the other hand there is a discrepancy with the results provide by AIM. Similar trends were found in [1], in that study the continuum measurements proved to give lower results for the electron density.

The results of  $T_e$  obtained with AIM can not be compared with the TS measurements. This is due to the electron heating induced by the laser-electron interactions. Under this condition the electron temperatures obtained with TS technique are not valid. Nevertheless, in [1] the values of  $T_e$  obtained with CRM (as used in AIM) were in a good agreement with TS results.

In [9, 10] passive and active spectroscopic techniques were applied to the TIA using pure Ar, with gas flows around 1slm and applied power in the range of 100 W-600 W. In those studies

the electron densities were found to be in the order of  $2 \cdot 10^{21} \cdot \text{m}^{-3}$  and the electron temperatures in the range 1.4 eV–1.8 eV. Even if a direct comparison is not possible between our setup and the TIA, it is clear that our results for  $n_e$  obtained with TS and Stark broadening are in a good agreement with previous studies. For the case of  $T_e$  the results provided by AIM are in the same order of magnitude, but they show lower values. In a future work a different laser system will be implemented in order to allow  $T_e$  determination via TS and to calibrate the AIM method completely.

method	$T_g$ (K)	$n_e$ ( $\text{m}^{-3}$ )			$T_e$ (eV)
	RS	TS	Stark broadening	AIM	AIM
Ar flow = 1,45slm H <sub>2</sub> % = 0% power = 74W	1300	$1,52 \cdot 10^{21}$	$1,1 \cdot 10^{21}$	$3,42 \cdot 10^{20}$	1,16
Ar flow = 1slm H <sub>2</sub> % = 0,3% power = 88W	750	$5,96 \cdot 10^{20}$	$6,04 \cdot 10^{20}$	$2,75 \cdot 10^{20}$	0,97
Ar flow = 1slm H <sub>2</sub> % = 0,3% power = 57W	950	$3,03 \cdot 10^{20}$	$1,65 \cdot 10^{20}$	$2,21 \cdot 10^{20}$	0,95

Table 1: Results for the present study. The passive spectroscopy measurements were taken collecting the light coming from a plasma zone centred 1mm after the end of the surfatron tube. For the active spectroscopy the laser was centred exactly at 1mm after the end of the surfatron tube.

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