

Optical Emission Spectroscopy diagnostics of helicon plasma thruster operating with Argon

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Y. Babou ^{*}, M. Wijnen [†], J. Navarro Cavalle [‡], P. Fajardo Peña [§], O. Masset [¶] and E. Ahedo Galilea ^{||}
Universidad Carlos III de Madrid, Leganés, Madrid, 28911, Spain

Argon plasma generated by a Helicon Plasma Thruster (HPT) is characterized by means of Optical Emission Spectroscopy diagnostic. The adopted arrangement allowed to probe the plasma in a region not accessible to conventional probes, namely in the region of generation by radio-frequency heating and the region of confinement by the magnetic field. The absolute number densities of the $3p^5 4s$ levels of Ar I and their variation with operating settings has been determined by means of the branching ratio method, which is independent on the knowledge of excitation processes, hence bypassing the substantial lack of data on excitation cross-sections affecting the reliability of traditional Collisional-Radiative models. The increase of applied radio-frequency power from 200 to 900 W leads to a decrease of the population densities. Also depending on the region of magnetic field application, its augmentation leads to opposite evolution of the population densities. The excitation temperature of electronic levels of argon neutral and ion has been estimated on the basis of the conventional Boltzmann plot method. The excitation temperature of argon ion of about 14000-16000 K was found two times higher than the one of argon neutral. Starting from these measurements and on the basis of simple model, it was possible to obtain a fair estimation of the electron temperature achieved by HPT operating with argon, to be of $\sim 6 - 8$ eV.

I. Introduction

ELECTRIC propulsion systems based on helicon radio-frequency plasma source, are a promising step in the technological evolution of electric propulsion (offering electrode-less operation and achieving high ionization degree).¹ However such systems still require substantial improvement and optimization that rely on dedicated experimental investigations undertaken by means of well-suited ground facilities. Numerous diagnostic methods can be adopted to measure the physical quantities relevant to characterize the plasma production its confinement and acceleration obtained with the Helicon Plasma Thruster (HPT). As a rule, particle density, energy distribution and flux are obtained in a standard manner by means of probes (electrostatic/Langmuir, Faraday, etc). Although well-suited for the plume region, such intrusive diagnostics are less applicable to the internal part of a thruster, where any probe would irretrievably perturb the plasma production and transport processes. Optical diagnostics, by nature being non-intrusive, overcome the inherent drawbacks of probes (and other intrusive diagnostics) and therefore they present a valuable alternative for plasma characterization. Nowadays, the Optical Emission Spectroscopy (OES) technique is commonly applied to probe the excited state densities and rebuild the plasma excitation temperature almost effortlessly,

^{*}Visiting Professor, Bioengineering and Aerospace Engineering, ybabou@ing.uc3m.es

[†]Ph.D. candidate, Bioengineering and Aerospace Engineering, mwijnen@pa.uc3m.es

[‡]Scientist, Bioengineering and Aerospace Engineering, janavarr@pa.uc3m.es

[§]Professor, Bioengineering and Aerospace Engineering, pfajardo@ing.uc3m.es

[¶]Visiting Ms.candidate, University of Rouen, France

^{||}Full Professor, Bioengineering and Aerospace Engineering, eduardo.ahedo@uc3m.es

providing an adequate optical access. Then ion density and electron temperature can be estimated by means of appropriate processing of the measured plasma spectral intensities.

The present work addresses the characterization by means of low resolution OES of the plasma produced by the HPT developed jointly by SENER Spanish company and the Space Propulsion and Plasmas research group at Universidad Carlos III de Madrid. This contribution reports the experimental investigations conducted to characterize the HPT operating with argon under various operating conditions. Starting from measured spectral intensities of argon plasma, the investigations are intended to provide a meaningful picture of the evolution of the plasma parameters in the region of coupling with radio-frequency power and magnetic field intensity, especially where probe measurements are prohibited. The details of the diagnostic setup is provided in Section II. In Section III are described the methods adopted to determine excitation temperature of Ar I and Ar II electronic levels and the absolute population density of the four levels belonging the Ar I $3p^5 4s$ group. The results obtained for three distinct measurement campaigns are reported in Section IV and followed by a short discussion on the HPT performances in Section V.

II. Experiments

A. Helicon Plasma Thruster

The Helicon Plasma Thruster that was characterized is the HPT-05 prototype that is developed jointly by SENER company and the Space Propulsion and Plasmas research group at University of Carlos III, Madrid. The HPT-05 consists of a 30 mm diameter quartz tube which is closed at one end with a custom ceramic injector plate. Two electro-magnets in a Helmholtz configuration provide an approximately axial magnetic field inside the tube of up to 800 G. A third electro-magnet close to the exit of the tube creates a convergence-divergence of the magnetic field that acts as a magnetic nozzle. Situated in between the main magnets is double-loop antenna that can be operated in the 0.1-1 kW range at a frequency of 13.56 MHz. A propellant feed line connected to the injector plate can provide either Argon or Xenon with a nominal mass-flow rate of 50 sccm. The prototype was designed to be a modular test-platform where the influence of many operational parameters can be studied. Chamber length, mass-flow rate, RF power, propellant type and magnetic field configurations can all be modified. A photograph of the HPT-05 is proposed in Figure 1 and more detailed design of the thruster can be found in.²

B. Optical Emission Spectroscopy measurements

The spectral intensity of the plasma in its region of generation and confinement has been measured by means of a simple optical emission spectroscopy setup. The plasma emission is collected by means of an optical collimator consisting of channel of 50 mm length and 1 mm diameter. The plasma intensity collected by the collimator is transmitted to an optical fiber connected to a spectrometer Ocean Optics HR4000 well-suited to record the light in the UV, visible, and near infrared domains with a typical spectral resolution of about 1 nm. The adopted optical arrangement is schemed in Figure 1.

In a first step, the collimator was setup inside the chamber to collect the radial emission of the plasma in the RF antenna coil region. With the application of the magnetic field by powering either the circular electro-magnet S1 or S2, the bright blue plasma emission, following on to Ar II emission in the range ~ 400 -500 nm, was clearly observable in the region of electro-magnets. However, this blue plasma remained at the vicinity of the electro-magnets and was not measured when collimator was arranged to collect the radial intensity from the RF coil antenna region (as illustrated on the Figure 1 with well separated blue and pink colors). Therefore, in order to record also the intensity due to Ar II electronic transitions (produced subsequently to the application of the magnetic field), the optical collimator was located outside the chamber to collect the intensity integrated along the plasma column axis in the quartz tube. The measured spectral intensities were calibrated in relative units with the spectral response determined for the resulting arrangement, approximated to the response of the spectrometer with its optical fiber (the spectral transmission of the quartz tube and of the axial window remains constant in the considered spectral range). The calibration was conducted by means of Deuterium-Halogen light source Ocean Optics DH-2000-CAL with its documented irradiance.

The typical spectra measured with both configurations are respectively plotted in the Figure 2. The spectral emission recorded radially at the RF antenna coil region does not exhibit any substantial contribution of Ar II emission lines. Only a very weak contribution can be seen typically for power above 500 W, and is shown in the in inserted plot in the case of 900 W. Using the axial collection arrangement (with the collimator

located outside the chamber), the Ar II emission lines start to be clearly observed with the application of the magnetic field, and this happens only when the electro-magnets, either S1 or S2, are powered, even with low intensity current. For 3 A current intensity, Ar II emission lines are clearly observable and recorded, and for higher values argon ion emission in the range $\sim 400\text{-}500\text{ nm}$ becomes of the same order of argon neutral emission lying above 600 nm .

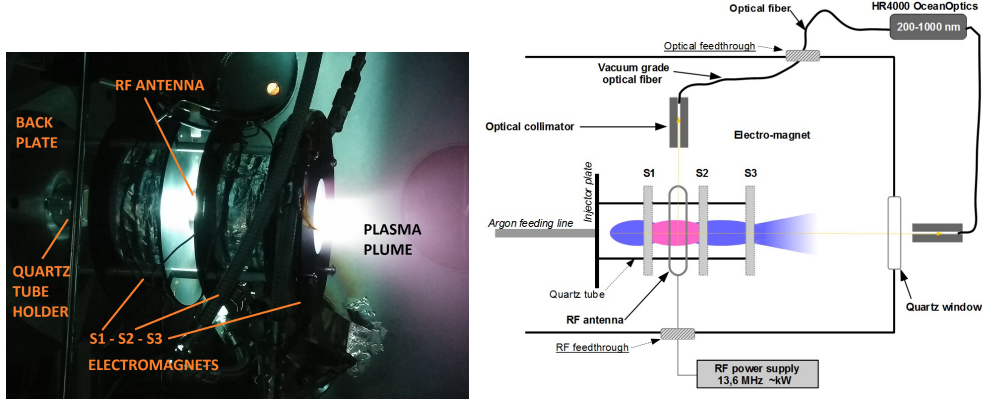


Figure 1. Left: photograph of HPT-05 thruster operating with Xenon. Right: scheme of the optical diagnostic setup.

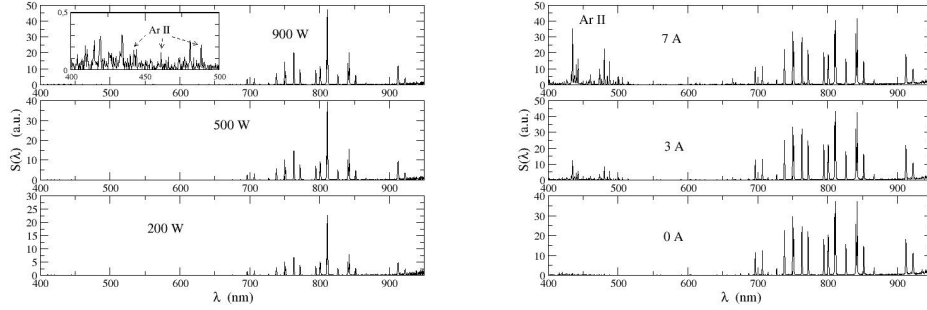


Figure 2. Spectral intensities. Left: only RF-power is applied. Right: with application of magnetic field intensity with S1 electro-magnet.

III. Methods of plasma characterization

The excitation temperature and the population density of the argon plasma are derived from photon rates measured for various electronic transitions of neutral and ion species. For a given transition $i \rightarrow j$, the rate of photons Φ_{ij} at position $\mathbf{r}$ that reach a photo-detector is given by the product of the population density of the upper state $n_i(\mathbf{r})$, the Einstein coefficient A_{ij} , the escape probability $\theta_{ij}(\mathbf{r})$ and the fraction of the solid angle seen by the detector $c(\mathbf{r})$:

$$\Phi_{ij}(\mathbf{r}) = c(\mathbf{r})\theta_{ij}(\mathbf{r})A_{ij}n_i(\mathbf{r}), \quad (1)$$

where the escape probability accounts for photon re-absorption along the optical path which connects $\mathbf{r}$ and the detector location. In the case of line-of-sight intensity measurements, the averaged photon rates can be then expressed as:

$$\overline{\Phi_{ij}} = \overline{c\theta_{ij}n_iA_{ij}}, \quad (2)$$

Table 1. Ratio of lines used in the branching ratio method.

$2p_2 \rightarrow 1s_5$	$2p_2 \rightarrow 1s_4$	$2p_3 \rightarrow 1s_5$	$2p_3 \rightarrow 1s_3$	$2p_4 \rightarrow 1s_3$
$2p_2 \rightarrow 1s_2$	$2p_2 \rightarrow 1s_2$	$2p_3 \rightarrow 1s_2$	$2p_3 \rightarrow 1s_2$	$2p_4 \rightarrow 1s_2$

where the bar designates quantities averaged over the volume probed by the photo-detector.

In practice, the $\overline{\Phi_{ij}}$ is determined from spectral intensity records by integrating the spectral line and removing the contribution of the background. Because the intensity has been measured at low spectral resolution in the present work, such processing has to be cautiously performed to account for the contribution of neighboring line edges that would need to be removed. We adopted the approach proposed by Shicong Wang *et al.*³ that provides satisfactory results.

A. Metastable density

The absolute number densities of atoms in metastable and resonance levels are determined by means of branching ratio approach. Considering only two transitions, involving the same upper level i , that decay to two distinct lower levels j and k , the effective branching ratio evaluated from photon rate measurements is expressed as:

$$\frac{\overline{\Phi_{ij}}}{\overline{\Phi_{ik}}} = \frac{\gamma_{ij}A_{ij}}{\gamma_{ik}A_{ik}}, \quad (3)$$

where the escape factor $\gamma_{ij} = \overline{c\theta_{ij}n_i}/\overline{c\bar{n}_i}$, designates the averaged emission intensity weighted escape probabilities and ranges in the interval 0-1; being close to 0 for high opacities, and close to 1 in the optically thin regime.

Since the intensity ratio of two different lines with the same upper level does not depend on the population of the upper level, it comes out that, the effective branching only depends on the Einstein coefficients and to the radiation trapping stemming to the self-absorption described by the escape factor.

The exact evaluation of the escape factor is tedious in practice since it depends explicitly on the distribution of low level number densities n_j , the gas temperature T_g and the plasma extent L ($\gamma_{ij}(n_j, T_g, L)$). Note that the escape factor determination does not depend on the collisional processes. Hence, the diagnostic idea is to exploit this branching ratio to determine the population densities of the lower level. Selecting a judicious set of pairwise transitions it is possible to obtain a functional relation between photon rates ratio and the density of the lower states involved in the branching ratio through the escape factor.

In the current work, we adopted the method proposed by Schultze *et al.*⁴ for the transitions occurring between $3p^54s$ and $3p^54p$ of levels of argon. On the basis of only 8 emission lines, a set of algebraic equations is created by combining several line ratios with pairwise common radiating levels (for detail see associated reference⁴). Leaning on their approach, the escape factor is evaluated assuming a homogeneous density profile for the radiating state and gas temperature, i.e. $n_i(\mathbf{r}) = \text{constant}$ and $T_g(\mathbf{r}) = \text{constant}$. In than frame, the calculation of the escape factor is abridged using the analytical expression of Mewe⁵ which stands for a good analytical approximation to the exact escape factor for uniform excitation profiles:

$$\gamma_{ij} \approx \frac{2 - \exp(-10^{-3}\kappa_{ij}(\Delta\nu = 0)L)}{1 + \kappa_{ij}(\Delta\nu = 0)L}, \quad (4)$$

with L designating the depth of the plasma volume probed by the photo-detector and the absorption coefficient κ_{ij} evaluated at the central frequency $\Delta\nu$ is defined as:

$$\kappa_{ij}(\Delta\nu = 0) = \frac{\lambda_{ij}^3}{8\pi} \sqrt{\frac{m}{2\pi k_B T_g}} \frac{g_i}{g_j} \bar{n}_j A_{ij}. \quad (5)$$

As a result, the densities of the metastable levels n_{1s_3} and n_{1s_5} and of the resonant levels n_{1s_2} and n_{1s_4} are determined on the basis of the five line ratios listed in Table 1. The resulting system of equations for the four unknown densities has been solved using the method of nonlinear least squares available under MATLAB environment. By using more line ratios than unknowns, the reliability of the least squares fit is enhanced and the influence of noise in the input data is alleviated.

Note that the output of this method is the line integrated population densities $n \cdot L$, expressed in m^2 and requires the knowledge of the gas temperature. In the followings, we assume that the gas is at room temperature of 300 K. Nevertheless, we evaluated the sensitivity of the method to the uncertainty on T_g by determining the population densities for $T_g=400$ and 500 K. The resulting population densities obtained for a typical experimental conditions, reported in Figure 3, show that the difference with respect to 300 K is of about 15 and 30 %.

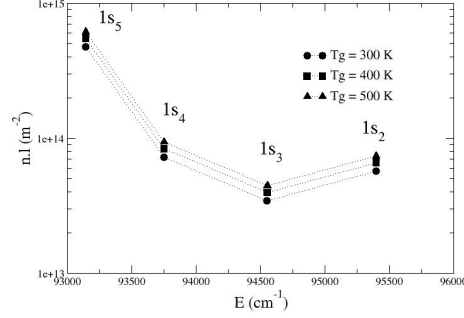


Figure 3. Effect of T_g value on resulting absolute density populations.

B. Excitation temperature

The characterization in terms of excitation temperature T_{ex} is performed on the basis of the Boltzmann plot method. Considering only two transitions, involving distinct upper level i and k , and decaying respectively to lower levels j and l , the line ratio evaluated from photon rate measurements is expressed as:

$$\frac{\overline{\Phi_{ij}}}{\overline{\Phi_{kl}}} = \frac{\overline{n_i} A_{ij}}{\overline{n_k} A_{kl}}, \quad (6)$$

where the escape probabilities, with respect to Eq. 2, are approximated to one. In contrary to the previous method, such approximation stems to the fact that the line ratio involve distinct upper levels hence, in the present conditions of optically thin plasma, the line ratio is weakly dependent on small variation of opacity.

Assuming that collisional processes governing the population of the upper level of a given transition of energy E_u are in equilibrium, the population density is determined by means of the Boltzmann distribution expressed as:

$$n_u = \frac{N}{Q_{int}} g_u \exp\left(-\frac{E_u}{k_B T_{ex}}\right), \quad (7)$$

with N , Q_{int} and g_u designating respectively the species concentration, the internal partition function and the degeneracy of level u .

Injecting the latest expression in 6, the excitation temperature is then obtained from the line ratio as:

$$T_{ex} = -\Delta E_{ik}/k_B \times \ln\left(\frac{\overline{\Phi_{ij}}}{\overline{\Phi_{kl}}} \cdot \frac{g_k}{g_i}\right)^{-1}, \quad (8)$$

where $\Delta E_{ik} = E_i - E_k$ is the difference between upper energy levels. Assuming a critical uncertainty of 10 % on photon rate measurements, the error on T_{ex} determination might be roughly evaluated as $\Delta T_{ex}/T_{ex} \approx 10 \times T_{ex}/(1.44 \Delta E_{ik})$ (with temperature expressed in Kelvin and energy in cm^{-1}). Hence the higher is the energy difference, or energy range, the more accurate is the temperature determination.

Accounting for the great number of emission lines, the excitation temperature is obtained by using photon rates measured for a broad set of transition involving upper levels covering a large energy range. The temperature is then determined by means of a straight line fitting on the distribution of the measured photon rates as:

$$\ln\left(\frac{\overline{\Phi_{ij}}}{g_i}\right) = \frac{E_i}{k_b} \cdot \frac{1}{T_{ex}} + \ln\left(\frac{N}{Q}\right) \quad (9)$$

Table 2. Spectroscopic data of argon lines⁶ used for the calculation of excitation temperatures.

Transition	Wavelength (nm)	A_{ul} (s ⁻¹)	E_{ul} (cm ⁻¹)	g_u
$3p_1 \rightarrow 1s_2$	425.9362	3.98e+06	118870.9170	1
$4d_3 \rightarrow 2p_{10}$	675.2834	1.93e+06	118906.6110	5
$4d_5 \rightarrow 2p_{10}$	687.1289	2.78e+06	118651.3950	3
$2p_2 \rightarrow 1s_5$	696.5431	6.39e+06	107496.4166	3
$3s_4 \rightarrow 2p_9$	703.0251	2.67e+06	119683.0821	5
$2p_3 \rightarrow 1s_5$	706.7218	3.80e+06	107289.7001	5
$2p_4 \rightarrow 1s_5$	714.7042	6.25e+05	107131.7086	3
$2p_2 \rightarrow 1s_4$	727.2936	1.83e+06	107496.4166	3
$2p_3 \rightarrow 1s_4$	738.3980	8.47e+06	107289.7001	5
$2p_1 \rightarrow 1s_2$	750.3869	4.45e+07	108722.6194	1
$2p_4 \rightarrow 1s_3$	794.8176	1.86e+07	107131.7086	3
$2p_2 \rightarrow 1s_2$	826.4522	1.53e+07	107496.4166	3
$2p_3 \rightarrow 1s_2$	840.8210	2.23e+07	107289.7001	5
$2p_4 \rightarrow 1s_2$	852.1442	1.39e+07	107131.7086	3
$2p_7 \rightarrow 1s_3$	866.7944	2.43e+06	106087.2598	3
$2p_{10} \rightarrow 1s_5$	912.2967	1.89e+07	104102.0990	3

Table 3. Spectroscopic data of argon ion lines⁶ used for the calculation of excitation temperatures.

Wavelength (nm)	A_{ul} (s ⁻¹)	E_{ul} (cm ⁻¹)	g_u
442.6001	8.17e+07	157673.4134	6
460.9567	7.89e+07	170530.4040	8
487.9863	8.23e+07	158730.2995	6

The overall transitions considered for excitation temperature measurements are reported in Tables 2 and 3 respectively for Ar I and Ar II electronic levels. The Boltzmann plots obtained for typical conditions are reported in Figure 4 for argon neutral and ion.

IV. Results

The excitation temperature of Ar I and Ar II electronic levels and the population density of all four levels of the $1s$ group (following Paschen notation) have been determined in the region of RF power and magnetic field application during three distinct campaigns of OES measurements. During the first campaign, the effect of the applied RF power is evaluated starting from spectral intensity recorded radially. During the second and third campaign of measurements, the effect of the magnetic field, applied by means of the electro-magnets S1 and S2 respectively, has been evaluated on the basis of spectral intensity measured axially as specified in Section B. In these campaigns the applied RF power was kept constant and set to 750 W. Also, in order to assess the repeatability of the measurements and identify possible fluctuation of the plasma, the spectral intensity have been recorded several times for several operating conditions.

A. Effect of RF power

The spectral intensity measurements have been performed (without any application of magnetic field) starting from 200 W of applied power and by increasing by increment of 100 W up to 900 W and then decreasing from 900 W to 500 W. The calculated population density of levels of the $1s$ group and the excitation temperature of Ar I electronic levels are reported in Figure 5. As first observation, the density of $1s_5$ is higher than expected with respect to $1s_3$. Indeed, the density of the $1s_5$ metastable level exceeds the density of the $1s_3$ level by a factor of higher than 10 at 200 W and this factor increases with RF power augmentation. While

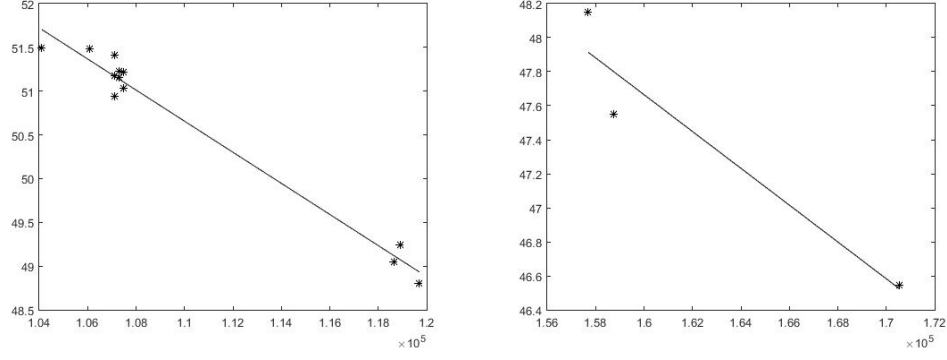


Figure 4. Typical Boltzmann plot. Left: electronic levels of Ar I. Right: electronic levels of Ar II.

the ratio of the statistical weights for these two levels would predict a factor of 5. Such difference could be attributed to the electron-induced excitation into higher levels which is more efficient for $1s_5$.⁷ Besides, it should be noted that the population density for all levels, decreases with the applied power. The density of the $1s_5$ metastable level is approximatively divided by a factor 2. Such decrease with applied RF power is also consistently observed on the excitation temperature profile, although it follows a less pronounced decay: $T_{ex} \approx 7800$ K at 200 W and $T_{ex} \approx 7100$ K at 900 W. Such odd feature is not intuitive and so far any satisfactory argument has not been found to explain the decrease of temperature with augmentation of applied RF power. This point will be inspected in the Section V.

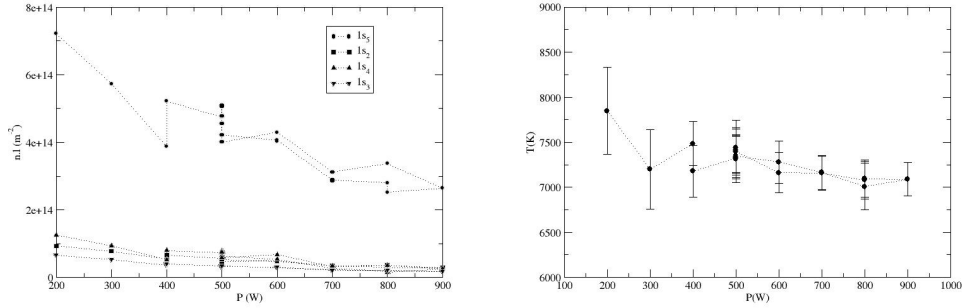


Figure 5. Left: Variation of the absolute number densities of the $3p^5 4s$ levels with applied RF power. Right: variation of the excitation temperature of Ar I with applied power.

B. Effect of magnetic field: S1

The spectral intensity have been measured with the application of magnetic field by powering the electro-magnet S1. The measurements have started with electro-magnet operated at 7 A, then the intensity was decreased by steps of 0.5 A up to 0 A (i.e. up to extinction of magnetic field) and then increased up to 9.5 A. The calculated population density of levels of the $1s$ group and the electronic level excitation temperatures are reported in Figure 6.

The same remarks can be formulated as in the previous campaign. The population density of $1s_5$ is higher than expected with respect to $1s_3$ and more oddly the population densities and excitation temperature for Ar I decreases this time with the augmentation of applied magnetic field intensity. However, the excitation temperature profile for argon ion follows a slightly different behavior, starting by increasing up to 1 A and then decaying over the rest of current intensity range. In comparison to argon neutral excitation temperature, the decay is nonetheless much more pronounced, going from about 17000 K at 1 A up to about 13500 K at

9.5 A.

In addition, the population density of $1s_5$ level exhibits a hysteresis-like behavior which still stands for the other levels but in a lesser pronounced manner. Depending on the variation of the applied magnetic field (increasing or decreasing), the measured population differs of about 30 %. Such puzzling feature could be attributed to a sensitivity of the RF impedance matching circuit to the magnetic field variation, substantiated by the difference observed in excitation temperature profiles (for Argon neutral and ion) following on the ascending or descending variation of magnetic field intensity.

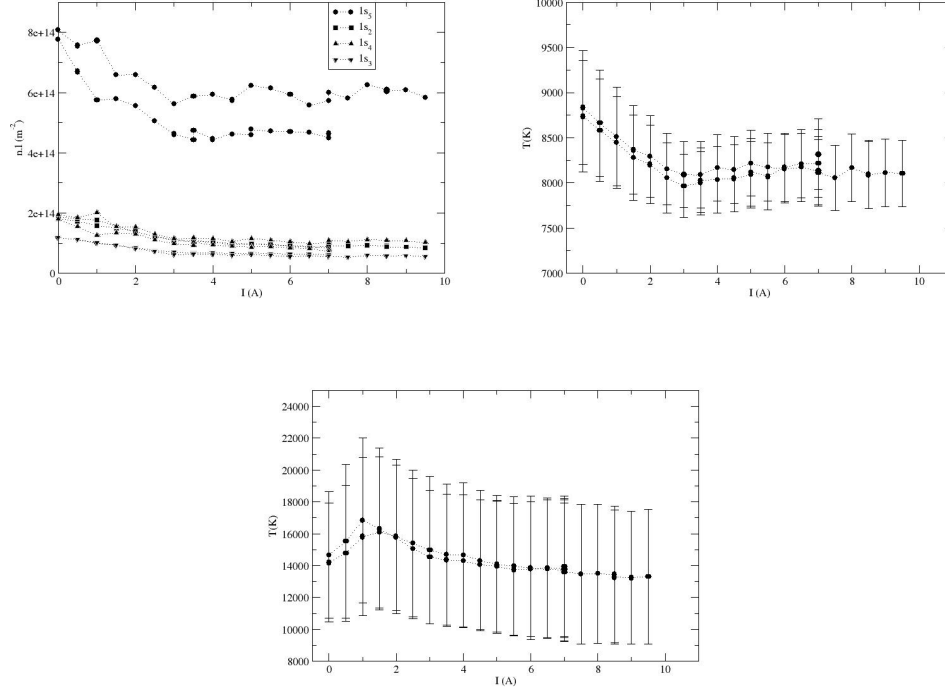


Figure 6. Left: absolute number densities of the $3p^5 4s$ levels. Right: excitation temperature of Ar I. Bottom: excitation temperature of Ar II. Variation with applied current intensity to S1 (RF power = 750 W).

C. Effect of magnetic field: S2

The spectral intensity have been measured for varying current intensity in the electro-magnet S2 and keeping a constant current intensity of 7 A to the electro-magnet S1. During this campaign, the measurements have been performed increasing current intensity from 0 to 7 A and then decreasing from 7 to 0 A. The calculated population density of levels of the $1s$ group and the electronic level excitation temperatures are given in Figure 7.

Again, the population density of $1s_5$ is higher than expected with respect to $1s_3$ as observed in the previous campaigns. Nevertheless, the evolution with increasing current intensity applied to S2 follows an opposite behavior. Indeed if the density profiles decreases from 0 to 2 A, beyond, the profiles substantially increase and are almost doubled for the case of $1s_5$ population density. Consistently the excitation temperature of Ar I follows the same behavior and, in a lesser extent the one of Ar II too. Note that, the hysteresis-like behavior well observed in the previous measurement campaign has vanished when S2 electro-magnet is operated.

V. Discussion and concluding remarks

The reported experimental investigations have enabled to provide significant information about the effect of operating conditions to the regime achieved by the plasma in its region of generation and confinement.

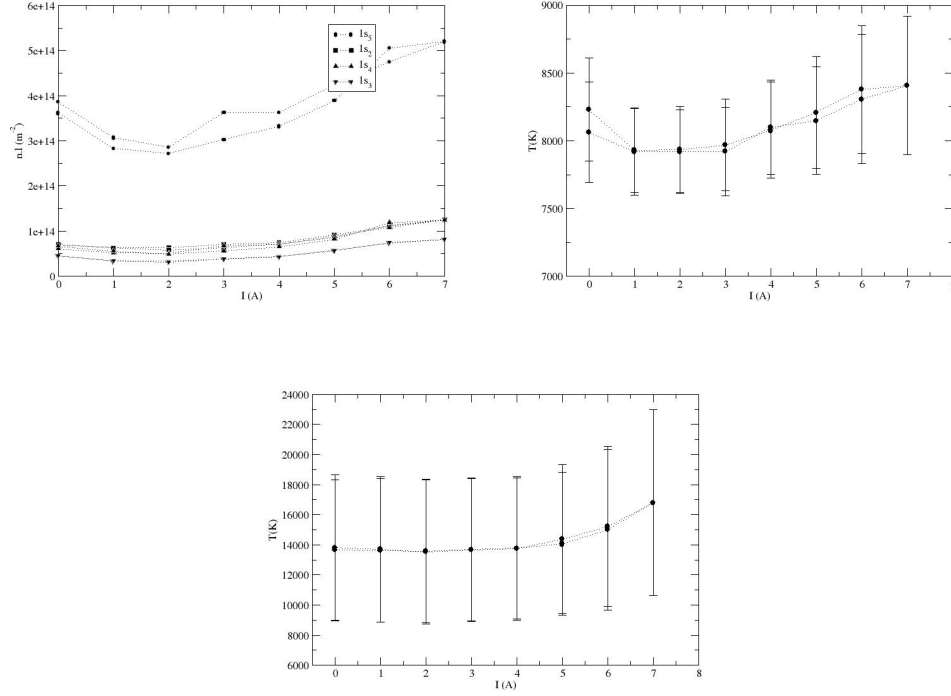


Figure 7. Left: absolute number densities of the $3p^5 4s$ levels. Right: excitation temperature of Ar I. Bottom: excitation temperature of Ar II. Variation with applied current intensity to S2 (S1 current intensity = 7 A. RF power = 750 W).

A significant outcome of the resulting measurements of the population densities of the $3p^5 4s$ levels and excitation temperature of Ar I and Ar II is that their respective evolution do not follow an intuitive behavior when is increased either the RF power or magnetic field intensity generated by S1 electro-magnet. Indeed, following on the increase of the power or magnetic field intensity at S1 stage, it came out that temperatures as well densities decrease. As mentioned before we did not find any meaningful argument to clarifying this trend, however such odd feature has been also observed and documented in analogous situation. The experimental investigations conducted by Drake *et al.*⁸ to characterize a microwave cavity discharge sustained in a supersonic flow of Ar/H₂/Air mixture have also given the same odd feature. By increasing the microwave power applied to the discharge they have reported a decrease of the temperature (excitation temperature of argon and gas temperature) measured by means of OES diagnostic. They attributed this “apparent paradox” to a loss of power subsequent to the surfaguide nature of the discharge obtained with their experimental setup (for details refer to Ref.⁸). Although their argument sounds fuzzy, such odd feature could stem to the discharge generation in a supersonic flow. Clearly, the question remains open and this point has to be elaborated more rigorously.

Besides, the major outcome of these investigations is the measurement of absolute population density of metastable levels in HPT-05, since it can be related to electron temperature and electron density by means of mere model describing the population loss and production mechanisms. In low pressure plasma such dynamic can be obtained using corona model assuming that upward transitions are all due to electron collisions while downward transitions occur only by radiative decay, implying that all the other de-excitation processes are irrelevant. Under our experimental conditions, this can be a reasonable assumption although the metastable-metastable ionization collisions can be important and can not be rigorously neglected (even in our pressure range ~ 0.1 -1 mbar). In the frame of that considerations, we use the analytical expression recently derived by Silva *et al.*⁹ to estimate the electron temperature in pure argon plasma. In their expression, the determination of the electron temperature T_e is based on the absolute density of $1s_5$ level and on the knowledge of the intensity ratio of transitions $3p_1 \rightarrow 1s_2$ to $2p_1 \rightarrow 1s_3$ which emission lines

are respectively located at 425.9 nm and 750.4 nm. The resulting electron temperature obtained for the second measurement campaign, when the electro-magnet S1 is powered, is documented in Figure 8. Hence, if the excitation temperature and consistently the density of 1s levels decrease, it turns out that finally the electron temperature increases, with applied current intensity, from 6 to almost 8 eV. Finally, with simple OES setup and using the least assumption necessary, it was possible to realize a fair estimation of the electron temperature achieved by HPT-05 operating with argon in a region not accessible to conventional probes.

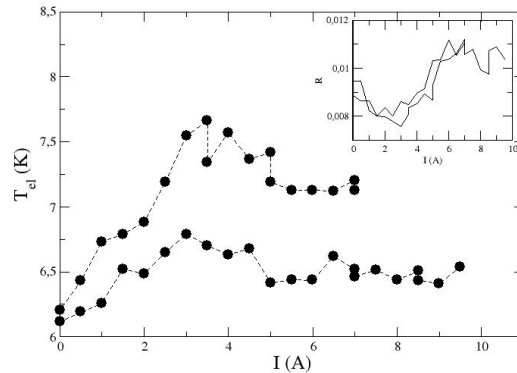


Figure 8. Electron temperature T_{el} when S1 is powered. In insert: line ratio R profile used in T_{el} evaluation

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