# **CHAPTER 3**

# RESULTS OF THE OPTICAL MEASUREMENTS

# **3.1 Results for the MPD thruster**

#### 3.1.1 Spectra of emitted radiation

In this section the spectra recorded with the optical probe of the OMA system placed both outside and inside of the vacuum chamber (see figures 2.7 and 2.8 in the chapter 2) are presented. As reported in Chapter 2, each spectrum is an average of three measurements recorded at the same nominal conditions (discharge current and external magnetic field) to reduce the background noise. We consider in fact two spectra characterized by an emission line having equal signal peak  $S_a$  and equal noise  $N_a$ . The resulting signal/noise ratio S/N, average of the two measurements, is given by the following relation:

$$S/N = \frac{2S_a}{\sqrt{2N_a^2}} = \sqrt{2} \frac{S_a}{N_a}$$
(3.1)

So, the signal/noise ratio is risen at 1.414. Taking the average of three measurements, the S/N will be about 1.732.

# Non intrusive probe configuration



Figure 3.1 – Recorded spectra at B = 40 mT,  $\Delta t = 0.5-1 \text{ ms}$ , different discharge current: I = 4500 A (a) and I = 7500 A (b).

Figure 3.1 shows the spectra observed in a test performed at B = 40 mT, for a time interval  $\Delta t = 0.5-1$  ms, and a discharge current

corresponding to I = 4500 A (3.1a) and I = 7500 A (3.1b). All recorded spectra are completely dominated by argon emission. Neutral argon lines (ArI) are detected in the wavelength range of 690 - 900 nm. On the other hand, singly ionized argon lines (ArII) are detected in the wavelength range between 400 and 500 nm.



*Figure 3.2* – *Recorded spectra at B* = 40 mT, *I* = 6000 A, *different time intervals:*  $\Delta t = 0.0.5 \text{ ms}$  (a) and  $\Delta t = 0.5-1 \text{ ms}$  (b).



Figure 3.3 – Recorded spectra at I = 4500 A,  $\Delta t = 0.05 \text{ ms}$  and different applied magnetic fields: B = 0 (a), B = 40 mT (b) and B = 80 mT (c).

Other emission lines of different elements has been detected, mainly oxygen and nitrogen due to residual air in the vacuum chamber, copper due to electrodes erosion, hydrogen and carbon due to the oil of the diffusion pumps. The intensity of ArII lines rises (about 3 - 4 times) when the discharge current is increased (see figure 3.1a and 3.1b). On the other hand, ArI lines remain very weak and only  $4p \rightarrow 4s$  transitions are detected. This indicates a condition of nearly full ionization.

In the figure 3.2, the spectra observed in a test performed at B = 40 mT, discharge current I = 6000 A for different time intervals  $\Delta t = 0.0.5 \text{ ms}$  (a) and  $\Delta t = 0.5-1 \text{ ms}$  (b) are shown. While a wean increase of ArII lines are observed, no particular trend is observed for ArI lines.

Figure 3.3 shows the spectra observed at I = 4500 A,  $\Delta t = 0.0.5$  ms and different external applied magnetic fields, B = 0 (a), B = 40 mT (b) and B = 80 mT (c). Without applied B, the ArII lines and ArI lines have comparable intensity (figure 3.3a). When the external magnetic field is applied, the intensity of ArII lines rises strongly (up to 100 times with B = 80 mT in figure 3.3c). Also the intensity of neutral argon lines increases, but less strongly and the spectra are totally dominated by singly ionized argon emission. Again, this indicates a condition of nearly full ionization.

#### Intrusive probe configuration

The spectra collected by the optical probe in position 1 of figure 2.8 are dominated by the argon emission. ArIII lines (doubly ionized argon lines) are recorded in the wavelength range of 320-350 nm, ArII lines in the range of 350-500 nm and ArI lines in the range of 690-900 nm. The intensity of the ArIII lines is comparable with ArII lines. As in the spectra with the detector placed outside the plasma plume, ArI lines are very weak and only

 $4p\rightarrow 4s$  transitions are observed. Impurities due to oxygen, nitrogen, copper, hydrogen and carbon are detected. In figure 3.4 the emission spectrum recorded in position 1 at a discharge current of 4500 A, without externally applied magnetic field, in the time interval  $\Delta t = 0.5$ -0.75 ms, is shown.



Figure 3.4 - Emission spectrum recorded in position 1 at  $\Delta t = 0.5$ -0.75 ms, B = 0 mT, I = 4500 A.



Figure 3.5 - Emission spectrum recorded in position 2 at B = 80 mT,  $\Delta t = 0.5 \cdot 0.55 \text{ ms}$ , I = 6000 A.

Due to these impurities present in the plasma, as already mentioned in chapter 2, the formation of a coat on the probe has been observed. The progressive degradation of the probe transparency, resulting from the mentioned coat, created difficulties when evaluating the relation of the spectrum intensities emitted at different thruster working conditions is performed, even if a general increase of emitted intensity should be observed.



Figure 3.6 - Emission spectra recorded in position 4 (a) and 5 (b) at B = 0 mT,  $\Delta t = 0.5$ -1 ms, I = 6000 A.

When the optical probe is placed inside the plasma near the exit of the thruster (position 2 through 5), marked lines from carbon and copper are observed. In these positions, the observed emission lines come mainly from ArII. Figure 3.5 shows a spectrum measured on position 2 at I = 6000 A, B = 80 mT, in the time interval  $\Delta t = 0.5$ -0.55 ms. In figure 3.6 the spectra measured in the peripheral positions 4 (a) and 5 (b) are shown. They both refer to a test at B = 80 mT, I = 6000 A and  $\Delta t = 0.5$ -1 ms. In the spectrum of figure 3.6(b) the continuum emission is an important contribution to the total radiation. Continuum emission can be observed only in position 2 and 5 which are in front respectively of the central cathode and of the anodic straps. Therefore, it can be due to the copper vapors.

Also for the spectra observed in the peripheral position 6, the observed emission lines come mainly from singly ionized argon. Again, a marked contribution of carbon and copper lines is observed. Figure 3.7 shows a spectrum measured at I = 7500 A, B = 80 mT, in the time interval  $\Delta t = 0.5$ -1 ms.



Figure 3.7 - Emission spectrum recorded in position 6 at B = 80 mT,  $\Delta t = 0.5$ -1 ms, I = 7500 A.

The analysis of the spectra recorded with the optical probe placed in different positions (both outside and inside the vacuum chamber) permits to illustrate in a qualitative way the distribution of the argon emission in the plasma plume. This scheme is shown in the figure 3.8.



Figure 3.8 - Scheme of the emission regions of the plasma plume.

#### **3.1.2 Calculation of the plasma parameters**

A plasma parameter of huge interest is the electron temperature, that is determined by means of the Boltzmann plot. The radiation intensity of a generic emission line  $I_n$ , in fact, is proportional to the spontaneous emission probability  $A^{n \rightarrow l}$  and to the population density of the up level of the transition  $n_n$ :

$$I_n = c_1 A^{n \to l} n_n \frac{hc}{\lambda_n}$$
(3.2)

If the particle density are distributed over the energy levels as Boltzmann distribution, then the relation holds:

$$\frac{n_n}{n_0} = \frac{g_n}{g_0} e^{\frac{-E_n - E_0}{kT_e}}$$
(3.3)

where  $T_e$  is the electron temperature. After the substitution of equation (3.3) into (3.2) and after some manipulations, the following relation is obtained:

$$y_n = \ln\left(\frac{I_n\lambda_n}{A^{n\to l}g_n}\right) = C - \frac{E_n}{kT_e}$$
(3.4)

Each equation (3.4) represents a point  $(E_n, y_n)$  in a semi-logarithm plot (also called *Boltzmann plot*). The slope of the line fitting the data points, obtained by several emission lines, is proportional to the electron temperature. If the points are perfectly aligned, the plasma is in partially local thermodynamic equilibrium (pLTE). Deviation from this equilibrium condition are reflected in the Boltzmann plot by a scattering of the points. In this case, the plasma is not characterized by a unique temperature and it is more appropriate to speak of excitation or population temperature.

An estimation of the electron density could be carried out by means of the ratio of two emission lines of the same element but proper to different systems (for example neutral and singly ionized). If the plasma is in local thermodynamic equilibrium (LTE), the neutral and singly ionized particle density,  $n_0$  and  $n_+$  respectively, are related together the by the Saha equation:

$$\frac{n_e n_+}{n_0} = \frac{2U_+}{U_0} \left(\frac{m_e k T_e}{2\pi h^2}\right)^{\frac{3}{2}} \exp\left(-\frac{\chi_i - \Delta \chi_i}{k T_e}\right)$$
(3.5)

where  $\chi_i$  is the ionization potential and  $\Delta \chi_i$  is the lowering of  $\chi_i$  due to Coulombian interactions. Writing the relation (3.2) for a neutral and singly ionized line and combining their ratio with (3.5), the following relation is obtained:

$$n_{e} = \frac{A_{+k}g_{+k}\lambda_{n}}{A_{n}g_{n}\lambda_{+k}}\frac{2I_{n}}{I_{+k}}\left(\frac{m_{e}kT_{e}}{2\pi\hbar^{2}}\right)^{3/2}\exp\left(-\frac{E_{+k}-E_{n}+\chi_{i}-\Delta\chi_{i}}{kT_{e}}\right)$$
(3.6)

Finally, the neutral density  $n_0$ , and then the ionization degree of the plasma, can be evaluated by means of the Saha equation (3.5). The validity of this method depends on the validity of the condition of pLTE for the levels of the transitions considered. It is well known from the theory of collisional-radiative processes that the upper levels of an atom reach a thermal distribution with the continuum of free electron more easily than the lower levels. Thus, it is possible to define the levels of an atom as being in pLTE from level p if equation (3.5) applies to it and all higher-lying levels. Many authors studied this problem. Griem [39], for example, studied how the emission of radiation affects the distribution with respect to excited states in hydrogen (or hydrogen-like ions) plasma. He found the following relation:

$$N_{e} \ge 7 \times 10^{18} \frac{z^{7}}{p^{\frac{17}{2}}} \left(\frac{kT_{e}}{z^{2}E_{H}}\right)^{\frac{1}{2}} cm^{-3}$$
(3.7)

where  $E_H$  is the hydrogen ionization energy and p is the effective principal quantum number defined as:

$$p = Z_{\sqrt{\frac{E_{H}}{E_{ion} - E_{p}}}}$$
(3.8)

Other criteria are presented by Wilson, Drawin, Biberman, McWirter and recently by Fujimoto [40],[41]. For atoms or ions that are not hydrogen-like, as the ArII system is, the applicability of these criteria is a critical point. Experiments on ArII, in fact, shows that the criterium (3.8) is too restrictive.

Another way to calculate the electron density is based on the line broadening theories. This method is to prefer because it does not require any hypothesis on the equilibrium condition in the plasma. Unfortunately, the OMA spectral resolution is in the range of 0.4-1 nm, too high to measure the line broadening.

Recently, a new density diagnostic method based on the emission line intensity ratio of neutral hydrogen is developed. The population density of excited levels, in fact, is evaluated by Fujimoto et al. for ionizing phase plasma in a wide range of electron densities  $(10^{17} \div 10^{21} \text{ m}^{-3})$  and temperatures  $(1.5 \div 10 \text{ eV})$  and under conditions of optical thinness for all of the radiation emission.

#### **3.1.2.1** Evaluation of the electron temperature

#### Non intrusive probe configuration

In the figure 3.9, a typical Boltzmann plot of excited states of ArII system is shown for a test at I = 7500 A,  $\Delta t = 0.5-1$  ms and B = 40 mT. From it, the excitation temperature  $T_{exc} \approx 10800$  °K is calculated. For all the test conditions, only the ArII emission lines are useful to calculate the temperature. ArI lines are in fact too weak and the up level energies of the transitions are distributed in the range of 0.5 eV. Not for all thruster working conditions, the temperature is calculated. In fact, at low current and without the applied B, also the ArII lines are too weak.



*Figure 3.9* - Boltzmann plot of the ArII system for a test at I = 7500 A,  $\Delta t = 0.5-1 \text{ ms}$ , B = 40 mT.

As previously reported, the OMA spectral resolution is too low to evaluate the line broadening. So, only maximum values are considered and integral intensities are calculated by an iterative procedure.



*Figure 3.10* - *Boltzmann plot of the ArII system* for a test at I = 6500 A,  $\Delta t = 0.5-1 \text{ ms}$ , B = 40 mT.

Another example of Boltzmann plot is shown in figure 3.10 for a test at I = 6500 A,  $\Delta t = 0.5-1$  ms and B = 40 mT (T<sub>exc</sub>  $\approx 11265$  °K).



Figure 3.11 – Excitation temperature vs. interval time at different currents and applied magnetic fields: B = 0 mT(a), B = 40 mT(b) and B = 80 mT(c).

Figure 3.11 shows the behaviour of the excitation temperature as function of time for different discharge current and applied magnetic fields: B = 0 mT (a), B = 40 mT (b) and B = 80 mT (c). The temperature is in the range of 0.9 - 1.3 eV and any particular trend is observable neither with the current nor especially with the applied B. Only for B = 80 mT, an increase of temperature with current is found.

These results are not well in agreement with previous temperature measurements by means of Langmuir probes performed in the same position by the research group of the "Consorzio RFX" (Padova) [29]. Tests have evidenced that electron temperature is in the range of 4 - 6 eV (without applied magnetic field) and 7 - 9 eV (with B = 40 mT). Moreover, values of electron density are in the range of  $10^{19} \div 10^{20}$  m<sup>-3</sup>. In order to evaluate if, in these conditions, the radiation is trapped into the plasma, the characteristic length for absorption of radiation is estimated. The absorption coefficient at the centre of the line is given by the following expression:

$$k_0 = \frac{\lambda_0^3 N_1 g_2}{8\pi} \frac{A_{21}}{g_1} \frac{A_{21}}{\sqrt{\pi}v_0}$$
(3.9)

where  $v_0$  is the line broadening,  $N_1$  is number density of lower state,  $\lambda_0$  is central wavelength,  $A_{21}$  is spontaneous emission coefficient,  $g_1$  and  $g_2$  are statistical weights and  $M_{atom}$  is the atomic mass. In these conditions of high electron temperature and low electron density, the dominant mechanism of line broadening is the Doppler effect and  $v_0$  takes the expression:

$$v_0 = \sqrt{\frac{2kT_{ion}}{M_{atom}}}$$
(3.10)

where  $T_{ion}$  is the ion temperature.

The inverse of the absorption coefficient expressed by the equation 3.9 is the free mean path  $\lambda$  of the radiation. This parameter is reported in table 3.1 for various ArI and ArII emission lines at two different radial positions: r = 0 (axial) and r = 115 mm.

	Emission lines [nm]	<u>λ<sub>ax</sub></u> [m]	<u>λ<sub>ax</sub></u> [m]	<u>λ<sub>115</sub> [m]</u>	<u>λ<sub>115</sub> [m]</u>
		$(T_i = 0.5 T_e)$	$(T_i = 6 T_e)$	$(T_i = 0.5 T_e)$	$(T_i = 6 T_e)$
ArI	811.531	1.526E+04	5.285E+04	5.426E+04	1.880E+05
ArI	763.510	4.909E+04	1.700E+05	1.746E+05	6.050E+05
ArII	480.602	1.009E-03	3.494E-03	2.178E-03	7.544E-03
ArII	473.591	2.351E-03	8.145E-03	5.076E-03	1.758E-02
ArII	484.782	2.576E-03	8.925E-03	5.567E-03	1.928E-02
ArII	434.806	5.858E-04	2.029E-03	1.265E-03	4.381E-03
ArII	442.601	1.133E-03	3.926E-03	2.449E-03	8.482E-03
ArII	433.120	2.231E-03	7.728E-03	4.820E-03	1.670E-02
ArII	437.967	2.882E-03	9.984E-03	6.229E-03	2.158E-02
ArII	487.987	7.375E-04	2.555E-03	1.597E-03	5.533E-03
ArII	454.505	7.577E-03	2.625E-02	1.642E-02	5.688E-02
ArII	457.935	1.490E-03	5.163E-03	3.228E-03	1.118E-02
ArII	458.990	7.426E-03	2.573E-02	1.610E-02	5.577E-02
ArII	460.956	9.998E-04	3.464E-03	2.183E-03	7.561E-03

**Table 3.1** – Calculated values of the mean free path of radiation for several ArI andArII emission lines at different electron and ion temperatures, referring to thefollowing experimental conditions: I = 7500 A and B = 40 mT.

Calculations show that the free mean path is of the order of few millimetres in the wavelength range of the singly ionized emission lines and is of the order of  $10^4 - 10^5$  meters at wavelength range. So, the plasma results optically thick in the wavelength range of ion lines and optically thin in the wavelength range of neutral lines.

In order to take into account the absorption of ArII radiation, their intensities are corrected by means of the escape factor g. Under the condition of moderate to low line-centre optical depth  $[k(\lambda_0)l \le 5]$  and line shape described by a single line broadening mechanism (Doppler, in this case), a simple expression for escape factor, solution of Milne theory, is derived<sup>5</sup>:

$$g = \frac{1}{1 + (k_0 L/\varepsilon)^2}$$
(3.11)

where  $\varepsilon$  is the first root of  $\varepsilon \tan(\varepsilon) = k_0 L$  and L is slab's thickness of the plasma. The results are presented in the figures 3.12 and 3.13 for the same conditions of figure 3.9 and 3.10 respectively.



*Figure 3.12* – Correction of the ArII system Boltzmann plot at the same test condition of figure 3.9.

Because of the ion temperature is unknown, the evaluation of the escape factor is performed at the following condition:  $T_{ion} = T_e$ .



*Figure 3.13* - Correction of the ArII system Boltzmann plot at the same test condition of figure 3.10.



*Figure 3.14* - *Excitation temperature vs. interval time after the correction at different applied magnetic fields and currents:* I = 6500 A (*a*), I = 7500 A (*b*).

In figure 3.14 the behaviour of excitation temperature with time after the correction at different applied magnetic fields and currents: I = 6500 A(a) and I = 7500 A (b) is shown. The application of the external B causes an increase of the temperature of about two times in agreement with the increase measured with the Langmuir probes.

#### Intrusive probe configuration

Figure 3.15 shows the line intensities (in relative units – r.u.) as a function of the energy of the upper levels for the test of I = 4500 A, B = 0 mT and  $\Delta t = 0.5-0.75 \text{ ms}$ , for the optical probe placed in position 1. The relative unit error is about 30% and it is determined mainly by the accuracy of the measurements.



Figure 3.15 - Boltzmann plot of the ArII system at  $I = 4500 \text{ A}, B = 0 \text{ mT}, \Delta t = 0.5-0.75 \text{ ms}.$ 

The lines used to calculate the temperature of ArII excitation levels are listed in table 3.2. In the table also their characteristic parameters [36] are reported.

λ [nm]	$E_k[eV]$	$g_k$	$A_{kj} (10^8 \text{ s}^{-1})$
480.602	19.22	6	0.79
434.806	19.49	8	1.30
433.120	19.61	4	0.64
457.935	19.97	2	0.92
458.990	21.12	6	1.05
460.956	21.14	8	1.13
358.844	22.95	10	2.98
397.936	23.08	2	1.16
399.479	23.85	2	1.66

**Table 3.2** - Characteristic values of Ar II lines used ( $E_k$  energy level,  $g_k$  statisticalweight of this level,  $A_{kj}$  transition probability).



**Figure 3.16** - Temperature  $T_H$  vs discharge current at different values of applied B in the start-up phase (a) and stationary phase (b).

The plasma is not in pLTE. The ArII levels can be divided in two categories: the high levels and the low levels. The high levels are characterized by an high excitation temperature  $T_H$ . The low levels are characterized by a low temperature  $T_L$ .  $T_H$  is close to the electron temperature  $T_e$  measured by means of Langmuir probes.  $T_L$  is much lower than  $T_H$ . In figure 3.16, the variations of  $T_H$  as a function of the discharge current with and without applied magnetic field in the time intervals  $\Delta t = 0$ -0.25 ms (3.16a) and  $\Delta t = 0.5$ -0.75 ms (3.16b), are shown. At these regime conditions,  $T_H$  assumes values between 3 and 9 eV.  $T_L$  is measured between 0.5 and 1 eV. When the external magnetic field is applied, a decrease of the  $T_H$  is observed.



Figure 3.17 - Temperature  $T_P$  vs discharge current at different values of applied B in the stationary phase evaluated with ArIII lines.

For ArIII system, the transitions corresponding to high energy levels are outside the wavelength range of the spectrograph (<300 nm). Therefore only the excitation temperature  $T_{exc}$  between low levels is calculated. Figure 3.17 shows the variations of  $T_{exc}$  as a function of the discharge current with and without applied magnetic field, in the time interval  $\Delta t = 0.5$ -0.75 ms.  $T_{exc}$  assumes balues between 2 and 3 eV and is not apparently dependent on I and B.

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As previously mentioned, the spectra observed by the probe placed inside the thruster (position 2 to 5), are strongly affected by the carbon and copper line emissions. Therefore, only an indication of the excitation temperature  $T_{exc}$  between a few ArII levels (tipically four or five in the range of 19-23 eV) could be derived. In figure 3.18  $T_{exc}$  as a function of the discharge current, with the probe placed in position 2, with and without applied magnetic field, in the interval time  $\Delta t = 0.5-0.55$  ms, is shown.



Figure 3.18 - Temperature  $T_{exc}$  vs discharge current in the peripheral position 2 at different values of applied B in the stationary phase.

In the figure 3.19, the variation of excitation temperature  $T_{exc}$  with working conditions, calculated with the probe positioned in the peripheral positions 4 (a) and 5 (b), is shown. For the position 5,  $T_{exc}$  does not show any particular trend with the working conditions. In particular, the application of external B does not affect the temperature probably because the focused region of the plasma is very close to the electrode (where the lines of current close) and the applied magnetic field is negligible respect to the self-induced magnetic field. On the other hand, in the position 4, a weak increase both with discharge current and external applied B is found.



*Figure 3.19* - *Temperature*  $T_{exc}$  *vs discharge current in the peripheral position 4 (a) and* 5 (b) at different values of applied B in the stationary phase.

#### 3.1.2.2 Comparison with the results of the CR model

The measured population distributions with the optical probe in position 1 (see figure 3.15) are compared with those calculated by the CR model. The results are shown in figure 3.20 for E = 100 V/m and  $N_e = 10^{19} \text{ m}^{-3}$ . The normalization level is at 19.97 eV. The two distributions are in excellent agreement. The CR model reproduces the double slope of the energy levels being to the observed transitions. The more pronounced

scattering of the lower calculated levels is probably due to the less accuracy of the cross section data.



*Figure 3.20* – *Comparison of the calculated and measured population distribution over the energy levels.* 

These results confirm the considerations on the mechanism populations reported in chapter 1. The radiative decay from the higher levels is an significant contribution of the low-lying levels. On the other hand, the high-lying levels (over 20 eV) are mostly populated by collisions with electrons. It should be noted that the separation level corresponds to the energy where the calculated electron energy distribution function departs from the Maxwellian form. So, it is evident the role of the high energy tail in the determination of the distribution over the levels of the argon ionized population. Finally, it can be observed as the population temperature  $T_H$  is 4-5 times lower than the calculated electron temperature giving a rough estimation of it.

# 3.1.2.3 Evaluation of the electron density

#### Non intrusive probe configuration

Because of the distribution of excited states of ArII in the Boltzmann plot do not consent to formulate any hypothesys on the state of this system (ionizing phase, recombining phase), the evaluation of the electron density is carried out by means of the equation (3.6). In figure 3.21 the variation of  $N_e$  with the discharge current, at different external applied B, in the interval times  $\Delta t = 0.5$ -1 ms (a) and  $\Delta t = 0.5$ -1 ms (b), is shown.



**Figure 3.21** – Electron density  $N_e$  vs discharge current at different B applied in the interval times  $\Delta t = 0.5$ -1 ms (a) and  $\Delta t = 0.5$ -1 ms (b).

The electron density is in the range of  $10^{18}$ - $10^{19}$  m<sup>-3</sup>, about one order lower than that ones measured by means of Langmuir probes, and do not show any particular trend when the external magnetic field is applied. Inserting the calculated values of N<sub>e</sub> into equation (3.7), an extimation of the boundary level p is performed. Results show that p varies between 6.6 and 7.3 which corresponds with excitation energy of 26.3 eV and 26.6 eV. These values are much higher than the high excitation energy level (21.14 eV) observed, but, as previously mentioned, the applicability of equation (3.7) at nonhydrogen-like atoms is critical. Spectroscopic measurements, in fact, show that for N<sub>e</sub> > 2×10<sup>19</sup> m<sup>-3</sup> the level 4p' <sup>2</sup>F[7/2] at 21.14 eV is collisionally dominated, demonstrating that the hydrogenic criterium is too restrective.

Finally, the neutral density  $n_0$ , and then the ionization degree of the plasma, are evaluated by means of the Saha equation (3.5). The neutral density is in the range of  $10^{14}$ - $10^{15}$  m<sup>-3</sup> showing that the plasma is fully ionized.

## Intrusive probe configuration

The emission line intensity ratio of the first two lines of the Balmer series ( $H_{\alpha}$  at 656.280 nm and  $H_{\beta}$  at 486.130 nm) is used to perform an estimation of the electron density for the probe placed in position 1. The results are shown in figure 3.22. The electron density is again in the range of  $10^{18}$ - $10^{19}$  m<sup>-3</sup> and is higher when the external magnetic field is switched on. The accuracy of these results depends completely on the excitation cross section data employed in the calculation of population density of excited levels of hydrogen. The accuracy would be about a factor of two. Also in this case, applying equation (3.7), values of p in the range of 5-7 are found. Nevertheless this, due to the previous considerations about its applicability, the energy levels higher than 21.14 eV are collisionally dominated and the temperature  $T_H$  provides a good extimation of electron temperature.



*Figure 3.22* - *Electron density vs discharge current at different values of applied B in the stationary phase.* 

Finally, calculation of neutral density shows that is again in the range of  $10^{14}$ - $10^{15}$  m<sup>-3</sup> and the plasma is fully ionized.

Unfortunately, due to the already mentioned impurities present in the plasma, it is not possible to perform any calculation of the electron density for the optical probe placed in the positions 2 to 6.

# 3.2 Results of the optical measurements on the RF discharge

Typical emission spectra recorded at 80 °C after 28 seconds from the ignition of the discharge are shown in figure 3.23 for the spectral range from 410 to 490 nm (a) and from 610 to 690 nm (b). Both spectra show

several spectral line of neutral argon which dominate the plasma emission in the entire spectral range from near ultraviolet to the red indipendently of the experimental conditions. The dominance of ArI lines is a consequence of the fact that the argon carrier gas presents 95% of the Ar-SiH<sub>4</sub> mixture. Besides ArI transitions, the Si-H line at 414.2 nm (a) and H<sub> $\alpha$ </sub> at 656.200 and He line at 632.8 nm are identified in figure 3.23. Due to the low spectral resolution of the OMA system, the R-branc and Q-branch of Si-H line are not detected.



Figure 3.23 – Spectra recorded for T = 80 °C and after 28 seconds from the ignition of the discharge.

#### 3.2.1 Time evolution of Si-H line

In figure 3.24 the evolution of the Si-H line at different gas temperatures is shown. At 17 °C the intensity increases rapidly to a maximum value within a few seconds after the ignition of the discharge, subsequently it falls down to a constant value. At 80 °C the behaviour is very similar, but a delay in the evolution occurs. This delay is most pronounced at 180 °C, when the intensity keeps rather constant at a low value until 53 s and then increases very slowly until it reaches a maximum value at about 120 s. Another notable effect of the higher gas temperature on the Si-H line is a decrease of the maximum line intensity. At 180 °C the value is 3 times smaller than at 17 °C. Obviously, this cannot be described by a simple temperature induced density effect, but reflects changes in plasma chemistry.



*Figure 3.24* – *Time evolution of Si-H emission line at gas temperatures* of 17 °C, 80 °C, 120 °C and 180 °C.

## 3.2.2 Time evolution of $H_{\alpha}$ line

The same considerations are true for the evolution of  $H_{\alpha}$  line plotted in figure 3.25. At 17 °C the intensity reaches the maximum value at 11 s and then keeps rather constant. At that time, also the Si-H intensity line reaches its maximum. When the gas temperature is increased, the same delay described for Si-H line is observed: the line intensity keeps constant during the first seconds and then increases more slowly than at 17 °C. At 180 °C, the maximum line intensity is only half that of 17 °C.



**Figure 3.25** – Time evolution of  $H_{\alpha}$  emission line at gas temperatures of 17 °C, 80 °C, 120 °C and 180 °C.

The initial increase in emission intensity is a well known effect caused by an increased electron temperature during the particle nucleation phase. In order to have an extimation of this effect, the time evolution of excitation temperature between two levels (15.19 and 13.48 eV corresponding respectively at the transitions 646.655 and 667.728) is carried out. The results show that the temperature increase from 0.8 to 2.53 eV. The subsequent stationary level of  $H_{\alpha}$  emission indicates a constant temperature and H density. The reduction in the Si-H emission thus must be explained by silicon consumption during particle growth. The simultaneous reduction of the maximum intensity of the Si-H and  $H_{\alpha}$  lines with increased temperature indicates a lower plasma activity and correlates with a lower particle production rate at higher temperatures.

# 3.2.3 Time evolution of He line and video camera recording

Reduced particle formation at elevated temperatures is supported also by the evolution of the laser light scattering signal plotted in figure 3.26.



*Figure 3.26* – *Time evolution of He emission line at gas temperatures* of 17 °C, 80 °C, 120 °C and 180 °C.

The intensity increases very slowly in the beginning of the discharge when particles are smaller and then increases rapidly due to the particle agglomeration. In this phase detector saturation is easily reached. At 180 °C, the signal is delayed and significantly smaller. Measurements of scattered light inside the plasma are combined with video camera recordings to visualise scattered light from particles, expelled by the plasma and coming out off the plasma chamber through the grid-slits. Again, the same trend is observed - the higher the temperature the longer it takes for particles to emerge and the smaller the scattered signal in the end. The time needed to see the first particles exiting the plasma chamber by eye is about 75 s after the ignition of the discharge at 80 °C, while at 120 °C it takes 115 s. These data correlate with the previously described electrical measurements. Again, we observe that with temperature all phases of particle formation are delayed. Moreover, the optical data show that the final overall particle density is lower at higher temperature.



**Figure 3.27** – Video images of the particles coming out of the slit in the discharge chamber: (a) – the discharge is running; (b,c) – the discharge is switched off. The particle cloud moves to the vacuum reactor wall taking the form of a sphere.

Figure 3.27 shows some pictures of the particles streaming out of the plasma, even though the plasma is contained inside the box by the grid. This shows that at high particle concentration large particles can also reach the electrode or the substrate even during plasma operation. When the discharge is turned off, particles trapped inside the discharge neutralize and flow out with the gas flow. This results in an easily visible burst of dust particles coming from the plasma chamber immediately after switching off

the discharge (figure 3.27b). The particle burst coming through the slit moves towards the vacuum reactor wall (figure 3.27c) and takes the form of a sphere. It should be noted that we observed the dust burst using a laser beam, so in reality particles flow in all directions.

From the video images, a drift velocity of about 7 cm/s of these particles is estimated. This is only slightly less than the calculated gas velocity (10 cm/s) at the slit exit. At a gas temperature of 180 °C, no particles leaving the discharge were detected by the video camera during plasma operation, only after switching off the discharge after about 285 s the particle burst is visible. Note that at this temperature the scattered light in the centre of the plasma (see figure 3.26) reaches a maximum after 150 s. This is probably caused by the fact that larger particles gather at the plasma sheath boundary, thus leaving the central plasma area.