Spectroscopic diagnostics for deriving electron temperature and density from an Argon plasma in GyM

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1. Introduction The electron temperature (T_e) and electron density (n_e) are important parameters for characterizing the plasma status in the Scrape-Off-Layer (SOL) and the divertor of magnetically confined fusion devices and investigating its physical and chemical properties in different operating conditions [1]. These parameters are usually derived locally using Langmuir Probes (LP), which are intrusive techniques. Optical diagnostics, such as Optical Emission Spectroscopy (OES), utilizing plasma radiation, offer a non-invasive complementary technique providing extremely powerful insights when supported by an accurate atomic modelling [2, 3].

This work focuses on the implementation of the OES technique to analyze an argon plasma in the linear device GyM and to derive an estimate of the line-of-sight averaged T_e and n_e. The spectrum arising from neutral and single ionized Ar is investigated to assess the feasibility of using ratios of emission line intensities from these two ions. Since accurate measurements of T_e and n_e depend critically on the theoretical atomic data underpinning the model, attention is given to the choice of appropriate atomic data and to the lines selected for comparing to measured ratios. In this work, GyM is used to test atomic data in a specific range of T_e and n_e in order to identify the critical issues, from both theoretical and observational points of view, which need to be improved to provide an accurate estimate of these plasma parameters. The experimental set up is discussed in Section 2, while the theoretical atomic modelling is described in Section 3. Finally, Section 4 provides the results derived by the model and a comparison with the values measured by LP, drawing the final conclusions.

2. Experimental setup GyM is a linear machine [4] consisting of a stainless steel (SS) vacuum chamber ($\varnothing$ = 0.25 m, length 2.11 m) mounted in a solenoid with an electron resonance magnetic field of 0.087 T. Plasmas are generated and continuously sustained by means of microwave power (up to

4.5 kW CW) at the electron cyclotron frequency 2.45 GHz. A SS liner (∅ = 0.20 m) covered with tungsten on its inner side has been mounted inside the chamber for plasma-wall interaction studies.
LP measurements provide local T_e and n_e values by extracting them from the 4-parameters fit of the Langmuir characteristics, assuming a Maxwellian electron energy distribution function [5].
In this work a comparison between OES and LP measurements has been made at three different values of the coil current (560 A, 655 A, 600 A) for three different values of the microwave power (600 W, 1500 W, 2400 W), at a pressure of 1.2×10^{-2} Pa (Table 1). The OES line-of-sight is perpendicular to the machine axis and the LP is placed at 1 cm from the machine axis at the same longitudinal position.

Table 1. Number of LP measurements and GyM parameters.

Num. of measurements	1	2	3	4	5	6	7	8	9
GyM conditions	560A 600W	560A 1500W	560A 2400W	655A 600W	655A 1500W	655A 2400W	600A 600W	600A 1500W	600A 2400W

3. Atomic model and diagnostic method A common technique to derive T_e and n_e from observed spectra is to use the ratios of two emission line intensities which arise from the same ion. The intensity of a spectral line emitted by an atom or an ion depends on the excited atomic population which is established by the interaction between the different species (atoms, ions, free electrons) collectively within the plasma through collisional and radiative processes and reflects the key plasma parameters, including T_e and n_e. The emissivity of a spectral line, $\varepsilon_{ji}=A_{ji}\ N_j$, depends on the spontaneous radiative transition probability, A_{ji}, and the population density of the upper excited level N_j. In a finite density plasma [6], such as the one produced by GyM, the population density N_j depends on T_e and n_e and should be calculated using a Collisional-Radiative (CR) model [7], rather than a simplified coronal (or zero-density) assumption. This approach has been fully developed in the ADAS (Atomic Data and Analysis Structure) code package[1], where the CR rate coefficients are available for all elements up to neon and extended to silicon and argon. Theoretical line ratios for Ar^0 and Ar^+ have been calculated using the population model routine ADAS208 with a Maxwellian energy distribution of the free electrons.

3.1. Density measurements from Ar^+ The principle for a line ratio n_e diagnostic is that one of the lines is connected to a metastable level (or term) [1]. For this work, two ratios from Ar^+ have been identified from the observed spectra with the above characteristics: $R_1 = I(Ar^+\ 487.6\ nm)/I(Ar^+$

[1] http://www.adas.ac.uk/

489.8 nm) and $R_2 = I(Ar^+ 436.1\ nm)/I(Ar^+ 465.4\ nm)$. The wavelengths in these ratios are term wavelengths rather than the individual lines within the multiplets. This is due to the theoretical atomic data only being resolved by terms. The dependence on n_e of the two ratios is shown in Figure 1.

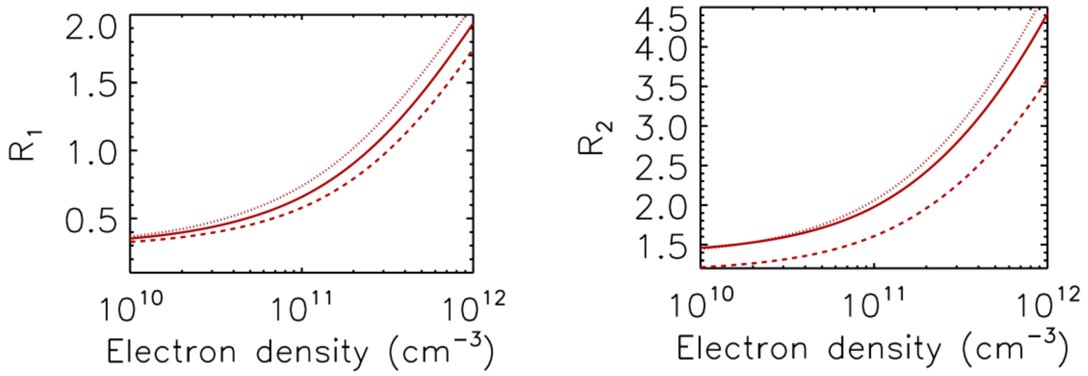

Figure 1. Theoretical ratios R_1 (left panel) and R_2 (right panel) for Ar^+ multiplets as a function of n_e, calculated at 4 eV (dotted line), 8 eV (solid line) and 15 eV (dashed line), using excitation rate coefficients from an R-matrix calculation [8].

3.2. Temperature measurements from Ar^0 For electron temperature the line ratio of the two lines must have different excitation energies [9]. Three ratios from Ar^0 have been identified: $R_3 = I(Ar^0\ 751.6\ nm)/I(Ar^0\ 738.6\ nm)$, $R_4 = I(Ar^0\ 463.7\ nm)/I(Ar^0\ 452.1\ nm)$ and $R_5 = I(Ar^0\ 463.7\ nm)/I(Ar^0\ 425.0\ nm)$. The theoretical atomic data have been revised by updating the radiative transition probabilities from the NIST[2] database. The dependence on T_e is shown in Figure 2.

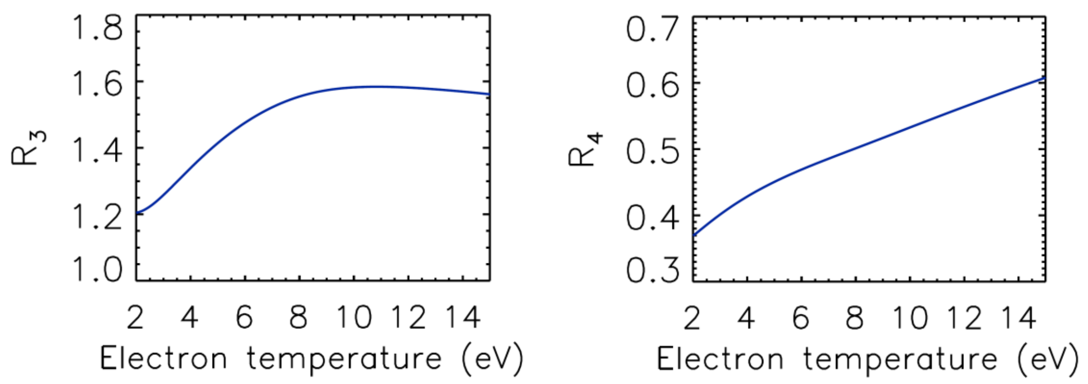

Figure 2. Theoretical ratios R_3 (left panel) and R_4 (right panel) for Ar^0 lines as a function of T_e, calculated at $n_e = 10^{11}\ cm^{-3}$. R_5 shows similar behaviour to R_4. The fundamental excitation data are from R-matrix calculations (Ballance 2015, private communication).

[2] https://www.nist.gov/pml/atomic-spectra-database

4. Results and Discussion Figure 3 shows the comparison between the values of n_e and T_e derived by the probe and the line ratio (LR) method, for the nine measurements listed in Table 1.

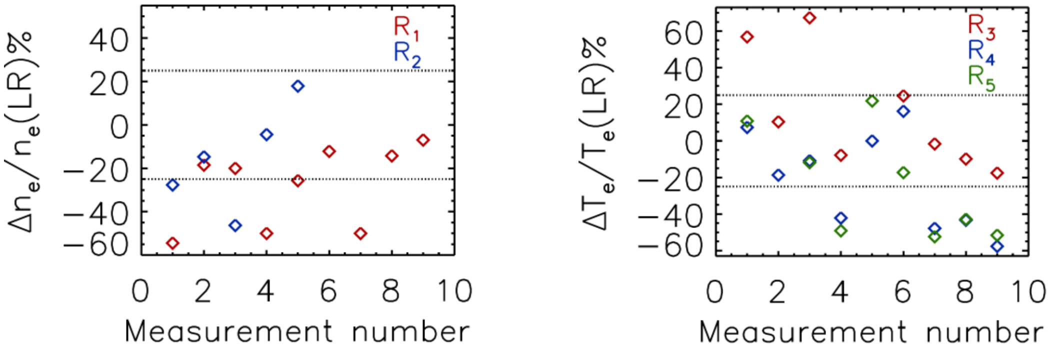

Figure 3. Percentage difference of the values of n_e (left panel) and T_e (right panel) , where $\Delta n_e = n_e(LP) - n_e(LR)$ and $\Delta T_e = T_e(LP) - T_e(LR)$. Note that the last three values of R_2 are not shown in the plot since the theoretical values were out of the measured density range. In addition, three percentage values are beyond ±70% and so not shown in the plots.

In most cases the agreement between LP measurements and the LR method is within 25%. However, in some cases the agreement is poor. Several possibilities, all of which necessitate a more sophisticated analysis, are under investigation. The LR value is averaged along the line of sight whereas LP is a local value. A fitting method combining line emission measurements which sample different parts of the T_e and n_e profile is being developed. The term-resolved excitation data for Ar^+ is not sufficient and new fundamental calculations are underway. The microwave heating may make the assumption of a Maxwellian electron distribution unsafe. A preliminary two temperature test reduced the discrepancy by ~5% and the effects of a more realistic distribution is under investigation. This work has shown the potential of OES based techniques as a viable diagnostic of GyM plasmas, but a more sophisticated approach than simple line ratios is needed for a robust interpretation of the measurements.

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