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Radiative properties of neutral Helium plasma

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Abstract

We investigate helium line emission from singlet and triplet levels showing advantageous diagnostic properties even for complex parameter conditions in ITER divertor plasmas: high density, opacity and interlocking effects. Particular attention is paid to the emission from the singlet levels at λ (1s3d ^{1}D – 1s2p ^{1}P) = 667.8 nm and λ (1s3s ^{1}S – 1s2p ^{1}P) = 728.1 nm and the triplet levels at λ (1s3s ^{3}S – 1s2p ^{3}P) = 706.5 nm, λ (1s3d ^{3}D – 1s2p ^{3}P) = 587.7 nm and λ (1s4d ^{3}D – 1s2p ^{3}P) = 447.1 nm. Data from complementary experiments (1. MISTRAL, PIIM laboratory, 2. High Density Discharge, LULI laboratory) are contrasted with theory to validate multilevel collisional radiative simulations which explicitly take into account singlet and triplet levels up to large quantum numbers (SOPHIA code [1]). The use of "ab initio" LSJ-split cross sections calculations carried out with the FAC-code [2] are tested.

I. Introduction

Helium is one of the most important species for plasma fusion magnetic confinement devices. In ITER recombining α-particles produced from fusion reactions lead to the formation of He^{1+} and He^{0+} and the corresponding line emission. Helium is also used in gas puffing for density control and plasma cooling in divertor physics. The analysis of the He radiation emission provides therefore the possibility for a wide and unique characterization of the plasma. Of particular interest are line emissions, which enable to characterise the plasma under extreme conditions: high density, opacity, particle transport, supra-thermal electrons and charge exchange coupling with the neutral hydrogen background. For these purposes, a complex atomic physics code “SOPHIA” [1] has been developed. In the present work we focus on He I line emission originating from the 1s3l and 1s4l singlet and triplet levels.

II.1 MISTRAL, PIIM Laboratory

The MISTRAL device is described in Figure 1. The magnetized plasma column is produced by primary energetic electrons (energy of several tenth of eV) coming from the 32 tungsten filaments located in the source chamber. The polarized fixed collector, at the end of the column, is used to collect the plasma electron current. During the experiments, the helium neutral pressure varies from 10^{-4} to 10^{-2} mbar. The homogeneous magnetic field is 200 gauss. The collimated spectroscopic line of sight allows to record the plasma light emission from the central plasma with a spectrometer device (Czerny-Turner configuration, focal length 1.25 m, resolution 3.5 pm/pixel). A polarized Langmuir probe was used to measure the electron temperature T_e and the electron density n_e.

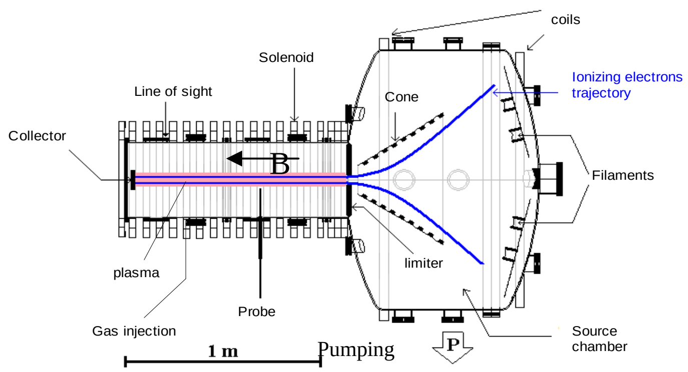

Figure 1 : Cross section of the MISTRAL device

II.2 High density discharge (HDD), LULI laboratory

A plasma channel (300 mA) is started by a high voltage of 30 kV for a few µs. The discharge is maintained by the use of a set of capacitors loaded by a voltage of 1-5 kV. The electron density can be varied from 10^{12} cm^{-3} (“simmer mode”) [6] up to some 10^{18} cm^{-3}, the temperature is a few eV. Several spectrometers in Czerny-Turner configuration are available. For the present experiments the spectrometer with a focal length of 25 cm and a corresponding resolution of 0.064 nm/pixel was used. The filling pressure in the capillary was 133 mbar.

III. Atomic physics in dense plasmas: SOPHIA simulations

The population densities n_j are calculated from a system of non-Maxwellian atomic population equations:

$$\frac{\partial n_j}{\partial t} + \nabla(\Gamma_j) = \sum_{i=1}^{N} n_i \{W_{ij} + A_{ij}\Lambda_{ij}\} - n_j \sum_{k=1}^{N} \{W_{jk} + A_{jk}\Lambda_{jk}\}$$

j runs over levels including all ionization stages, N is the total number of states. Γ_j is the related flux. A_{ji} is the spontaneous transition probability for a transition j $\rightarrow$ i, Λ_{ji} is the radiation transport operator and W_{jk} is the matrix containing all atomic physics processes. More details are described elsewhere [1, 3-5].

IV. Comparisons between experimental results and simulations of line ratios

In high density plasmas, photo-absorption of the He_β-resonance line (1s3p $^1P_1$ – $1s^2$ $^1S_0$) leads to a considerable photo-pumping of the 1s3p $^1P_1$ - level and subsequent collisional redistribution of this pumping to the closely located levels 1s3s ^1S and 1s 3d ^1D. Due to these interlocking effects the line emission at 667.8 nm and 728.1 nm is seriously perturbed although their line center opacity itself is negligible.

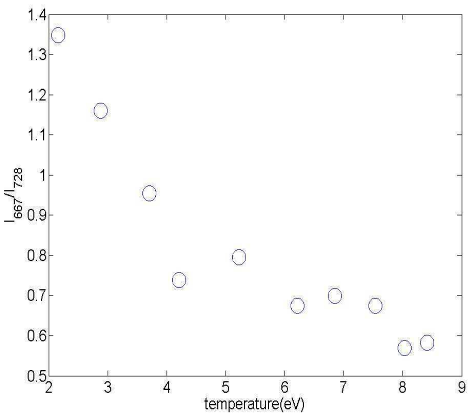

Figure 2 : Experimental line ratios obtained from the MISTRAL magnetised plasma

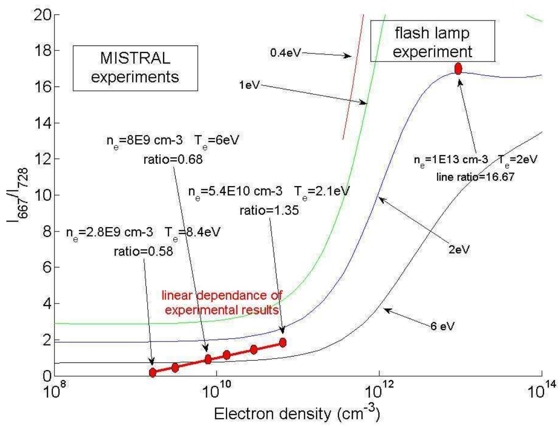

Figure 3: SOPHIA simulations employing ab initio cross sections from FAC

The experimental (MISTRAL) variation of the singlet line ratio I(667 nm)/I(728 nm) over a large range of temperatures is shown in Fig. 2. SOPHIA simulations (Fig. 3) show that for the density range of MISTRAL (10^8 – 10^{11} cm^{-3}), the ratio I_{667}/I_{728} is essentially sensitive to temperature. The agreement with experimental results is good especially for kT_e close to 6 eV. The line ratios I_{447}/I_{587} is in rather good agreement (exp.: 0.3, theory: 0.21), whereas other ratios are not always in good agreement: I_{587}/I_{706} (exp.: 0.7, theory: 1.7, but for kT_e = 2eV we have exp: 1.4, theory: 1.5), I_{728}/I_{706} (exp.: 1.0, theory: 0.16). Inconsistencies between experimental and numerical results are found to depend on T_e, for example, the theoretical ratio I_{587}/I_{706} is three times higher for T_e = 6 eV but is in good agreement for T_e = 2 eV. Two potential reasons can be identified: the temperature dependence of the cross sections is not quite correct or, the experimental conditions are such that for different temperatures also other parameters are changed (diffusion, suprathermal electrons,..) which are not included in the present simulations (note that dependencies on particle diffusion do affect the singlet and the triplet levels in a different manner).

Higher electron densities and somewhat more simple parameter conditions (means no diffusion, no suprathermal electrons) can be achieved in the LULI “HDD”-experiment. The simulations of the line ratios I_{667}/I_{728} (exp.: 16.7, theory: 16.4) and I_{728}/I_{706} (exp.: 0.048, theory: 0.045) are in very good agreement with the data for T_e = 2 eV and $n_e = 1.10^{13}$ cm^{-3} (low density) see Figure 3 (note, that for the HDD-experiment, probe measurements are impossible because the discharge tube is closed). Less good agreement, however, is obtained for ratios containing the line at 587 nm: I_{587}/I_{706} (exp.: 3.79, theory: 11.3) and I_{447}/I_{587} (exp.: 0.033, theory: 0.12).

In order to identify the possible sources of disagreement, implementation of different data sets, as well as recordings and simulations of the spectral distribution is in preparation.

Acknowledgements

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