Radiative properties of non-equilibrium helium plasma in the MISTRAL experiment : analysis with the collisionnal-radiatif code SOPHIA

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Abstract

Anomalous line intensities of neutral helium lines are observed in the MISTRAL magnetized plasma column that cannot be explained within the framework of standard collisional radiative model. Moreover, for the typical plasma temperatures in Mistral, the models predict ionic helium lines that are not observed. The SOPHIA simulations show that the combination of hot electrons with Bohm diffusion processes provides an overall satisfactory description of the experimental observations.

I. Introduction

Helium is an important component for plasma fusion magnetic confinement devices. It is present as ashes of the fusion reactions, and is also used in gas puffs for plasma density control purposes in the divertor zones. It can also be used for the measurements of edge plasma parameters [1]. Due to the great importance of helium in divertor physics, numerous small-scale experimental are developed in order to investigate fundamental physics issues [2,3].

II. Experiments

Energetic ionizing electrons (primary electrons) are emitted in the source chamber (1.2 m of diameter, 80 cm of length) by thermo-electronic emission of tungsten filaments. These energetic electrons are injected into the interaction chamber through a diaphragm to ionize the helium gas and create a plasma column. A 60 mm diaphragm limits the diameter of the plasma column. No primary electrons are present in the shadow of the diaphragm [4] and a Bohm radial diffusion of the plasma is observed [5]. The line of sight LOS1 allows the spectroscopic study of the plasma parallel to B, inside the central column and in the shadow of the diaphragm. The line of sight LOS2 is used to analyze the light emitted by the central plasma column, perpendicular to B. A complete description of MISTRAL can be found in ref.

6. The Fig. 1 shows the near-UV helium emission lines (Rydberg series 1s5p ^{1}P-1s2s ^{1}S and 1snd ^{3}D-1s2p ^{3}P) in the central plasma and in the shadow of the diaphragm (line of sight LOS1). The intensities of these lines are very sensitive to the experimental conditions. Moreover, no ionic helium lines are experimentally observed in MISTRAL.

III. SOPHIA simulations of spectra

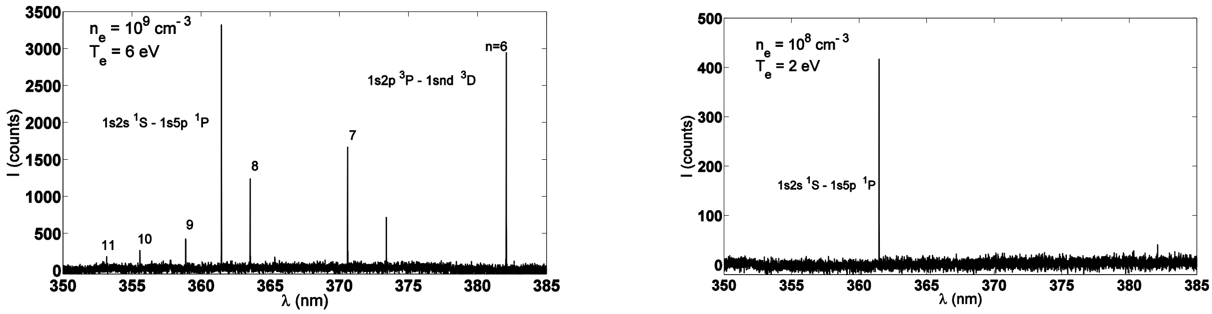

Fig. 1 : Experimental spectra in MISTRAL for LOS1 parallel to B looking at the central plasma column (left Fig., r = 0 cm) and in the shadow of the diaphragm (right Fig., r = 14 cm).

The theoretical results are obtained with the collisionnal-radiative code SOPHIA [7, 8, 9], that calculates atomic population densities employing an atomic structure in intermediate coupling LSJ. The atomic structure is spin resolved: HeIII, HeII (1s, 2s, 2p …) and neutral helium HeI (1snl 1L 1snl, 3L for n = 1-5 and l = 0-4, et nl, 1snl 1L et 1snl 3L for n = 6-9 and upper n = 9 scales laws are established). Two populations of electrons are taken into account in the SOPHIA code :

$$F(E,T_e,T_{ep}) = (1-f_{ep})F_e(T_e) + f_{ep}F_{ep}(T_{ep}) \qquad (1)$$

with $F_e(T_e)$ and $F_{ep}(T_{ep})$ being the energy distribution functions of the bulk cold electrons (temperature T_e) and of the energetic primary electrons (fraction of total population f_{ep}, temperature T_e), respectively. Their influence on helium spectra has already been shown [4]. However, this effect alone seems not to allow matching the experimental observations. The diffusion of particles can also have a strong influence on the populations of atoms and ions. This effect has been recently implemented in SOPHIA for the ground states of ionized helium [10]. In cylindrical coordinates, the atomic population equilibrium equations can be expressed as follows:

$$\frac{\partial n_i(r,t)}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left[rD_F(T_e(r))\frac{\partial n_i(r,t)}{\partial r}\right] = \sum_{j=1}^{N} n_j(r,t)W_{ji}(T_e(r)) - n_i(r,t)\sum_{k=1}^{N} W_{ik}(T_e(r)) \qquad (2)$$

W is the transition matrix [7], D_F is the diffusion coefficient due to frictionnal forces=1\20 $D_{Bohm}(T_e(r))$ [5] and D_{Bohm} is the Bohm coefficient. The radial distribution of electron temperature $T_e(r)$ is obtained with a Langmuir probe. Fig. 2 shows the SOPHIA simulations of the helium spectrum for the experimental conditions in MISTRAL corresponding to the spectra of Fig. 1.

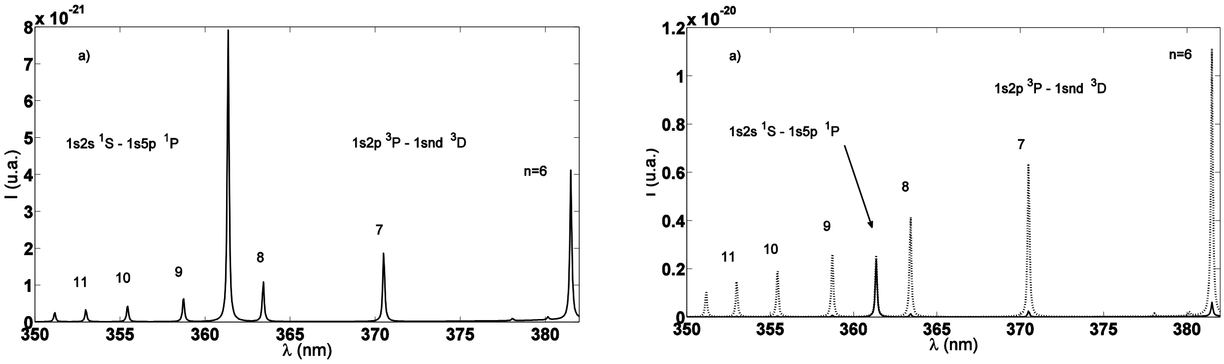

Figure 2 : calculated spectra with SOPHIA for the experimental conditions in MISTRAL (LOS1) in the central column (left Fig., r = 3 cm) and in the shadow of the limiter (right Fig., r = 14 cm), with (-) and without (--) the diffusion term in equation (2).

We observe that the diffusion of charged particles influences the ratios of emission lines for the transitions 1snd ^{3}D - 1s2p ^{3}P (Rydberg series) and 1s5p ^{1}P - 1s2s ^{1}S. This allows to retrieve the observed behavior of the helium spectra in MISTRAL. For diffusion coefficient larger than 1\20 D $_{Bohm}(T_e(r))$, a saturation effect is observed : the line ratio are no longer influenced [4]. SOPHIA simulations with diffusion of ground states of ionized helium explain also drastically reduced HeII emission in MISTRAL.

The figure 3 shows the comparison of the calculated and experimental emission lines ratios HeI(667nm)/HeI(728nm) and HeI(587nm)/HeI(706nm) corresponding to the transitions n=3→n=2 for singlet and triplet levels, respectively. 5 % of primary electrons are considered in SOPHIA for these calculations, with and without diffusion.

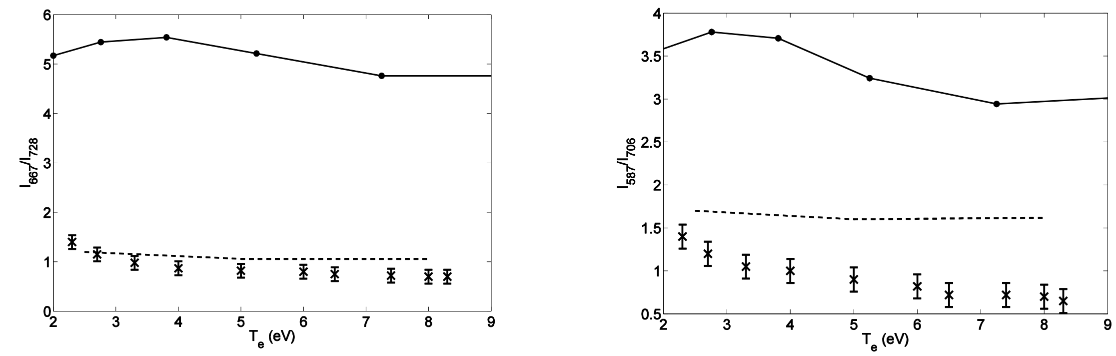

Fig. 3 : Intensities lines ratios HeI(667 nm)/ HeI(728 nm) and HeI(587 nm)/ HeI(706 nm): experimental (×), theoretical with $n_e = 3x10^9$ cm^{-3}, 5% of primary electrons 65 eV without (ө) and with (- -) diffusion.

The implementation of the diffusion of ions leads to a noticeable lowering of the populations of the excited levels 1s3d ^{3}D (upper level of HeI(587.6 nm)) and 1s3d ^{1}D (upper level of HeI(667.8 nm)). This leads to a good agreement between theoretical and experimental results for the emission line ratio HeI(667 nm)/ HeI(728 nm). The calculated emission line ratio HeI(587 nm)/ HeI(706 nm) are in better agreement with the experimental values when considering diffusion compared to the case without diffusion.

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