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Influence of hot electrons on radiative properties of helium plasma in MISTRAL-B

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Abstract

Space resolved spectroscopic investigation of the helium driven MISTRAL-B plasma experiment have shown anomalous large emission of the singlet lines 1s2s ^{1}S – 1snp ^{1}P compared to the triplet lines 1s2p ^{3}P – 1snd ^{3}D. Theoretical analysis carried out with the non-Maxwellian SOPHIA code indicate that hot electrons play an important role for the radiation emission. The simulation parameters are consistent with Langmuir probe measurements.

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 the possibility for a wide and unique characterization of the plasma. A large impact from the spectroscopic analysis stems from the fact that it is essentially based on a collisional-radiative approach and therefore provides a plasma model independent information.

II. Experiment

The MISTRAL-B device is described in figure 1. For more details, see reference 1, 2 and 3. the magnetized plasma column (solenoid S, with B_{max} = 0.03 T) is produced by primary energetic electrons (energy of several tenth of eV) coming from the source plasma. A positively polarized fixed plate FC (3 cm in diameter) is used at the end of the column to collect the plasma electron current. During the experiment, the helium neutral pressure was kept at about 4×10^{-1} Pa. The collimated spectroscopic line of sight LOS1 allows to record the plasma light emission from the central plasma with a spectrometer device. The anomalous helium spectra, influenced by the primary electrons, are observed in this configuration. A plane polarized Langmuir probe was used to measure the electron temperature T_e while the electron density n_e was obtained with high frequency resonance probes connected to a network analyser [4]. A second plasma configuration is used to study the same spectrum without the influence of the primary electrons [5]. In this case, the relative biasing ΔV between two end collectors leads to an E×B extraction of the central plasma jet in the shadow of the limiter L with ion velocities of a few km/s [6] and no primary electrons. The collimated spectroscopic line of sight (LOS2) corresponding to this configuration is positioned inside this plasma jet, as indicated in figure 1. In this case, no light of the central plasma is seen by the spectroscopic device.

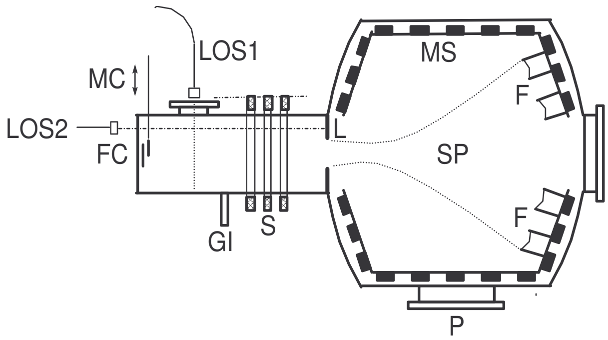

Figure 1 : MISTRAL-B experimental device. SP: source plasma ; F: filaments ; MS: ferrite magnets ; P: pumping system ; L: limiter ; S: solenoid ; GI: gas injection ; FC : fixed collector ; MC : moving collector (ΔV); LOS1 : line of sight 1 (radial observation of central plasma) ; LOS2 : line of sight 2 (axial off-axis observation of the ejected plasma).

II. Analysis of the neutral helium line emission

The upper and lower right spectra of Fig. 2 were observed in the first and second experimental configurations, respectively. The two spectra differ essentially in the relative intensity of the singlet line $1s2s\ ^1S - 1s5p\ ^1P_1$ (indicated by arrow). When the Langmuir probe is positioned inside the central plasma, the ion saturation region of the probe current characteristics shows a slope indicating the presence of hot electrons coming from the source plasma. A detailed analysis of the probe current versus its polarization, gives an estimation of the hot electrons population of a few percents [7]. Radial measurements of n_e and T_e with probes do not show inhomogeneities larger than ±10 % of their mean values and serious effects on the spectra are therefore not expected. The mean electron temperature and density found with the probes in the central plasma are : $kT_e = 2.4$ eV and $n_e = 4.8\cdot10^9$ cm^{-3}. In the ejected plasma, we obtain : $kT_e = 0.7$ eV and $n_e = 7\cdot10^9$ cm^{-3}.

The simulation of the spectral emission has been carried out with the non-Maxwellian version of the SOPHIA-code [8]. The spectral emission is given by

$$I(\omega) = \sum_{i,j} \hbar\omega_{ji}\, n_j\, A_{ji}\, \Lambda_{ji}\, \Phi_{ji}(\omega).$$

A_{ji} is the spontaneous transition probability for a transition j → I, Λ_{ji} is the radiation transport operator and Φ_{ji} is the line profile. The population densities n_j are calculated from a system of non-Maxwellian atomic population equations:

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

j runs over all levels including all ionization stages, N is the total number of states. Γ_j is the related flux. For the present simulations particle transport (e.g., diffusion, flow) is calculated in τ-approximation, i.e., the flux divergence term $\nabla(n_j V)$ is replaced by $\frac{n_j}{\tau}$. The non-Maxwellian rate coefficients are given by

$$X_{ij} = \int_{\Delta E}^{\infty} \sigma_{ij}^{X}(E)\, V(E)\, F(E) dE \qquad (3)$$

F(E) is the electron energy distribution function, σ the cross section and ΔE is the threshold energy. More details are described in [8, 9].

Figure 2 (left) shows the simulation of the spectral distribution of helium of the Rydberg series 1s2p ^{3}P – 1snd ^{3}D, n = 8 – 14 and the transition from the singlet system 1s2s $^1S_0$ – 1S5p $^1P_1$. The relative ratio of the singlet line and the triplet series is sensitive to hot electrons (see arrows) because the excitation cross sections for ΔS=0 and ΔS=1 transitions have a different asymptotic energy dependence. The investigation of non-Maxwellian electrons discovers, however, that they do not induce a large perturbation of the relative singlet and triplet emission because the ionization due to hot electrons masks this effect (which is included in the self-consistent SOPHIA simulations). However, a flow of neutrals can compensate this effect dramatically and a strong relative rise of the singlet emission is observed. The non-Maxwellian simulation shown in figure 2 (upper curve) shows very good agreement with the experimental spectra. In the experiment, neutral gas is flowing into the plasma channel which is heated by supra-thermal electrons being in agreement with the simulation analysis. The spectral emission observed in the outer part of the plasma (which is not heated by hot electrons) do not show a strong rise of the singlet line. This is also in agreement with the simulations. These results are corroborated by the Langmuir probe characteristics analysis which show the presence of a few percents of hot electrons in the central plasma. We note, that certain variation of the temperature and density parameters do not change the main effects discussed above.

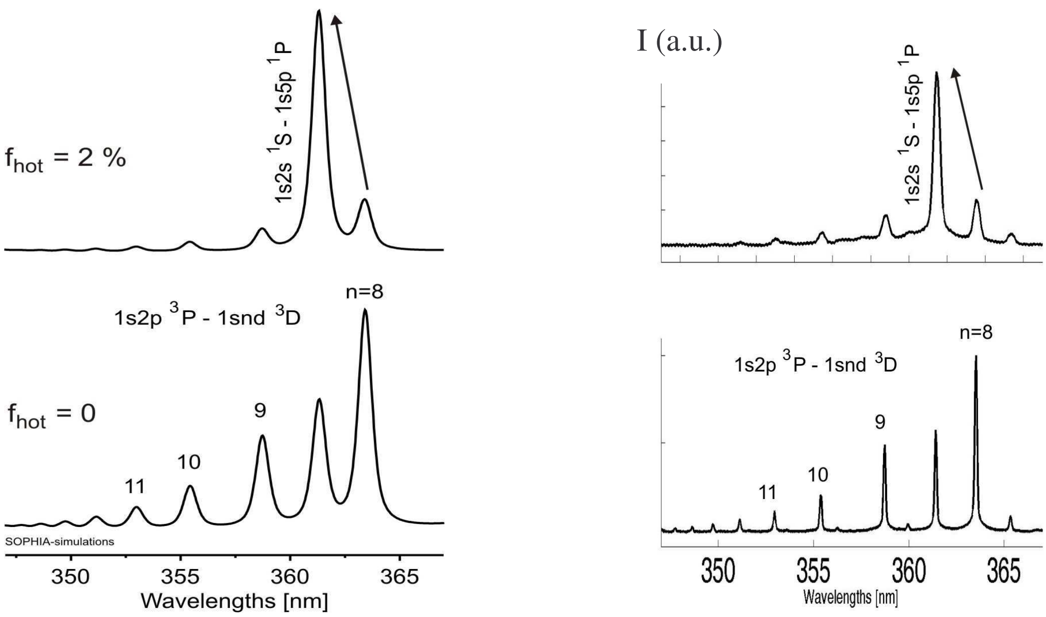

Figure 2: **Left spectra**: SOPHIA simulations of the spectral emission of Helium inlcuding hot electrons, $n_e = 10^{10}$ cm^{-3}, kT_{Bulk} = 3 eV, kT_{hot} = 85 eV, $\tau = 10^{-3}$ s, upper spectrum f_{hot} = 0.02, lower spectrum f_{hot} = 0.0. **Right spectra**: experimental spectra in MISTRAL-B with hot electrons (upper figure – 1st plasma configuration) and without hot electrons (lower figure – 2nd plasma configuration).

We therefore conclude that characteristics of supra-thermal electrons have been identified in helium plasma with the non-Maxwellian SOPHIA simulations which are in very good agreement with the observed emission spectra and Langumir probe measurements.

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