Non-CLTE spectral modeling approach for hydrogen pellet ablation cloud in the Large Helical Device

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Abstract. Spatially-resolved spectral measurement of a hydrogen pellet ablation cloud has been conducted in the Large Helical Device. Least square fittings of one of the obtained spectrum are inconsistent when the complete local thermodynamic equilibrium (CLTE) condition is supposed. A better agreement is found when a more general spectral model is used. The electron density of 1.4 × 10²³ m⁻³ obtained is similar to that obtained in a previous study [M. Goto et al., Plasma Phys. Control. Fusion 49, 1163 (2007)]. The electron temperature of 0.4 eV is however significantly lower than the value of 1 eV derived in the same previous study.

1. Introduction

In high density hydrogen plasmas, the complete local thermodynamic equilibrium (CLTE) is often supposed to extend the LTE condition to the atomic ground state [1]. In a previous study [2], the suggestion that the CLTE condition is valid in ablation clouds (or plasmoids) appeared from the spectroscopic observation of the temporal evolution of a plasmoid in the Large Helical Device (LHD).

However, in a subsequent study [3], the claim has been put into question after an inconsistent electron temperature profile has been obtained from the attempt to study the internal structure of a similar ablation cloud with a spectral model that supposed the CLTE condition. A possible explanation for this inconsistency is that the CLTE condition may not always be valid in plasmoids at any given location and time. The scope of the present study is to qualitatively verify if the CLTE condition is valid in the entire region of a plasmoid with a spectroscopic observation system that has been especially developed for that purpose [4].

Least squares fittings are conducted on a recorded spectrum in an attempt to reproduce the broadened isolated emission lines and the continuum radiation between 420 and 700 nm. Two spectral modeling approaches are taken. On one hand, the atomic ground state density is calculated from the CLTE condition. On the other hand, the atomic ground state density is seen as a fitting parameter in a newly proposed non-CLTE approach.

2. Experimental method and spectral model

The LHD is a magnetic confinement fusion experimental machine of heliotron type which is equipped with a fuel pellet injector [5] that has been used in some of the plasma discharges produced during the 19th LHD experimental campaign. Spectra of slices of plasmoids are
recorded with an observation system [4] that has a narrow band-shaped field-of-view. It should be noted that due to some design restrictions, the effective area of observation of this system is limited to the core region of the LHD plasma. Plasmoids cannot be observed while they are located in the edge region of the LHD plasma.

The spectral model used for the data analysis considers some of the isolated Balmer lines and the continuum radiation principally located between the Balmer-α and β lines. The input parameters of the model are the electron density \( n_e \) [m\(^{-3}\)], the electron temperature \( T_e \) [K], the volume of the observed slice of plasmoid \( V_s \) [m\(^3\)], and the ground state atom density \( n_{\text{a}} \) [m\(^{-3}\)] in the non-CLTE case only. No self-absorption effect is taken into account. The ion density \( n_i \) is interpreted through hydrogen plasma approximation \( (n_i \equiv n_e) \) and the electron velocity distribution function is supposed to follow Maxwell-Boltzmann statistics.

The intensity of the isolated lines is obtained from the spectral power \( \Phi_l \) [Wm\(^{-1}\)]. For an emission line associated with a transition \( p_1 \rightarrow 2 \) where \( p_1 \) is the principal quantum number of the upper level for the transition, the radiant power [W] is given as

\[
\int \Phi_l(p_1, \lambda) d\lambda = \frac{hc}{\lambda} A(p_1) n_{\text{a}} V_s, \tag{1}
\]

Here, \( A(p_1) \) [s\(^{-1}\)] is the Einstein coefficient for the transition \( p_1 \rightarrow 2 \) and \( \lambda \) is the wavelength of the photon produced by this transition. The lineshapes are calculated with a Stark-broadening database [6] with a given combination of \( n_e \) and \( T_e \). Each lineshape is then convoluted with a Gaussian instrumental function whose width is derived from spectra recorded during the recombinating phases of LHD plasmas. Due to the weak \( T_e \) dependence of the Stark-broadening, the lineshape of the Balmer-β line is first isolated from the continuum to derive \( n_e \). The obtained value is then fixed for the rest of the fit to ease the complexity of the procedure.

The continuum radiation consists of the radiative recombination continuum and the radiative attachment continuum. The radiative recombination processes considered occur between electrons and protons that settle into excited atoms. The spectral power of the radiative recombination continuum is equal to the product of \( V_s \) and the spectral power density \( \rho_{\text{rec}}(p_r, \lambda) \) [Wm\(^{-4}\)] which is given as a function of \( n_e \) and \( T_e \). The radiative attachment processes considered occur between electrons and neutral particles in the atomic ground state that settle into negative ions. The spectral power of the radiative attachment process is obtained in a similar manner as the radiative recombination process and is given as a function of \( n_e \), \( T_e \), and \( n_{\text{a}} \).

Two approaches are taken as to how \( n_{\text{a}} \) is processed by the spectral model. In the non-CLTE case, \( n_{\text{a}} \) is considered as an independent fitting parameter. In the CLTE case, \( n_{\text{a}} \) is calculated from the Saha-Boltzmann equation such that

\[
n_{\text{a}} = \left( \frac{h^2}{2\pi m_e k_B T_e} \right)^{3/2} \exp \left( \frac{R_H}{p^2 k_B T_e} \right) n_e n_i, \tag{2}
\]

where \( R_H \) [J] is the Rydberg constant for hydrogen atoms.

3. Results and discussion

The spectrum analyzed in this study is plotted with dots in Fig.1. The least squares fitting results with CLTE and non-CLTE cases are also shown with the dashed and solid lines, respectively. The background-subtracted Balmer-β line profile is first fitted with the Stark broadening profile and \( n_e = 1.4 \times 10^{23} \text{ m}^{-3} \) is derived. The Balmer-α line is discarded from the fitting due to a signal saturation problem and a probable self-reabsorption contribution that has already been observed under similar plasma conditions [2].

The CLTE fitting gives \( T_e = 1.0 \text{ eV} \) and the synthetic spectrum is significantly different from the experimental data, especially in the continuum located between the Balmer-α and β
Figure 1. Experimental spectrum (dots) collected from a slice of plasmoid and fitting results for the CLTE condition (dashed-line) and the non-CLTE approach (continuous line).

lines. The region near the Balmer-γ line is overestimated as well. Therefore, the CLTE fitting is judged inappropriate for the present situation. The non-CLTE fitting gives $T_e = 0.4 \text{ eV}$ and $n_a^1 = 3.2 \times 10^{26} \text{ m}^{-3}$. The obtained spectrum shows satisfactory agreement with the measurement. With $n_a^1$ given independently from $T_e$ and $n_e$, the newly proposed fitting procedure allows for the height and the slope of the continuum to be adjusted separately from the line intensities.

The most noticeable change comes from $T_e$ which is far below 1 eV, which is the approximate result obtained in the previous studies [2, 3]. This difference could explain why CLTE is not established in the present plasmoid. The exact reason for such difference in $T_e$ is still unclear. However, it is worth to remember that, the present method only observes plasmoids as they are in the core plasma region of the LHD. The plasmoids observed in the previous studies mostly evolved in the edge plasma region of the LHD. It is possible that the characteristics of a plasmoid differ in respect to where it is in the background plasma.

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