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Time-dependent analysis of visible helium line-ratios for electron temperature and density diagnostic using synthetic simulations on NSTX-U

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Helium line-ratios for electron temperature (T_e) and density (n_e) plasma diagnostic in the Scrape-Off-Layer (SOL) and edge regions of tokamaks are widely used. Due to their intensities and proximity of wavelengths, the singlet, 667.8 and 728.1 nm, and triplet, 706.5 nm, visible lines have been typically preferred. Time-dependency of the triplet line (706.5 nm) has been previously analyzed in detail by including transient effects on line-ratios during gas-puff diagnostic applications. In this work, several line-ratio combinations within each of the two spin systems are analyzed with the purpose of eliminating transient effects to extend the application of this powerful diagnostic to high temporal resolution characterization of plasmas. The analysis is done using synthetic emission modeling and diagnostic for low electron density NSTX SOL plasma conditions by several visible lines. Quasi-static equilibrium and time-dependent models are employed to evaluate transient effects of the atomic population levels that may affect the derived electron temperatures and densities as the helium gas-puff penetrates the plasma. The analysis of a wider range of spectral lines will help to extend this powerful diagnostic to experiments where the wavelength range of the measured spectra may be constrained either by limitations of the spectrometer or by other conflicting lines from different ions. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4955286]

I. INTRODUCTION

Transient effects on atomic populations of neutral helium emission used for plasma characterization can become important, particularly when determining electron temperatures from combinations of ratios between lines populated from the two different helium spin systems (singlet and triplet ^1S and ^3S), where equilibrium models have shown a tendency of overestimating the value of electron temperatures during low electron density regimes ($n_e < 1.0 \times 10^{13}$ cm^{-3}).[1] It has also been observed that transient effects do not have a significant impact on electron density sensitive ratios.[1] A time-dependent model for line-ratio diagnostic becomes very useful when an average characterization of the local plasma electron temperatures and densities is sufficient without the need of high temporal resolution measurements, and when the selection of wavelengths of the measured lines is constrained due to instrument limitations. Ratios between the most intense lines are usually preferred due to their higher signal to noise ratio.

This work shows that in order to expand the applications of this powerful diagnostic to high temporal resolution characterization of plasmas, transient effects for electron temperature sensitive ratios can be greatly diminished by selecting spectral lines that originated within the same spin system. The order of the temporal resolution achieved with this method is inversely proportional to the value of the branching ratios of the specified spectral lines, which can vary from microseconds to tenths of nanoseconds. The analysis presented here employs synthetic emission analysis using low electron density ($n_e < 1.0 \times 10^{13}$ cm^{-3}) plasma conditions on NSTX,[2] and compares ratios between lines populated from both singlet and triplet spin systems. The visible lines selected for this analysis include: 318.7, 388.9, 447.2, 471.3, 492.2, 501.6, 504.8, 587.6, 667.8, and 706.5 nm. By eliminating transient effects, this powerful diagnostic can be more effectively employed during high temporal resolution characterization of plasma regimes such as ion cyclotron resonant heating (ICRH) conditions,[4] microwave generated plasmas,[5] edge turbulence characterization,[6,7] and high-speed imaging of edge turbulence.[8]

II. TRANSIENT EFFECTS ON LINE-RATIOS

The time evolution of the atomic states of helium during the gas-puff penetration through the plasma is caused by the different collisional interactions between the plasma charged particles and the orbital electrons of the introduced neutral atoms. During plasma conditions typically found in the SOL and edge regions, both collisional processes and branching ratios compete with each other, and all of the important interactions must be included in the form of a collisional radiative time-dependent coupled differential equation whose solution

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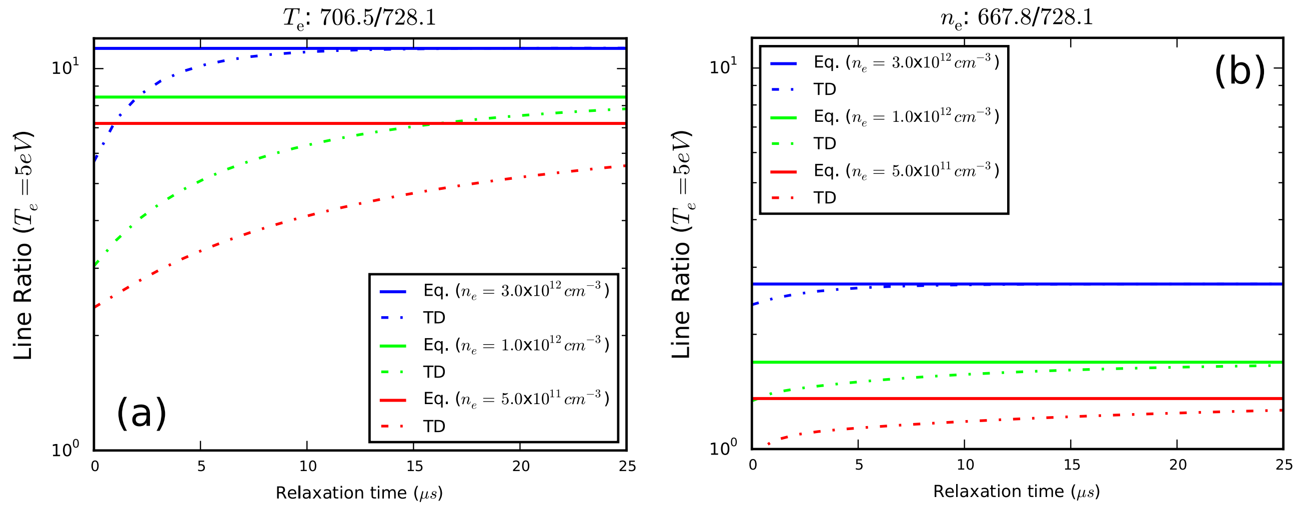

FIG. 1. Comparisons between equilibrium and time-dependent line-ratios as a function of relaxation time for three different electron densities using the standard helium lines (T_e : 706.5/728.1 and n_e : 667.8/728.1).[1,3,9] The solid lines represent the equilibrium (Eq.), while the dashed lines the time-dependent (TD) solution. (a) shows the significantly greater level of sensitivity to transient effects of the electron temperature dependent ratios in comparison to the electron density dependent ratios shown in (b). It is also noticed that the transient effects greatly diminish as the electron density increases; therefore, during higher electron density plasma regimes a time-dependent model is not necessary for diagnostic purposes.[1]

is given by[1]

$$n_{nl}(t) = \sum_{\gamma=1}^{N} V_{nl,\gamma} \sum_{\iota=1}^{N} V_{\gamma,\iota}^{-1} n_\iota(0) e^{\lambda_\gamma t}, \qquad (1)$$

where $n_{nl}(t)$ is the time-dependent atomic population of the nl-term, λ_γ, $V_{nl,\gamma}$, and $V_{\gamma,\iota}^{-1}$ are the eigenvalues and eigenvectors (and inverse eigenvectors) of the collisional radiative matrix, $n_\iota(0)$ are the initial populations at $t = 0$, while t represents the arbitrary relaxation time of the states.[1]

The quasi-static equilibrium solution assumes that the collisional processes are so frequent that the atomic populations equilibrate in a very short period of time, and therefore transient effects can be neglected. This approximation is often accurate within most fusion plasma conditions; however, for the case of helium the quasi-static approximation cannot always be applied due to the relatively long relaxation time of the triplet spin system populated from the metastable in comparison to the singlet. To illustrate the impact of transient effects on diagnostic applications, both equilibrium (Eq.) and time-dependent (TD) line-ratios between the standard helium lines 667.8, 706.5, and 728.1 nm[1,3,9] have been calculated. Figure 1 shows the comparison between both ratios using a scan of three different densities, and a set value for the electron temperature (T_e = 5.0 eV).

The introduced gas-puff into the plasma can be represented using a Gaussian distribution with a mean propagation velocity ~1.5 km/s.[3] For the relaxation times of t = 25.0 μs (Figure 1), the beam would have traveled an average distance of 3.75 cm through the plasma; therefore, the evolution of the atomic populations must be taken into account when interpreting ratios between lines from the two different spin systems, especially if high temporal measurement resolution is required. To diminish the transient effects on the plasma characterization, ratios of lines within the same spin system are selected.

III. SIMULATED EMISSION AND SYNTHETIC LINE-RATIO DIAGNOSTIC RESULTS

A 1-D kinetic collisional radiative model is used to simulate line-of-sight integrated intensities for different helium visible lines.[2] A Hybrid-Time-Dependent/Independent (HTD/I) helium line-ratio model is employed to derive electron temperature and density radial profiles.[1,2]

Figure 2 shows the simulated line emission and synthetic diagnostic results using different sets line-ratios to evaluate transient effects on the derived electron temperatures and densities.[1,2]

Figure 2(I) shows eleven different simulated helium line emission intensities in order to compare their magnitudes. (II) shows derived results from ratios between the commonly used singlet, 667.8 and 728.1 nm, and triplet, 706.5 nm, lines.[1,3] These lines have the advantage that besides being very close in wavelength and in intensity emission magnitude, they are also very sensitive to temperature and density; however, due to the ratio between triplet and singlet lines, the derived electron temperatures are very sensitive to transient effects.[1] These effects are responsible for the overestimation of electron temperatures for the equilibrium case (Eq.) in (II).[1] Figures 2(III) and 2(IV) show electron temperature profiles derived from ratios within the singlet (^1P and ^1P) and triplet (^3D and ^3S) spin systems, and as predicted, both of them appear to be insensitive to transient effects. Due to its lower gradient sensitivity with respect to temperature, (III) yields greater error bars than (IV).[1]

In order to assess the feasibility of a diagnostic using a determined set of spectral lines, synthetic analysis that takes into account the instrumental detection limit becomes necessary.[2] The specified diagnostic may also be limited by its wavelength range.

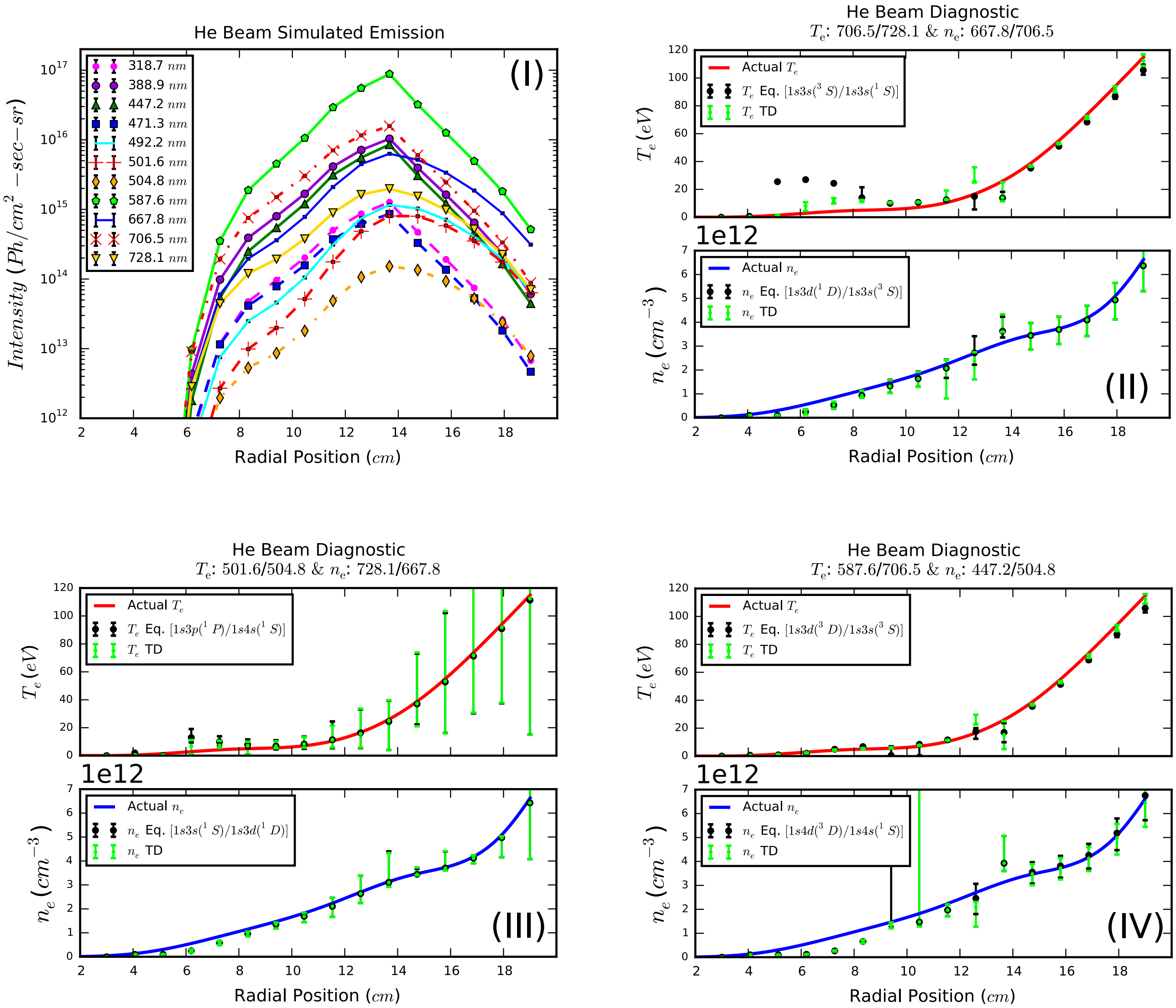

FIG. 2. Modeled line-of-sight integrated emission from helium gas-puff, as well as electron temperatures and densities derived from equilibrium (Eq.) and time-dependent (TD) line-ratio models.[1] (I) shows the simulated intensity emission for different spectral lines calculated using the radial and toroidally symmetric electron temperature and density profiles shown in the other figures.[2] (II) shows derived results from the most common sets of helium lines (667.8, 706.5, and 728.1 nm), which consist of ratios between both the singlet (^1S, ^1D) and triplet (^3S) spin systems. Notice that for derived electron temperatures using the ratio between lines that originated from different spin systems the transient effects become apparent by overestimating the equilibrium temperatures. This overestimation is consistent with measurements obtained from TEXTOR,[1] and it is characteristic during lower electron density regimes. (III) consists of ratios between lines that originated only within the singlet spin system (^1S, ^1P, ^1D). The higher error bars are the consequence of a lower gradient dependence of the ratios with respect to electron temperature.[1] (IV) employs ratios within the triplet spin system (^3S, ^3D) to derive electron temperatures, and combines ratios between the singlet and triplet (^1S, ^3D) to derive electron densities. This combination yields a higher sensitivity with respect to temperature, and thus it reduces the derived uncertainties; however, measurements of the 504.8 nm singlet line may be limited by the instrumental detection threshold due to its lower intensity of about two orders of magnitude with respect to the 447.2 nm triplet line.

IV. CONCLUSIONS

Transient effects on helium line-ratios between the two different spin systems particularly affect determination of electron temperatures. These effects can be greatly reduced by selecting ratios between lines within the same spin system. The analysis presented in this work suggests that electron temperatures derived from ratios within the triplet spin system are more sensitive than those from the singlet, and thus a lower level of uncertainty can be obtained. Eliminating transient effects in this powerful diagnostic removes the need of complicated time-dependent models,[1,10] and opens the possibility to applications that require high temporal resolution measurements;[4,5] however, the wavelength range and the intensity detection threshold of the instrument can limit the application of this powerful technique to high temporal resolution plasma characterization. These limitations can be overcome by employing filterscope systems that combine the use of photomultiplier tubes (PMTs) with narrow-bandpass filters for the specified wavelengths, and background subtraction. This approach has proven to increase signal-to-noise, and allowed simultaneous high sampling measurement rates.[4]

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